28th INTERNATIONAL KARSTOLOGICAL SCHOOL
"Classical Karst"

28. MEDNARODNA KRASOSLOVNA ŠOLA "KLASIČNI KRAS"

REGIONAL KARSTOLOGY - LOCAL AND GENERAL ASPECTS
* within International Year of Caves and Karst

REGIONALNO KRASOSLOVJE - SPLOŠNI IN LOKALNI VIDIK
*ob Mednarnodnem letu jam in krasa

ABSTRACTS & GUIDE BOOK

POVZETKI & VODNIK

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Postojna
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GENERAL INFORMATION

SPLOŠNE INFORMACIJE

PROGRAM

PROGRAM

Monday, June 14th, 2021 (CET, UTC+2) **Ponedeljek, 14. junij 2021 (SEČ, UTC+2)**	
9:00–9:15	**EVENT OPENING** / **OTVORITEV DOGODKA**
	SESSION 1 / **SKLOP 1** Conveyer: P-Y. Jeannin
9:15–10:00	*Home lecture* / *Domače predavanje* N. Zupan Hajna: International Year of Caves and Karst - karst, caves, and people worldwide
10:00–10:30	R. Watson: Connecting the dots - the inter-relationship between sinkholes, uvalas and conduits in evaporite karst at the Eastern Dead Sea shore, Jordan
10:30–11:00	V. Iurlii: Polycyclic speleogenesis and tectonics in Apulia (Italy), forty years later. A review and new data.
11:00–12:00	*Break* / *Break*
	SESSION 2 / **SKLOP 2** Conveyer: A. Tyc
12:00–12:30	T. Faulkner: The general model of cave development in the metalimestones of the Caledonide terranes
12:30–13:00	M. Todorović: The REE and trace elements in karst hydrogeothermal systems of Carpatho-Balkanides, Serbia
13:00–13:30	J. Tičar: Advanced approach in evaluating the cave pollution in Slovenia
13:30–14:00	J. Stemberk: The role of gravitational movements and active tectonics in the Driny Cave development in the Malé Karpaty Mts. (the Western Carpathians)
14:00–15:00	*Break* / *Break*
	SESSION 3 / **SKLOP 3** Conveyer: C. Ramsey
15:00–15:30	*Invited lecture* / *Vabljeno predavanje* G. Schindel: Emergency response strategies for hazardous materials releases in karst
15:30–16:00	T. Chen: Adapting to hazardous karst events with a novel machine learning approach
16:00–16:30	T. Stokes: What is needed for improving the reconnaissance karst potential mapping of British Columbia, Canada
16:30–17:30	*Home presentation* / *Domača predstavitev* F. Gabrovšek & M. Blatnik: The Classical Karst: History and current research trends

Tuesday, June 15th, 2021 (CET, UTC+2) **Torek, 15. junij 2021 (SEČ, UTC+2)**	
	SESSION 4 / **SKLOP 4** Conveyer: F. Gabrovšek
9:00–9:30	M. Blatnik: Ice thickness measurements in ice caves using terrestrial LiDAR scanner; examples from Slovenia
9:30–11:00	**POSTER SESSION** / **POSTERJI**
9:30–10:00	Quick poster presentations / Hitra predstavitev posterjev
10:00–11:00	Poster display in 3 groups / Ogled posterjev v treh skupinah
11:00–12:00	*Break* / *Break*
	SESSION 5 / **SKLOP 5** Conveyer: A. Gessert
12:00–12:30	*Invited lecture* / *Vabljeno predavanje* P. Audra: Monitoring of Mescla karst spring in the French Southern Alps: a rare case of stratified waters out of coastal areas
12:30–13:00	M. Marinić: Significance and comparison of sediments of Northern Velebit deep caves, Dinaric karst, Croatia
13:00–13:30	V. Johnston: Cave air and water monitoring of moonmilk-containing caves
13:30–14:00	J. Obu: What can patterned ground in karst caves tell us about Arctic carbon cycle?
14:00–15:00	*Break* / *Break*
	SESSION 6 / **SKLOP 6** Conveyer: F. Gabrovšek
15:00–16:30	**POSTER SESSION** / **POSTERJI**
15:00–15:30	Quick poster presentations / Hitra predstavitev posterjev
15:30–16:30	Poster display in 3 groups / Ogled posterjev v treh skupinah
16:30–17:30	*Home presentation* / *Domača predstavitev* C. Mayaud, U. Novak & N. Ravbar: Dinaric karst of Notranjska region

Wednesday, June 16th, 2021 (CET, UTC+2) **Sreda, 16. junij 2021 (SEČ, UTC+2)**	
	SESSION 7 / **SKLOP 7** Conveyer: L. Kukuljan
9:00–9:30	R. F. Muhammad: Tidal karst notches as indication of Holocene sea levels in peninsular Malaysia
9:30–10:00	M. Kázmér: Coastal karst in Bali (Indonesia) describes repeated late Holocene seismic uplift
10:00–10:30	M. Surić: Croatian coastal karst - treasury of karst features, yet just a piece of the global jigsaw
10:30–11:00	A. Švara: Active water cave Vodna jama v Lozi and Loza Unroofed Cave - a case of morphogenesis in the Slavina Corrosional Plain (SW Slovenia)
11:00–12:00	*Break* / *Break*
	SESSION 8 / **SKLOP 8** Conveyer: V. Johnston
12:00–12:30	W. Dreybrodt: Early hypogene carbonic acid speleogenesis in unconfined limestone aquifers: A model
12:30–13:00	A. Martín-Pérez: In situ formation of cryogenic calcite on seasonal ice in Snežna jama
13:00–13:30	R. Lončarić: Driving mechanisms and spatiotemporal variations of radon concentration in Modrič Cave (Croatia)
13:30–14:00	M. Breg Valjavec: Dolines - important soil organic carbon pools on Kras Plateau
14:00–15:00	*Break* / *Break*
	SESSION 9 / **SKLOP 9** Conveyer: M. Timo
15:00–15:30	*Invited lecture* / *Vabljeno predavanje* L. E. Panisset Travassos: Research possibilities in the Tropical Karst: past, present and future
15:30–16:00	V. Gajović: Preliminary analysis of vadose zone water pulses from Postojnska and Planinska jama drips, SW Slovenia
16:00–16:30	K. Voudouris: General characteristics of karst aquifers in Greece
16:30–17:30	*Home presentation* / *Domača predstavitev* F. Gabrovšek & N. Zupan Hajna: Dinaric karst of Primorska region

Thursday, June 17th, 2021 (CET, UTC+2) **Četrtek, 17. junij 2021 (SEČ, UTC+2)**	
	SESSION 10 / **SKLOP 10** Conveyer: N. Zupan Hajna
9:00–9:30	N. Kalantari: Hydrochemical and stable isotope methods to determine karstic aquifers water circulation in the Izeh area, southwest of Iran
9:30–10:00	D. Gillieson: Geoheritage and conservation of karst on Kangaroo Island, South Australia
10:00–10:30	E. Gokkaya: Development and morphological evolution of bedrock-collapse sinkholes in the Sivas gypsum karst, Turkey
10:30–11:00	S. Bahadorinia: Karst in arid Central Region of Kerman Province, Iran
11:00–12:00	*Break* / *Break*
	SESSION 11 / **SKLOP 11** Conveyer: D. Paar
12:00–12:30	M. Švob: Water flow in karst soil: implementing preferential flows in one-dimensional model
12:30–13:00	D. Grozić: Large scale test of ALS LiDAR data utilization for cave entrance detection: a case study from the UNESCO World Heritage Site - Plitvice Lakes National Park, Croatia
13:00–13:30	J. Knežević-Solberg: Building a Norwegian Cave and karst database
13:30–14:00	P-Y. Jeannin: Tunnels and karst springs, a case-study from the South-Eastern border of the Jura Mountains (Lake Biel, Switzerland)
14:00–15:00	*Break* / *Break*
	SESSION 12 / **SKLOP 12** Conveyer: T. Stokes
15:00–15:30	*Invited lecture* / *Vabljeno predavanje* D. Ford: Mahony and Tunago limestone plateaus and the Lac Belot hydration ridges, adjoining but contrasting karstlands in the lowlands of the Northwest Territories, Canada
15:30–16:00	R. Bosch: Landscape evolution of the Central Kentucky Karst
16:00–16:30	P. Griffiths: The Paradise Lost cover-collapse feature on northern Vancouver Island (British Columbia, Canada)
16:30–17:30	*Home presentation* / *Domača predstavitev* M. Blatnik & M. Petrič: Alpine karst
17:30–17:45	**EVENT CLOSING** / **ZAKLUČEK DOGODKA**

LIST OF POSTER PRESENTATIONS

SEZNAM PREDSTAVITEV PLAKATOV

Morning session / **Dopoldanski sklop**

	CORRESPONDING AUTHOR	TITLE
GROUP 1	Abdul Samad Umi Salmah	Qatar confirmed sinkholes
	Kalantari Nasrollah	Assessment of the karstic aquifers water flow using geological structure in the Izeh area, southwest of Iran
	Knez Martin	Lithomorphogenesis of karst surface - karren
	Lyu Xiaoxi	Riverine carbonate system, CO_2 partial pressure and CO_2 emission from a subtropical karst river network, South China
	Mazina Svetlana	Geochemistry of Snezhnaya cave system (Western Caucasus, Bzybsky Ridge)
GROUP 2	Ivanović Čeda	Underground of the Brskovo silver mine
	Kos Anja	Facilitating the use of subterranean biodiversity data in nature conservation - examples from Slovenia and Bosnia and Herzegovina
	Mulaomerović Jasminko	New findings of the water snail of the genus Emmericia in the karst springs of Herzegovina
	Ojovan Bianca-Oana	Cold active lipases from Scarisoara Ice Cave and their applicative potential
	Paun Victoria-Ioana	Ancient antimicrobial resistance in Scarisoara Ice Cave
GROUP 3	Ćalić Jelena	A comparison between the Dinaric and Carpatho-Balkan karst(s) in Serbia
	Selaković Tea	The influence of caves as an extreme environment on the physiological functions and mental state of individuals
	Šegina Ela	Regional undulations: an ultimate stage of the karst landscape?
	Vidić Pava	Morphogenesis research as basis for conservation and interpretation of karst landscape in the area of West Medvednica Mt. (Croatia)
	Vlatković Karla	Rockfall dynamics in caves: Velebit Mt., Croatia

Afternoon session / **Popoldanski sklop**

	CORRESPONDING AUTHOR	TITLE
GROUP 4	Krklec Kristina	Karst denudation measurements on North Dalmatian plain using rock tablet method
	Lipar Matej	Imaging solution pipes - case study from Miocene calcarenites in Poland
	Pondelicek Michael	Czech Karst as a part of Prague in last 20 Years
	Sala Przemysław	Healed speleothems in the Demänová Cave System (northern Slovakia)
	Schwarzová Mária	Karst relief denudation based on limestone tablets weight loss (Slovak karst)
GROUP 5	Bajraktari Fadil	The mountain of Akovan (Zatriq) Nature Karst Museum
	Čeligoj Biščak Jamsina	Development of research infrastructure (RI) for the international competitiveness of the development of Slovenian RI space - RI-SI-EPOS and RI-SI-LifeWatch
	Likar Mojca	Metagenomic insight into microbial communities of two pristine Karst aquifers
	Novak Uroš	The use of new technologies for understanding structural geology and hydrogeology of the karst unsaturated zone
	Vidmar Ines	Regional water balance analysis of karstic areas by remote sensing
GROUP 6	Dos Santos Macedo Songe Heleno	Importance of karst in Sergipe, Northeast Brazil
	Simoes Santos Matheos	Hydrological and physical-chemical processes and its controlling effect on the karst landscape in the Peruaçu river canyon, Cavernas do Peruaçu National Park, Minas Gerais, Brazil
	Sousa Lima Pericles	Map of karst phenomena of Natividade and Chapada da Natividade, Tocantins, Brazil
	Vajda Viktória Zsuzsanna	Changes in the hydrogen sulfide content of Hévíz thermal lake
	Vargas Danny	Preliminary results of speleothem U-Th dating and paleoclimate reconstruction from Garganta del Dino Cave (Ecuador)

INSTRUCTIONS FOR PRESENTATIONS

NAVODILA ZA PREDSTAVITVE

Meeting lobby

- For a better orientation during virtual conference we will establish a “lobby” with an access to the next elements:
    - Conference program
    - Book of abstracts
    - Meeting room
    - Virtual coffee room
    - Poster presentations
    - Recorded oral presentations

Oral presentations

- Due to virtual event, presentations will be given through ZOOM application and screen sharing.
- Maximum duration of the lecture is 25 min (25 min for talk and 5 min for discussion).
- Desired format of presentations are PPT or PDF, both 4:3 and 16:9 ratios are acceptable. Make sure, that presentation is functioning while sharing the screen.
- All sessions and questions after oral presentations will be managed by chairman. Questions will be collected in chat box (a tool in ZOOM).

Posters

- Due to virtual event, presentations will be given through ZOOM application and screen sharing.
- Posters will be presented in two ways:
    - 30 min long session for quick poster presentation – authors are invited to prepare a 2 min long PPT presentation with 1–2 slides to attract attention.
    - 60 min long session in which presenters will be divided in three rooms with 4–5 presenters, who will have an opportunity to present posters in more details (10 min).
- Both sessions including presentations and answering questions will be managed by moderator.
- Poster can be shown in any format, which enables sharing the screen, and keeping good resolution during zooming the details of poster. Make sure, that everything is functioning while sharing the screen.
- Authors are invited to send their posters to organizers before Wednesday 9th June to be uploaded to the “lobby”, where they will be accessible for viewing prior to the conference.

Konferenčno preddverje

- Za boljšo orientacijo ob izvedbi virtualne koference ob tej priložnosti pripravljamo virtualno "konferenčno preddverje" s povezavami do naslednjega gradiva:
    - Program konferecne
    - Knjiga izvlečkov
    - Povezava do virtualne konferenčne dvorane
    - Povezavca do virtualea kavne sobe
    - Povezava do posterjev
    - Povezava do posnetkov predavanj
    - Poster presentations

Predavanja

- Tekom virtualnega dogodka bodo predavanja izvedna prek platforme ZOOM ob delitvi zaslonske slike.
- Dolžina predavanja je omejena na 25 minut (25 minut za govor in 5 minut za razpravo).
- Zaželena je predstavitev v PPT ali PDF obliki, razmerje stranic pa 4:3 ali 16:9. Prosimo, da se predhodno prepričate, da vaša predstavitev normalno deluje ob delitvi zaslona.
- Sklope predavanj in vprašanja po predstavitvah bodo povezovali moderatorji. Vpršanja se bodo zbirala v oknu za klepet (orodje, ki ga omogoča ZOOM).

Posters

- Tekom virtualnega dogodka bodo predstavitve posterjev izvedne prek platforme ZOOM ob delitvi zaslonske slike.
- Posterji bodo predstavljeni v dveh oblikah:
    - 30 minutni sklop za hitre predstavitve – avtorje vabimo k pripravi 2 minutne PPT predstavitve z 1–2 diapozitivoma, kjer pritegnete pozornost na vsebino posterja.
    - 60 minutni sklop, v katerem predstavittve razdelimo v tri sobe s 4–5 predstavitelji, kjer bo priložnost za obširnejno predstavitev (10 minut) in razpravo.
- Oba sklopa hitrih in podrobnejših predstavitev vključno z razpravo bo povezoval moderator.
- Posterji so lahko predstavljeni v kakršni koli obliki, ki omogoča delitev zaslona in ohranja dobro ločljivost tudi ob povečevanju slike. Prosimo, da se predhodno prepričate, da vaša predstavitev normalno deluje ob delitvi zaslona.
- Avtorje naprošamo, da postejre posredujete organizatorju najkasneje do srede 9. junija, da jih lahko predhodno naložimo v konferenčno preddverje, kjer bodo udeležencem na voljo na ogled.

HOME PRESENTATIONS

DOMAČE PREDSTAVITVE

THE CLASSICAL KARST - HISTORY AND CURRENT RESEARCH TRENDS

Monday, 14. 6. 2021, Afternoon lecture

Matej Blatnik, Franci Gabrovšek, Andrej Mihevc

Klasični kras - zgodovina in trenutni raziskovalni trendi

Klasični kras obsega območje med Ljubljano (Slovenija), Trstom (Italija) in Reko (Hrvaška), zanj pa velja, da ima najdaljšo zgodovino znanstvenih raziskav kraških območij. Prvi geografski opisi teh območij segajo v antične čase, medtem ko so se intenzivne znanstvene raziskave pričele v 17. stoletju. Zaradi dolge zgodovine raziskav so se v mednarodni terminologiji uveljavile tudi nekatere besede s teh območij, kot so kras (v nekatere druge jezike preoblikovano kot "karst"), dolina, uvala, polje ali ponor. Na območju klasičnega krasa je bil prvi inštitut, ki je bil v celoti posvečen raziskavam krasa ustanovljen skoraj stoletje nazaj (1929). Osnoven namen je bil interdisciplinarna raziskava kraških območij, s takim ciljem pa deluje še dandanes.

Classical Karst is part of Dinaric karst roughly limited by a triangle with Ljubljana, Trieste and Rijeka in its vertices (Fig. 1.01 & 1.03). It comprises the recharge area of several important rivers eg. Ljubljanica, Reka and Rižana. The area is characterized by karst plateaus, eg. Javorniki, Hrušica, Nanos, Trnovski gozd and the most famous Kras/Carso, which presents an origin for widespread term "karst". Between plateaus there are large flat depressions – poljes, among which the best known are Planinsko and Cerkniško poljes. Surface is densely populated by dolines, collapsed dolines and unroofed caves, whereas underground by numerous karst caves.

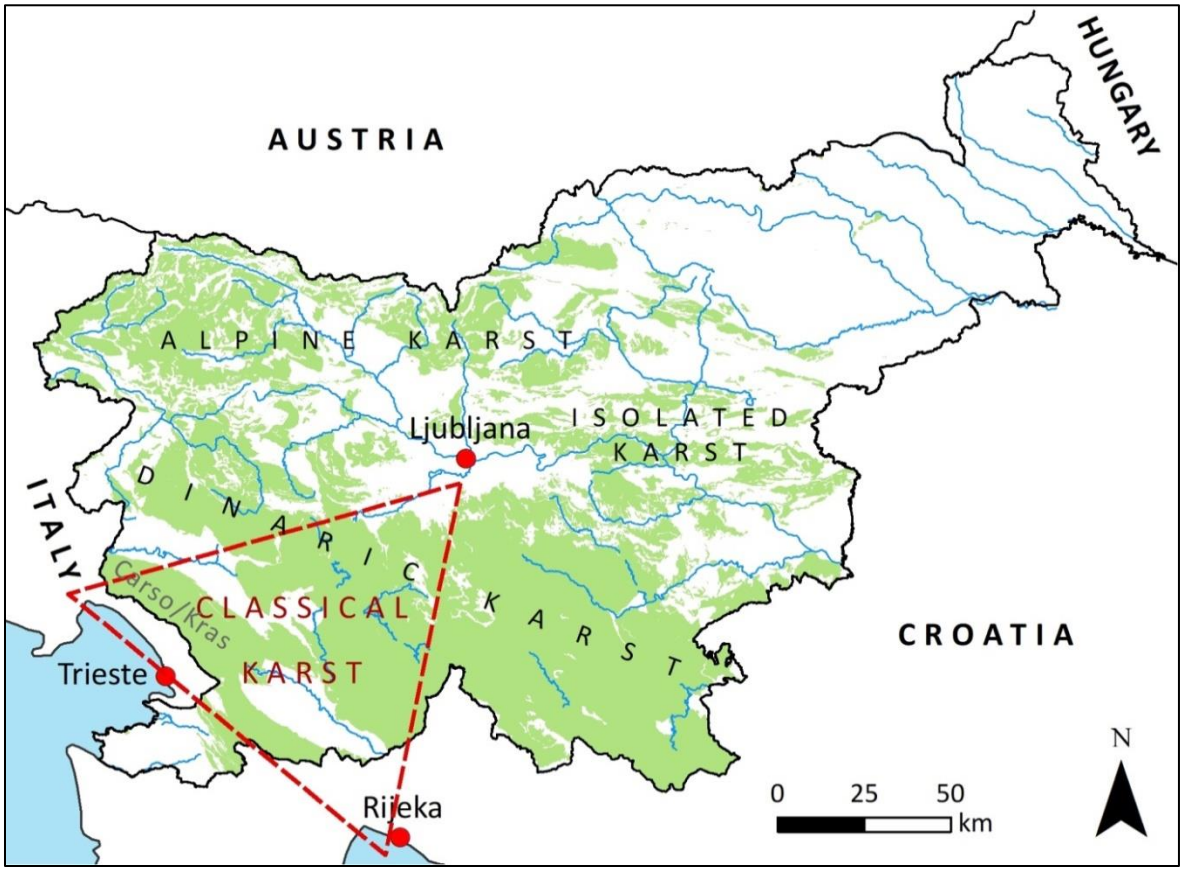

***Figure 1.01**: Position of the Classical Karst.*

HISTORY OF KARST EXPLORATION IN SLOVENIA

The phenomena of Classical Karst were already mentioned in antiquity and the middle ages, such as large springs, sinking rivers and caves (Shaw & Čuk 2015). Based on observation of floods and springs on Cerkniško polje Kircher (1678) discussed ground water flow in karst. Valvasor (1689) described many caves and especially the karst hydrology of the Cerkniško polje (Fig. 1.02). The explanation was improved by Steinberg (1758) and others. These were the first attempts to describe and understand karst hydrology (Mihevc *et al.* 2016).

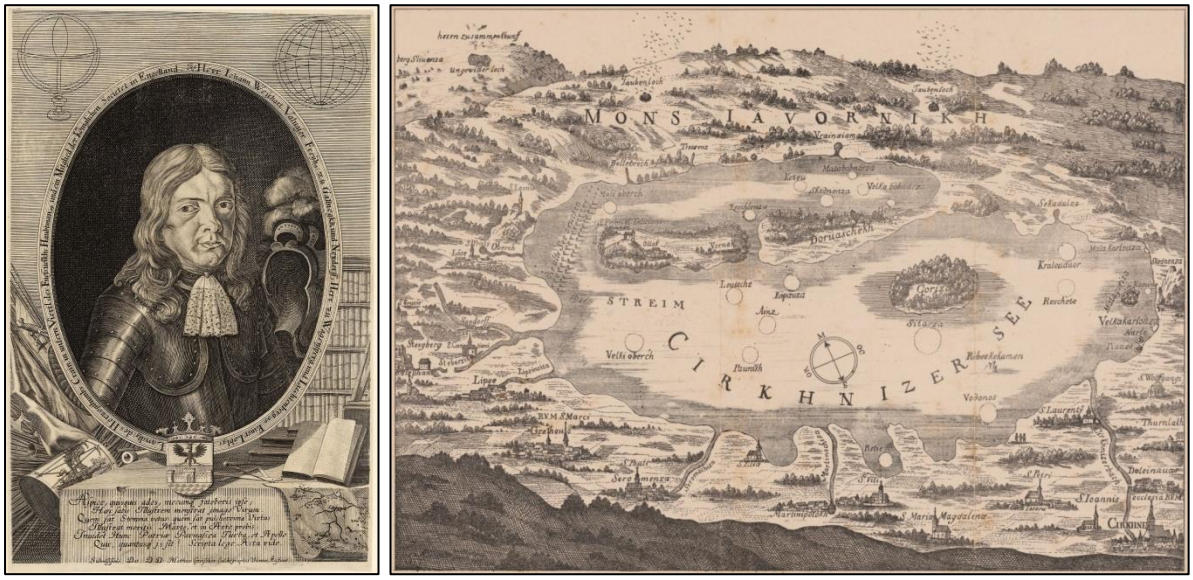

***Figure 1.02**: Portrait of Valvasor (left) and his drawing of the Cerkniško Polje (Right) (Valvasor 1689).*

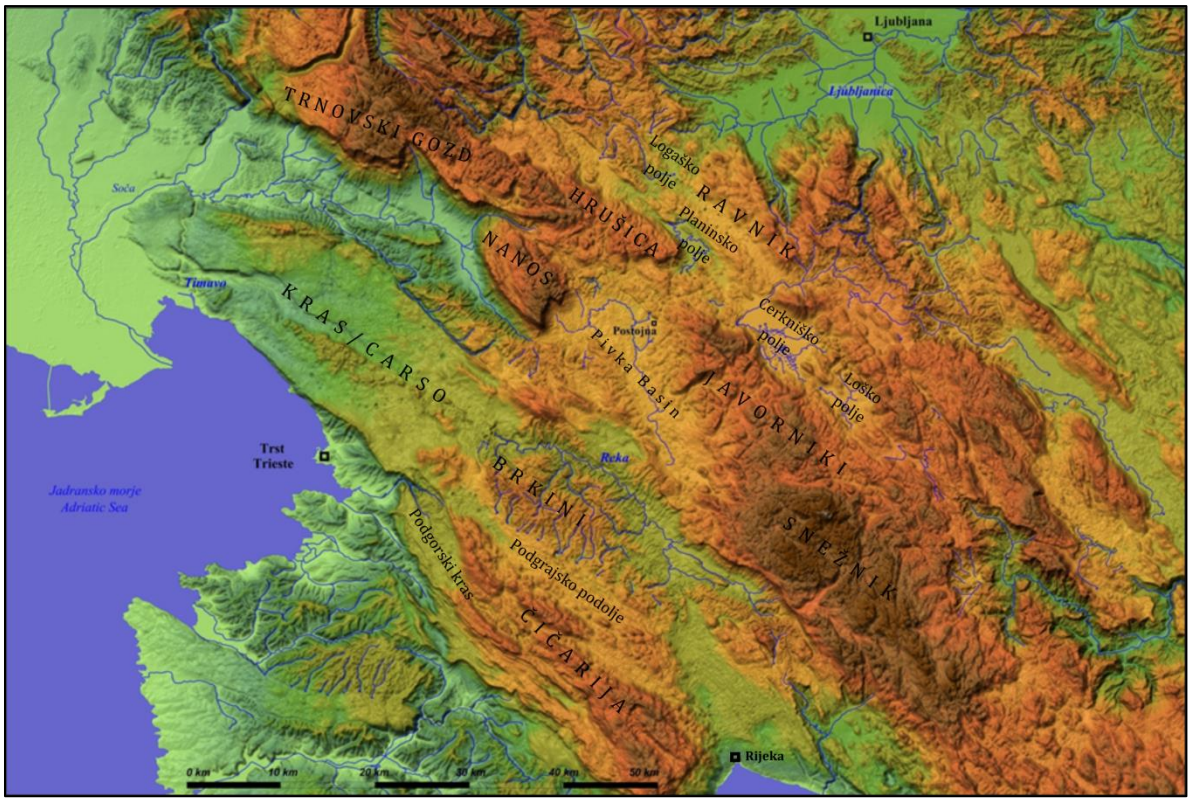

***Figure 1.03**: The main morphostructures of Classical Karst.*

Proper cave explorations started in 19th century. The explorations focused to the surrounding of Postojna (Postojnska jama, Planinska jama, Tkalca jama …) and Kras/Carso plateau (Škocjanske jame, Kačna jama, Vilenica, Abisso di Trebicciano). Many caves were explored and mapped. Among them a large part of the Postojnska jama cave and the Abisso di Trebicciano, which was explored to a depth of 320 m in 1840 and was for the next 60 years the deepest known cave in the world (Shaw & Čuk 2015). The basic work on speleology was done by Schmidl (1854) and Kraus (1894). At about same time the geological survey and production of first geologic maps started which facilitated the study of karst. Geomorphology of the area was also studied by Martel (1894), Grund (1914) and A. Penck's student, Cvijić (1893). The term "karst" was widespread globally to label the landscapes with surface and underground phenomena originating from solubility of rocks in water.

New discoveries of attractive and spacious cave passages were sometimes followed by guided tours. Cave Vilenica was the world's first show cave with visits started already in 1633. Guided tours in caves Postojnska jama and Škocjanske jame followed in 1819, soon after discoveries of currently known main passages (Fig. 1.04).

Figure 1.04: *Picture by G. Rieger (1860) showing early guided visits in cave Postojnska jama (Shaw & Čuk 2015).*

Intensive explorations of caves resulted in important observations and findings on cave fauna. The most characteristic cave amphibian of Dinaric karst – *Proteus anguinus* was described already in 1768 by Laurenti. In 1832 a cave beetle *Leptodirus Hohenwarthii* (Fig. 1.05) was discovered in Postojnska jama (Polak 2015). Nowadays, the system of Postojnska jama and Planinska jama is known as one of the best-studied and world's hot spots of subterranean fauna, with more than 80 troglobiont species (Mihevc *et al.* 2016).

Figure 1.05: *Left Proteus anguinus (Photo: M. Blatnik) and right Leptodirus hohenwartii (Photo: S. Polak).*

At the end of 19th and the beginning of 20th century engineering works were done to mitigate flooding in karst poljes in Notranjska region. The works included regulation of river beds, widening of ponors, construction of dams etc. The best examples of these attempts are the ponor zone on Planinsko polje (Putcik 1889) and river beds (Fig 1.06) and entrances of water active caves on Cerkniško Polje (Fig 1.06). These attempts also triggered intensive cave exploration in the surroundings of poljes. Similarly, in Kras/Carso plateau the cave exploration in late 19th century was part of the research related to the water supply of Trieste (Mihevc *et al.* 2016).

Figure 1.06: *Reconstructed entrance of cave Velika Karlovica at the NW border of the Cerkniško Polje (Photo: M. Blatnik).*

In 1906 Postojna was already an important tourist karst site and preparation for a special karst research institution started. During the Italian occupation in 1929 the Instituto Italiano di Speleologia was established and in 1947, the Inštitut za raziskovanje krasa within the Slovene Academy of Sciences and Arts continued the research (Mihevc *et al.* 2016). The initial idea of the institute was multidisciplinary research of karst including geomorphology, speleology, hydrology, climate and speleobiology. Nowadays the work continues in the same direction with some upgrades on karst vulnerability, quality and quantity of water, geochemistry, water flow modelling, and monitoring during various activities on karst, such as road and railway construction.

Figure 1.07: *Istituto Italiano di Speleologia at about 1935 (Photo: M. Šeber).*

RECENT RESEARCH TRENDS

Despite the long history of research, Classical Karst still kept many open questions to be answered by use of novel techniques and approaches. Strenuous and persistent work, particularly on magnetostratigraphy of cave sediments enabled new insights into evolution of the landscape and catchment areas during Cenozoic.

Complex structure and evolution in the tectonically active zone resulted in very irregular pattern of caves/conduits, and consequently groundwater flow, which is as complex as it can get in karst. New observation techniques focused not only to recharge points and springs but also to caves as an integral part of the aquifer, combined with computational approaches are giving new insights on the flow dynamics and aquifer structure.

Access to lidar data of the entire region enables new interpretation and statistical evaluation of surface patterns. This may give new ideas on the origin of closed depressions at all scales: from solution dolines, to collapse dolines and polje, particulary when combined to simple computational tools. Lidar has also accelerated discovery rate of new cave entrances (Fig. 1.08).

Figure 1.08: *Lidar scanning of caves (Photo: J. Obu).*

Figure 1.09: *Exchange of knowledge with other karstologists (Photo: M. Blatnik).*

The main exploration challenges in Classical Karst has been left to divers; connection of the Postojnska jama, Planinska jama and caves around Cerkniško polje, connection of caves Škocjanske jame and Kačna jama are just the most outstanding challenges. We are sure that new connections will open new question on the genesis of these systems as well as provide new point for groundwater observation.

We believe that we have very limited knowledge on the large scale structure of the aquifers in Classical Karst. Promising new geophysical techniques, such as time-lapse gravimetry, may provide new insights.

Physical speleology also includes cave climate studies, which have a long history in the Classical Karst. Data of the monitoring networks in show caves have lead us to new findings on the dynamics and composition of cave atmosphere and their relation to external driving forces. This brings us to eternal questions on how much (irreversible) damage do we make to cave environment and life therein with our activities.

Systematic monitoring of groundwater and surface water, cave environments, active tectonics, geophysical events is being established in the entire area of Classical Karst. The monitoring network is already providing streams of data, which need to be analysed and interpreted. When operating over decades, such networks may record also long-term changes. But long-term observations need long-term financing of stable research groups.

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DINARIC KARST OF NOTRANJSKA REGION

Tuesday, 15. 6. 2021, Afternoon lecture

Cyril Mayaud, Nataša Ravbar, Uroš Novak

Dinarski kras Notranjske

Dinarski kras na območju Notranjskega polja je v največji meri zaznmovan s porečjem Ljubljanice, za katerega je značilno, da vodo prejema z dveh smeri (Pivške Kotline ter niza kraških polj od Prezida do Cerkniškega polja), ta pa se podzemno združi v Planinski jami, od koder prek Planinskega polja podzemno odteka do izvirov Ljubljanice pri Vrhniki. Predstavitev obsega splošen opis posameznih predelov porečja Ljubljanice in zadnje raziskave, ki so bile opravljene na tem območju. Med njimi prevladujejo raziskave, ki so bile opravljene z namenom iskanja rezervenga vodnega vira, poplavne dinamike kraških polj in podzemlja, ter ugotovitve povezane s smerjo pretakanja podzemne vode.

GENERAL INTRODUCTION

The Notranjska Region covers most of the central part of the Slovene Dinaric karst. The main regional flow is drained towards the springs of Ljubljanica River located at the southern rim of the Ljubljana Basin (Fig. 2.01). Although the region is about 26 km of straight-line distance close to the Adriatic Sea, the intensive tectonic activity triggered the drainage system towards the Sava-Danube catchment that flows towards the Black Sea thousand km further East. The total estimated size of the Ljubljanica recharge area is almost 1800 km^2, of which about 1100 km^2 is karstic. The karst catchment has been delineated during the extended tracing campaign that was carried out in the seventies (Gospodarič & Habič 1976).

The karst rocks are mostly of Mesozoic age. These are generally micritic, locally oolitic limestones and dominantly late-diagenetic dolomites. They were formed on the Dinaric platform under conditions of continuous sedimentation which enabled high rock purity, generally with less than 5 %, but locally as little as 0.1 %, insoluble residue. The total thickness of the carbonate sequence is almost 7 km.

Structurally, the whole of the Ljubljanica catchment belongs to the Adriatic plate. The area is composed of several nappes that were over thrust during the peak of Alpine orogeny in Oligocene in a NE to SW direction (Placer 2008; Placer *et al.* 2010). Later change of the plate movement direction resulted in the formation of the Idrija Fault Zone, a dextral strike-slip fault, which crosses the area in a NW-SE direction (Fig. 2.02) (Vrabec 1994). The Idrija fault zone largely determines direction of the regional flow (Fig. 2.02). Generally, the steepest hydraulic gradient is oriented northwards, from the southeast towards the Ljubljana Basin, which represents a regional base level. However, the fault zone acts as a barrier for the groundwater flow and forces the water to surface in the poljes. At the same time, it deflects the flow along the Dinaric (SE-NW) direction (Šušteršič 2006).

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

Generally, the water follows the SE-NW direction with surface flow on the poljes and groundwater flow in-between (Fig. 2.03). Additional water enters the flow system at numerous springs draining the areas of Snežnik and Javorniki mountains on the South of the Idrija Fault Zone. Several sinking rivers that drain dolomite or flysch areas also contribute to the system (Gams 2004). The elevation of the poljes drops from about 750 m to 450 m. The streams flowing on them have different names: Trbuhovica, Obrh, Stržen, Rak, Pivka and Unica. Apart from a relatively small amount of water, which flows directly from Cerkniško Polje to the springs of Ljubljanica, most of the water surfaces at the southern rim of Planinsko Polje. The water sinks back underground along its eastern and northern border and flows northwards towards several large and many small springs aligned along the southern edge of the Ljubljana Basin, which is connected with 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/s. An additional amount of water flows from the low to medium permeable plateau of Rovte and contributes to the Ljubjanica springs by sinking in the ponors of Logaško Polje (Mihevc *et al.* 2010).

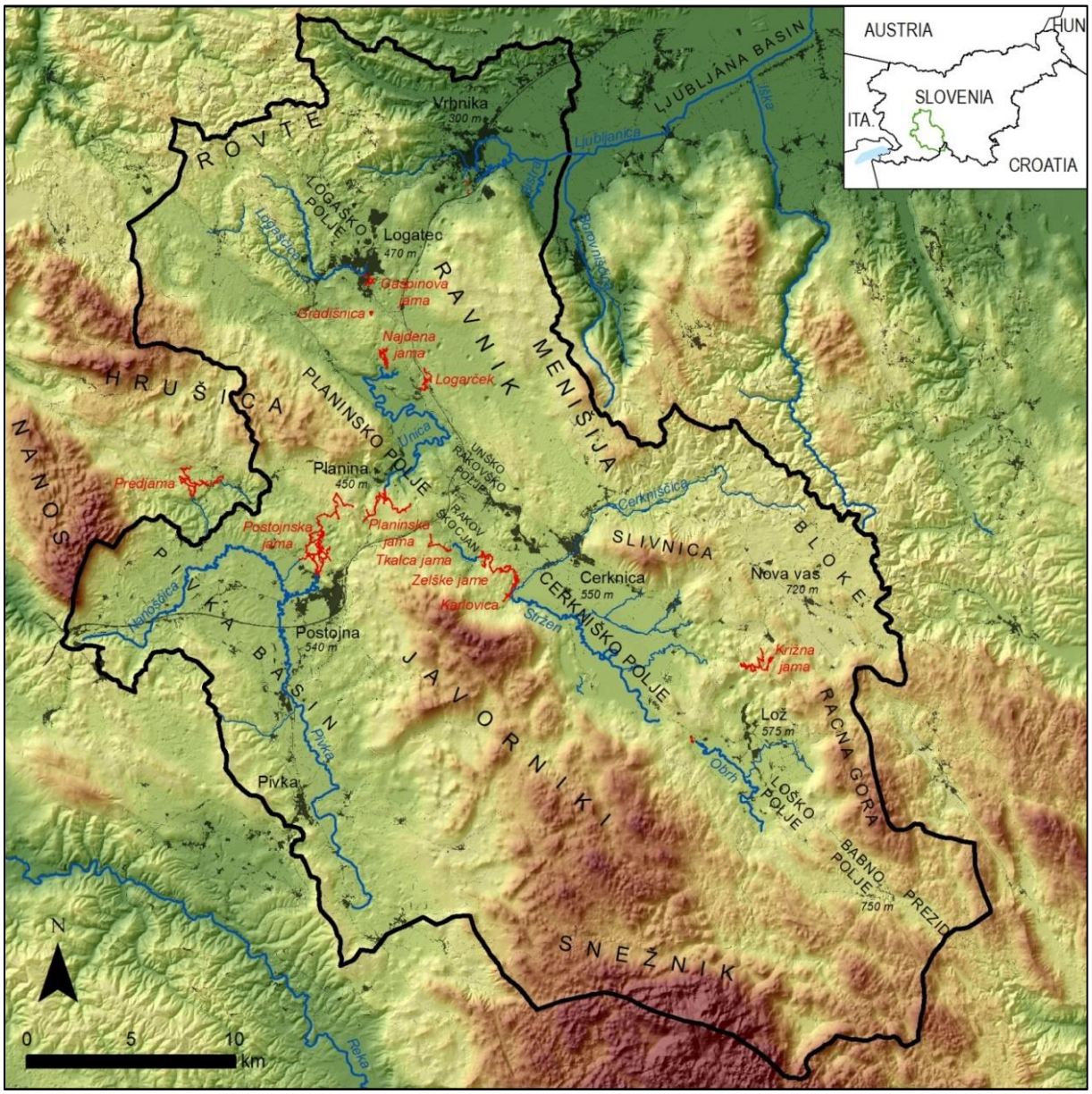

Figure 2.01: *Map of the Ljubljanica River recharge area covering most of the Notranjska Region, with high karstic plateaus, karst poljes and surface rivers. The main caves are shown with red lines.*

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. 2.03).

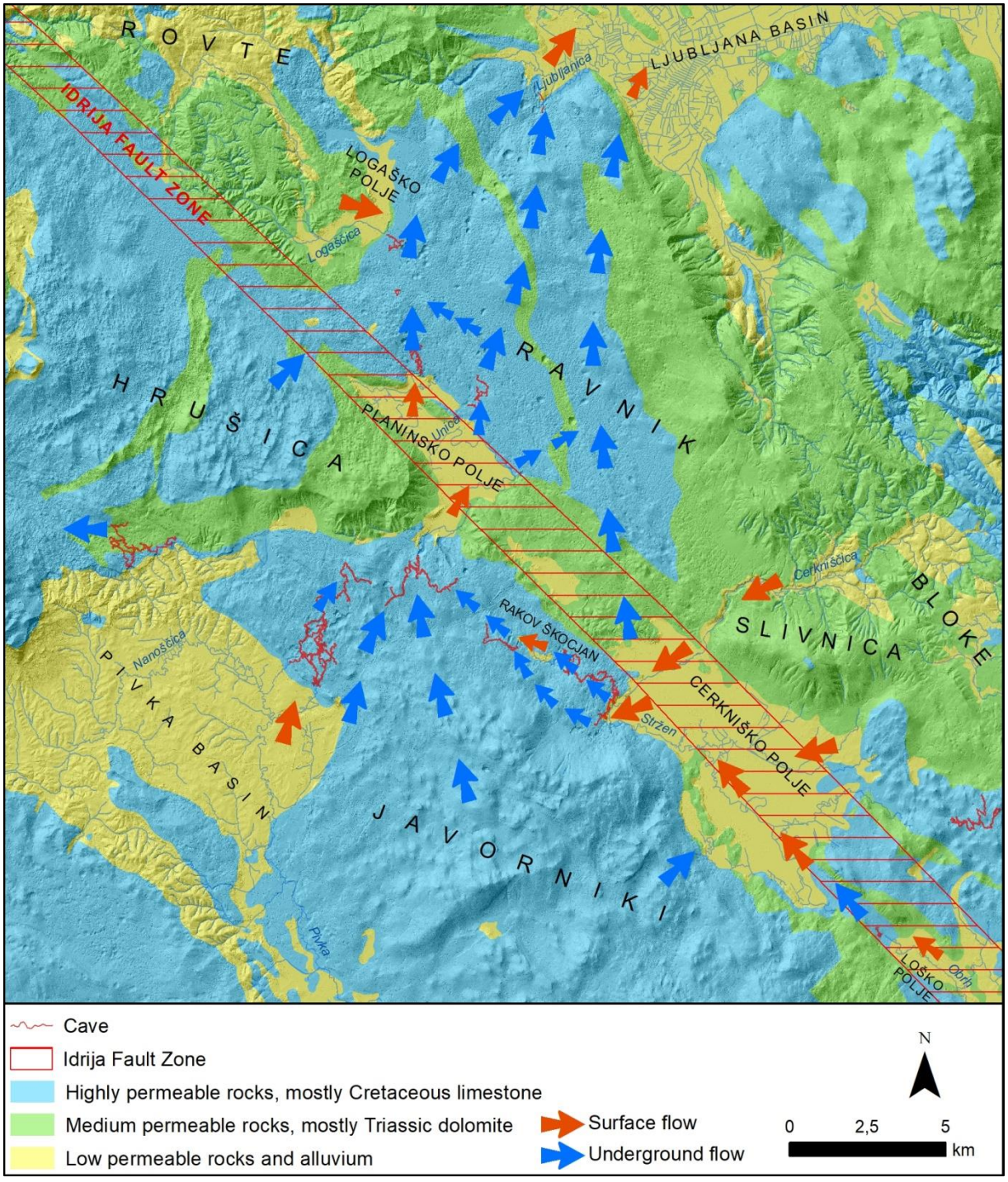

Figure 2.02: *Geology and hydrology of the Ljubljanica recharge area (adapted from Krivic et al. 1976).*

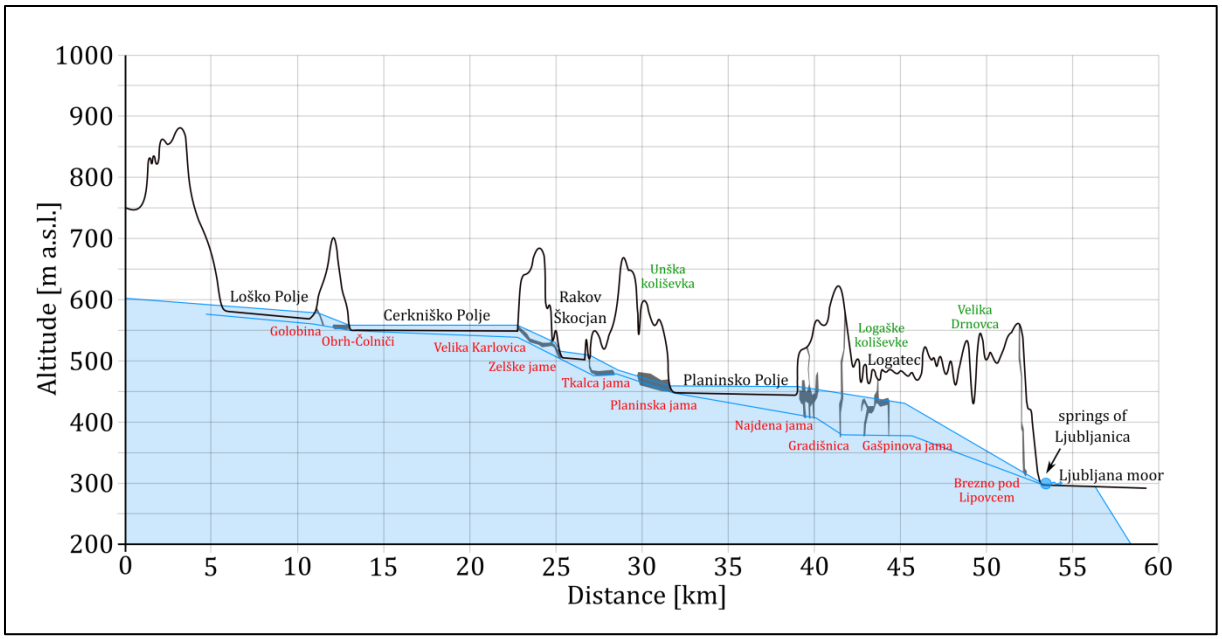

Figure 2.03: *Cross section of Ljubljanica River recharge area following an initially SE-NW trend along the Idrija Fault Zone between Loško and Planinsko Polje, and turning N from Planinsko Polje toward the Ljubljanica springs near Vrhnika. The major caves are indicated in red, large collapse dolines in green.*

CERKNIŠKO POLJE

Cerkniško Polje is the largest karst polje in Slovenia (Gams 1978, 2004). Due to its regular flooding it is often called Cerkniško Jezero (Lake of Cerknica) (Fig. 2.04 Up). When full, the intermittent lake covers up to 26 km^2 out of 38 km^2 of the polje's total surface area. The bottom elevation is about 550 m. Its intermittency has attracted many scholars since the beginning of the New age including polymath Valvasor, who published his famous study on Cerkniško Jezero in 1689 (Shaw & Čuk 2015). The main part of the polje is underlained by Upper Triassic dolomite in its N, E and SE borders. Conversely, areas on the W and NW are mainly underlain by Cretaceous limestone (Fig. 2.02).

The polje is regularly flooded for several months (Fig. 2.05), mostly during autumn, winter and spring time (Kovačič & Ravbar 2010). In average, water is about 10.2 days/year above the level 550.3 m asl., which represents a flooded surface of 21.84 km^2 (Ravbar *et al.* 2021).The main inflows into the polje comes from a set of karst springs named Žerovniščica, Šteberščica and Stržen which are located at its eastern and southern borders. The springs located on its SW side (e.g. Suhadolca, Vranja jama) present important recharge during floods. In addition, an important allogenic component comes from the Cerkniščica River, which drains an about 44 km^2 large dolomitic area located in the E (Gams 2004). Finally, several estavelles (Vodonos, Rešeta) contribute also to the polje inflow.

Besides the estavelles, several ponor zones located in the inner part of the polje drain some amount of water directly to the springs of Ljubljanica (Krivic *et al.* 1976) (Fig. 2.04 Down), whereas the main ponors are aligned along the polje western side, with Velika and Mala Karlovica being the most prominent. Both caves extend over 8.5 km between Cerkniško Polje and the Rakov Škocjan karst valley. Up to now, only a small segment between Velika Karlovica and Zelške Jame (located in Rakov Škocjan) is unexplored due to the presence of an important collapse zone. Recent studies have shown that during low to medium hydrological situations (Gabrovšek *et al.* 2010; Ravbar *et al.* 2012), important part of the water sinking in the ponors of Mala Karlovica arrives at the Kotliči springs

positioned in the middle of the Rakov Škocjan karst valley. Conversely, a smaller part emerges at Zelške Jame, which would be the most logical direction.

During the last centuries, several plans have been made to change the hydrological behaviour of the polje, but none was finalized. In 1960-ies a plan to transform Cerkniško Jezero into a permanent lake started. The entrances of the caves Velika and Mala Karlovica were closed by concrete walls, and a 30 m long tunnel was made to connect Karlovica with the surface. However, a small effect on retention of waters during dry periods was assessed (Shaw & Čuk 2015).

Figure 2.04: *(Up) Flooded Cerkniško Jezero (Spring 2013) (Photo: C. Mayaud). (Down) Ponors of Rešeta during low flow conditions (Summer 2017) (Photo: M. Blatnik).*

Figure 2.05: *Cerkniško Jezero. Left: Lake and Javorniki Mountains at sunset. Right: View toward the village of Dolenje jezero (Photos: M. Blatnik).*

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. 2.06). On the upstream (SE) side, the water emerges as Rak River from Zelške Jame (Zelše Caves). Zelške Jame is about 5 km long and ends in the large collapse doline of Velika Šujca, where water arrives from Cerkniško Polje via the Karlovica cave system. The entrance part of the Zelške Jame is a fragmented system of channels and collapse dolines. The most prominent feature is Mali Naravni Most (Small Natural Bridge; Fig. 2.07 Left), where an impressive narrow arch that belonged to the former cave ceiling, crosses the collapse doline (Gams 2004).

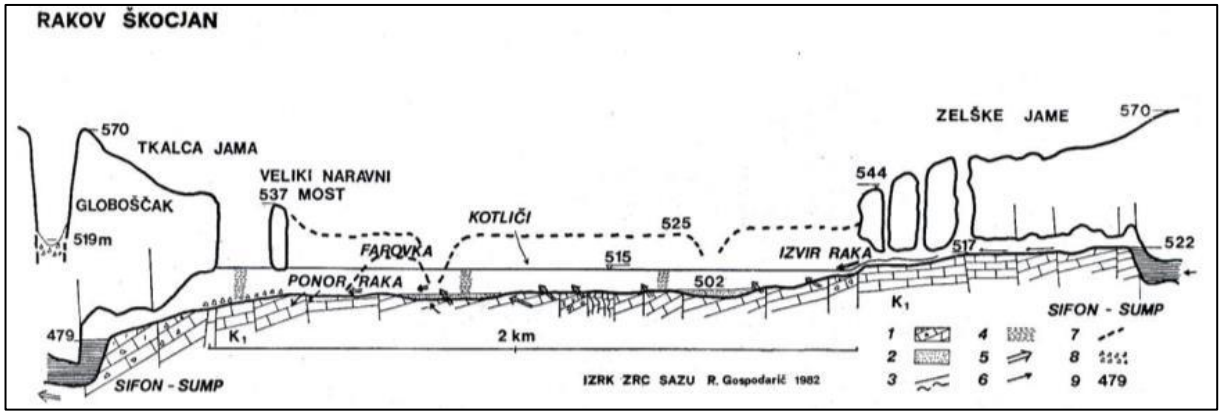

Figure 2.06: *Cross-section of the Rakov Škocjan karst valley between the Rak spring at Zelške Jame and the terminal ponor in Tkalca Jama. Legend: 1. rocky bottom; 2. alluvia; 3. fault zone; 4. flood level in 1982; 5. karst spring; 6. water flow directions; 7. terraces; 8. boulder rocks; 9. altitude.*

Downstream, the valley widens and several springs (Fig. 2.07 Right) located along the SW side of the valley (i.e., 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. 2.08). 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 composed of thick-bedded and anticline-folded Lower Cretaceous limestone.

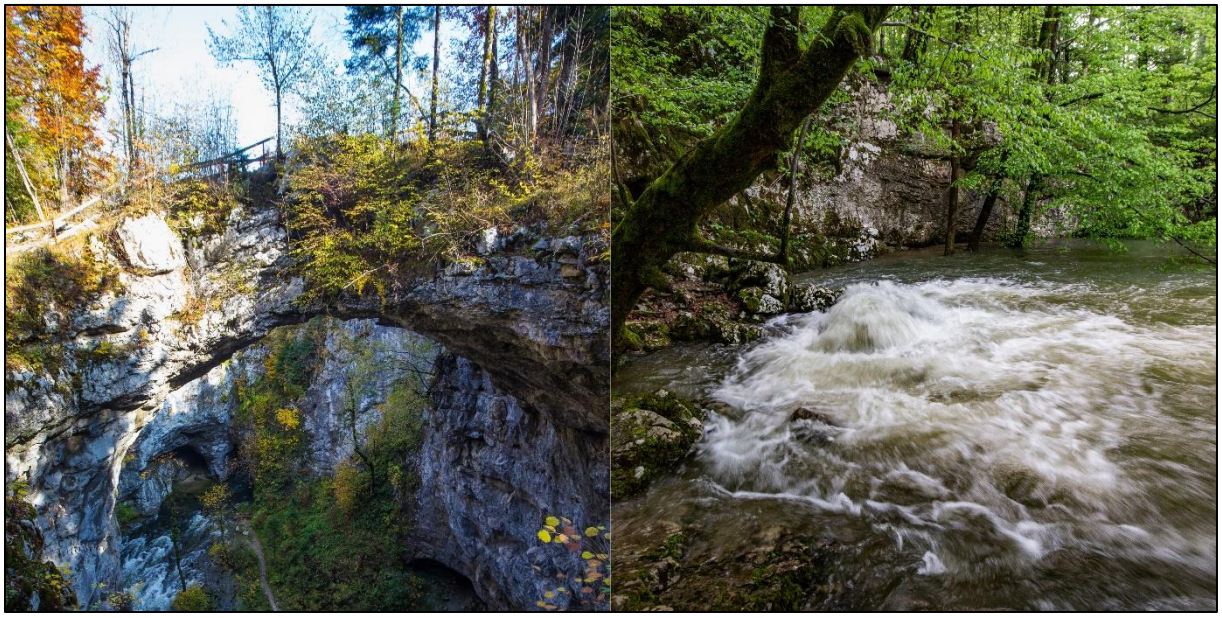

Figure 2.07: *Rakov Škocjan karst valley. Left: The arch of Mali Naravni Most. Right: Kotliči spring at the beginning of a hydrological event (Photos: M. Blatnik).*

After Veliki Naravni Most, the channel opens into a 150 m long canyon that ends in the entrance of Tkalca Jama, an almost 3 km long cave that drains water towards Planinsko Polje. The connections of the Rak with water from Cerkniško Polje and with the Unica springs at Planinsko Polje were proved 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 an elevation 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. 2.08). Before the 1st World War, Rakov Škocjan was a private park owned by the Windischgrätz family; whereas the Italians used it as a military area between 1st and 2nd World War. Since 1949, Rakov Škocjan is a Landscape Park open for the public.

Figure 2.08: *(Up) Flooded Rakov Škocjan Karst Valley in October 2020, (Left) Veliki Naravni Most (Big Natural Bridge) during dry period in summer; and (Right) during high water event in winter (Photos: M. Blatnik).*

PLANINSKA JAMA – THE MYSTERIOUS LAKE

Planinska Jama (Planina Cave) is a major spring located on the southern rim of Planinsko Polje (Figs. 2.01 & 2.09). The cave is about 6.6 km long and mostly composed of large active river passages with cross-sections frequently larger than 100 m^2 (Fig. 2.11 Left). The cave is known for being the confluence of two important regional streams (Fig. 2.09 Right; Fig. 2.10): the Pivka River that drains a large allogenic catchment through Postojnska Jama (Gabrovšek *et al.* 2010; Kaufmann *et al.* 2016) and arrives at the cave confluence via the Pivka Branch. Conversely, the Rak River brings water from Rakov Škocjan and Cerkniško Polje via the Rak Branch (Gabrovšek *et al.* 2010). Finally, an important amount of water also enters additionally the Rak Branch via the siphon of the Javornik current that is located below the Mysterious Lake (Fig. 2.10). The water emerges from the cave under the common name of Unica with a discharge ranging between 0.2 and 75 m^3/s (Frantar 2008).

There are significant differences in water contribution of the different parts of the aquifer that recharge the Unica spring (Savnik 1960). 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 massive. Then, the nearby Malenščica spring (Fig. 2.10), which is predominantly fed by the allogenic water coming from Rakov Škocjan and by the autogenic Javorniki water reaches a maximum discharge of 9–10 m^3/s (Kogovšek 1999; Kovačič 2010, 2011). Because the spring is damped, the Rak Branch activate and acts as an overflow, while the Unica also receives waters from the Pivka Branch. Under low water conditions, after the emptying of Cerkniško Jezero, the outflow is solely directed towards the Malenščica spring, while the Unica spring is exclusively fed by the Pivka Branch (Kaufmann *et al.* 2020). The inversion of flow direction between the Mysterious Lake and the Malenščica spring has been simulated numerically with a pipe flow model (Kauffmann *et al.* 2020).

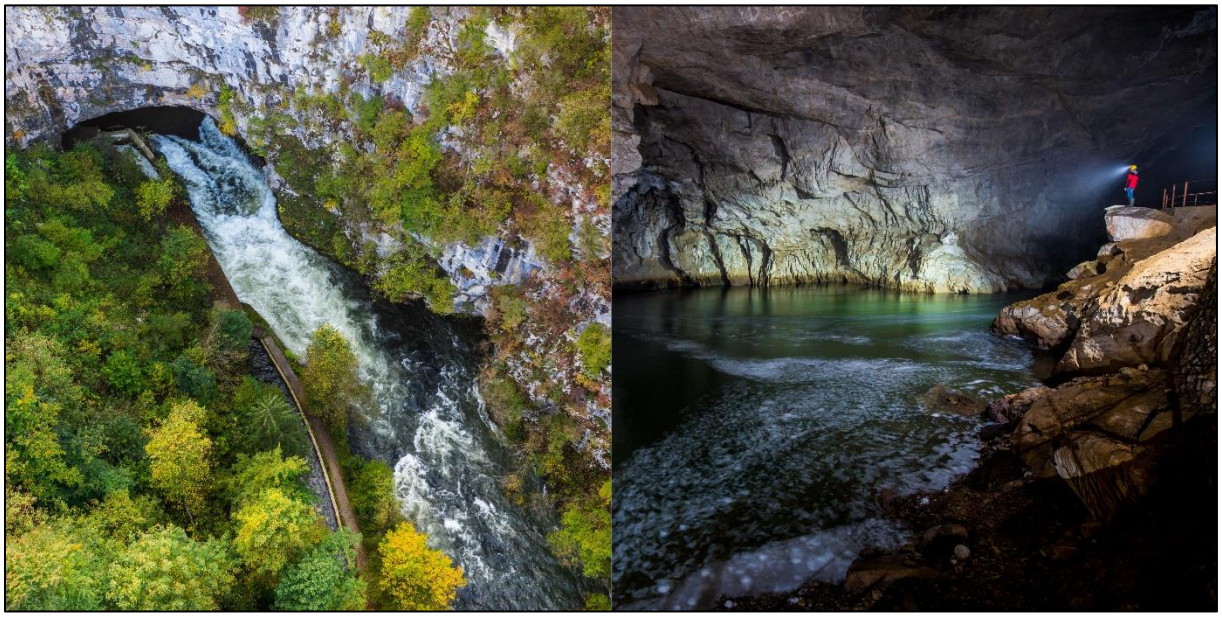

Figure 2.09: *Planinska Jama. Left: Cave entrance. Right: Confluence of the Pivka and Rak Branches (Photos: M. Blatnik).*

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 conditions (between 20 and 25 m/h) compared to low water conditions (~ 4 m/h). In the well-developed conduit networks of Karlovica-Zelške Jame, Tkalca-Planinska Jama, and Postojnska-Planinska Jama, the flow velocities during high waters were up to fifty or even ninety

times higher (between 170 and 1000 m/h) in comparison to the velocities observed at low waters (~ 4–23 m/h) (Petrič *et al.* 2018).

The cave entrance is located in Upper Cretaceous limestones and dolomites (Fig. 2.09 Left). The entrance part and the Rak Branch are developed in Lower Cretaceous bedded limestones, limestones with chert and limestone breccia. Conversely, the Pivka Branch and Rudolfov Rov (passage to the south of the Rak Branch) are developed in Upper Cretaceous massive limestone and breccia with Caprinidae and Chondrodontae (Habič 1984). Both parts of the cave end with sumps that have been dived, but no connection to the upstream systems of Tkalca and Postojnska caves has been yet accomplished. However, the recent dive explorations in the terminal siphon of the Pivka Branch give reasonable hope that a connection to Postojna cave system could be realized in a near future.

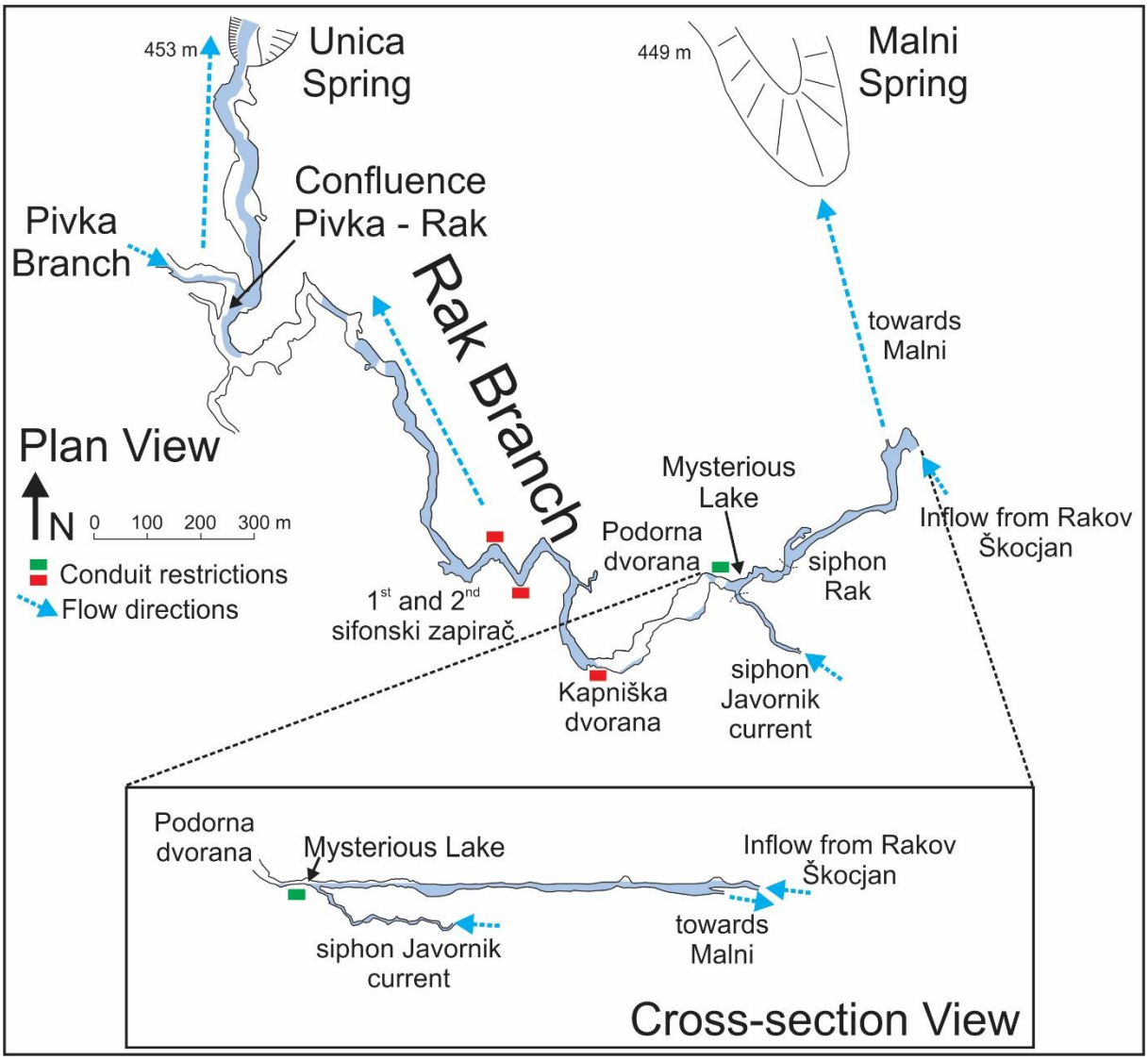

Figure 2.10: *Detailed view of the Rak Branch of Planinska Jama and cross-section of its terminal siphon in the Mysterious Lake (Gams 2004; Kauffmann et al. 2020).*

Recent research studies not only focused on understanding the hydrological processes occurring inside the cave system but also considered both surface and unsaturated zone. Therefore, two projects investigated the impact of vegetation changes on the amount and distribution of recharge upon time (Kovačič *et al.* 2020), and the effect of the surface and subsurface karstification on the flow direction of the infiltrated water (Novak *et al.* 2021).

Figure 2.11: *Planinska Jama. Left: example of typical large cave passage in the Rak Branch. Right: recent diving exploration in the Mysterious Lake and Javornik Current (Photos: M. Blatnik).*

Last three years of research carried out in Planinska Jama were mostly focused on studying the hydrological behaviour of the Javornik current (Gabrovšek *et al.* 2019), a partly explored siphon that joins to the Rak Branch in the so-called Mysterious Lake (Fig. 2.10 & 2.11 Right). To do so, water pressure, electrical conductivity and water temperature have been automatically recorded in the Mysterious Lake as well as in the sump of the Javornik current. The main goal was to see if the water coming out from the siphon would be suitable for human consumption in order to use it as a back-up reservoir for the municipalities of Postojna and Pivka (Gabrovšek *et al.* 2019).

While the discharge coming out of the siphon is relatively constant, the origin of the water and its hydrogeological behaviour are more complicated. For many years, it was expected that the siphon of the Javornik current is solely recharged by autogenic waters infiltrating through the Javorniki and Snežnik Mountains (Petrič *et al.* 2018). However, recent observations recorded by the automatic data-loggers are showing a much-complicated dynamics (Fig. 2.12). Measurements of temperature and EC indicate an evident switching of flow direction within the siphon of the Javorniki Current. This means that, depending on the hydrological situation, the flow direction is from Mysterious Lake into the siphon or vice versa. In former case, the water in the siphon is almost the same as in Mysterious Lake dominated by inflow from Rakov Škocjan. In the latter case, the water in the syphon is the "true" Javorniki current. The exact mechanism and conditions is yet to be determined (Gabrovšek *et al.* 2019).

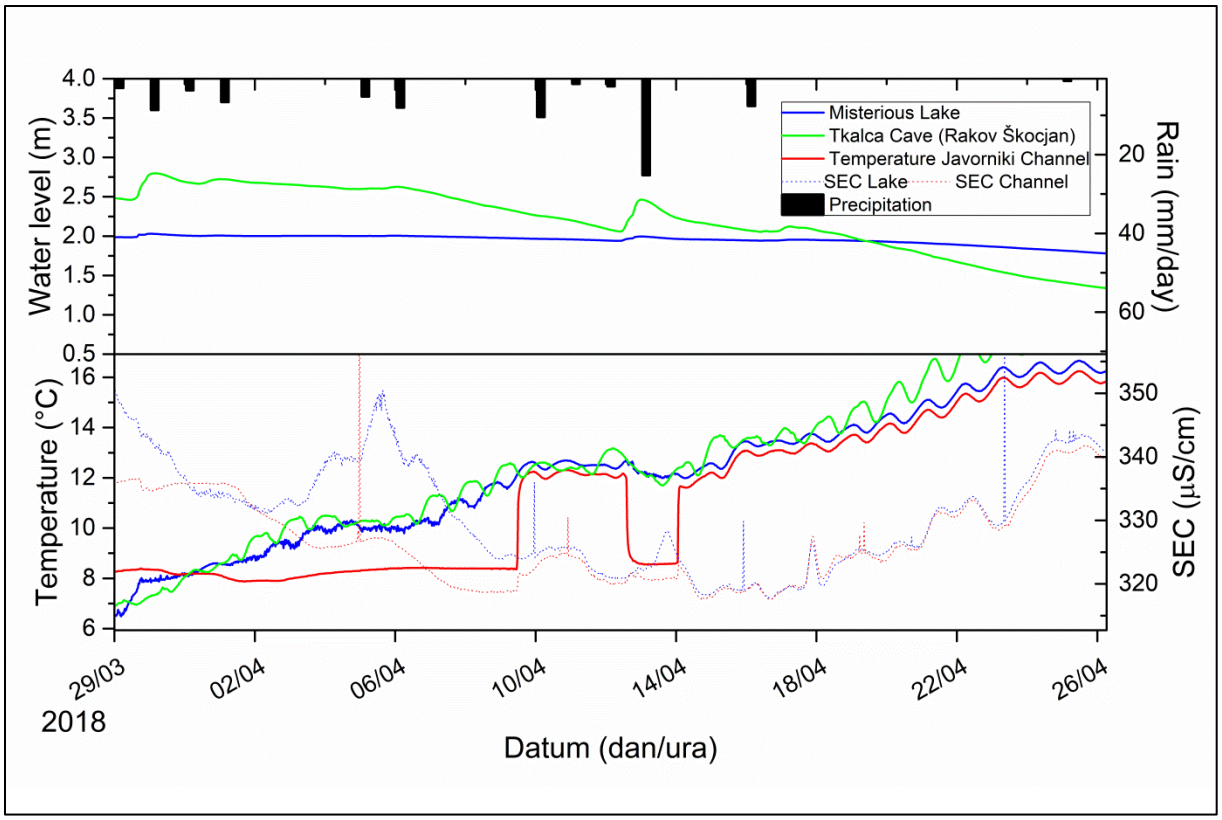

Figure 2.12: *Example of hydrological event showing a flow reversion in the siphon of the Javornik current.*

PLANINSKO POLJE

Planinsko Polje is a typical example of overflow structural polje (Gams 1978; Šušteršič 1996). Its springs are located on one side and recharge the Unica River that sinks in two major outflow zones located along the polje eastern and northern borders (Savnik 1960) (Fig. 2.13). The polje surface is slightly undulating and about 10 km^2 large, with a bottom elevation mostly comprised between 444.5 m and 450 m a.s.l (Blatnik *et al.* 2017). Apart from the wetlands close to the Unica, the polje is used for field crops and grass. Three settlements are located on the elevated slopes around Planinsko Polje, which is surrounded by forested karst plains at elevations between 520 m and 600 m a.s.l. and by mountains reaching up to 1000 m a.s.l. after.

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

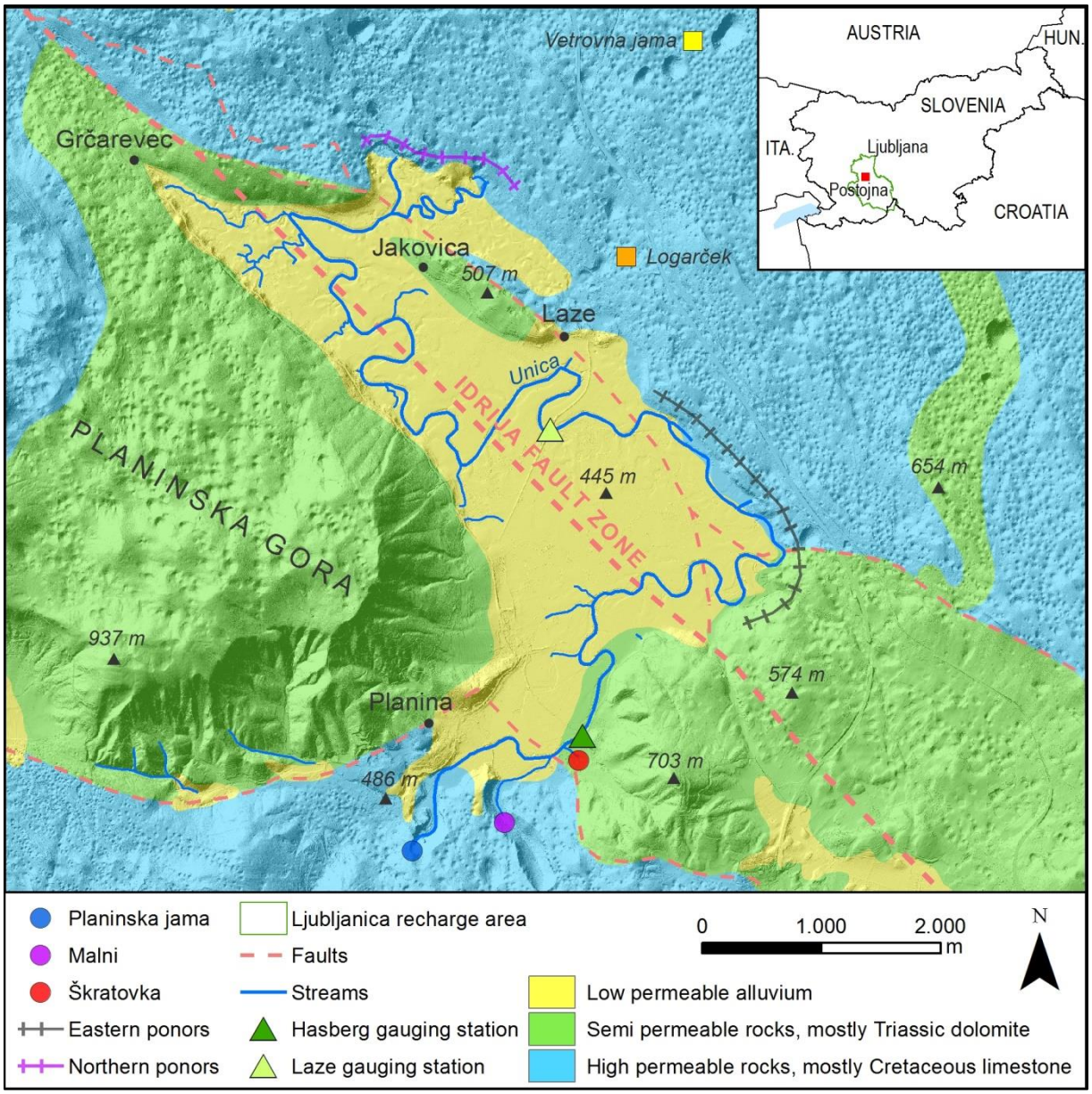

Figure 2.13: *Planinsko Polje and its surrounding area with the position of caves, springs, ponor zones and main gauging stations. The upper right insert shows the regional position of the area in Slovenia.*

Besides Planinska Jama, the most important recharge input is the Malenščica spring (Q_{min} = 1.1 m^3/s, Q_{mean} = 6.7 m^3/s, Q_{max} = 9.9 m^3/s; Frantar 2008), which receives water from Rakov Škocjan and the Javorniki mountains. The Malenščica spring is used as a water supply for more than 20,000 inhabitants (Petrič 2010). The Unica River flows rather uninterrupted over the polje's surface for the first 7 km. Along its course in proximity to the eastern border, it loses water along a 2 km long reach due to the presence of several groups of ponors and zones of intense leakage (Fig. 2.14 Right). The water sinks into well-expressed ponors, along lines of diffuse discharge into fractures and small dissolutional openings, as well as into small blind valleys entrenched into the sediment (Fig. 2.15). A recent study carried out by Blatnik *et al.* (2017) revealed new details on the location and capacity of the eastern ponor zone, with a total outflow capacity of about 18 m^3/s and individual outflow ranging between 1.0 and 5.6 m^3/s at each group of ponors. After 2 km of flow along the eastern border, the river crosses the polje and follows the western border. Then the Unica turns northeast towards the second ponor zone that are distributed along the polje northern border. The capacity of northern group of ponors was estimated between 40 and 60 m^3/s (Šušteršič 2002).

Figure 2.14: *Flooded Planinsko Polje. Left: Hasberg Bridge and castle. Right: Northern ponors (Photos: M. Blatnik).*

Similarly to Cerkniško Polje, Planinsko Polje can be flooded up to several times per year (Kovačič & Ravbar 2010). The period with the greatest probability that an extreme flood occurs is the coldest part of the year, tied to the mid-autumn rainfall peak, winter rains and snowmelting (Fig. 2.14 Left; Fig. 2.16). Although historical data are difficult to compare to current regular measurements, several extreme floods have been recorded in the past such as in 1801, in 1851/52; when the water level presumably reached an elevation between 456 and 458 m a.s.l.; and in 1923 when water level reached 453.4 m a.s.l. (Gams 1980). In February 2014, the floods reached an altitude of 453.2 m a.s.l. and 72 million cube meters of water were stored in the polje (Frantar & Ulaga 2015). The lake extended over 10.3 km^2 and more than forty houses and other facilities have been flooded (Mihevc 2014).

Figure 2.15: *Two of the many ponors draining Planinsko Polje. Left: Velike Loke located at the eastern border. Right: So-called Putick's Well (Putickova štirna) located at the terminal outflow zone at the northern border (Photos: M. Blatnik).*

During the period between 1954 and 2014, high waters on the polje occurred on average 37.9 days per year (Ravbar *et al.* 2018). The longest periods the polje has been overflown were recorded in 1960 (altogether 137 days) and in 2014 (altogether 126 days). An event of high waters lasts on average for ten days, but can also be as long as 78 days such as the flood that occurred in autumn and winter 2000/01 (Ravbar *et al.* 2018). To prevent extreme flooding in Planinsko Polje, different measures have been undertaken in the beginning of 20th century (Putick 1889). They consisted to increase the outflow capacity of the ponors zone by mean of different constructions to prevent their plugging by flotsam (Fig. 2.15).

Figure 2.16: *Planinsko Polje under various hydrological situations (Photos: M. Blatnik).*

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

Water level and temperature have been monitored in all active caves between Planinsko Polje and Ljubljana basin in years from 2006 to 2009 and from 2015 on (Turk 2010; Gabrovšek & Turk 2010; Blatnik *et al.* 2019; Blatnik *et al.* 2020). Data loggers are installed in 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 2.17 presents the recorded dynamics of underground water in March and April 2018.

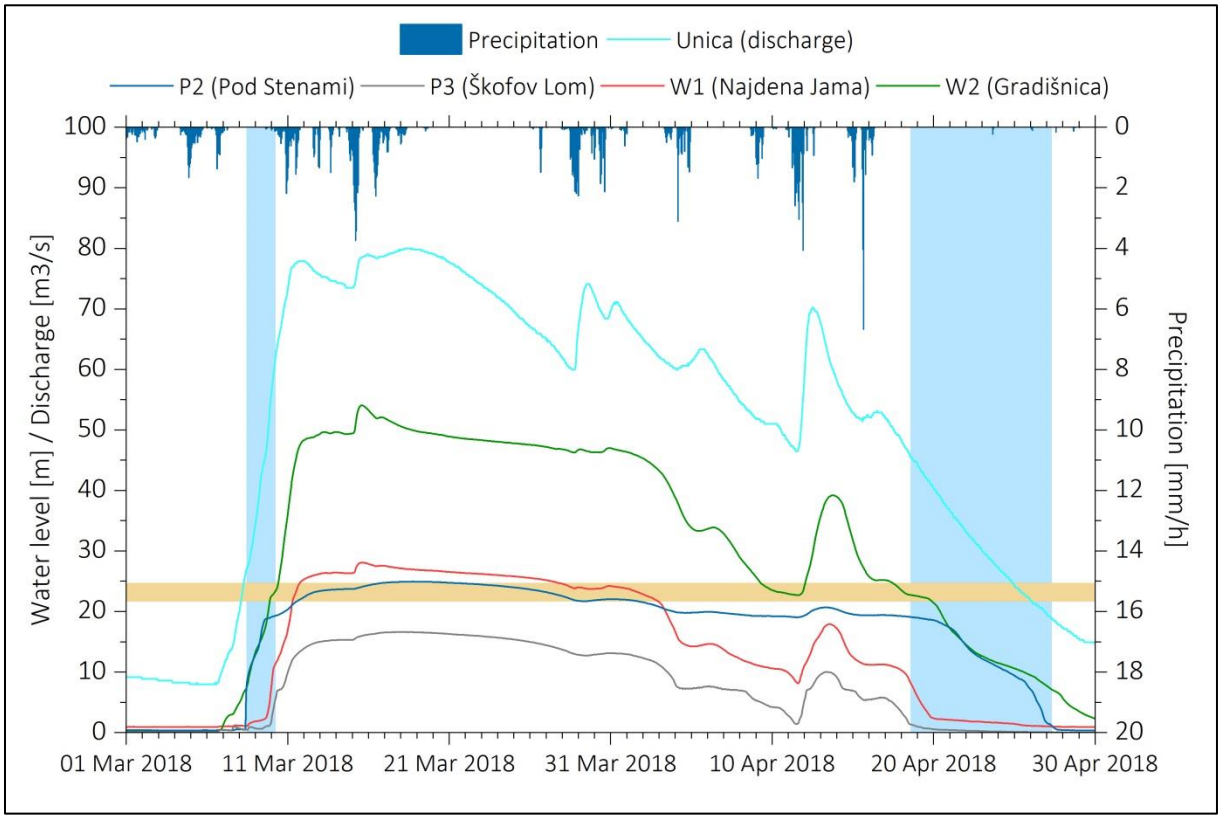

Figure 2.17: *Water level dynamic in selected caves between Planinsko Polje and Ljubljanica springs during high water event in March and April 2018. Blue areas denote different response of water level change; orange area denotes temporal slower increase (decrease of water level in cave Gradišnica).*

Water level measurements showed complex dynamics in water level variations (up to 60 m, Fig. 2.17: Fig. 2.19) and different rate of changes of groundwater level (from several hours during increase to several weeks during decrease). The duration of the high water event is dependent on the duration of flooding of Planinsko Polje (Fig. 2.16). During all high water events there is different response in water level increase. When the discharge of the Unica River is increasing, water reaches different ponor zones at different time (in Planinsko Polje first eastern, then northern ponors), resulting in different response in downstream located caves (Figs. 2.17 & 2.18). This dynamic explains late response in cave Najdena Jama in comparison to nearby located ponor zone Pod Stenami. There, water bypasses cave Najdena jama, which is recharged through more apparent ponor zone Škofov Lom (Fig. 2.17). Considering the geological structure, this explanation is plausible (Blatnik *et al.* 2019). Water level hydrographs also shows inflection points, presenting temporal slower increase/decrease of the water level. This dynamic indicate presence of overflow passages at certain levels. Temperature and EC hydrographs have been interpreted for the travel time estimation between successive observation points. Finally, a direct connection between the caves located on the Hrušica Plateau (Veliko Brezno v Grudnovi Dolini and Andrejevo Brezno 1) and the caves Gradišnica and Gašpinova Jama has been proven by the analysis of several hydrological events of different amplitude and duration (Blatnik *et al.* 2019, Blatnik *et al.* 2020).

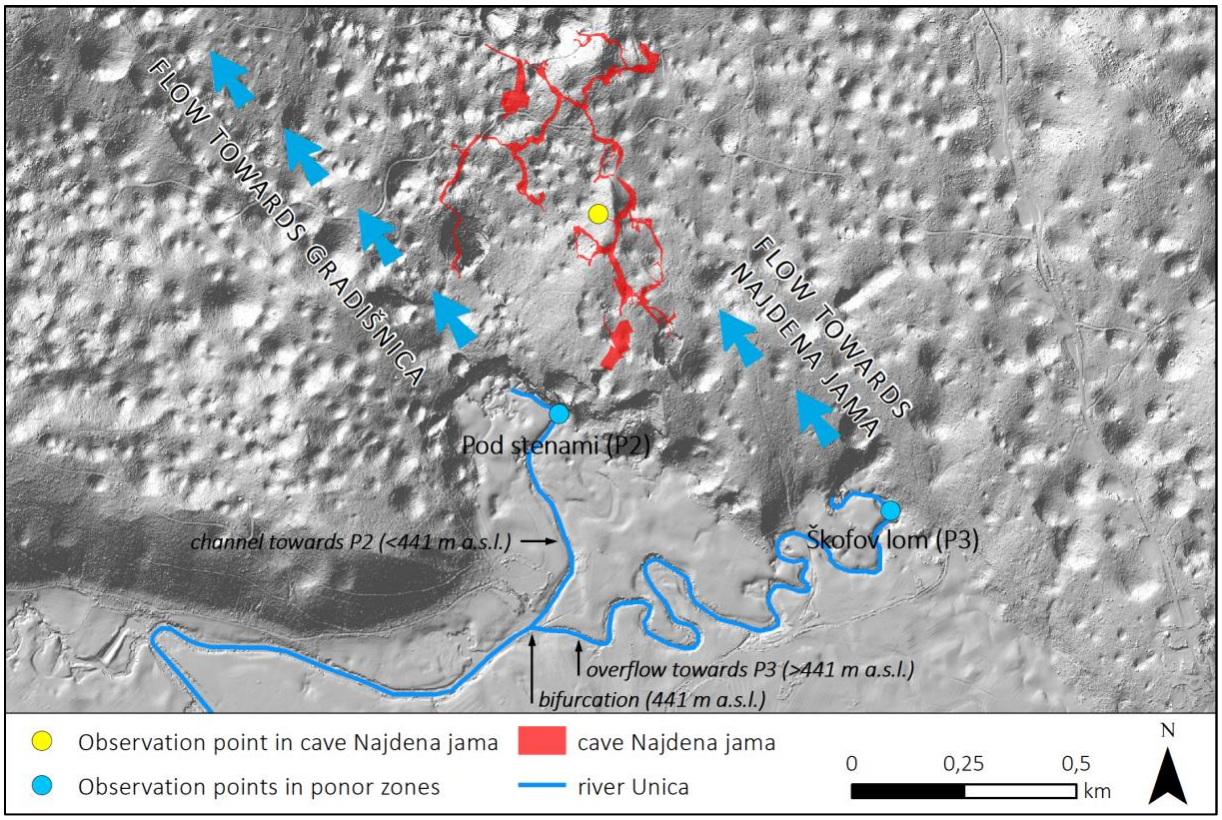

Figure 2.18: *Assumed groundwater flow directions between the northern ponors (Pod Stenami and Škofov Lom) and Najdena Jama and Gradišnica.*

Figure 2.19: *Main chamber of the cave Gradišnica during low water conditions. Dark colour on the rock wall indicates the position of high water level, approximately 50 m above the cave sump (Photo: M. Blatnik).*

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DINARIC KARST OF PRIMORSKA REGION

Wednesday, 16. 6. 2021, Afternoon lecture

Nadja Zupan Hajna, Franci Gabrovšek, Andrej Mihevc

Dinarski kras Primorske

Za Primorsko je značilno prepletanje kraških in nekraških (predvsem fliša) kamnin, ki se pogosto med seboj tudi izmenjujejo. Kraška območja deloma pripadajo Alpskemu krasu, povečini pa Dinarskemu, ki obsega kraški del porečij Reke, Rižane, izvira Boljunec in kraške planote, ki napajajo izvire, ki se kasneje združijo z Vipavo in Sočo. Reka sprva površinsko teče prek fliša, nato pa skozi Škocjanske jame vstopi v podzemlje Krasa, skozi katerega nadalje teče skozi več prostornih jam do izvirov Timava (Italija). Za Reko je značilen zelo visok razpon v pretoku, kar se odraža tudi v izrazitih nihanjih vodostajev podzemne vode v Krasu. Kraški del porečja Rižane in Boljunca vodo pridobiva z različnih območij, kot so Podgrajsko podolje, Čičarija in Podgorski kras. Površje je na gosto prepredeno z vrtačami, na stiku med kraškimi kamninami Podgrajskega podolja in Brkinov pa je niz slepih dolin. Številne med njimi se nadaljujejo z vodnimi jamami, v njihovi okolici na površju pa je mogoče najti tudi brezstrope jame in nekoč aktivne vodne jame. V njih in številnih drugih jamah primorskega krasa so bile narejene obsežne analize jamskih sedimentov, ki so razkrile pomembne informacije o preteklem dogajanju v teh jamah.

KARST OF PRIMORSKA REGION (SLOVENE LITTORAL)

The region forms the westernmost part of Slovenia, bordering the Italian region of Friuli-Venezia Giulia, and it stretches from the Adriatic Sea in the south up to the Julian Alps in the north. Karst of the region is represented by Dinaric karst in the south and Alpine karst in the north. All karst areas of south Slovenia belong to the Dinaric karst, and the karst forms there represent the main type of relief of Dinaric mountains (Dinarides). Dinaric mountain range stretches from the southeastern edge of the Alps towards SE of Slovenia. The central part of the mountains consists of a row of 1,000–1,700 m high karst plateaus, descending in the step-like form to low karst plateaus and planation surfaces. The lowest plateau on the littoral side of Dinaric karst, on the border to Italy, is Kras (Fig. 1). Dinaric karst is most prominent in terms of size, geomorphology, hydrology, and caves. The dominant relief features are extensive leveled surfaces at various elevations, closed depressions, dolines, uvalas, poljes, and residual conical hills. The surface morphology is also characterized by intermittent soil cover resulting in outcroppings of limestone with various types of karren shaped by corrosion. Karst rivers only appear at the bottoms of poljes depending on the level of the groundwater. Allogene surface rivers flowing from non-carbonate regions can (i) sink at the edge of the karst forming blind valleys, (ii) sink dispersively at longer contact, or (iii) cross the karst in canyons. Numerous simple shafts and extensive cave systems were formed by sinking rivers. The interaction between surface and underground features has resulted in collapse dolines, cave entrances, and unroofed caves exposed by denudation.

From a geological point of view, the Dinaric karst of the Primorska region is located in the northwestern part of the Dinarides, in the collision zone between the Adria microplate and Eurasia. The tectonic development was largely controlled by the rotations of Adria (e.g. Handy *et al.* 2010). 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). Karstified rocks were deposited on Adria microplate where sedimentation lasted from Triassic to Eocene, but in the SW Primorska region, Cretaceous and Palaeocene carbonate successions are presented. Marine

sedimentation ended by Eocene siliciclastic flysch. The geologic structures and major relief units are connected with late Tertiary tectonic evolution. The larger relief features are extensive leveled surfaces uplifted to different elevations.

The southwest of the Primorska region represents the NW edge of Dinaric karst and comprises Kras (Karst) Plateau, Podgrajsko podolje, and Podgorski kras (Podgora Karst).

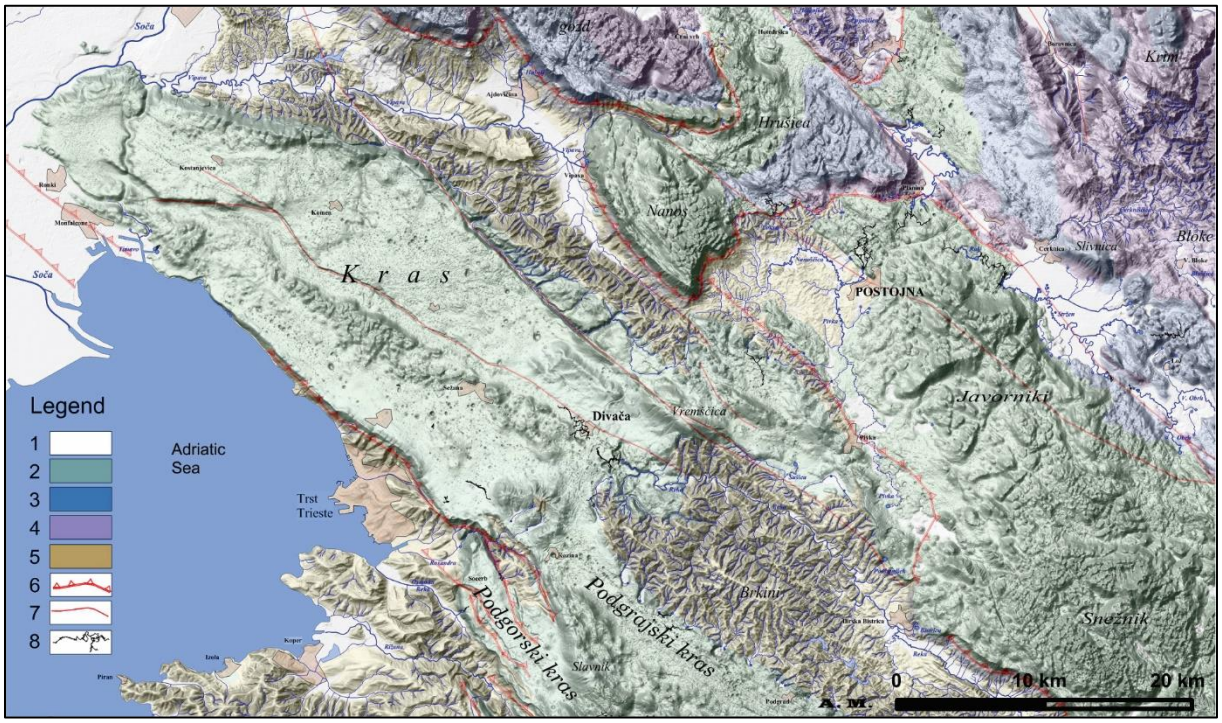

Figure 3.01: *Relief and simplified geological map of SW Slovenia and NE Italy with locations of Kras Plateau, Podgrajski, and Podgorski kras. Most of the area has no surface river network and fluvial morphology, and that relief on large scale depends on structural (nappe) and lithological elements. Legend: 1 – alluvium, 2 – K and Pc carbonates, mostly limestone, 3 – Jurassic limestone and dolomite, 4 – Triassic carbonates, mostly dolomite, 5 – sandstones and other noncarbonate rocks (E), 6 – main overthrust fronts, 7 – regional faults, 8 – outlines of main caves.*

Kras Plateau

Kras Plateau is 40 km long and up to 13 km wide; the 45°45´´N and 14°00´´E lines of latitude and longitude cross the Kras near Divača village. The main part of the plateau is essentially leveled, inclined slightly towards the northwest, with numerous dolines, caves, and other karst features. Kras plateau became a textbook example for such kind of landscape because of the extraordinary karst phenomena, and explorations were done in the 19th Century. The name Kras in the German form of the word (der Karst) became an international scientific term. Plateau consists of Cretaceous and Paleogene limestones and dolomites and it is surrounded by Eocene flysch sediments (Buser *et al.* 1968; Šikić *et al.* 1972; Gospodarič 1983; Jurkovšek *et al.* 1996, 2013). The flysch rocks represent the last marine sedimentation in the area (Zupan Hajna *et al.* 2010). From a tectonic point of view, the Kras belongs to Komen nappe of the NW part of External Dinarides (Placer 1999, 2008, 2015). Two basic groups of tectonic structures can be distinguished here, they resulted from: (1) the Cretaceous–Paleogene NE – SW-directed compression as Dinaric structures (NW – SE-trending regional folds and reverse faults, also cross-Dinaric normal faults), and (2) the Neogene and Quaternary N – S-directed compression (NW – SE-trending strike-slip faults; Jurkovšek *et al.* 1996, 2013; Placer *et al.* 2010; Placer 2015; Žvab Rožič *et al.* 2015).

About 3500 caves are known on the plateau. Kras is a carbonate plateau that is spread out between Trieste Bay, Vipava valley, and river Soča in NW-SE direction (i.e. ‘‘Dinaric’’ direction). The main part of the plateau is essentially leveled, inclined slightly towards NW, with numerous dolines, caves, and other karst features. About 3,490 caves are known on the plateau. There are about 300 m of the accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it. In seven caves we can reach passages of the underground river Reka which flows between 200 and 300 m below the surface. In the NW part, the plateau descends to below 50 m a.s.l.; on its SE edge, altitudes are about 500 m a.s.l.

In the NW part, the plateau descends to below 50 m a.s.l.; on its SE edge, altitudes are about 500 m a.s.l. No superficial streams occur on the Kras surface, because all rainwater immediately infiltrates to carbonate rocks. Two dry valleys are crossing the plateau. NW-SE-trending belt of lower relief in the center of plateau is a result of younger tectonics.

The climate of the Kras is sub-Mediterranean with warm dry summers and most of the precipitation in autumn and spring. Cold winters, with NE wind "burja" (bora = Borealis), show a strong influence on the continent. Average yearly precipitation varies from 1,200 to 1,650 mm. Because of intensive pasturing in past centuries, Kras was bare, with a rocky and grassy surface. In the last decades, the trees have overgrown the landscape.

The Kras receives water not just from the precipitation but also from allogenic rivers like Reka on SE, some smaller brooks on NE, and strong inflow from alluvium along Soča River on N. Because of the flysch barrier along the coast water can spring out only where this is below the water table. The largest springs join into the river Timavo.

The age of the Kras plateau can be defined as the time when the karst rocks were uplifted out of the sea in the late Eocene since after that there is no evidence of younger marine sediments. As soon as the carbonate rocks were exposed, we can expect that the karst was formed, but there are no remnants of karst relief or other features from that time. The age of the karst evolution of the area can be gained by dating of karst surface and cave sediments. Since 1997 eleven sites on Kras were studied regarding the origin and age of the sediments (e.g. Bosak *et al.* 1998, 2000; Zupan Hajna *et al.* 2008, 2010, 2020, 2021). The main results were that the oldest sediments are over 10 Ma old and that sediments in the caves represent some distinct phases of massive deposition in caves, dated to about 5.4 – 4.1 Ma (Miocene–Pliocene), 3.6 – 1.8 Ma (Pliocene - Pleistocene) and Pleistocene. The research of cave sediments is not finished; in progress are interpretations of obtained data regarding tectonic, climate, geomorphological, and speleological evolution of specific karst areas.

Podgrajsko podolje

From the southern side of the Brkini hills water sinks in 18 separate streams into the karst of Podgrajsko podolje (Figs. 3.01, 3.09 & 3.11). 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. 3.01). 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. 3.02 & 3.10). 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 to the southeast.

The allogenic discharge into the karst is responsible for the creation of several large blind valleys and large caves filled with allogenic sediments (Mihevc 2001, 2007). 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.

Podgorski kras

The Podgorski kras is about 5 km wide and up to 15 km in length karst plateau, which represents the continuation of the Kras towards the SE, but is separated from it by an important tectonic line with a neotectonic drop of about 50 m. The plateau is formed on Eocene bedded alveolinid and nummulitid limestone and narrow zones of flysch in an imbricated structure with dips of about 20–30° towards the north-east. The plateau is at elevation 500 to 450 m a.s.l. Only small allogenic surface streams exist on its surface and they sink at the carbonate/flysch contact karst zone. Numerous shallow dolines with flat bottoms, in which some sediments are preserved, represent the principal surface karst forms. A total of 92 caves are known at Podgorski kras with maximum depths up to 150 m. There are also several unroofed caves, remnants of larger cave systems indicating the high age of the karst.

The contact karst of Reka river, Podgrajsko podolje and Podgorski kras

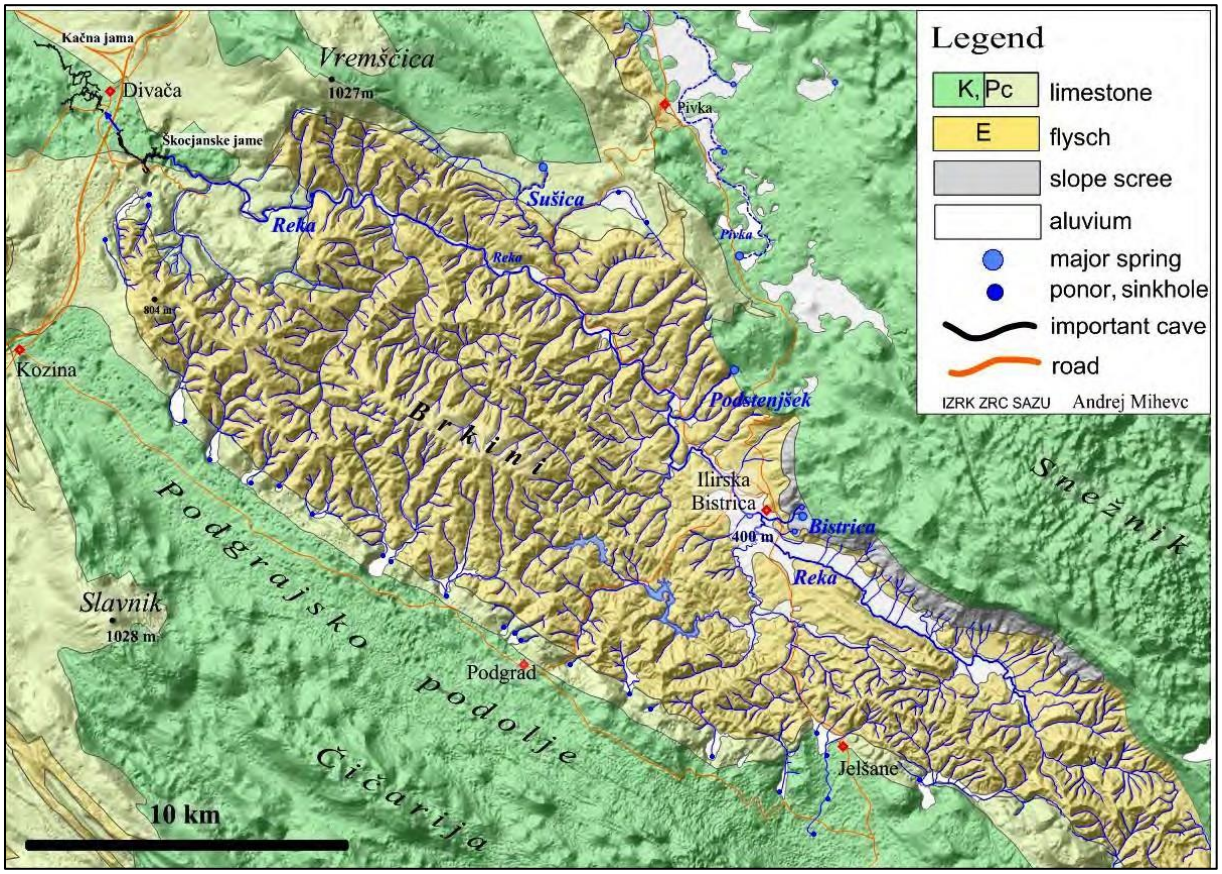

Figure 3.02: *Flysch landscape (Brkini hills) on SE edge of the Kras Plateau with fluvial topography and surface rivers that all sink on the edge into karst. DEM made on 12.5 m grid. Source of DEM data: Geodetski oddelek ARSO.*

Karst formed by the influence of the allogenic rivers with a large quantity of water, specific water regime, and sediment inflow could be designated by the term of contact karst. The term grows familiar in Dinaric karst where are several such areas, which sharply contrast the karst without such influence. In the international karstological literature, such forms and phenomena are treated as karst influenced by allogenic rivers. This type of karst is rich in cave and surface sediments. Blind valleys are valleys formed by allogenic rivers that flow to karst and sink. Allogenic rivers with a large quantity of water, sediment transport, and regime enhance and modify the shaping of the karst. But

the shape of the blind valley and especially the width of its bottom is controlled by the karst drainage system and the height of the groundwater table. They are the most characteristic forms of contact karst (e.g. blind valleys of Podgrajsko podolje on figure 3.02).

On the SE edge of Kras plateau is an area built of Eocene flysch with developed surface drainage and fluvial morphology. Most of the flysch area belongs to the Brkini hills. All surface waters from flysch flow and sink in the karst (Fig. 3.02). Water from the northern side of the flysch hills as well as water from some karst springs is collected into the river Reka which sinks in Škocjanske jame (Škocjan Caves). On the southern side of the Brkini are 18 separately sinking streams, which all sink in Podgrajsko podolje, a 20 km long and 2–5 km wide leveled karst surface between mountain Slavnik and the Brkini hills (Fig. 3.02), and flow below Podgorski kras towards Rižana spring or to Kvarner Bay (Fig. 3.03).

Water tracing confirmed that the sinking streams flow into directions towards Trieste Bay, submarine springs along the coast in the Kvarner Bay on the south, springs in Istria on the south-west, and to the Rižana springs on the west (Fig. 3.03; Krivic et al. 1987; Petrič *et al.* 2007, Zupan Hajna *et al.* 2015).

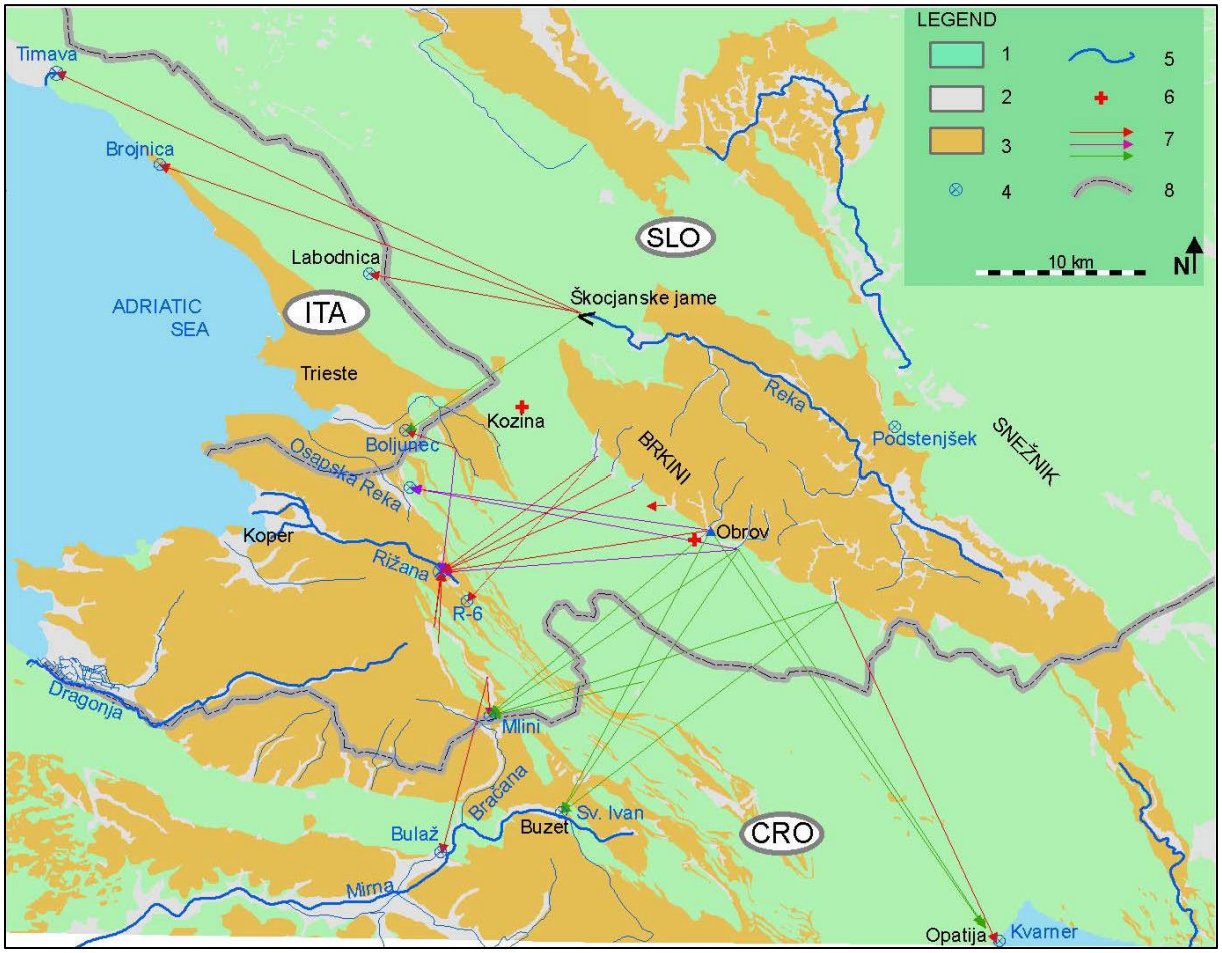

Figure 3.03: *Hydrogeological map of the area between Trieste and Kvarner bays of the Adriatic sea with underground water connections (from Petrič et al. 2007). Legend: 1. Karst-fissured aquifer, 2. Porous aquifer, 3. Very low permeable rocks, 4. Karst spring, 5. Surface stream, 6. Location of oil spillage, 7. Main, secondary and uncertain underground water connection, 8. State border.*

THE REKA RIVER AND ITS CONTACT KARST

The Reka

The Reka is the main sinking river at the edge of the Kras plateau. The catchment area of river Reka (Figs. 3.02 & 3.03) exceeds 350 km^2 with about 60% of the surface drainage network on Eocene flysch. The river flows about 50 km in the fluvial valley formed in impermeable flysch rocks. When the valley enters limestone bedrock, the Reka river starts to lose water into ponors which are immediately at the contact. If the discharge or Reka is larger than 1 m^3/s, the Reka river flows on for another 7 km in the limestone valley and sinks into Škocjanske jame cave. In the period 1961–1990, the minimal measured discharge of the Reka was 0.18 m^3/s and the mean discharge 8.26 m^3/s. During extreme floods, the discharge can surpass 300 m^3/s. The ratio between maximal and minimal flow is thus over 1:1700.

Reka along with autogenic water infiltrates into Kras and surfaces again at the springs along the NW coast of Adriatic, mainly at the springs of Timavo about 35 km NW from Škocjanske jame. Springs are also recharged from the Soča, Vipava, and Raša rivers. Three large springs with a mean discharge of 30.2 m^3/s are connected by a network of passages that reach a depth of about 80 m below sea level. No superficial streams occur on the Kras surface, because all rainwater immediately infiltrates to carbonate rocks. Two dry valleys cross the plateau.

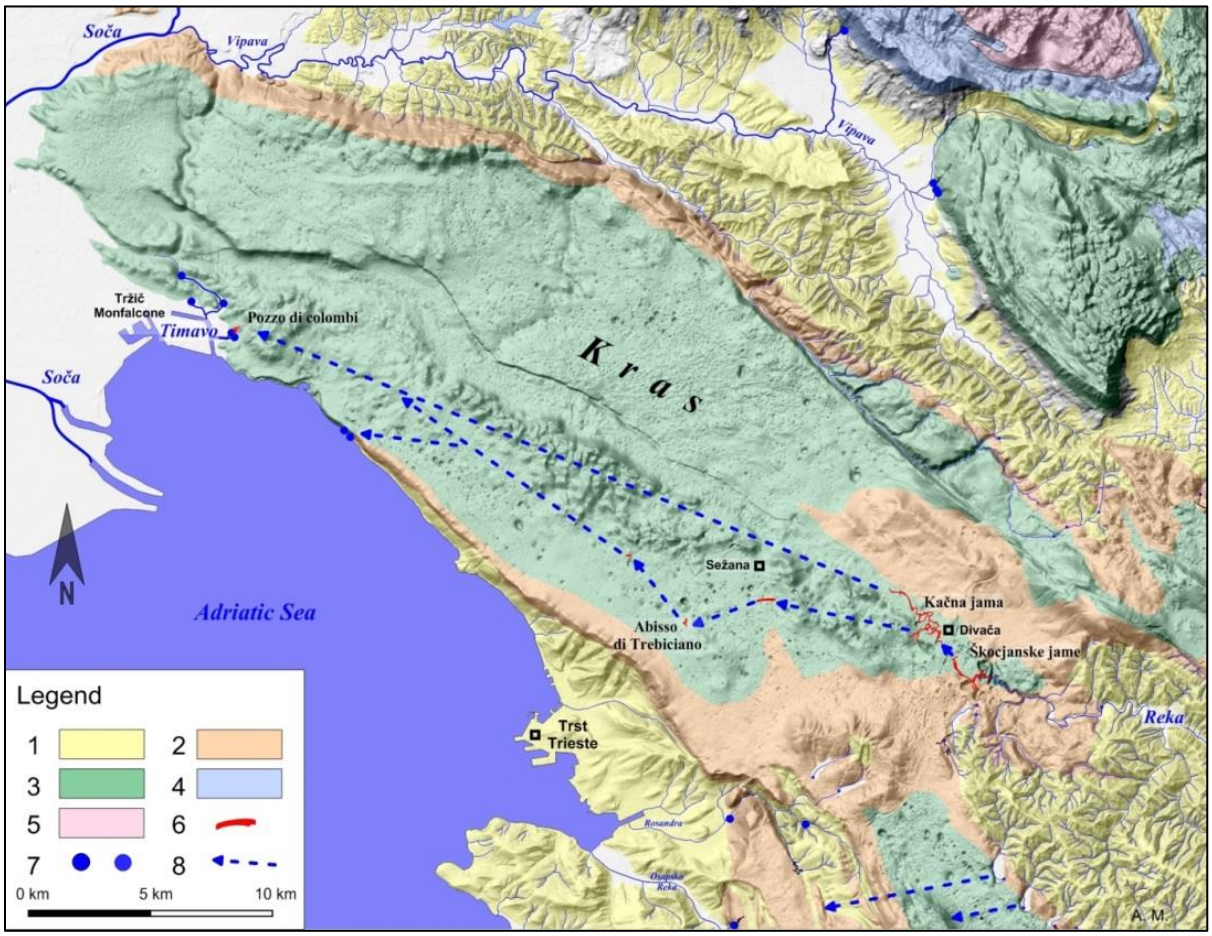

Figure 3.04: *Lithology and hydrology of Kras Plateau. Legend: 1. Eocene flysch; 2. Paleocene limestone; 3. Cretaceous limestone and dolomitic limestone; 4. Jurassic limestone and dolomite; 5. Triassic dolomite; 6. important cave; 7. springs; 8. supposed flow of underground Reka. Source of data: Geodetski oddelek ARSO.*

The first ponors of Reka are on the contact of flysch and limestone (Figs. 3.02 & 3.04). When the river in the valley reaches limestone bedrock, the river starts to lose water into ponors which are immediately at the contact. If at that point the discharge or Reka is larger than 1 m^3/s, the river flows on for another 7 km and sinks into Škocjanske jame cave.

Škocjanske jame are situated at the SE edge of the Kras Plateau (Karst Plateau; Fig 3.04). Reka sinks into Škocjanske jame and then flows about 250 - 300 m below the surface. In eight caves (see Fig. 3.04) after Škocjanske jame underground river Reka can reached: Brezno treh generacij, Kačna jama, Brezno v Kanjeducah, Jama Sežanske Reke, Jama v Strašinkini dolini, Labodnica (Abisso di Trebiciano), Abisso Skilan and Pozzo di colombi (Fig. 3.05). Further NW no caves with an open flow of Reka are known.

There are about 300 m of the accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it.

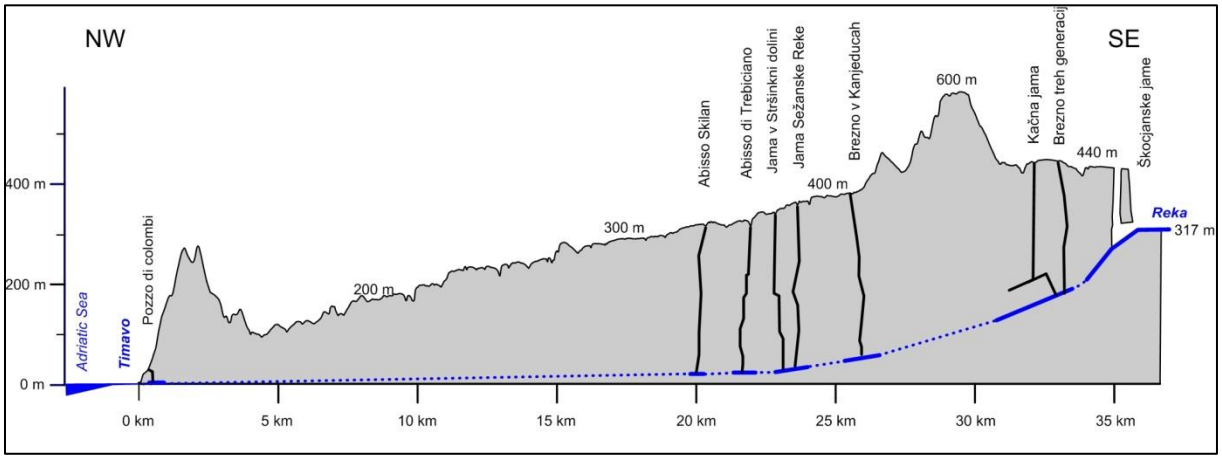

Figure 3.05: *Cross-section of Kras Plateau from the sink of Reka in Škocjanske jame, to the springs of Timavo with caves in which the underground water flow can be reached. Source of Lidar data: Geodetski oddelek ARSO.*

Karst of Škocjanske jame

The karst surface between the ponor of the Reka River and the village of Divača (Fig. 3.06) represents the SE part of Kras and it is named Divaški kras (Divača Karst). The karst morphology of Divaški kras (Fig. 3.06) is exceptional; on a small area of about 32 km^2, there are sinks of river Reka, 15 large collapse dolines, and hundreds of dolines. These features represent about 12 % of the area (Mihevc 2001). Numerous caves are known, the biggest among them are Škocjanske jame, Kačna jama, Divaška jama and Trhlovca.

Where Reka riches limestones at is a large blind valley is formed named Vremska dolina (Fig. 3.02). It is about 3 km long and 1.5 km wide, and some karstologists count it as border polje. Reka flows through it in elevation between 345 m and 335 m, above the riverbed, there are two higher rock terraces, at about 360 m and 380 m. The evolution of the blind valley was controlled by the height of water level in the karst and caves (i.e. Škocjanske jame) and regional tectonic uplift (Placer 2015). On the NW edge of the blind valley, Reka enters into a narrow canyon, which ends with Škocjanske jame at an elevation of 317 m.

Towards NW, above the Škocjanske jame, the higher leveled surface of Kras is on the elevation of about 410 – 450 m. No fluvial sediments are preserved there, but on the surface, many unroofed caves are located. Unroofed caves were proved by allogenic cave sediments and massive flowstone (Fig. 3.06). The first recognized unroofed cave was a 350 m long cave near Povir village which was

filled with fluvial sediments and speleothems (Mihevc & Zupan Hajna 1996; Mihevc *et al.* 1998). The largest, 1.8 km long, is known in Lipove doline above Škocjanske jame. The actual underground river bed in Škocjanske jame is 230 m below those unroofed caves. Morphological analysis of several unroofed caves on the Divaški kras (Mihevc 2001) and paleomagnetic dating of sedimentary fills (Zupan Hajna *et al.* 2008, 2010), have indicated cave origin and the age of few million years.

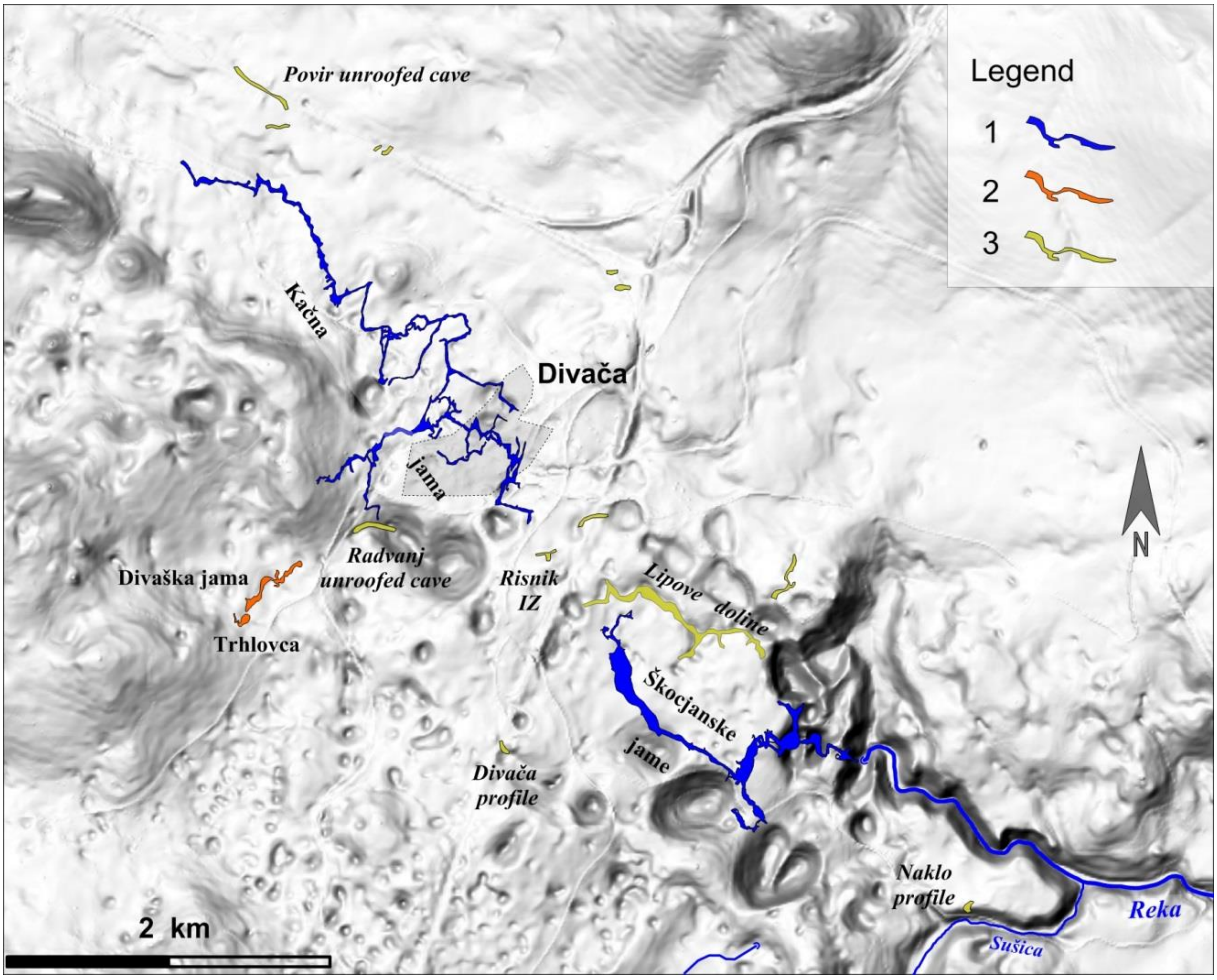

Figure 3.06: *Divaški kras with studied caves and unroofed caves. Legend: 1- caves with active water flow; 2 - relict caves with sediments; 3 - unroofed caves. Source of Lidar data: Geodetski oddelek ARSO.*

Reka with its tributaries is a typical allogenic river bringing sediment load into Škocjanske jame (Fig. 3.06). From the ponor and along the riverbed various clastic sediments are present. In the gravel clasts of flysch sandstone dominate, but the parts before the terminal siphon, limestone pebbles prevail (Kranjc 1989). Recent flood clay from the end part of the cave (Martelova dvorana at 214 m a.s.l) consists mainly of quartz, there are present some other minerals as plagioclase, illite, kaolinite, chlorite and calcite, and montmorillonite in traces (Zupan Hajna 1995). In older flood loams from the upper part of the caves (Tiha jama at 334 m a.s.l.) also quartz prevails, with some plagioclase, illite, chlorite, and microcline in traces. In Černigojeva dvorana (at 334 m a.s.l.) Gospodarič (1984) described fossil deposits of chert, flysch sandstone, and limestone pebbles. Also in other parts of the caves are preserved various fluvial sediments but flood loams prevail. Their characteristics color (always yellow tint) and position, indicate the origin of weathered flysch. Also, sediments from unroofed caves above the Škocjanske jame have a very similar mineral composition; in IZ Risnik unroofed cave (at 455 m a.s.l.) and in by sediments filled cave at Naklo (slope of Sušica valley, at 385 m a.s.l.), were also found alluvial sediments. Sediments were mainly flysch sandstone pebbles and

sand. Sand consists of quartz, calcite, muscovite/illite group of minerals, montmorillonite, microcline and plagioclase in traces (Zupan Hajna *et al.* 2017).

Studied paleomagnetic properties of the sediments in the caves Divaška jama, Trhlovca and in Divača profile (on Fig. 3.06; Bosák *et al.* 1998, 2000; Zupan Hajna *et al.* 2008, 2010), gave results that the age of the alluvial sediments is most probably up to 5 Ma; also study of sediments from the unroofed cave in Risnik Industrial Zone indicate the same age. Clastic fills of unroofed caves and still existing caves of Divaški kras consist mainly of weathering products of Eocene flysch rocks eroded from the Reka catchment. In all the cases relatively equal mineral composition prevailed, indicating the main source from flysch sediments which were weathered in different degrees. The mineral composition of Eocene flysch sandstones of the Brkini SE of Divača, which is the catchment area of the Reka, varies more in the number of individual minerals than in the presence of different minerals. On Divaški kras fluvial sediments from unroofed caves are also an important source of superficial soils (Zupan Hajna 1998).

The unroofed cave in Lipove doline is similar to Škocjanske jame in its dimensions, as the width of the passage was in some places likely to be more than 20 m. Concerning the massive stalagmites and flowstone, the ceiling was a least 100 m thick during the time flowstone was depositing in the cave. Flowstone deposited between phases of sedimentation of allogenic fluvial sediments. The origin of the sediments is the Eocene flysch, transported to the cave by a sinking river. A rough estimate would be that there are still approximately 45,000 m^3 of allogenic cave sediments preserved in the unroofed cave. The process of flysch transport into the caves of Divaški kras continues from about 5 Ma ago till now, just the intensity varied during the time.

Škocjanske jame

Because of the caves' extraordinary significance for the world's natural heritage, in 1986 the Škocjanske jame were included in UNESCO's World Heritage List. The Republic of Slovenia pledged to ensure the protection of the Škocjanske jame area and therefore adopted the Škocjanske jame Regional Park Act. The first paths in the cave area were made in 1823, but the construction of paths for exploration and visitors started in 1884. Cave exploration was done by cavers of DÖAV (Littoral section of Austrian Alpine Club) from Trieste. The most important explorers were Anton Hanke and Joseph Marinitsch. In 1891 they already reached the final sump in the cave.

Škocjanske jame are formed on the contact area of Cretaceous thick-bedded rudist limestone and Paleocene thin-bedded dark limestone (Gospodarič 1983). The river Reka sinks into Škocjanske jame (Figs. 3.02, 3.04 & 3.06), the underground channel is after a few hundred meters interrupted by two large collapse dolines Velika and Mala dolina. Cave then continues with a 2.6 km long channel to the Martelova dvorana (Martel's Chamber) at 214 m a.s.l. At low water levels, Reka sinks before it enters the cave. Floods usually reach up to 30 m. The largest known flood in the 19th century raised the water table level by 132 m.

Cave of almost 6 km long passages with dimensions approx. 30 m x 40 m and maximal heights up to 145 m in the underground canyon with flowing river, was scanned by terrestrial laser scanner from 370 stands (Walters & Zupan Hajna 2020). 3D model of the caves produced in a Cloud Compare is shown on figure 3.07. Overall cave volume from ponor in collapse doline Velika dolina to Martelova dvorana is 6.13 million m^3. Martelova dvorana chamber volume was calculated to 2.55 million m^3 with max. length of 314 m and width of 143 m and height of 158 m. Comparison with the largest chambers of the world has shown that the range of the Martelova dvorana in 2019 reaches 11th place in the world and 2nd in Europe for Salle de la Verna (3.6 million m^3). But in any case, Martelova dvorana is the largest river passage in Europe.

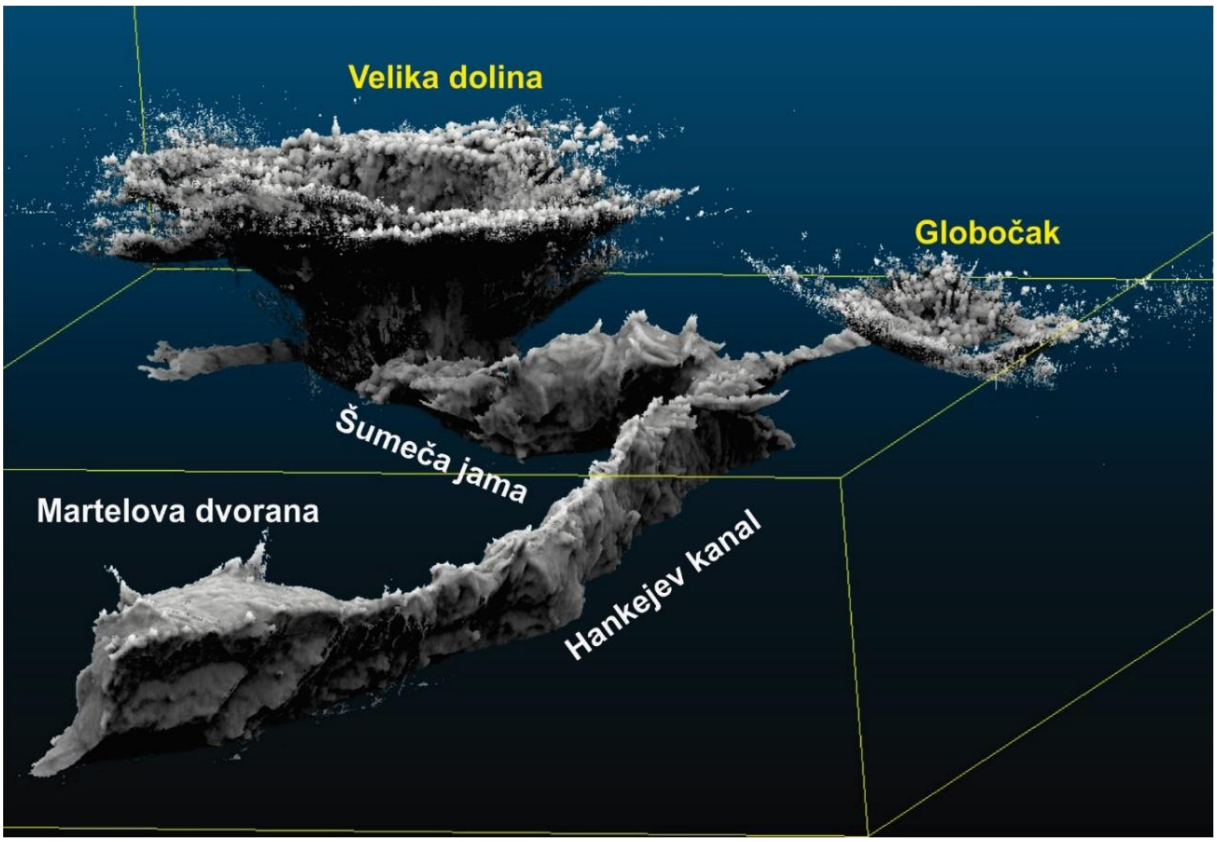

Figure 3.07: *3D model of Škocjanske jame made in Cloud Compare. View from NW: collapse dolines Velika dolina and Globočak with main parts of the cave: Šumeča jama, Hankejev kanal and Martelova dvorana (from Walters & Zupan Hajna 2020).*

REKA HYDROGEOLOGY

Some characteristics of Reka river underground flow between Škocjanske jame and Kačna jama

In tectonically active areas, karst systems continuously adapt to relatively rapid changes of structural and boundary conditions. The flow pathways in such systems are characterized by high variability of channel cross-sections and breakdowns, which restrict the flow and cause back-flooding with high fluctuations of groundwater level, particularly where the recharge variations are high.

An important role in the groundwater dynamics in Kras plays the allogenic Reka river, which sinks underground at *Škocjanske jame* and emerges about 40 km northwest at the coast of Adria near Duino in the springs of Timavo. The Reka river reaches the flysch-limestone boundary about 7 km upstream from Škocjanske jame. Before reaching Škocjan, it flows along a limestone canyon, where about 0.5 m^3 already leaks into the aquifer. At the entrance to Škocjanske jame the canyon turns into an underground channel (approx. 30 m x 40 m), which is after a few hundred meters interrupted by two large collapse dolines and continues with 2.6 km long, 10-60 m wide and 80 m to 145 m high underground canyon which. There, the channel is interrupted by a cross-Dinaric fault and cross-sections drop abruptly for roughly three orders of magnitude, to “only” several tens of square meters. Here, at 214 m.a.s.l., is the position of first observation station **P1,** where an automatic logger of level, temperature and specific electric conductivity was installed. The flow follows a sequence of channels (with a cross-section of several tens of m^2) and continues along with an 800 m long sump, which is still unexplored, but the connection to the second cave, *Kačna jama* is not questionable.

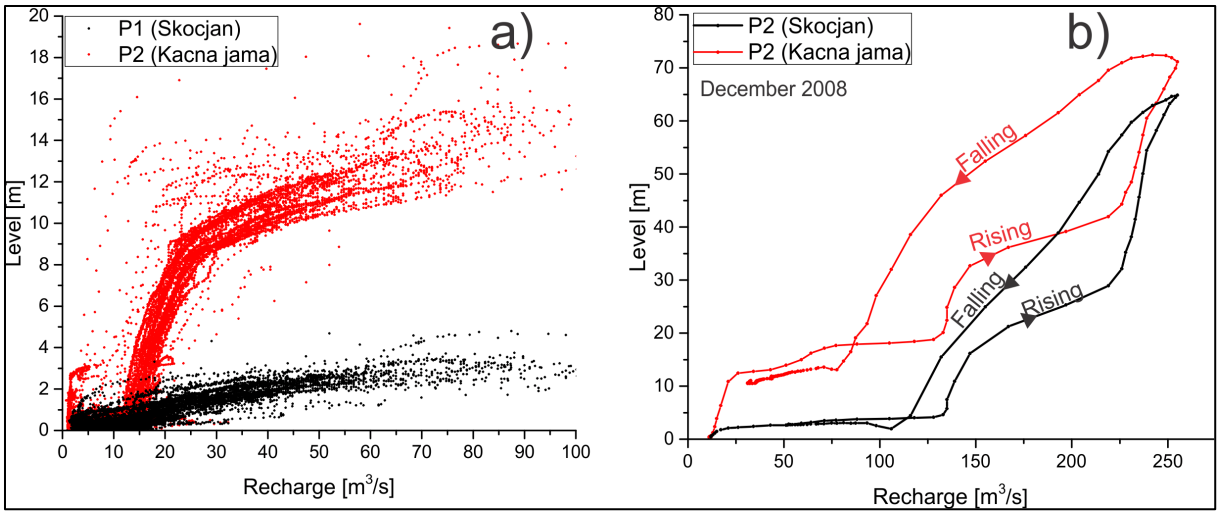

Figure 3.08: *Relation between Reka River discharge (=Recharge to the system) and water levels in Škocjanske jame (P1) and Kačna jama (P2) . a) Complete dataset. b) Large flood event in December 2008.*

The entrance to the Kačna jama is a 186 m deep shaft that connects to a complex system of phreatic, epiphreatic and vadose channels aligned along with at least two distinct levels. The cave is over 13 km long and 280 m deep. The lower epiphreatic level is dominated by the flow of Reka river, which mostly flows in an open channel during low to medium hydrological conditions when the water leaves the cave through the terminal sump at 156 m.a.s.l. The position of observation station **P2** (with the same logger as in P1) in Kačna jama was at the section called Brzice (rapids) about 300 m upstream from the sump, at 176 m.a.s.l. When the sump capacity is exceeded the water flows along with a system of overflow channels along the Dinaric direction for over 2 km. Several sumps with stagnant water were dived along this flow pathway, currently sump No. 4 is awaiting eventual new explorers. The major flow restriction is at Ozki rov with the sump at 156 m a.s.l., and at the end and the passages behind the first sump in an overflow gallery (Fig. 3.09). During high flow, most of the lower galleries are flooded. Historical markings of floods reach more than 100 m high.

Figure 3.08 shows the correlation between streamflow of Reka and levels at P1 and P2. Figure 3.09a shows all available data for the streamflow of Reka less than 100 m^3/s. A clear difference between P1 and P2 can be seen: while the level at P1 rises only for few meters within the shown range of discharge, the level at P2 rises steeply to about 8 m when discharge rises above 15 m^3/s. At discharge between 20 and 100 m^3/s the rise is slow again. The rise can be interpreted based on the known geometry of Kačna jama (P2). The flow from P2 continues to the sump at 156 m.a.s.l., which drains discharges lower than 15 m^3/s efficiently. At higher discharges, the surplus of water is diverted through a system of bypass channels with an apex about 8-10 m above P2. This is conceptually shown on figure 3.09, which shows (schematic) profile through the system with the positions of base flow and overflow channels.

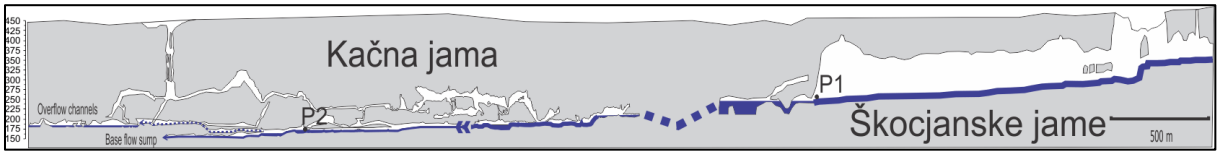

Figure 3.09: *Schematical profile between Škocjanske Jame and Kačna Jama. P1 and P2 indicate the positions of observation points. Blueline shows the flow during a low stage. Note the elevated position of overflow channels in Kačna jama.*

Figure 3.08b shows an extreme event during the highest recorded floods in December 2008 when peak discharge reached 260 m^3/s. At about 130 m^3/s levels in both caves increase abruptly for almost 15 m and continue to rise with several inflections. Particularly the rising parts of both curves exhibit high correlation pointing to a conclusion that the flooding at both points is controlled by the same restriction beyond P2 (Kačna jama).

CONTACT KARST OF PODGRAJSKO PODOLJE

From the southern side of the Brkini hills water sinks in 18 separate streams into the karst of Podgrajsko podolje (Figs. 3.02 & 3.10). 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. 3.01).

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. 3.10; Krivic *et al.* 1987; Petrič *et al.* 2007; Zupan Hajna *et al.* 2015).

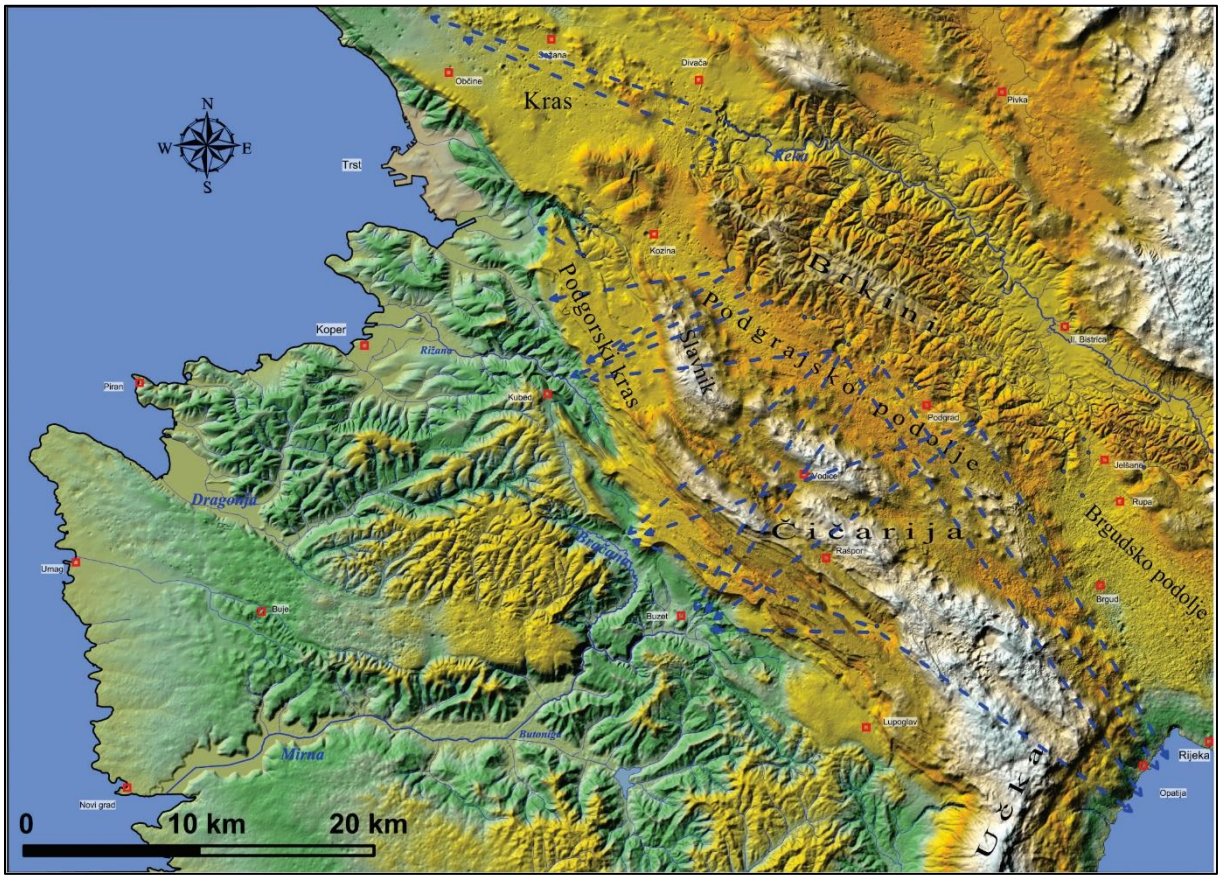

Figure 3.10: *Sinking streams of Podgrajsko podolje and theirs underground water flows towards karst springs. (modified from Zupan Hajna et al. 2015).*

Characteristic forms of this contact karst are blind valleys with corrosion-widened bottoms (Fig. 3.11). The surface of the Podgrajsko podolje probably developed as a base-leveled plain. 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.

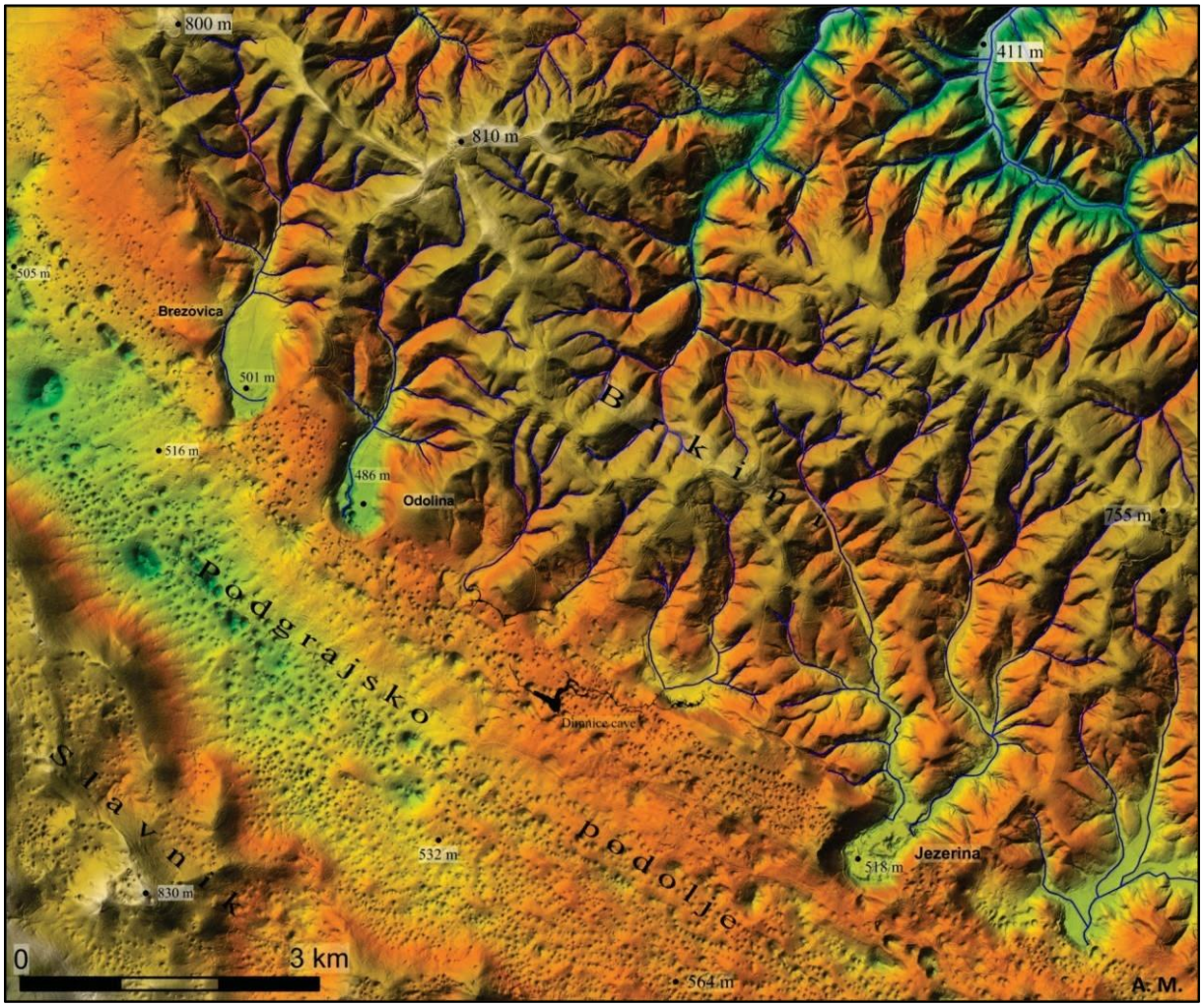

Figure 3.11: *Contact karst is morphologically expressed (central part of Podgrajsko podolje) as a row of blind valleys that are fed by surface streams flowing from fluvial relief (Brkini). On leveled karst surface relief was sculptured by precipitations (solution dolines) and underground karst processes (large collapse dolines). DEM is made of 1 m grid lidar data, Geodetski oddelek ARSO.*

As in the blind valleys are the contacts between the surface and underground flow which is limited by the capacity (diameter) of the ponors, floods and resulting sedimentation are normal and depending on distribution and intensity of precipitations. The sedimentation was especially intensive in the cold periods of the Quaternary and such deposits are preserved on the bottom of most of the blind valleys. In present conditions, sediments are eroded by the sinking rivers or are washed deeper into the karst by suffusion processes. Cave sediments from Pečina v Borštu (Fig. 3.13; Zupan Hajna *et al.* 2008; Pruner *et al.* 2010) and Račiška pečina were studied (Figs. 3.12 & 3.13; Zupan Hajna *et al.* 2008, 2010, 2021).

The Račiška pečina cave sediment sequence represents Late Pliocene up to Holocene chronostratigraphy and climate records. It is one of the best-preserved cave records of paleoenvironmental changes for the last 3.4 Ma. In the sequence are by magnetostratigraphy well recorded Pliocene/Pleistocene transition at 2.59 Ma, the Matuyama/Brunes boundary at 0.773 Ma, and the presence of Olduvai subchron between 1.78–1.925 Ma. The investigated sedimentary sequence was mainly characterized by the deposition of layers of huge speleothem domes with long

hiatuses which started to grow when the cave was detached from its hydrological function. Occasional deposition of speleothem layers was interrupted by the sedimentation of infiltrated clay to silt material originating from the surface above the cave. In these clastic sediments, a Pleistocene fauna was present, in which specimens of subterranean gastropods *Zospeum* sp. were also found (in samples RP20-22, RP 51-52, RP F2). Records of small mammals from the lower part of the section (sample RP F; *Apodemus* cf. *atavus Borsodia* sp., and *Pliomys* sp.) suggest MN17 age, while *Clethrionomys* cf. *glareolus* (samples RD1(A), PONV(RP20-22)) from the upper part suggests the Late Early or Middle Pleistocene age. In the upper part of the section *Ursus* ex gr. *spelaeus* was confirmed in the yellow clay layer (samples RP C, RP B) older than ~72 ka, and soot material at the top of the section was radiocarbon dated on ~11 ka, ~9 ka, and ~3 ka (all in sample RP II).

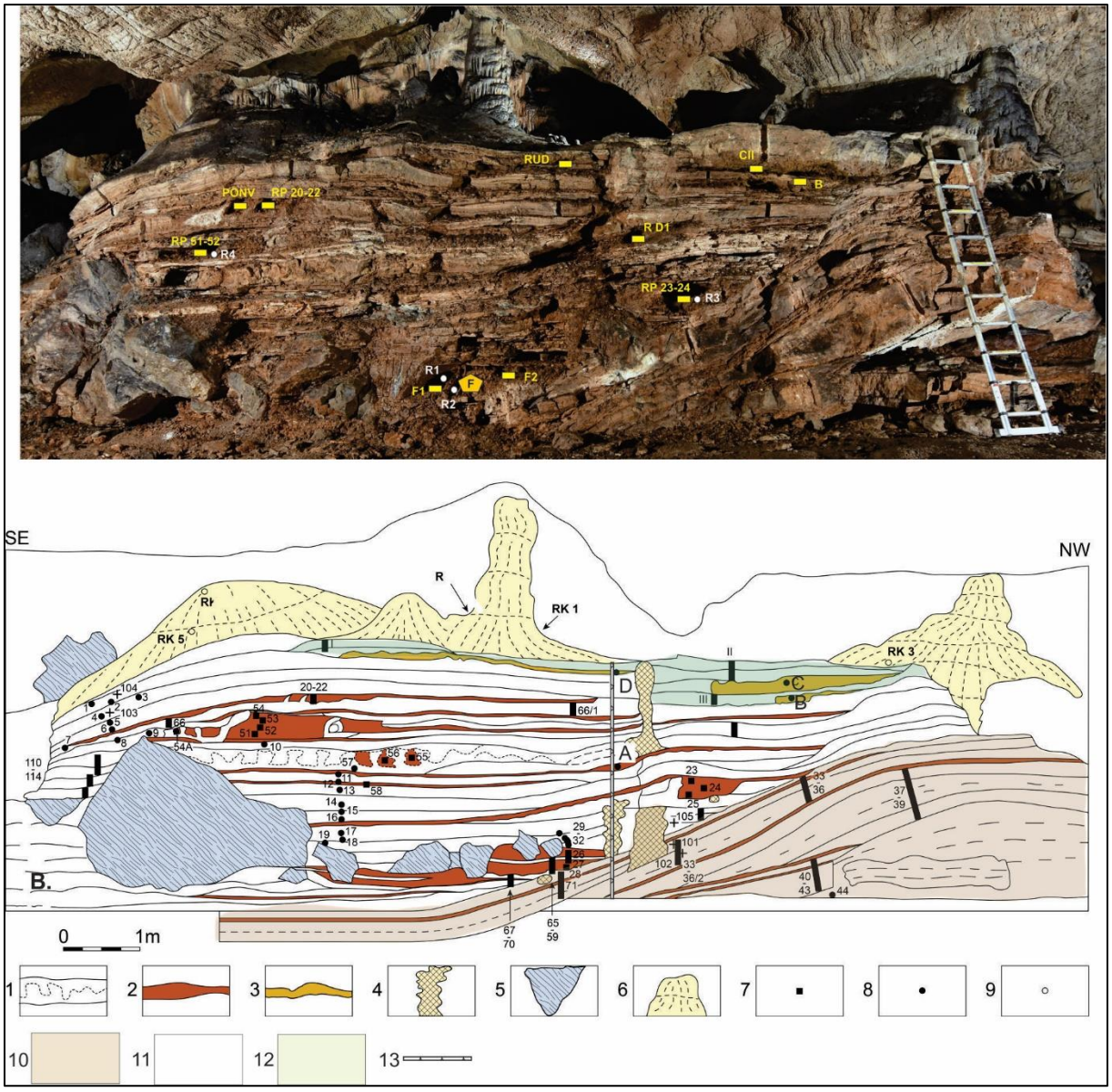

Figure 3.12: *The studied sedimentary section Račiška pečina (RP) with the positions and numbers of fauna and paleomagnetic samples (after Zupan Hajna et al. 2021). Legend: 1 – rimstone pools, 2 – red clay layers, 3 – yellow clay layers, 4 – stalagmites, 5 – breakdown blocks of limestone, 6 – youngest speleothems, 7 – slices of speleothem layers for paleomagnetic analyses, 8 – cubes, 9 – positions of cores (RK), 10 – lower segment, 11 – middle segment, 12 – upper segment, 13 – schematic position of stable isotopes samples.*

PODGORSKI KRAS

The Podgorski kras *(Podgora Karst)* is about 5 km wide and up to 15 km in length, a karst plateau between Slavnik Mountain (1025 m a. s. l.) on the NE and littoral hills on the SW *also known as Kraški rob (Karst Edge) which rises above Trieste Bay (Figs. 3.01, 3.10 & 3.13)*. Its surface is located at 500 to 450 m a.s.l. The plateau surface is leveled and dismembered by numerous dolines and roofless caves (Zupan Hajna *et al.* 2008). Only small allogenic surface streams exist on its surface and they sink at the carbonate/flysch contact karst zone.

The term "kraški rob" ("karst edge") in general, denotes a geomorphologic step of vertical cliffs and steep carbonate slopes along the whole length of Underthrust Belt – between the Timavo river mouth and Učka mountain. These rocky cliffs and slopes mark the border between karstic plateaus Kras and Čičarija at one side, and flysch of Istria and Trieste coastline at the other side. The plateau descends by several structural steps to the depression of the Rižana and Ospaska river valleys which are developed in flysch. Karst springs of Rižana and Osapska rivers (maximum discharge of several m^3/s) are located under the plateau structural edge at altitudes of 50-100 m a.s.l.

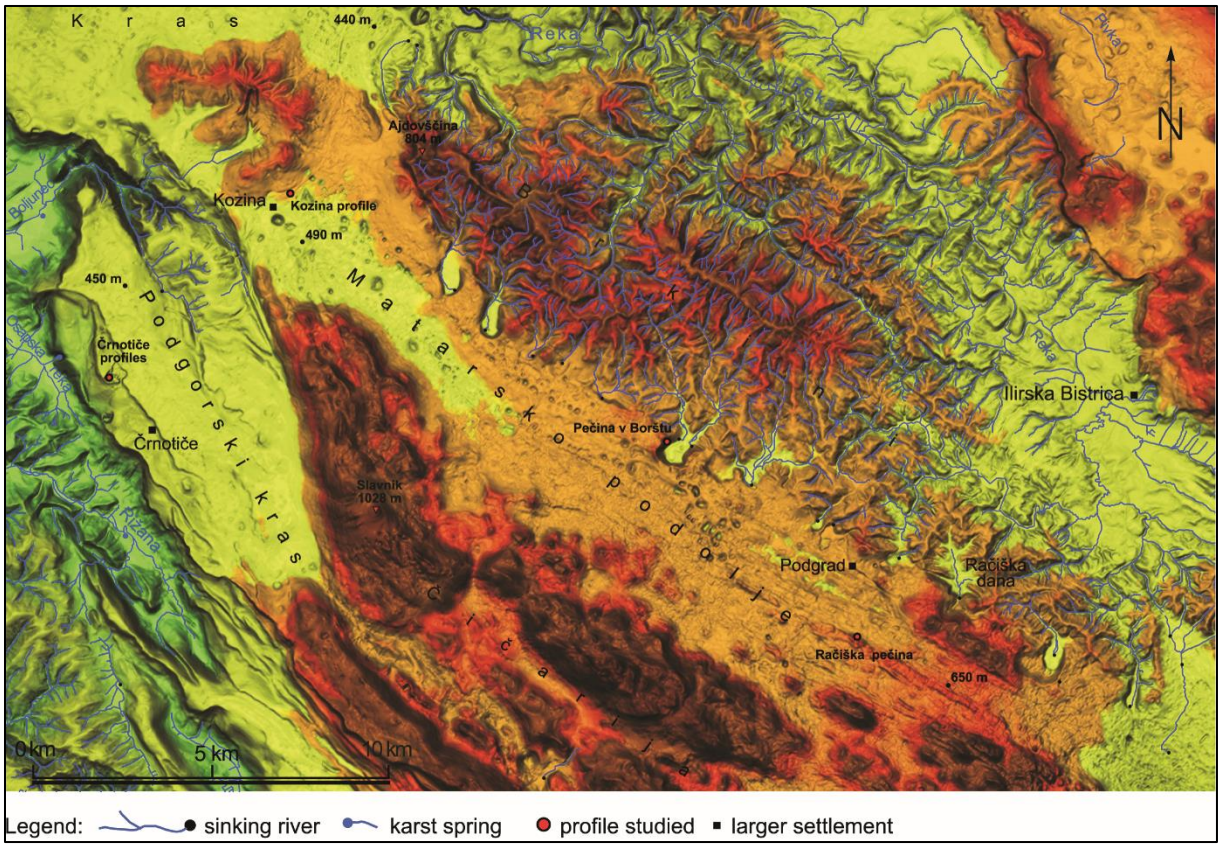

Figure 3.13: *Podgrajsko podolje and Podgorski kras (SW Slovenia) with locations of Pcaves Pečina v Borštu, Račiška pečina and unroofed cave Črnotiče (profiles). Well expressed are blind valleys on the NE edge of Podgrajsko Podolje, where small brooks sink into the karst.*

Numerous shallow dolines with flat bottoms, in which some sediments are preserved, represent the principal surface karst forms. A total of 92 caves are known at Podgorski kras with maximum depths up to 150 m.

There are also several unroofed caves, remnants of larger cave systems indicating that the karst is ancient. Three sections of cave sediments were studied in Črnotiče Quarry (Fig. 3.13). The quarry is excavated in the karst leveled surface to the depth of about 60 m. It uncovered several unroofed and

relict caves filled by allogenic sediments, speleothems, and younger red soils with Pleistocene fauna (e.g. Pohar, 1994). There were studied 3 sections in unroofed and relict passages (Zupan Hajna et al. 2008, 2020). The best results were obtained from section Črnotiče II (Fig. 3.14; Bosák *et al.* 2004; Horáček *et al.*, 2007; Zupan Hajna *et al.*, 2008b, 2010, 2020) which represents filled unroofed cave passage about 7 m wide and 17 m high cut by a quarry face. Allogenic laminated and cyclically arranged sediments originated from Eocene flysch rocks of Brkini hills (Zupan Hajna *et al.* 2008) were covered by breccia formed of blocks and fragments of massive flowstone. The side cave wall with scallops was covered by fossil calcareous tubes of *Marifugia cavatica*. Besides tubes of Marifugia, sediments also provided fragments of vertebrate and non-vertebrate fossil remains (see Horáček *et al.*, 2007). Remains of small mammals mostly belong to MN15–MN16b biozones (about 3.2–4.1 Ma; Horáček et al., 2007). Paleomagnetic analyses of the Črnotiče II fill and the magnetostratigraphy correlation with the GPTS indicate the deposition within the Gauss chron (2.581–3.58 Ma) confirming biostratigraphic results and vice versa (Horáček *et al.*, 2007). Črnotiče II profile starts in the N-polarized zone, which means that fauna cannot be older than about 3.58 Ma, due to R-polarized magnetozone below (3.58–4.18 Ma) at the top of the Gilbert Chron. Remains of *Marifugia cavatica* attached at cave wall and buried by sediments are of the same age or somewhat older.

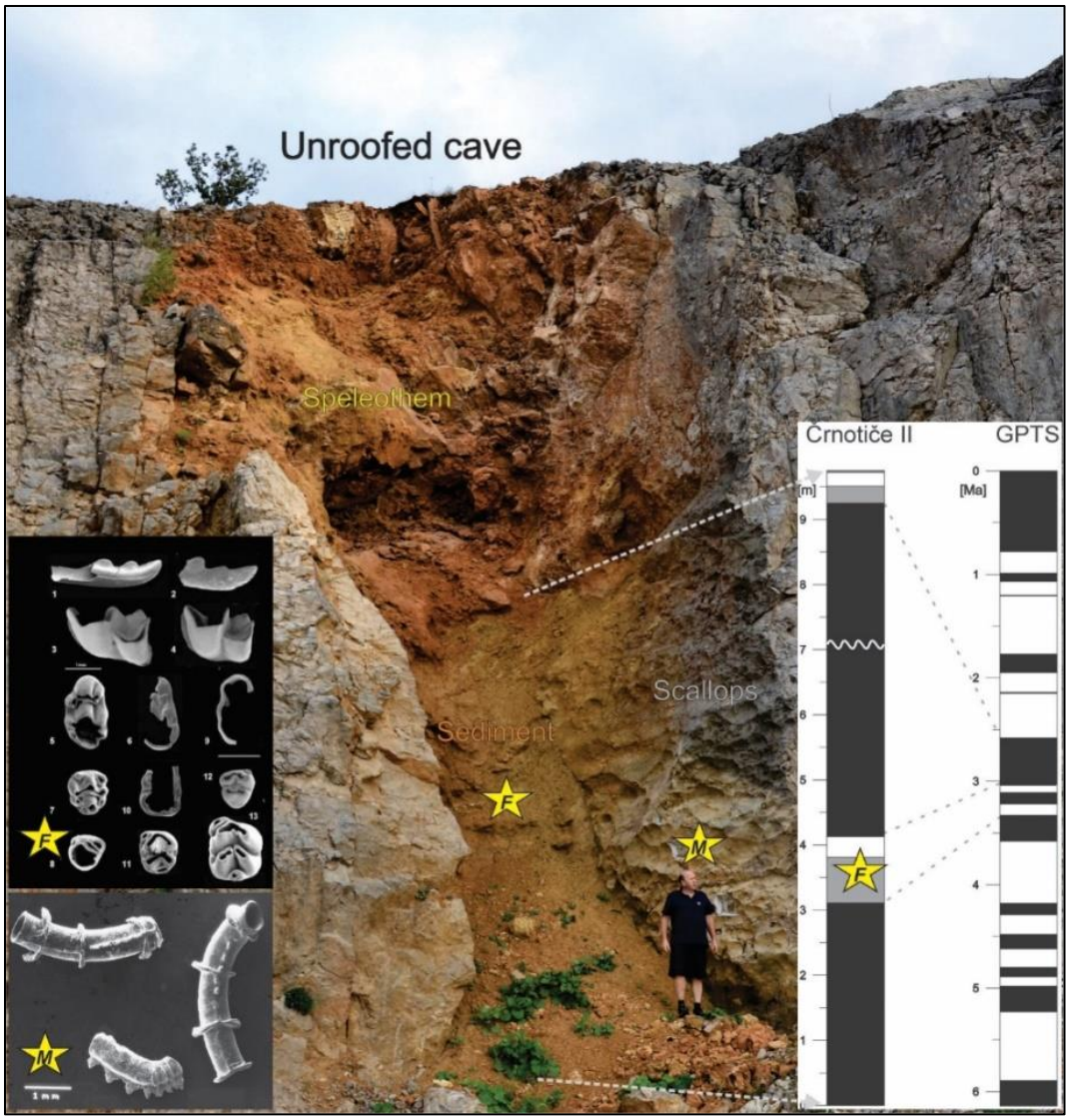

Figure 3.14: *Črnotiče II site. Allogenic fluvial sediments in the unroofed cave with fauna remains are covered by speleothems and red clays. Paleomagnetic results were correlated with the geomagnetic polarity timescale (GPTS) regarding paleontological remains (from Zupan Hajna et al. 2020).*

The allogenic sediments were deposited in caves by sinking rivers. After that, the surface was leveled by corrosion and uplifted for about 400 m relatively to the present altitude. After leveling, regional uplift caused the lowering of the groundwater table, surface has started to be slowly disintegrated by the formation of dolines.

Below the edge of the karst, which is defined by the contact of limestone and flysch, the karst springs of the Rižana, Bračana, Mirna, and Boljunščica emerge (Figs. 3.03 & 3.10). These rivers formed a ridge-and-valley relief in the flysch, which strongly disconnected and lowered the originally flattened surface.

RIŽANA KARST SPRING

Based on hydrogeological studies and numerous tracer experiments (Krivic *et al.* 1987; 1989; Gabrovšek *et al.* 2015) the catchment of the Rižana is estimated at 247 km2. For the most part it lies within Slovenia, with only a small part extending to the Croatian side of the border. It is characterized by an alternation of highly permeable Cretaceous and Palaeocene limestone and dolomite and very poorly permeable Eocene flysch (Fig. 3.01). From the tectonic point of view, the area is positioned in the border area between Dinarides and Adriatic–Apulian foreland (Placer 1999). The spring is located in the narrow SW-verging imbricate belt in the front of the External Dinarides, believed to have formed in response to Adriatic–Apulian (Istria, Friuli) underthrusting External Dinarides (Kras, Čičarija). Within the underthrusting belt, a geomorphological step was formed at sites where limestones are overthrust on flysch rocks (Placer 2007). This so-called Kraški Rob (»Karst Edge« in English) is cut by a series of reverse and thrust faults into a system of thrust-plane bounded slices which are partly hydraulically connected and form very complex hydrogeological conditions.
Karst aquifer with underground water flow developed in carbonate rocks, while flysch areas feature a network of surface streams along which alluvial sediments are deposited. Surface streams from flysch percolate into the karst underground at points of contact with carbonate rocks, while on the other side of the karst aquifer groundwater comes to the surface through karst springs at points of contact of this kind (Biondić *et al.* 2015).

At the southern margin of the Brkini hills (Figs. 3.02, 3.03 & 3.10), surface waters disappear underground into the karst aquifer at a contact approximately 20 km long, where the limestones dip steeply under the flysch. Blind valleys with solution-widened floors are a typical karst landform. Numerous small surface watercourses drain an area of approximately 30 km^2. The sizes of the catchment areas of individual sinking streams range from 0.5 to 13.2 km^2. The ponors are at 490 to 510 m a.s.l. Some of them continue into karst caves that end with siphons of trapped water at heights of between 370 and 430 m a.s.l.

The alternation of flysch and limestone is also typical for the area south of the Rižana spring.
At the contact, elongated shallow karst depressions called vale (singular: vala) have developed at heights of between 168 and 300 m a.s.l. In terms of their hydrological characteristics, these are a kind of periodically flooded boundary karst poljes. The floods are caused by the insufficient absorption capacity of ponors when the water level is high. They occur two to three times a year and last from a few hours to a few days (Habič *et al.* 1983).

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ALPINE KARST

Thursday, 17. 6. 2021, Afternoon lecture

Matej Blatnik, Metka Petrič, Nataša Ravbar, Franci Gabrovšek, Andrej Mihevc

Alpski kras

Za Alpski kras so značilne visoke nadmorske višine, debeli skladi karbonatnih kamnin, aktivna orogeneza in pretekle poledenitve, kar se odraža v veliki reliefni energiji, različni poraslosti z rastlinstvom, različni pokritosti s prstjo in kraškimi oblikami, med katerimi prevladujejo visoke kraške planote in pretežno verikalne jame. Jame kot so Renejevo brezno-Brezno rumenega maka ali Sistem Migovec sta dva primera kraških jam s snežno-dežnim režimom pretakanja vode in prepletajočim podzemeljskim tokom vode. Prvi se napaja z vodo s Kaninskega pogorja, drugi pa z vodo iz širše okolice Tolminskega Migovca, od koder se ta nadalje pretaka tako v Jadransko povodje kot povodje Črnega morja.

CHARACTERISTICS OF THE ALPINE KARST

Alpine karst landscape dominates the Julian Alps and Kamnik-Savinja Alps (Fig. 4.01), which are both part of the Southern Calcareous Alps. The latter separated from the Dinaric Mountains in the Miocene. The area has been subdued to folding, faulting and uplifting in Tertiary orogeny (Fig. 4.02). The karst is mainly developed in the upper Triassic limestone and dolomites (Mihevc *et al.* 2016).

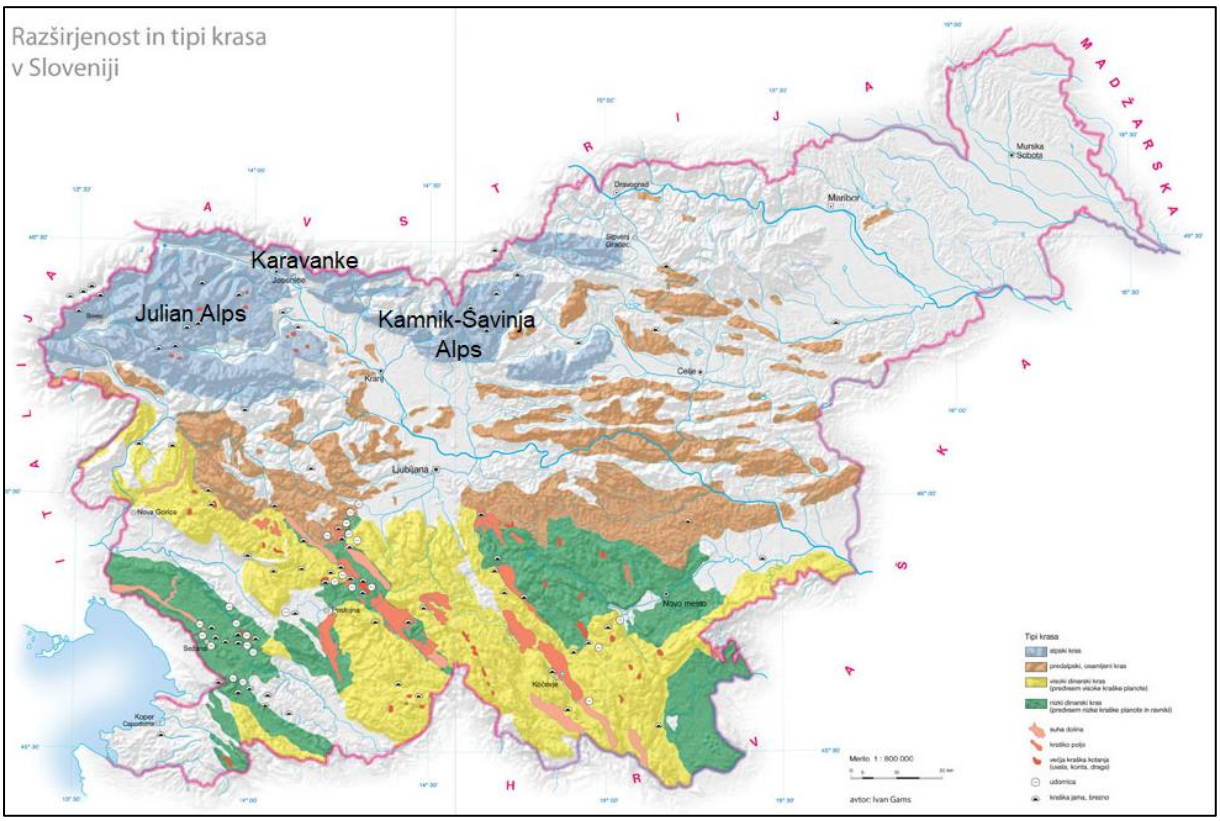

Figure 4.01: *Distribution of Alpine Karst in Slovenia, marked with blue colour (Gams 2004).*

Besides tectonic structure and lithology, several other factors influenced the exokarst and endokarst development of the area. Initial planation, especially on the southern side, formed extensive karst plateaus (Pokljuka, Jelovica, Mežakla, Komna and others) (Fig. 4.03). Uplift and Pleistocene glaciations formed and/or reshaped fluvial valleys, separating karst plateaus with the highest peaks (Triglav 2864 m a.s.l.). There up to a two-kilometre thick vadose zone developed between them (Mihevc *et al.* 2016).

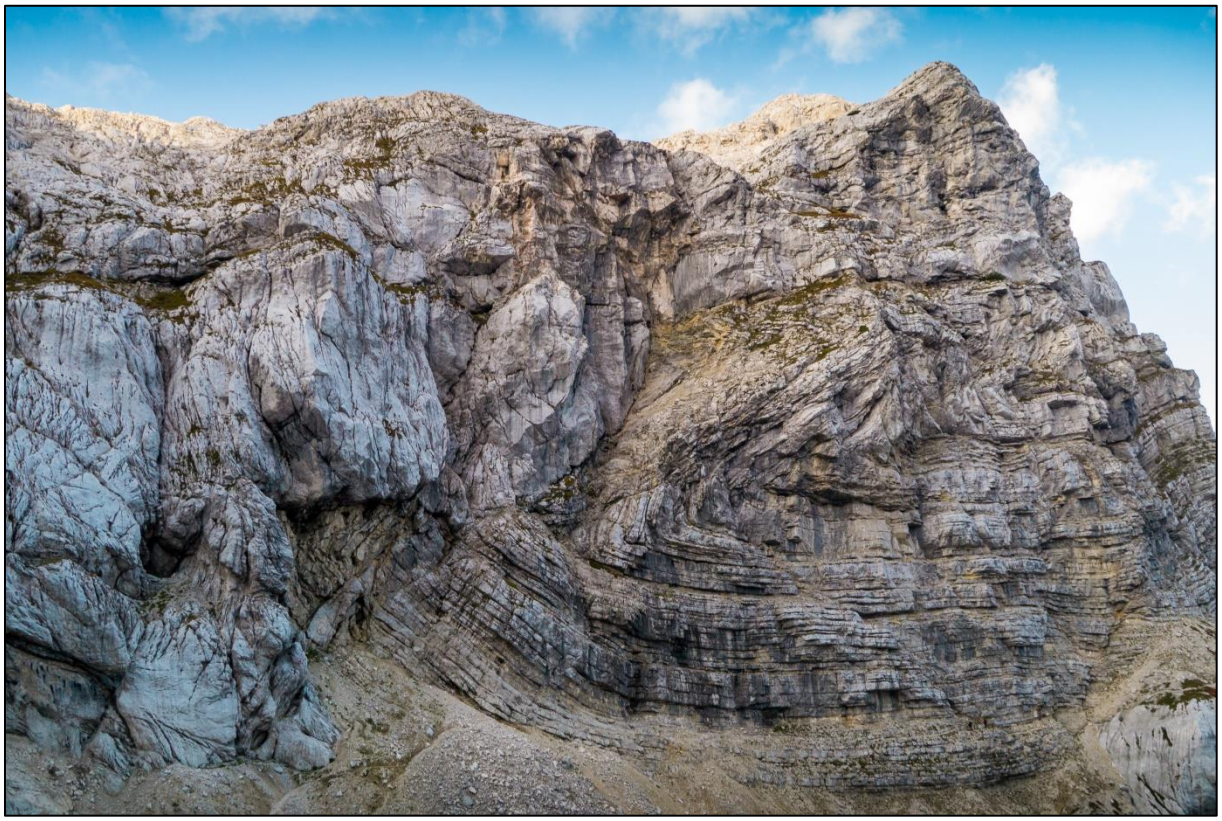

Figure 4.02: *A contact between two different formations at Kanjavec Mountain (Photo: M. Blatnik).*

Figure 4.03: *Plateau Komna with relatively big depressions surrounded by peaks (Photo: M. Blatnik).*

In the valleys large karst springs are recharging the alpine rivers. The largest are the Soča, Sava and Savinja rivers. In some places deepening of valleys was faster than the lowering of water flow, therefore many karst springs are situated higher in the slopes and there waterfalls are formed (Mihevc *et al.* 2016). Among them the most prominent are 140 m high Boka waterfall (Fig. 4.10) in the Soča valley, Savica and Peričnik waterfalls as contributors of the Sava River and Rinka as one of the spring of the Savinja River (Fig. 4.04). In Julian Alps is also an important division of waters; the Soča River flows towards the Adriatic Sea, and the other ones towards the Black Sea.

Large amount of precipitation (1600–3200 mm/year) and thick aquifers results in important amounts of groundwater stored in alpine aquifers. It was assessed on water balance that they can recharge an average outflow of 115 m^3/s (Petrič 2004). For the karst springs, the Alpine nival-pluvial regime with the main discharge peak in May or even June (as a result of the snow melt) and the secondary peak in October or November (arising from the precipitation maximum) (Mihevc *et al.* 2016).

Figure 4.04: *The waterfall Savica, presenting a spring of the river Sava Bohinjka (Photo: M. Blatnik).*

Distribution of caves varies quiet much from one part of the Alpine karst to another. The biggest density of caves is Kanin Plateau (Fig. 4.06) with more than 2000 caves registered on both Slovenian and Italian site. More than 10 are deeper than 1000 m, among which the deepest is Čehi 2 with 1505 m, located close to the mountain Rombon. Most of these caves are completely vertical, quite many of them also filled with snow and/or ice. Due to gradual snowmelt more caves and parts of existing are become accessible. Even though conditions in rest of Alpine karst in Slovenia are not much different than on Kanin Mountain, the density of caves is significantly smaller, as well as the depth of caves. In the mountain Migovec close to the town of Tolmin is the longest cave system in Slovenia. The cave system Migovec has multiple entrances with total vertical difference of 970 m and length of 43 km. The deepest in Kamnik-Savinja Alps is a system of caves Molička Peč, with 1135 m the only deeper than 1000 m outside from Kanin Mountains.

Alpine karst also includes fragments of pre-alpine cave systems, mostly of phreatic or epiphreatic origin, which are scattered within the massifs. These are sometimes intersected by younger vertical shafts, or on rare occasions, their entrances are exposed by surface processes (Kunaver & Gabrovšek 2001; Audra *et al.* 2007). Such a case is the Snežna jama na planini Arto (Fig. 4.05), at an elevation of about 1500 m a.s.l. The cave is rich in allogenic sediments that were brought in by a sinking stream. They were dated by combined a palaeontologic and palaeomagnetic method to an age of between 2.6 and 6 Ma. They were transported into the cave before the main uplift of the area and /or river valleys incision for about 950 m (Mihevc *et al.* 2013).

Figure 4.05: *Ice chamber in Snežna jama na planini Arto (Photo: J. Obu).*

Figure 4.06: *Karstified surface of the Kanin Plateau (Photo: M. Blatnik).*

GROUNDWATER DYNAMICS OF RENEJEVO BREZNO-BREZNO RUMENEGA MAKA (KANIN PLATEAU)

Cave Renejevo Brezno-Brezno Rumenega Maka is located on Kanin Plateau, which measures about 160 km^2 and extends in two countries. About half belongs to Slovenia and another half to Italy. Kanin is surrounded by Soča Valley and Bovec Basin on SE, Rezija Valley (Val Resia) on SW and valleys of Reklanska Dolina (Val Raccolana) and Jezerska Dolina (Val Rio del Lago) on N (Fig. 4.07). The elevation of area varies from about 300 m a.s.l. in valleys to 2587 m a.s.l. at the top of Kanin Mountain (Komac 2000; Zini *et al.* 2015). During the last glaciation that ended about 10.000 years ago, the area was covered with ice, which affected on the shape of relief and on concentrate flow of water during melting (Kunaver 2011).

The cave has two entrances, one named Renejevo Brezno and another Brezno Rumenega Maka. The total length is almost 6 km, whereas vertical difference 1322 m. Upper parts consists of vertical shafts and below 1000 m of depth the cave becomes horizontal with passages at different levels (Fig. 4.08). The lowest part presents a collector of waters with a stream flowing towards SE to the final sump called Copacabana (Figs. 4.08 & 4.09). From there on water presumably flows towards springs Boka (Fig. 4.10), Mala Boka and Glijun, located at the SE border of the Kanin Plateau in the valley of the Soča River (Fig. 4.07).

In 2016 continuous measurements of water level and temperature were established in the sump Copacabana (1240 m of depth, 1017 m a.s.l.) (Fig. 4.09). These measurements were supplemented with measurements of conductivity on December 2018. During individual visits of the cave, several manual measurements of temperature and conductivity were made at different places of the cave (Fig. 4.08) and discharge measurements of the stream before sinking into the sump. In summer 2020, continuous measurements of the temperature and conductivity were established also in the springs of Glijun and Boka (Fig. 4.10) in order to compare their dynamics with one in the lowest part of the cave.

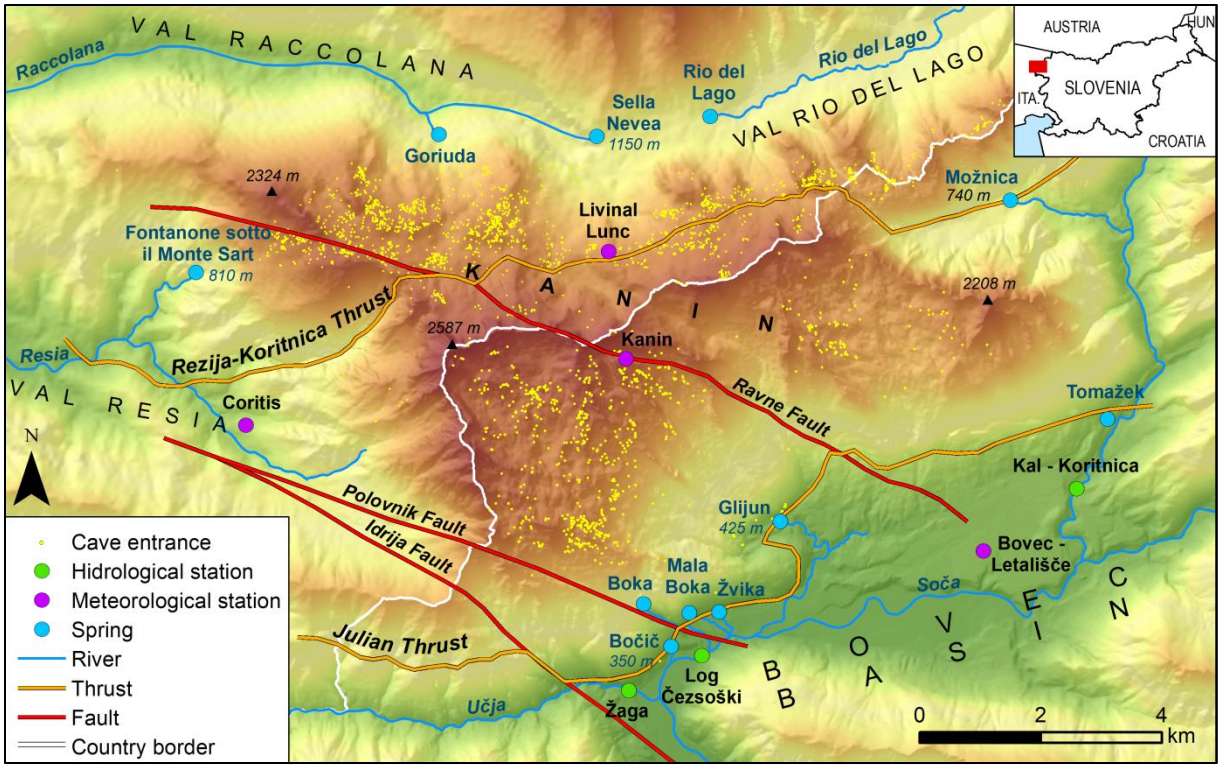

Figure 4.07: *Distribution of caves and springs around Kanin Mountain.*

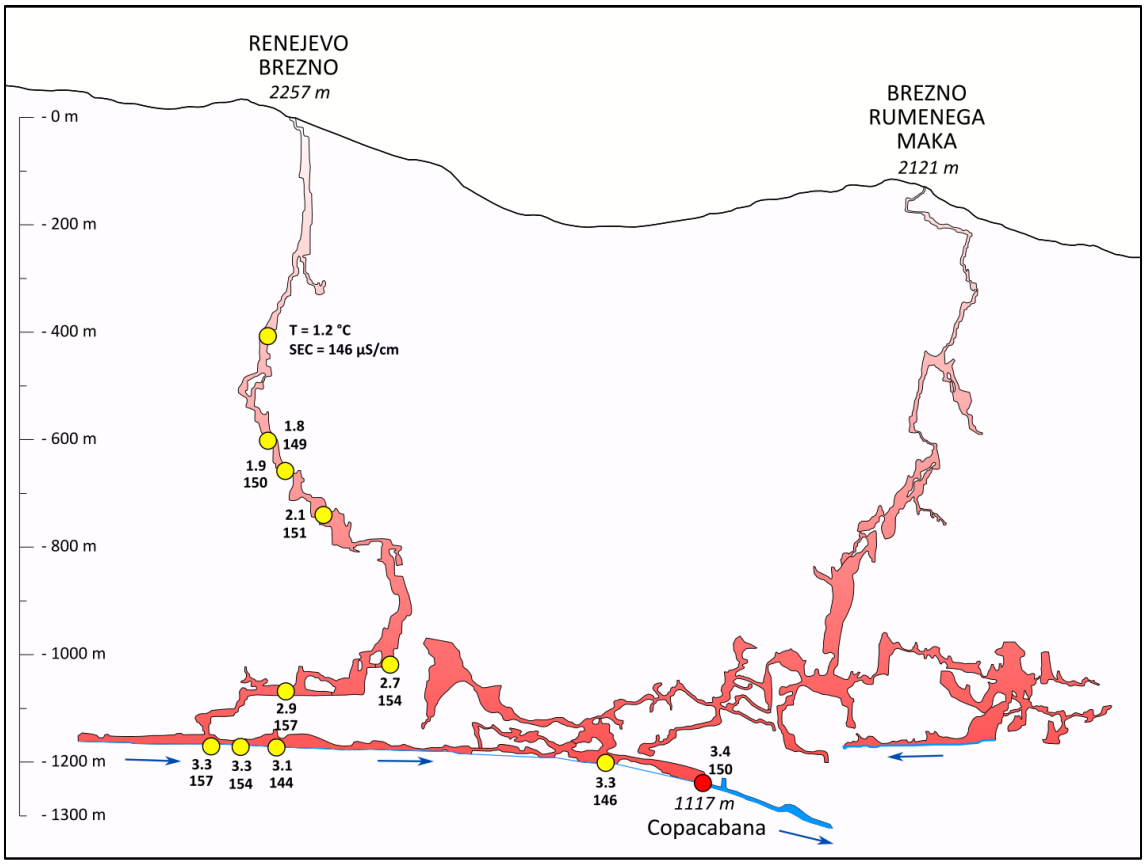

Figure 4.08: *Cave profile with marked positions of and measurements of T and SEC (yellow circles) and continuous measurements of H, T and SEC in the final sump (red circle) (Cave map from Društvo za raziskovanje jam Ljubljana).*

Figure 4.09: *The final sump Copacabana with the logger for continuous measurements of H, T and SEC (Photo: M. Blatnik).*

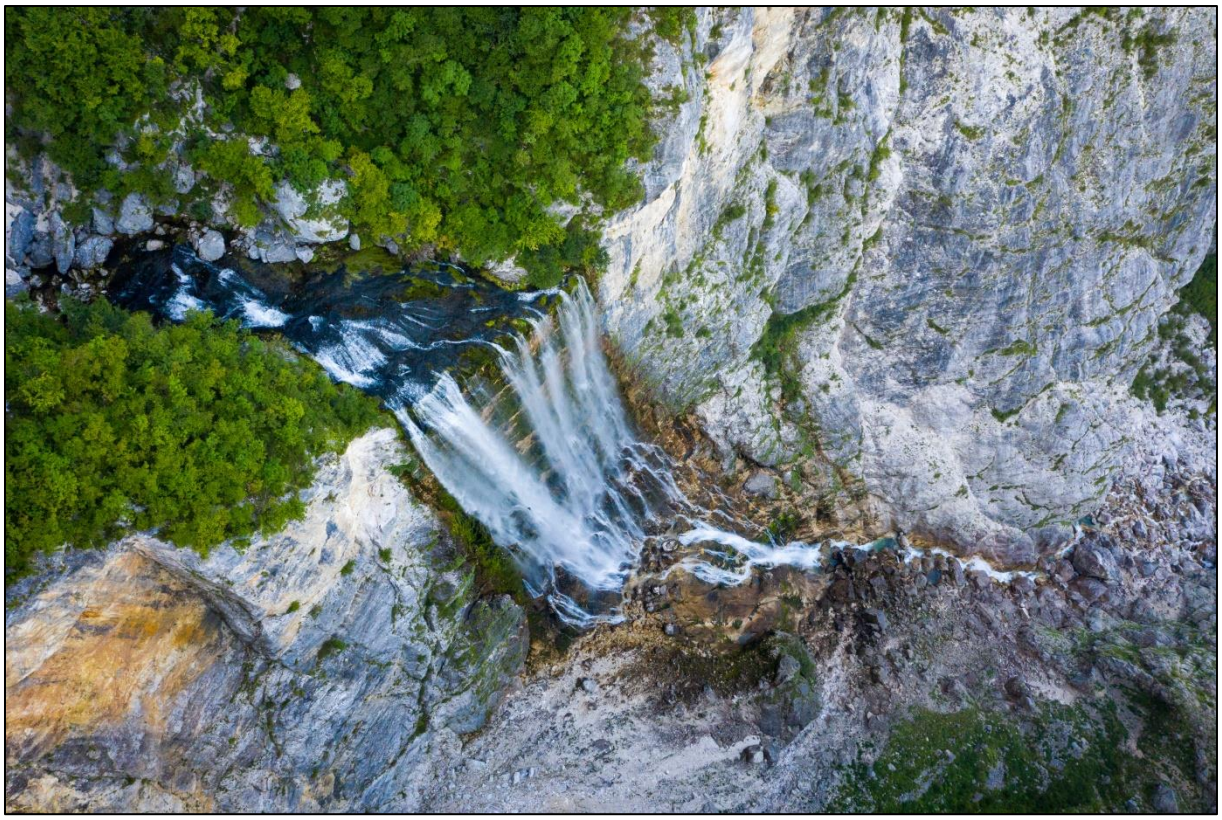

Figure 4.10: *The spring Boka which continues with an about 140 m high waterfall (Photo: M. Blatnik).*

Groundwater measurements showed that they are strongly dependent on climatological conditions of its recharge area. Because of high elevation (~1500–2500 m a.s.l.) there are relative long winters with snow accumulation and relatively short warm period of the year with rainfall events. During winter snow doesn't contribute a lot of water (Fig. 4.11), whereas during warm period of the year inflow of water is significantly bigger due to snowmelt on the surface and rainfall events (Fig. 4.11). Another factor that influences the groundwater dynamics is long flow of water through about 1 km thick vadose zone and processes that take place on the way (dissolution, heat exchange, mixing of water, etc.) (Fig. 4.08).

Besides annual water level oscillations also diurnal oscillations are present (Fig. 4.12). They occur during snowmelt period, where snowmelt activity is changing over day due to solar radiation. As a result amount of water flowing underground is changing as well with the highest peaks registered in the bottom of the cave in evenings due to several hours long travel times. Such oscillation can be up to 1 m high, whereas rainfall events can cause up to more than 20 m high increases. The duration of these events is very short, usually lasting less than one day (Fig. 4.12). The increase occurs almost immediately after rainfall events, the peak is very short and followed by a rapid decrease of the water level. This indicates good drainage of the final sump, which has insufficient outflow only for a very short period during the highest discharges. Continuous temperature measurements are showing very stable temperature over the year with slightly higher temperature during winter (Fig. 4.11). Lower temperature during summer, especially during high water events, are indicating that larger amount of cold snowmelt water cannot adapt completely to the cave ambient temperature. Due to absence of vegetation and soil on the surface, water entering the cave is less aggressive and its conductivity smaller (Fig. 4.12), especially when amount of water is bigger and its flow faster.

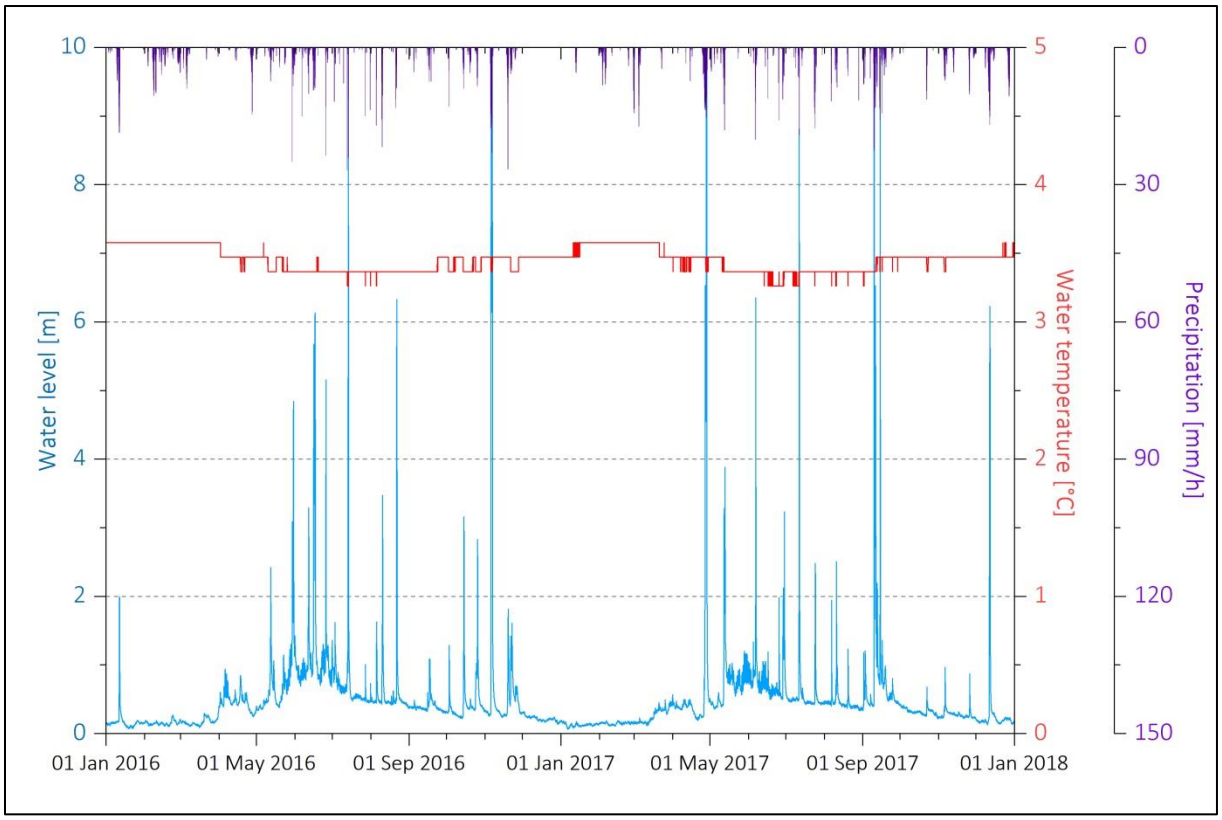

Figure 4.11: *Two years of water level and temperature measurements in the sump Copacabana, showing higher water level during snowmelt and summer rainfall events.*

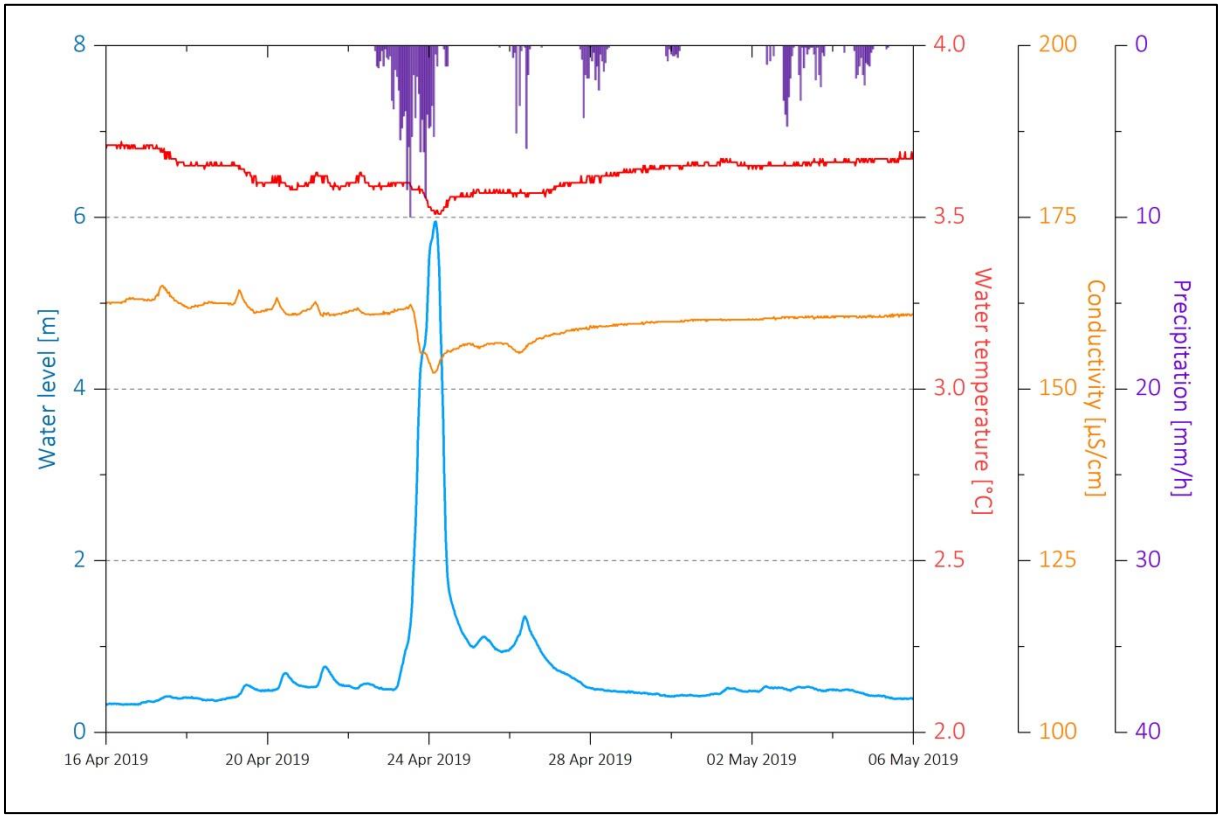

Figure 4.12: *Selected high water event from April 2019, showing rapid response to the high water event and occurrence of diurnal oscillations of the water level due to snowmelt prior rainfall event.*

GROUNDWATER FLOW IN MIGOVEC CAVE SYSTEM

Migovec is the longest cave system in Slovenia with a total length of cave passages of 43 km and 972 m of vertical difference. The cave lies below the mountain Tolminski Migovec (1881 m a.s.l.) in the direction towards Tolminka Valley and town Tolmin. The structural geology of the area is governed first by thrust nappes (locally the Zlatna and Krn nappes), which brought Upper Triassic Carbonate units over younger Jurassic and Cretaceous marls and limestone sequences. The high carbonate peaks form the backbone of the NW-SE oriented ridge to which Tolminski Migovec belongs. Sistem Migovec is formed principally in well stratified and heavily faulted Upper Triassic Dachstein Formation. The underlying formation of bedded to massive Upper Triassic Main Dolomite Formation outcrops on the NE side of the Tolminka valley (Racine 2019). This formation, less karstified than the overlying Dachstein Formation, acts as a local aquiclude (Audra *et al.* 2007).
The highest positioned of seven entrances is just below the top of the mountain at 1861 m a.s.l. (Kavkna Luknja), whereas the lowest positioned of several sumps called Watership down is at 899 m a.s.l. The whole system is at about 1 km^2 which presents big density of channels (Fig. 4.13), where upper parts are predominantly vertical and lower horizontal with some inclination along the geological structures (faults and bedding planes). The inclination of geological formations is towards the SE, but due to some faults, resulting in vertical shifts of blocks, they behave as hydrogeological barrier.

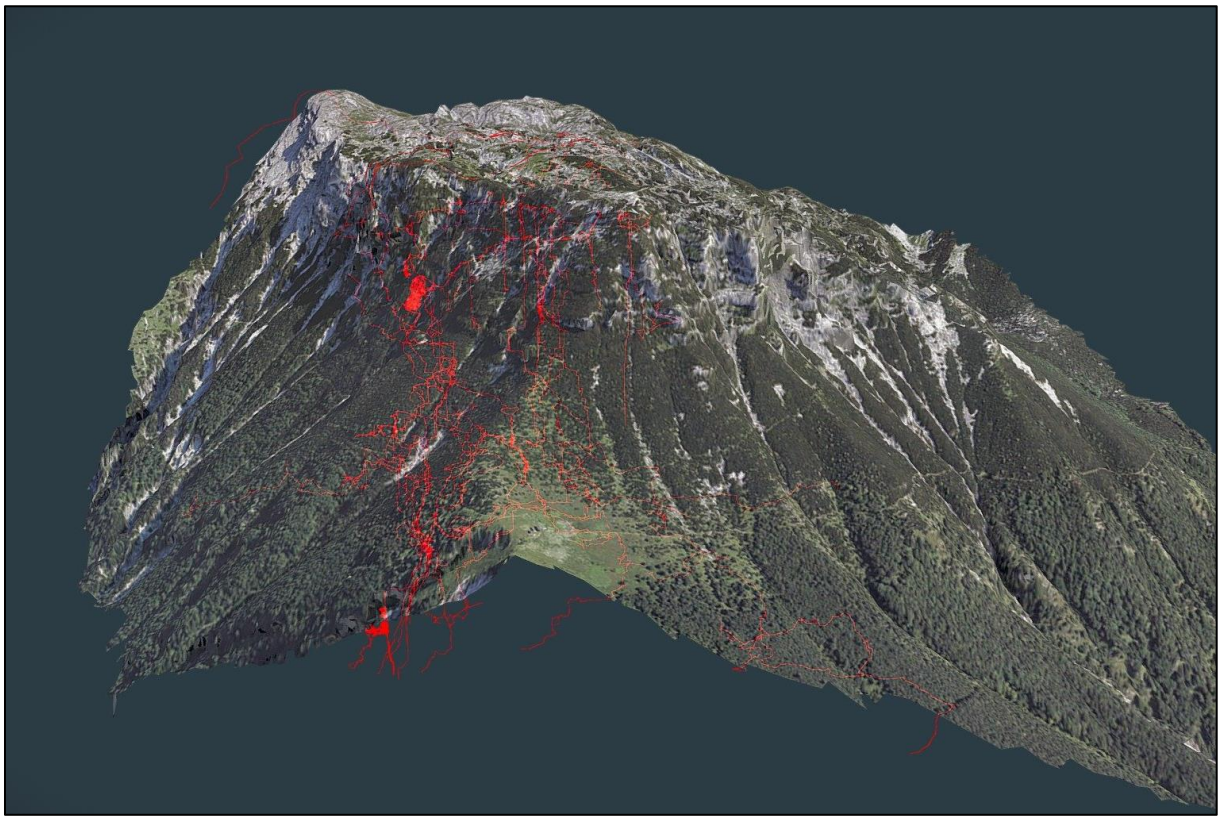

Figure 4.13: *Schematic view on distribution of cave passages in respect to the mountain Migovec (Author: P. Leban).*

Although the intersection of faulted blocks and local dolomite patches influence the direction of groundwater flow, it is more likely to be down-dip towards the Tolminka valley (Fig. 4.14), 200 m lower and 1 km away, than up-dip to the Zadlaščica spring, twice as far away, with a low hydraulic gradient. Since the northern branch of the Sistem Migovec reaches below the ridge between the Tolmin and Bohinj mountains, it is possible that some of the water also flows on NE towards the

springs in Bohinj. In order to obtain new information about the characteristics of groundwater flow in this area, a tracer test was conducted in early autumn 2019 by injecting a tracer into the northern branch as far away as possible. The chosen site is also interesting because of its location near the watershed between the catchment areas of the Soča (Adriatic Basin) and Sava (Black Sea Basin) rivers.

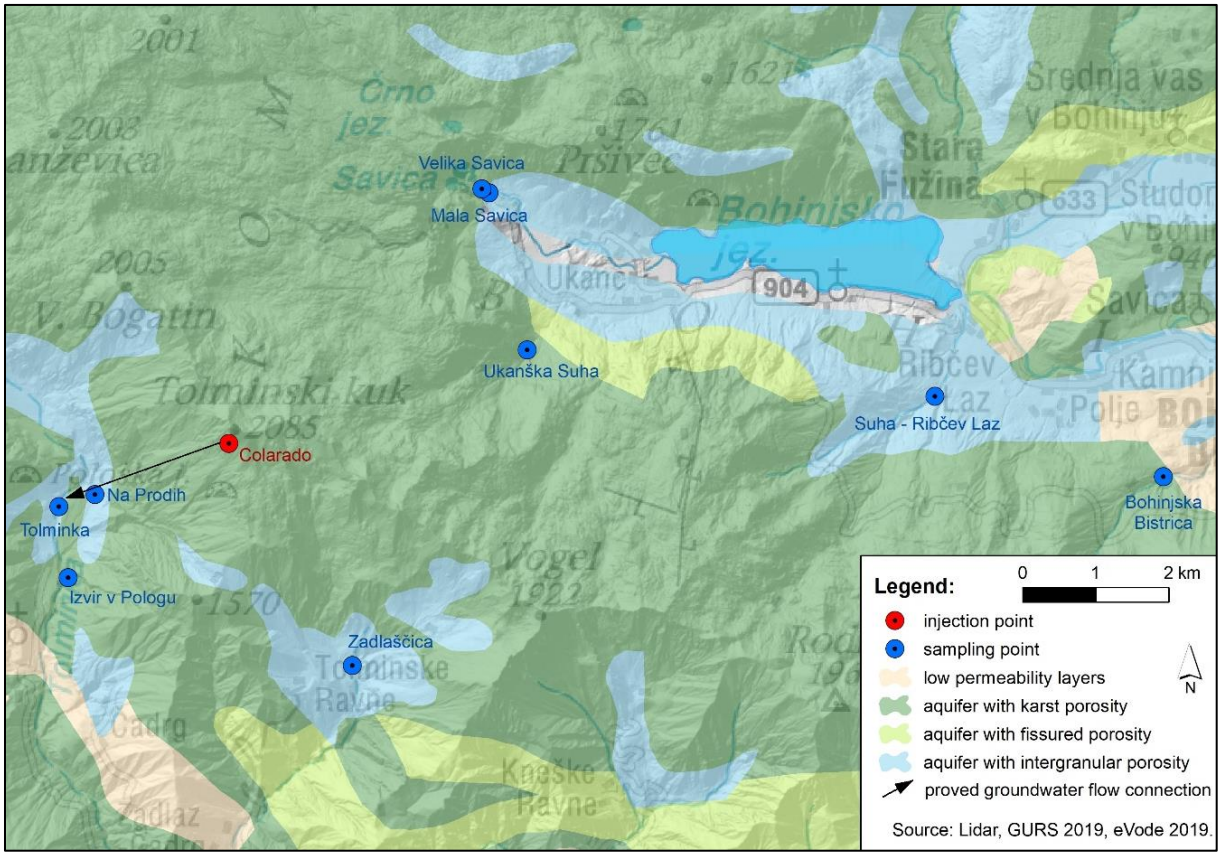

Figure 4.14: *Hydrogeological map showing proven groundwater connection.*

On 5th September 2019, an aqueous solution of 3 kg of Uranine was injected into Lake Colarado (Fig. 4.14) at an altitude of 982 m in the lower part of the Sistem Migovec. Behind it are 270 m of measured passages to the far northern part of the system under investigation, which were inaccessible with tracing equipment. Lake Colarado is located at a depth of -879 m relative to the highest entrance to the system and is a good 90 m above the level of the lowest syphons in the cave, which probably represent the water table. Sampling was carried out at 9 locations (springs, surface streams) (Figs. 4.14–4.16), and a total of 627 samples were collected and subsequently analysed.

Figure 4.15: *Colourful geological profile along the Tolminka Valley (Photo: M. Blatnik).*

Figure 4.16: *Water sampling during the tracer test (Photo: M. Blatnik).*

The injection was carried out when water levels were low and even the occasional rainfall in September and October 2019 did not result in a significant increase in discharges (Fig. 4.17). During this period, the tracer was not detected in any of the observed springs. Heavy rain in early November 2019 caused an extreme increase in flows when at Tolminka the discharges up to 105 m^3/s were measured. Only this rain wetted the vadose zone of the karst aquifer enough to push the tracer towards the Tolminka spring (Fig. 4.17). The peak flow velocity of 1.7 m/h was calculated considering the air distance between the injection site and the sampling site and the time from injection to the occurrence of the highest tracer concentration. The flow velocity is very low because the injected tracer was stored in the vadose zone for a long time due to unfavourable hydrological conditions. Due to the short distance between the injection site and the spring (2.5 km) and intensive recharge, further transport was rapid and the duration of the peak was short. If the time from the onset of heavier precipitation to the occurrence of the highest tracer concentration is taken into account when calculating the peak flow velocity, a value of 70 m/h is obtained. Measured tracer concentrations in other observed springs were not high enough to confirm groundwater connection.

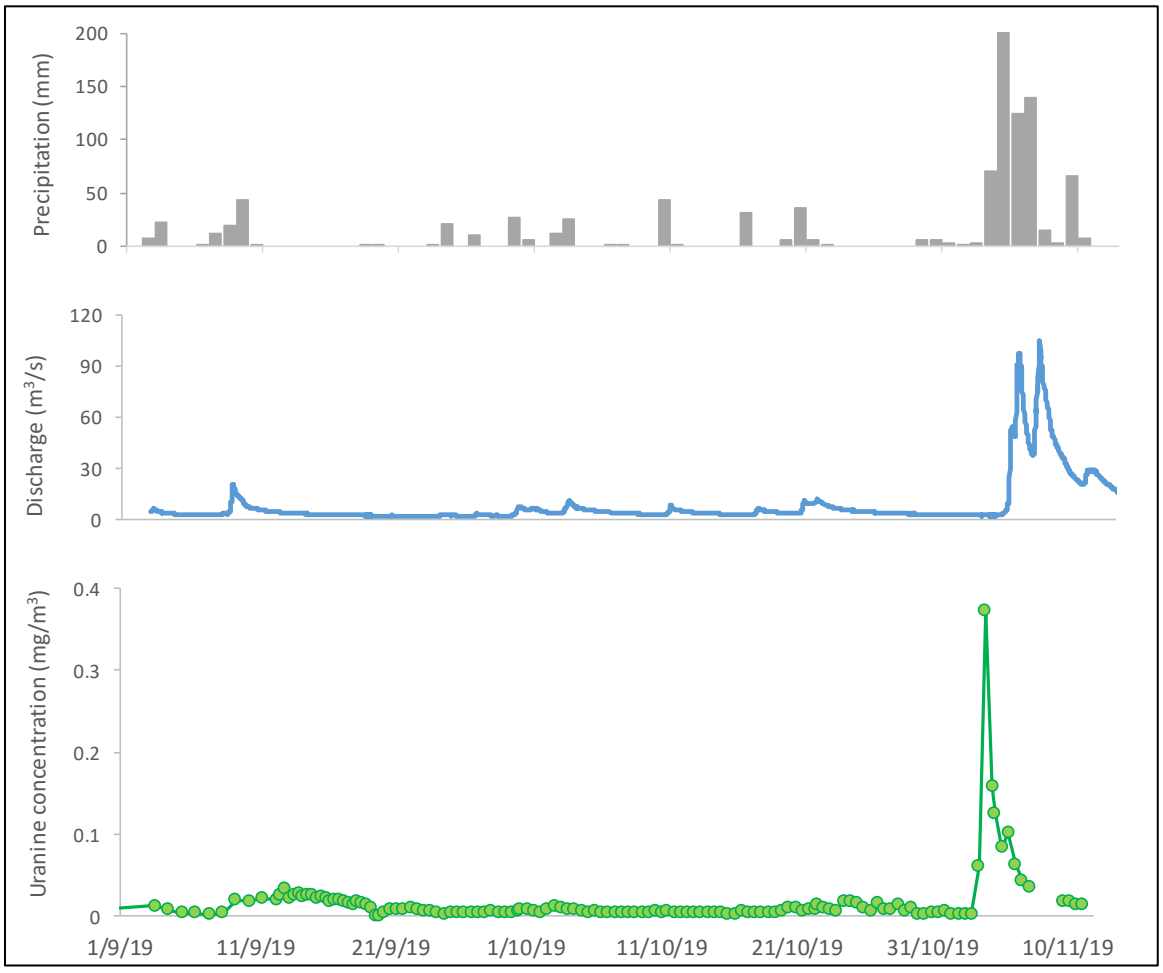

Figure 4.17: *Hydrological conditions and tracer concentrations in the Tolminka spring. Precipitation data (Vogel station) and discharge data (Tolminka River at Tolmin station) were obtained from Slovenian Environment Agency.*

The experience and results obtained confirm that in areas with a large thickness of the vadose zone, the execution of a tracer test is very demanding and usually time-consuming. The result is significantly influenced by the state of hydrological conditions of the vadose zone before the event and by precipitation. In recent years, several tracer tests have been carried out in the Alpine karst area, but no results were obtained because the sampling was completed too quickly. However, due to the possible short duration of the tracer breakthrough curve, it is also important that the sampling

frequency remains high enough. The described tracer test can be evaluated as an exemplary example of good cooperation between cavers (Jamarska sekcija Planinskega društva Tolmin, Jamarski klub Železničar Ljubljana) and researchers (Inštitut za raziskovanje krasa ZRC SAZU Postojna).

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ABSTRACTS

IZVLEČKI

*sorted according to the family names of the first authors
*razporejeno glede na priimke navedenih prvih avtorjev

Qatar confirmed sinkholes

Vrtače raziskane v Katarju

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Abstract

Karst is widespread on the peninsula of Qatar and in the Arabian Gulf with features of depressions, sinkholes, caves and solution hollows. In Qatar numerous large and small depressions, exposed sinkholes and caves have been studied and identified in different researches. In this recent study, a joint survey was conducted by Center of GIS and MME IPD team in different phases to confirm some known and newly reported sinkholes. The team visited and surveyed around 30 different locations and recordered 26 confirmed sinkholes. The locations, opening diameter, depth and elevation of each sinkhole was documented and registered. Based on field observations, the Qatar sinkholes appear genetically related and representing early phase in the development of karst and concentrated mainly within the Limestone, Dolomite, Gypsum and anhydrites horizon of the Eocene Rus formation and Dammam Formation. The majority of sinkholes in Qatar shows NE-SW and NW-SE orientations in line with the joints and fractures system. It is very clear that the Qatar geology (rock types), structural elements and presence of unique jointing & fractures system played major rule in the development of karst. Some of the sinkholes encountered are cylindrical bottle shaped compound and bowl shaped morphotype karst depression. Most karsts of central Qatar were formed due to extensive subsurface dissolution of carbonates and sulphate deposits under middle Pleistocene wet climatic conditions and consequent subsidence. Water flow through joints may account for differential dissolution resulting in the formation of pitted karst terrain in the northern part of Qatar and identified along the major anticline. There is a pattern to the overall distribution of sinkholes in the state of Qatar and this is discussed in more detailed.

Key words: karst, limestone, dolomitisation
Ključne besede: kras, apnenec, dolomitizacija

Monitoring of Mescla karst spring in the French Southern Alps: a rare case of stratified waters out of coastal areas

Monitoring kraškega izvira Mescla v Francoskih Južnih Alpah: redek primer slojevitosti vode izven obalnih območij

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Abstract

The development of reliable autonomous data loggers allow monitoring of detailed hydrologic behaviour. Physical parameters are commonly used, such as temperature (T), conductivity (C), and pressure (P), which can be used alone for assessment of water table oscillations or can be converted to discharge, providing some rating curve has been executed. Such parameters provide information about the various components of water arriving at the spring, transfer and residence time, flow velocities, and more.

Mescla spring is one of the deepest sumps in the world (dived to -267 m). It is also known for its thermo-mineral characteristics (T up to 22 °C, C up to 5300 µS/cm). The monitoring of 2019 autumn extreme events shows the contribution of deep thermo-mineral water dominant during recession, and its replacement by meteoric water during floods. Both water bodies, of very different physical characteristics, are not mixing during recession because of a net stratification, clearly observed during dives (salt wedge). Due to the large extension of the deep reservoir, Earth tides were also recorded during recession.

The recent development of such data loggers allow easily gaining very accurate information on the internal part of the karst aquifers, which are generally not or poorly accessible. Such information may help to better orientate further investigations, such as detailed hydrochemical investigations that are less easy to obtain in routine, dye tracing, and resource management.

Key words: monitoring, Mescla karst spring, stratified water bodies, earth tides, thermo-mineral component, karst hydrodynamic

Ključne besede: monitoring, kraški izvir Mescla, slojevito vodno telo, zemljine plime, termomineralna komponenta, kraška vodna dinamika

Karst in Arid Central Region of Kerman Province, Iran

Kras v aridnem osrednjem območju province Kerman, Iran

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Abstract
Iran covers a total area of about 1.75 million km². About 52 % of the country consists of mountains and deserts. The broad central plateau is bounded by the western uplands of Zagros, Alborz in the north and northeast mountains. It is partly occupied by a remarkable salt swamp (the kavir) and partly by areas of unconsolidated deposits such as dunes or stony plains. Kerman is the largest province of southern Iran. Bordering low-lying desert in the south, the province's north, and centre form a plateau typically 2,000 to 2,500 m in elevation, characterized by a succession of mountain ranges trending NW-SE across the province that offer shelter for its settlements. The province falls into the arid and semi-arid zones and like much of the Iranian plateau suffer from the scarcity of water. There are several, but mostly seasonal, mountain streams. There are a variety of geological settings in this large province. Karst landforms and springs are developed in carbonate rocks. The speleological conditions are different in Central Iran. Cave formation by normal meteoric water appears not to have made many explorable caves there. Known speleogenesis is more or less limited to fractured and faulted carbonate rocks. Central Iran is an active structural and geological zone today. On account of these movements and quite mobile geological settings caves have not been developed as complex deep down-dip phreatic networks. Most of the known caves have formed within joints and fracture networks. The investigation of caves in Iran, especially in the Central Iran zone shows the predominant role of hypogene processes in the formation of many of them. Mirza cave is one of the most developed caves in Kerman province. Field investigation and evidence of cave morphologies show that this cave has a hypogene origin.

Key words: karst, arid regions, hypogene, cave, Iran
Ključne besede: kras, aridna območja, hipogen, jame, Iran

The mountain of Akovan (Zatriq) Nature Karst Museum

Kraški muzej o hribovju Akovan (Zatrič)

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Abstract

The karstic terrains in Kosovo have irregular spread and different sizes and heights. The total area of karstic terrains in Kosovo is around 1423 km^2 or 13.1 %. The Mountain of Akovan (977 m a.s.l.), is located in the western part of Kosovo, northeast part of Zatriq village, municipality of Rahovec. It has a meridian form of extension, north–south, around 2.5 km long, around 1.5 km wide, with an area over 200 ha. The mountain of Akovan and the pit field of Zatriq constitute one of the most important and interesting karst areas in Kosovo. The geological construction of the Mountain of Akovan consists of massive limestone rocks of rudist Santonian-Maastrichtian period and limestone rocks of rudist of the Maastrichtian age.

In a small locality, all surface karst forms have been developed such as: karrenfeld, doline, karst valleys, etc., and underground karst forms such as: caves and gulfs. The forms of surface and underground relief are very well preserved and represent the values of a karst museum of nature. Caves are characteristic underground forms that we find almost everywhere on the Mountain of Akovan. At the Mountain of Akovan there is a large number of caves, but the most important are: Peshterri Cave, “Bali Aga” Cave, Residence Cave (Gergavica), White Queen's gulf (Humnera e Mbretëreshës së Bardhë), Pigeons gulf ad Endless gulf. The Mountain of Akovan has many values such as: geomorphological, geological, speleological, landscape, biological, archaeological, educational and tourist. In addition to the many values that caves have on the Mountain Akovan, nowadays they represent an important potential for the sustainable development of geo-tourism in Kosovo. For the scientific significance of the forms of surface and underground karstic relief, the Mountain Akovan should be taken under legal protection in future.

Key words: Kosovo, the Mountain of Akovan, Zatriq, karst, caves, gulfs, museum
Ključne besede: Kosovo, hribovje Akovan, Zatrič, kras, jame, zalivi, muzej

Ice thickness measurements in ice caves using terrestrial LiDAR scanner; examples from Slovenia

Spremljanje količine ledu v ledenih jamah z uporabo terestičnega lidarskega skenerja; primeri iz Slovenije

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Abstract
Due to rising air temperatures and changing precipitation patterns, significant decrease of ice volume has been observed not only on surface (glaciers) but also in karst caves.
First observations of ice thickness dynamics in karst caves in Slovenia have been made in a simple but efficient way, with tape meter and marking of position of ice during individual visits. At the same time, manual measurements of temperature have been performed, which were later supplemented with autonomous temperature measurements, some locations also with sporadic ground penetrating radar (GPR) measurements.
New technologies, such as terrestrial LiDAR scanning, enable detailed measurements of the ice surface and cave geometry. Among about 10 caves with historic measurements of ice content, two of them (Velika Ledena Jama v Paradani and Snežna Jama na Planini Arto) were chosen for pilot measurements. During summer 2020 and winter 2021, the ice surface was scanned for two times and measurements showed significant surface change (>10 cm) already within one season.
The preliminary results encourage us for further measurements to improve understanding of seasonal and long-term ice dynamics in context of climate changes. Taking into account GPR measurements and previous manual observations, more detailed calculations of ice volume changes would be possible.

Key words: karst, cave, ice, terrestrial lidar scanner, climate changes
Ključne besede: kras, jama, led, terestični lidarski skener, podnebne spremembe

Landscape evolution of the Central Kentucky Karst

Razvoj kraške pokrajine v osrednjem delu Kentuckyja

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Abstract
This work extends the established geochronology of the Central Kentucky Karst region, USA, spatially and temporally, to rigorously reconstruct the history of exhumation of the Sinkhole Plain in response to lowering of the Green River. We applied landscape reconstruction methods to the Upper Green and Barren River Basins as well as to their subsurface flow. We used exposure cosmogenic dating, burial cosmogenic dating, radiocarbon dating, and uranium series dating of sediments and speleothems collected from Crystal Onyx Cave in Prewitts Knob and from Little Sinking Creek in the Sinkhole Plain to constrain the age of this stage of karst development, to provide an estimate of the long-term erosion rate of the Sinkhole Plain. These results place the development of Crystal Onyx Cave and the denudation of the Sinkhole Plain in the context of the Mammoth Cave System geochronology. This has implications for revealing timescales of the evolution of karst systems as well as the interaction of hydrological flow paths in karst areas with the transience of drainage networks. A major research aim in geomorphology is the development of a comprehensive, mechanistic theory of landscape evolution that can account for the earth's primary topographic forms and their response to forcing factors such as climate change and human activity. Karst landscapes represent a key gap in that knowledge base, and one that impedes our ability to fully understand, interpret, and conserve karst landscapes. By taking advantage of cutting edge geochronological techniques and computational modelling, this project helps fill that gap.

Key words: geochronology, geomorphology, Kentucky, landscape evolution
Ključne besede: geokronologija, geomorfologija, Kentucky, razvoj pokrajine

Dolines - important soil organic carbon pools on Kras Plateau

Vrtače - pomembna skladišča organskega ogljika v prsti na planoti Kras

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Abstract

Dolines were investigated for their role of soil organic carbon (SOC) accumulation in the mineral part of the soils. At their bottom dolines have a thick pedosediment layer, which differs from the soils on the top of dolines. So, we aim to assess the role of dolines bottom Luvisoils, for sequestration of CO_2 - being potential organic carbon pool. Our hypothesis is that sequestered SOC in mineral soils is higher in dolines than in areas outside dolines. One of the reasons is thicker soil (Luvisol). Through this hypothesis we defined the effect of topography and soil thickness as well as landuse on SOC stock.

For the study 22 dolines in three different land use types (forest, grassland and succession by natural afforestation) were selected within the UNESCO heritage site of Škocjan Caves Regional Park. In the centre of the doline bottoms soil samples were taken with a metal core at different soil depth (0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm). For each soil depth SOC concentrations (% and g/kg) and SOC stocks (t/ha) were determined in laboratory and calculated on the surface area (ha).

We discovered that fine-grained clay-silty soils are rich in soil organic carbon (C_{org}) in the upper 40 cm. Regardless of land use, the mean SOC in the dolines is 117 t/ha, which is almost twice the amount of mean SOC on the top and outside of dolines (68 t/ha). On average, the soils in dolines exceed 100 t/ha C_{org} in all three land uses, led by dolines being in the young succession phase of natural afforestation (130 t/ha), followed by dolines in forest (116 t/ha) and grassland (106 t/ha). Further correlations were made with selected soil parameters: texture, especially clay content, soil reaction, C/N ratio and nitrogen (N). We conclude that abandoned dolines are sustainable SOC pools important for long-term SOC sequestration if they are covered by forest, are in succession phase or permanent grasslands.

Key words: CO_2 sequestration, soil, topography, land use, Kras Plateau, Slovenia
Ključne besede: sekvenstracija CO_2, prst, topografija, raba tal, planota Kras, Slovenija

Adapting to hazardous karst events with a novel machine learning approach

Prilagajanje naravnim nesrečam na krasu z novim pristopom strojnega učenja

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Abstract

Karst hazards, including collapse, slope movements, and floods, can cause life-threatening conditions, inspiring the necessity for accurate and efficient computational mechanisms for assessment before and after they occur. To achieve this, we use a deep learning-based remote sensing methodology that assesses any damage caused or other significant changes in landscape incurred after these potentially devastating events. In particular, we gather imagery data from unmanned aerial vehicles (UAVs) from before and after the occurrences of karst hazards. We process these images through the use of convolutional networks and obtain outputs indicating the level of landscape change caused (damage, movement, etc.). These convolutional neural networks are trained on 80 % of the imagery data and tested on the remaining 20 %. Specifically, the inputs consist of a concatenated pre-hazard and post-hazard pair of images by RGB channel. Our methodology paves the way for more efficient and accurate assessment of karst hazards that can be used for allocating post-event resources, which can potentially save property and lives and minimize economic and environmental loss.

Key words: machine learning, karst hazards, deep learning, UAVs

Ključne besede: strojno učenje, naravne nesreče na krasu, poglobljeno učenje, brezpilotni letalnik

Development of research infrastructure (RI) for the international competitiveness of the development of Slovenian RI space - RI-SI-EPOS and RI-SI-LifeWatch

Razvoj raziskovalne infrastrukture (RI) za mednarodno konkurenčnost slovenskega RRI prostora - RI-SI-EPOS in RI-SI-LifeWatch

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Abstract

ZRC SAZU (Karst Research Institute) is leading organization for two research infrastructure (RI) projects RI-SI-EPOS and RI-SI-LifeWatch. EPOS (European Plate Observing system) is pan-European RI project in the field of geosciences. It combines national Earth science facilities, the associated data and models together with the scientific expertise into one integrated delivery system for the solid Earth. RI-SI-EPOS officially started in 2019 and unites four national partner institutions: ZRC SAZU, University of Ljubljana (Faculty of Civil and Geodetic Engineering), Geological Survey of Slovenia and Institute "Jožef Stefan". Within RI-SI-EPOS partners were purchasing scientific equipment and providing technical support for its maintenance and data provision. ZRC SAZU is broaden scientific equipment to be used for specific karst research (micro-deformation monitoring in karst caves, cave meteorology monitoring, 3D laser scanning of caves and karst surface, seismology in caves, gravimetric monitoring on karst).

LifeWatch is an essential distributed infrastructure for research and management of biodiversity across Europe. It will provide computational resources integrated in an e-infrastructure that will enable its user groups to create virtual laboratories where data and analytical modelling tools could be shared.

Within RI-SI-LifeWatch project, five partners (ZRC SAZU, University of Ljubljana, University of Maribor, National Institute of Biology, Slovenian Forestry Institute) out of nine within the LifeWatch-SI national consortium are participating to strengthen the infrastructure by acquiring scientific equipment for the national node and to provide expertise. Scientific infrastructure will contribute to the interoperability among different European partners within LifeWatch ERIC, in full correspondence with its objectives and activities. It will enable to address scientific issues of societal relevance in regard to tackling biodiversity loss and the resulting negative effects of global changes on biodiversity and ecosystem services.

RI-SI-EPOS and RI-SI-LifeWatch are financially supported by Ministry of Education, Science and Sport and EC Cohesion Fund with original title: »Razvoj raziskovalne infrastrukture za mednarodno konkurenčnost slovenskega RRI prostora - RI-SI-EPOS in RI-SI-LifeWatch«.

Key words: LifeWatch, EPOS, research infrastructure, karst

Ključne besede: LifeWatch, EPOS, raziskovalna infrastruktura, kras

A comparison between the Dinaric and Carpatho-Balkan karst(s) in Serbia

Primerjava Dinarskega in Karpatsko-Balkanskega krasa v Srbiji

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Abstract
Karst outcrops in Serbia are present on a relatively small percentage of the total area of the country - only about 10.5 %, which is considerably less than in most of the neighbouring countries. However, even these relatively small absolute values exhibit significant examples of regional geodiversity. Two dominant areas of karst outcrops are (1) the Dinaric karst region on the west of the country, representing the easternmost parts of the whole Dinaric karst (Internal Dinarides and partially Central Dinarides), and (2) the Carpatho-Balkan karst region on the east of the country, which connects the Southern Carpathians branch to the Balkan Mt. Although lithologically and evolutionally completely different, with the Triassic limestones on the west vs. Jurassic and Cretaceous on the east, the geomorphological traits show many common characteristics, such as the occurrence in many karst patches, with long lines of contacts with the surrounding non-karstic terrains. In climatological terms, the differences are significant, the eastern part being much drier than the western. The impact of the variety of differences on one hand and similarities on the other is discussed in this contribution.

Key words: Dinaric karst, Carpatho-Balkan karst, regional karstology, Serbia
Ključne besede: Dinarski kras, kras Karpatov in Balkana, regionalno krasoslovje, Srbija

Importance of karst in Sergipe, Northeast Brazil

Pomen krasa v pokrajini Sergipe, severovzhod Brazilije

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Abstract
Most natural caves result from the actions and forces acting on the planet for millions of years. They are the result of a slow and delicate process of deconstruction and consequent reconstruction of the environment. Their existence, in most cases, is closely linked to a type of terrain that is internationally known as karst. In Sergipe, northeastern Brazil, the development of the underground karst was not similar to other karst provinces in Brazil due to geological, paleoclimatic and topographic factors. This setting instigated the need for scientific research, which had its main objective to analyse morphogenesis and morphodynamics. The underground karst of Sergipe is of fundamental importance for biospeleology but also for human survival. Among the many services provided by karst, water supply is the most important for the region. In the research area, sixty-one new caves were identified in differentiated climatic types, varying from humid to semi-arid, presenting a large variety of speleothems. Therefore, it is clear that these caves have great aesthetic and economic value as they may support tourism activities. If correctly managed by the public and private sector, such activities can represent an important asset for the economy of certain municipalities.

Key words: karst, caves, Sergipe, Brazil.
Ključne besede: kras, jame, Sergipe, Brazilija

Early hypogene Carbonic Acid Speleogenesis in unconfined limestone aquifers: A model

Začetna z ogljikovo kislino podprta hipogena speleogeneza v odprtem kraškem vodonosniku: model

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Abstract
We present first results on digital modelling of a specific setting of hypogene Carbonic Acid Speleogenesis (CAS). We study an unconfined aquifer where meteoric water seeps through the vadose zone and becomes saturated with respect to calcite when it arrives at the water table. From below, deep-seated water with high pCO_2 and saturated with respect to calcite invades the limestone formation by forced flow. Two flow domains arise, that host exclusively water from the meteoric or the deep-seated source. They are separated by a water divide. There by dispersion of flow, a fringe of mixing arises and widening of the fractures is caused by mixing corrosion (MC). The evolution of the cave system is determined by its early state. At sites with high rates of fracture widening regions of higher hydraulic conductivity are created. They attract flow and support one by one mixing with maximal dissolution rates. Therefore, the early evolution is determined by karstification originating close to the input of the upwelling water and at the output at a seepage face. In between these regions, a wide fringe of moderate dissolution is present. In the later stage of evolution, this region is divided by constrictions that originate from statistical variations of fracture aperture widths that favour high dissolution rates and focus flow into this region. This MC-fringe-instability is an intrinsic property of cave evolution and is present in all scenarios studied. We have investigated the influence of defined regions with higher fracture aperture widths. These determine the cave patterns and suppress MC-fringe-instabilities. We have discussed the influence of the ratio of upwelling water flux rates to the rates of meteoric water. This ratio specifies the position of the mixing fringe and consequently that of the cave system. In a further step, we have explored the influence of time dependent meteoric recharge. Furthermore, we have modelled scenarios where waters are undersaturated with respect to calcite. These findings give important insight into mechanisms of carbonic acid speleogenesis (CAS) in a special setting of unconfined aquifers. They also have implications to the understanding of corresponding sulphuric acid speleogenesis (SAS).

Key words: model, hypogene speleogenesis, unconfined aquifer, mixing corrosion
Ključne besede: model, hipogena speleogeneza, odprt vodonosnik, korozija mešanice

The general model of cave development in the metalimestones of the Caledonide terranes

Splošni model speleogeneze jam v meta-apnencu na območju Kaledonidov

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Abstract
A general cave development model is proposed that applies throughout the metacarbonates of the non-arctic Caledonide terranes in Scandinavia, New England (USA) and the British Isles, which have comparable geological structures and which experienced similar Quaternary glacial events. It builds on a previously-reported four-stage process for the inception and development of >1000 caves in the repeatedly-glaciated metalimestones of Central Scandinavia. The rankings of maximum and mean cave length and vertical range, and mean cave cross-section are commonly in the same order for each of five main Caledonide regions, and this ranking order is similar to that of local ice sheet thicknesses at the Last Glacial Maximum, local Holocene uplifts and maximum relief differences. It is therefore concluded that the main control on the extent of karstification in the non-arctic Caledonides is the thickness of the local Pleistocene ice sheets. Thus, the greater karstification in Northern Scandinavia arose partly because the thicker ice sheets and the higher mountains caused greater deglacial and neotectonic seismic activity. This produced longer and deeper inception fractures and caused deeper deglacial ice-dammed lakes to form that enabled underlying fractures, conduits and cave passages to be enlarged by phreatic dissolution for longer periods of time, and sporadically over more glacial cycles.

Reference:
Faulkner, T., 2009: The general model of cave development in the metalimestones of the Caledonide terranes.- Proceedings of the fifteenth International Speleological Congress, Kerrville, US,. Vol. 2, 863–870.

Key words: metalimestone, Caledonide, speleoenesis, quaternary, glaciation, ice-dam
Ključne besede: meta-apnenec, Kaledonidi, speleogeneza, kvartar, poledeitev, ledeni jez

Mahony and Tunago limestone plateaus and the Lac Belot hydration ridges, adjoining but contrasting karstlands in the lowlands of the Northwest Territories, Canada

Apnenčasti planoti Mahony in Tunago ter hidracijski grebeni Lac Belot, sosednje in obenem kontrastne kraške pokrajine v nižavju Severozahodnega Teritorija, Kanada

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Abstract

At the NW extremity of Great Bear Lake (Lat. 65–66° N; 157 m a.s.l.) highly deformed Precambrian Shield rocks are overlain by regular dolostones (Ordovician) that form a plateau dipping gently west. This was subjected to the Wisconsinan (Würm) glaciation, and divided by a spillway during its recession into (i) 'Mahony Dome' (south side, ~1000 km^2 and up to 460 m a.s.l.) and (ii) 'Tunago Dome' (north side, ~750 km^2 and up to 360 m a.s.l.). Both are drained karstically, chiefly to a small number of point-located springs in the spillway. Mean annual temperatures range is -7 to -10 °C, precipitation 200–350 mm. Permafrost is widespread to continuous except beneath lakes.

Mahony Dome is a plain with a thin veneer of till, chiefly chert insolubles. At its centre is an impoverished muskeg (the world's most extensive 'alvar'?) draining to stream and pond sinkholes around the perimeter. Larger, scattered, glacier-scoured depressions are or have been occupied by karst lakes that displaying a progression from perennial lakes with melt season surface overflow to being fully drained by big sinkholes. This progression may be correlated with local groundwater hydraulic gradients but there have been no dye traces to confirm it.

A small sector of Tunago Dome generally above ~325 m a.s.l. has similar form. Terrain below this elevation has been intensively dissected into upstanding tabular blocks (very large clints), with muskeg flourishing on re-worked till in broad areas between them. Deep depressions scoured against (glacially upstream) corners of the clints or at narrowings in inter-clint corridors now function as the dominant sinkhole drains. This tabular terrain is interpreted as the product of a sub-glacial flood tearing up a pre-existing shallow karst pavement. It is a type of 'scablands' noted at a few other places in northern Canada, but not at the scale seen here.

These karsts are terminated to the west where thrusting carried a *sabkha* mixture of dolomite and anhydrite beds (Devonian) over them. Injection of water along the thrust planes during the glacial recession has created spectacular hydration ridges up to 300 m in height and 1200 m in width. Lac Belot (300+ km^2) is impounded behind one of them and drains underground for 25 km to springs near the spillway.

Key words: low plateau karst, glaciation, permafrost, alvar

Ključne besede: kras nizkih planot, poledenitev, permafrost, alvar

Preliminary analysis of vadose zone water pulses from Postojnska and Planinska jama drips, SW Slovenia

Začetne analize pretakanja vode v vadozni coni Postojnske in Planinske jame, Slovenija

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Abstract
In recent years, many studies have focused on the dynamics of percolation and retention of water in the vadose zone of a karst aquifer and the associated transfer of contaminants, their influence on rock dissolution, and the role of the vadose zone on discharge dynamics. In this study, we aimed to characterise groundwater recharge processes in combination with the analysis of spatiotemporal meteorological, soil moisture and phenological information. Using modern data-loggers for continuous monitoring of different parameters inside Postojnska and Planinska Jama (Slovenia), we observed local heterogeneity of recharge thresholds in response to different hydrometeorological events. Results have been correlated with precipitation and phenological data from Slovenian Environment Agency (ARSO) and remotely sensed soil moisture data, snowmelt and evapotranspiration from Copernicus CDS. In 2018 and 2019 we analysed 66 recharge events in detail. Quantitative analysis of rainfall events and counted drips in various hydrological conditions can give insights on how water travels through vadose zones. We found that the monitoring point in Planinska Jama represents primary drainage paths with rapid response to rainfall events, while the points in Postojnska Jama respond only when a drainage basin above them reaches a certain threshold. Preliminary results show that, i.e., the drip counter in Planinska Jama in July 2018 reacted 12 hours after the beginning of the 15-hours rain event with 29 mm of precipitation with max intensity of 8 mm/h, while the dripping event had limited duration of 8 hours. In December 2018, Postojnska Jama drip counter reacted 7 hours after the beginning of 7-hours rain event with 32 mm of precipitation with max intensity of 4 mm/h. The results obtained are important to improve the understanding of infiltration rates and the modelling approaches of karst hydrological processes. We were also able to evaluate usability of data loggers and available databases under different hydrological conditions.

Key words: karst aquifer, in-cave monitoring, vadose zone, spatio-temporal data
Ključne besede: kraška voda, monitoring v jami, vadozna cona, prostorsko časovni podatki

Geoheritage and conservation of karst on Kangaroo Island, South Australia

Geodediščina in varovanje krasa na otoku Kangaroo Island, Južna Avstralija

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Abstract

Kangaroo Island is a large (440,000ha) continental island close to the South Australia coast, south of Adelaide. About 16 % of the island is Late Pleistocene dune limestone, with small areas of Late Eocene to Late Oligocene limestone as well. Over 150 dolines, solution tubes and caves have been recorded. The South Australian geoheritage register lists only 21 sites for Kangaroo Island, with only two karst or cave sites listed: the Ravine des Casoar cave near Cape Borda, and Admiral's Arch, as a part of Cape de Couedic. Exploration of caves and karst commenced in the 1960s, and in the last year more exploration after an extensive bushfire has revealed more than 50 new caves. The caves in Pleistocene dune limestone are entered by solution pipes and frequently comprise a series of collapse domes, linked by short rift passages. Progressive lowering of the karst water table led to a loss of stability of the cavities with roof breakdown forming a series of tensional arches. The caves have abundant speleothems whose orientation suggests ongoing settling of breakdown. The caves are also important for fossils and palaeoclimate studies carried out by scientists from Adelaide and Flinders Universities. Many karst areas on the western half of the island were burnt in late 2019 and early 2020. At Kelly Hill Conservation Park almost the entire area was burnt, including all above-ground infrastructure. Fire intensities were high resulting in widespread spalling of limestone outcrops, baking of soil and washing of soil and charcoal into closed depressions and cave entrances following intense rainfall of 60 mm in late January. A Friends of the Karst group has been formed with support from SA Parks Service, and frequent field trips are using LIDAR and drone imagery to locate, document and map the caves.

Key words: dune, limestone caves, geoheritage, conservation, bushfires

Ključne besede: sipina, jame v apnencu, geodediščina, varovanje, požari v grmičju

Development and morphological evolution of bedrock-collapse sinkholes in the Sivas gypsum karst, Turkey

Nastanek in morfološki razvoj udorov v evaporitnem krasu na območju Sivas, Turčija

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Abstract

The Sivas region in Turkey holds one of the most outstanding gypsum karst in the world, covering an area of 2820 km^2. Here, the different sinkhole types display a general spatial zonation controlled by the main geomorphological units and their hydrogeological role: (1) striking polygonal karst in the high plateau that functions as the main recharge area; (2) bedrock collapse sinkholes in the lower denudation surface and close to the water-table level, where well-developed caves are inferred; and (3) cover subsidence sinkholes mainly associated with the valley bottoms, locally showing high densities probably related to preferred groundwater discharge. This work is focused on the spatial distribution, characteristics and evolution of the sinkholes within the broad Plio-Quaternary geomorphological and paleohydrological evolution of the epigene karst system dominated by autogenic recharge. We have produced a detailed cartographic sinkhole inventory including 295 bedrock collapse sinkholes and 302 cover subsidence sinkholes. The morphology of the bedrock collapse sinkholes, varying from small cylindrical holes to large and deep tronco-conical depressions with gentle slopes, reflect their geomorphic evolution, ultimately reaching exceptionally large hectometre-scale diameters. Their evolution, involving substantial enlargement and deepening, is attributed to the solutional removal as solute load of large volumes of gypsum by downward vadose flow. This type of morphological evolution with significant post-collapse solutional denudation differs from that observed in carbonate rocks characterised by lower solubility and erodibility. The frequency-size relationships of the inventoried sinkholes are compared with those published for various sinkhole types and in different contexts. The bedrock collapse sinkholes of the Sivas gypsum karst show the greatest dimensions, which can be attributed to their post-collapse erosional enlargement and the old age of most of the depressions. The analysis of historical imagery reveals that bedrock collapse sinkholes have a very low probability of occurrence at the present time.

Key words: evaporite karst, collapse, sinkhole evolution, solutional denudation, morphometry
Ključne besede: evaporitni kras, udor, nastanek vrtač, deudacija, morfometrija

The Paradise Lost cover-collapse feature on northern Vancouver Island (British Columbia, Canada)

Udorni pojav The Paradise Lost na severnem predelu otoka Vancouver Island (Britanska Kolumbija, Kanada)

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Abstract
The Paradise Lost (PL) feature is an example of a cover-collapse feature in a larger size category for northern Vancouver Island. The collapse resulted from the breakdown of dense glacial sediments about 20 m thick (mostly clay and cobbles) overbridging a large cave chamber in relatively pure and massive Upper Triassic limestone.
The feature first manifested as a small surface opening in 1992. This opening had expanded enough to be viewable using Google Earth satellite imagery by 1995. From its initial discovery in 1992 until 2020, the feature evolved into a 30 m long, 18 m wide rounded hole of imposing depth (up to 40 m). We calculate that 25–30,000 m^3 of regolith material have dropped into the chamber from 1992 to 2020.
In our experience, dolines formed by the collapse of bedrock or regolith over a larger scale bedrock cavity are less common in the region than solution dolines or dolines of polygenetic origins. Nevertheless, they can pose potential karst geohazards where present. Loosened regolith material at the PL feature continues to drop into the newly unroofed void, potentially endangering cave visitors below. The more recent expansion of the feature has brought a pendulous rim to within 3–4 m of a forestry road.
We plan to use terrestrial and UAV-mounted LiDAR to produce a detailed georeferenced model of the collapse feature and its subsurface geometry, as well as a three-dimensional visualization of the feature in its topographical basin and karst catchment setting. This work will enable more detailed measurement of the horizontal propagation of the collapse toward the road and possibly elucidate mechanisms for the ongoing collapse.

Key words: karst, collapse hazards, Vancouver Island, British Columbia, Canada
Ključne besede: kras, nevarnost udora, Vancouver Island, Britanska Kolumija, Kanada

Large scale test of ALS LiDAR data utilization for cave entrance detection: a case study from the UNESCO World Heritage Site - Plitvice Lakes National Park, Croatia

Preizkus uporabe ALS LiDAR podatkov za iskanje jamskih vhodov v večjem merilu: primer z območja Narodnega parka Plitvička jezera, svetovne dediščine UNESCA, Hrvaška

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Abstract

The fact that ALS LiDAR data analysis offers great potential in remote cave entrance detection is by now well known. Nevertheless, the literature on its large-scale use and ground-truth testing is still scarce. In this paper we present an ALS LiDAR data analysis workflow for semi-automatic remote detection of cave entrances based on the local relief model algorithm, applied and tested on LiDAR data covering the area of 380 km^2, encompassing the UNESCO World Heritage Site Plitvice Lakes National Park, Croatia, and its surroundings. With more than 240 ground verified locations so far and a large-scale systematic field reconnaissance still underway, this work represents the largest case study in the published literature to date.

Key words: LiDAR, remote sensing, cave entrance, Plitvice lakes
Ključne besede: LiDAR, daljinsko zaznavanje, jamski vhod, Plitvička jezera

Polycyclic speleogenesis and tectonics in Apulia (Italy), forty years later. A review and new data.

Policiklična speleogeneza in tektonika v Apuliji (Italija), 40 let kasneje - pregled dosedanjih in novih podatkov

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Abstract

After studies about karst and caves in Apulia (Italy), carried out in the 1970's, an article was published in 1982 (Grassi *et al.* 1982, only in Italian). While studies were carried out in the field of hydrogeology and engineering geology, cave data collection was on the rise thanks to the innovation of the single rope, which suddenly facilitated explorations and new surveys. That paper focused on the relationships between karst and tectonics, since different phases had been recognized in both, depending on the migration of the Apennine front.

The synthesis, which is here reported, was a correlation between tectonic phases and karst morphogenetic phases, represented by numerous phenomena taken into consideration in the region, which stated the polycyclical character of the evolution of karst. Furthermore, the "paleokarst" forms were divided between two distinct and distant periods in time. Forty years later, the number of known caves has more than doubled, including few complex systems, which are rare in this region. Recent studies do not disprove the polycyclic karst model, but have made it possible to outline details and add case studies on regional karst, oriented both to relations with tectonics and to speleogenesis.

For instance, the recent hypothesis of a hypogenic origin for some caves (D'Angeli *at al.* 2019, 2020) appears interesting, also in relation to the activity of tectonic structures. Further analysis of cave forms and deposits lead to consider in more detail the relationship between morphogenesis and tectonics (Iurilli *et al.* 2009; Mastronuzzi *et al.* 2007), adding a piece to the complex mosaic of the geodynamics of this area between Hellenids and Apennines (Di Bucci *et al.* 2009). The Author also reports unpublished data, which help to delineate locally the picture of speleogenesis in relation to tectonics and changes in the base level.

Key words: Apulia, karst, tectonics, speleogenesis

Ključne besede: Apulija, kras, tektonika, speleogeneza

Underground of the Brskovo silver mine

Podzemlje rudnika srebra Brskovo

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Abstract
Speleological research in Montenegro began in the late 19th century when P. Rovinsky, E. A. Martel, G. Lahner and G. Gesseman arrived, to be continued by the arrival of Czech, later Polish and French speleologists. A large number of caves and pits encouraged local speleologists to continue exploring exclusively the karst underground, so that the exploration of artificial underground has no tradition in Montenegro. The Brskovo mine near Mojkovac is one of the largest silver mines in the Balkans. Beginning in the Middle Ages, mining in it lasted intermittently until the 1990s when the mine was closed. Mining was mainly followed by the veins of the ore, so that a whole labyrinth of corridors and vertical shafts for extracting ore was created below the surface. As there was no maintenance that artificial underground which stretches for miles below the surface is now under water and completely inaccessible. There is only a small part left that is accessible today. During the research of the bats of the future mine, we visited the available corridors and made topographic images and photo documentation. We found four Lesser horseshoe bats (*Rhinolophus hipposideros*) in the shafts near Okretnica, and one Lesser horseshoe bat (*R. hipposideros*) in the shaft where the explosives were stored. All these channels will disappear because surface exploitation is planned. Only a few underground openings will be visible when removing the mined material. Then there will be no more opportunities to explore. This first presentation of the artificial underground of Montenegro, although modest, we hope will encourage speleologists in the future, in addition to numerous caves and pits on the classic Dinaric karst, to pay attention to the artificial underground, which is completely marginalized in our region.

Key words: artificial underground, silver mine, Brskovo, Montenegro
Ključne besede: umetno podzemlje, rudnik srebra, Brskovo, Črna gora

Tunnels and karst springs, a case-study from the South-Eastern border of the Jura Mountains (Lake Biel, Switzerland)

Predori in kraški izviri - primer študije na jugovhodnem obrobju gorovja Jura (jezero Biel, Švica)

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Abstract

The Brunnmühle spring and its overflow springs are located at the foot of the steep flank of the Jura Mountain, aside of Lake Biel. Three tunnels have been built in this region and a fourth is being planned, all of them crossing the region between the perennial spring at lake side and the overflow springs located a little higher. The total flow-rate of the springs regularly exceeds 10 m^3/s. This amount of water could possibly break into the tunnel if the digging hits a main conduit feeding the springs. Therefore, a wide range of methods were applied to characterize the hydraulics and the geometry of karst conduits in this region.

All available data about the geology and hydrology of this small region (~3 x 1 km) were merged into a 3D model showing the expected shape of the flow system feeding the spring. This was part of the development of the KARSYS method. The probability and characteristics of conduits potentially found in the tunnels was assessed using the Karst ALEA method. Results of the prediction were later criticized by comparing the prediction with observations made once the tunnel was drilled.

In order to assess the water quantity, which could break into the tunnel, a flow-simulation model was established and calibrated. It was then computed in real time using meteorological forecast in order to stop the digging when conditions were too dangerous.

For the future tunnel, Visual KARSYS will be used to manage geological observations directly in 3D and dynamically along with new data coming from drillholes and from the drilling of the tunnel.

The detail analysis carried out on this site concerning karst hydrology and cave genesis helped a lot to develop approaches and tools which are now being applied on other sites.

Key words: tunnel, karst conduits, groundwater protection, civil engineering, models

Ključne besede: predor, kraški kanali, varovanje podzemne vode, gradbeništvo, modeli

Cave air and water monitoring of moonmilk-containing caves

Monitoring jamskega zraka in vode v jamah z jamskim mlekom

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Abstract
Moonmilk is predominantly composed of calcite that forms an interlocking mesh of needle- and nano-fibre crystals with high pore-water content (~90 wt%), creating a soft, plastic texture and peculiar shaped speleothem deposits. Contradicting hypotheses for the formation mechanism of moonmilk include: 1) purely geochemical reactions, such as condensation corrosion and evaporation, 2) as a direct microbiological process, or 3) as a geochemical reaction involving products from microbiological activity. The true formation mechanism of moonmilk remains elusive. Since moonmilk is only found in certain locations, we hypothesize that specific cave conditions are important in producing the ideal environment for moonmilk formation. We undertook seasonal cave air and water monitoring in two Slovenian moonmilk-containing caves to understand the environment required for moonmilk formation in an attempt to solve the mystery of the formation mechanism as part of a wider study including petrographic and microbiological analyses. Snežna jama (1514 m a.s.l., ~70 km N of Ljubljana) and Košelevka jama (645 m a.s.l., 25 km WSW of Ljubljana) contain moonmilk deposits, including flat-based moonmilk stalactites and moonmilk flowstones. In Snežna jama, moonmilk forms in a part of the cave with temperatures of 4–7 °C and relative humidity (RH) of 83–95 %. In Košelevka jama, moonmilk sites are at 3–12 °C with RH of 64–95 %. Accordingly, relatively low temperatures and high humidity appear characteristic; while the range of values may indicate that moonmilk only forms at certain times of year. The carbonate geochemistry shows that moonmilk-associated waters are over-saturated with calcite, and so a purely geochemical mechanism cannot be ruled out. However, precipitation of the peculiar needle- and nano-fibre crystals is not found in traditional speleothems, and so, we propose that a further ingredient is required for moonmilk formation; ergo, our investigations continue.

Key words: moonmilk, speleothem, cave monitoring, carbonate geochemistry, Slovenia
Ključne besede: jamsko mleko, speleotem, monitoring v jami, geokemija karbonatov, Slovenija

Hydrochemical and stable isotope methods to determine karstic aquifers water circulation in the Izeh area, southwest of Iran

Uporaba hidrokemičnih in izotopskih metod za opredelitev kroženja kraške vode v vodonosnikih območja Izeh, jugozahod Irana

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Abstract
The study area comprises of three anticlines (named; Monghasht, Shavish-Tanoosh and Kamarderaz), a syncline (Nal-e-Asbi) and impermeable Izeh Polje. As the impermeable Izeh Polje is a poor aquifer with respect to quantity and quality and is not able to furnish the water demand of the study area (Izeh City and the suburb), therefore, the water requirements relying on surrounding karstic aquifers. In general, the karstic aquifers are complex and their characteristics are quite different from other water bearing horizons with regards to their heterogeneity and groundwater flow. Because of high multiplicity in characteristics and low predictability of karstic aquifers, the solely classical assessments cannot be applied. The hydrochemical and environmental isotopes are robust tools to provide significant information about karstic aquifer characterization. In order to afford water needs of the Izeh City and nearby a number of wells drilled in Nal-e-Asbi Syncline and due to an intense exploitation, water level lowered down. The aim of this investigation is to improve the understanding of recharge sources of the Naal-Asbi Syncline, and to ascertain the probable groundwater flow between these geological structural features. To approach the goal, major, certain minor elements and environmental isotopes including oxygen ($^{18}O/^{16}O$) and deuterium ($^{2}H/H$) were taken into account. Composite diagrams of major elements such as Mg(Mg+Ca) versus $SO_4/(SO_4+HCO_3)$, Ca–HCO_3, Ca+Mg–HCO_3, Ca+Mg–SO_4+HCO_3, Mg–TDS and HCO_3–TDS were plotted and Ca/Mg ratio was computed. The concentration of trace elements, inclusive Al, Mn, P, Si and Sr were also taken into consideration and apart to the hydrochemical evidences a good correlation was observed among the oxygen and hydrogen of the collected samples. The collected data demonstrated the circulation dynamic in the karstic systems, and the role of the Mongasht and Shavish-Tanoosh anticlinorium to recharge the Nal-e-Asbi synclinorium. The data also displayed probable connection between Kamardaraz and the Mongasht aquifer in the area.

Key words: karstic aquifers, water circulation, recharge, hydrochemistry, isotope, Izeh
Ključne besede: kraški vodonosniki, pretakanje vode, napajanje, hidrokemija, izotop, Izeh

Assessment of the karstic aquifers water flow using geological structure in the Izeh area, southwest of Iran

Ocena pretakanja vode skozi kraške vodonosnike z analizo geološke strukture na območju kraškega polja Izeh, JZ Irana

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Abstract
The highly tectonized study area covers 1242 km^2 in the Zagros structural belt in the south-west of Iran. The main karstified structural features are two north-west trending anticlines (Mongasht and Kamarderaz), the combined north-south direction anticlines (Shavish-Tanoosh), Naal-Asbi syncline and the impermeable Izeh polje. The lithology of the structural features is dominantly limestone ranging in age from upper Cretaceous to Eocene. The Izeh City is situated on the Izeh polje and as its water demand is mainly supplied from the Eocene limestone of the Nal-e-Asbi synclinorium, a large number of bore wells were drilled for drinking water to support water requirements in the last two decades. Due to the heavy withdrawal, water table severely lowered down in this karstic aquifer and as the karstic aquifer is the only option for water supply in the area this investigation has been undertaken to assess; a) to determine the hydraulic connection among these karstifed aquifers, b) to ascertain water storage of the anticlines and c) to locate any other potential site for karstic groundwater exploitation in the area. A detailed hydro-structural analyses, including fault types, major and minor faults tracing, faults length, azimuth, dip, dip direction, ISO-fracture map, and anticlines characteristics with respect to impact on faulting, tilting, springs emergence and feeding nearby bore wells were conducted. The collected results indicated that due to the Mongasht anticline (1182 km^2) dip extension along the axis in the northwest -southeast direction and the upheaval of the anticline core, most of the water was flowing out either in the southeast plunge or at the western and eastern limbs. Therefore, the northwest part of this promising karstic aquifer, which is very close to the Shavish-Tanoosh anticlines (220 km^2) and the Nal-e-Asbi syncline (40 km^2), contains less amount of water to transport to the above structural features. But, the gathered data displayed a connection between the northwest part of the Mongasht anticline and the Shavish-Tanoosh anticlinorium and the Nal-e-Asbi syncline. In addition, the compiled data prove probable connection between the Mongasht anticline and the Kamarderaz anticline. In order to reduce the pressure on the Nal-e-Asbi synclinial aquifer, the only remain alternative to offer drinking water for the area, is groundwater withdrawal from the combined Shavish-Tanoosh anticlines.

Key words: karstic aquifers, geological structure, hydraulic connection, Izeh
Ključne besede: kraški vodonosniki, geološka struktura, hidravlična povezava, Izeh

Coastal karst in Bali (Indonesia) describes repeated late Holocene seismic uplift

Obalni kras na Baliju (Indonezija), ki nakazuje na seizmični dvig v poznem Holocenu

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Abstract
Limestone shores record earthquake-related uplift and subsidence wordwide. Detailed studies are available from the Mediterranean and in Japan, but there are few studies elsewhere. Here we describe a carbonate shore of the Sunda Arc in Bali Island, Indonesia. Coastal features indicating uplift were surveyed during a preliminary field study in Uluwatu Peninsula along the southern, ocean-facing coast. Coastal profiles of terraces and notches were measured, biofilm zones, bioerosion traces, and coastal karst features were identified and located relative to sea level. A set of marine terraces has been discovered at Uluwatu Beach. Level A (lowest). This is the active reef pavement. There are occasional surf pans. Level B: 0.5–0.7 m above level A: surf pans, surf mills, surf channels. Level C: 0.8 m above level B: heavily pitted by flat-bottomed pans, separated by heavily karstified ridges. Level D: 2 m above level C: surface is karstified, with several decimetres deep karren. Increasing depth of coastal karst features mark longer time of exposure to the sea, both in intertidal and supratidal zone. Holocene sea level reached its present-day position about 5000–6000 years ago, therefore all coastal features, which require the action of the sea, salt water and wave action to develop, formed following this date. Especially marine terraces, marine notches, beachrock, the coral reef and its various portions, are all younger than 6000 years. Bali is on the overriding plate in the Sunda arc. Seismicity there is expressed by uplift of the coastal zone. Known earthquakes had a hypocentre less than 25 km depth. Repeated surface uplift of 0.5 to 2 m at Uluwatu can be due to seismic events of moment magnitude 6.5–7, with a return period of a few hundred years.

Key words: coastal karst, bioerosion, seismicity, Sunda arc, uplift
Ključne besede: obalni kras, bioerozija, seizmika, Sundski lok, dvig

Lithomorphogenesis of karst surface - karren

Litomorfogeneza kraškega površja - žlebiči

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Abstract
Karren develops uniquely, yet characteristically on diverse rocks and in diverse environments. The knowledge of the network of karren throughout the world, which clearly reveals evolution of the surface of integral, three-dimensional karst landscapes, has been significantly enhanced also by the findings from presented examples.

1. Lithomorphogenesis and Rock Relief of Tropical Karren in Cuba (Mogote in Viñales and at the Cueva Afan Cave)
The mogote rock is highly monotonous throughout the examined geological profile. Micritic limestone is predominant. The rock in the entrance section of the Cueva Afán is of dolomite. Under the dense growth of trees and shrubs, on the rock denuded of soil and subsoil shaped, weathered debris accumulates and creates cups underneath.

2. Karst Karren on Marbles with Characteristic Rock Relief and Scaly Splitting of the Rock, Altai Republic (Russian Federation)
Investigated rocks belong to marbles. Scaly splitting of the rock imprints the most distinct stamp on the rock relief.

3. Shilin Stone Forests (Yunnan, China), a UNESCO World Heritage Site
Stone forests are a unique karst surface landform and a unique form of pinnacle karst. The area of Shilin stone forests is composed of limestone and dolomite. A unique development of stone forests is reflected in their rock relief. Exposed subsoil karren is reshaped by rainwater which sharpens tops of pillars and transforms traces of the original subsoil formation.

Acknowledgement:
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Key words: karren, lithomorphogenesis, karst surface, Cuba, Altai Republic, Shilin
Ključne besede: žlebiči, litomorfogeneza, kraško površje, Kuba, Altajska republika, Shilin

Building a Norwegian cave and karst database

Izdelava podatkovne baze o norveških jamah in krasu

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Abstract
Caves have been on the Norwegian red list of vulnerable habitat types since 2018. In the same year the Geological survey of Norway (NGU) began developing a UML model for a national database for caves and karst in collaboration with the Norwegian biodiversity information centre (Artsdatabanken) and the University of Bergen (UiB). The project was supported by the Norwegian biodiversity information centre. This year an internal project was initiated at NGU, continuing the work to collect, store, and preserve data about karst caves, other karst forms and non-karst caves in Norway. The starting point for creating a data structure for a cave and karst database was a data register of about 1900 karst caves and other karst forms, which NGU received from professor Stein-Erik Lauritzen (UiB). In 2020 and forward NGU gained access to further data sets. Currently, NGU have more than 4,000 registered caves and karst forms such as dolines, poljes, springs, swallow holes, natural bridges and blind valleys. This number is expected to increase significantly in the future as we gather more data. Besides karst caves NGU is also gathering information on non-karst caves, such as talus caves, abrasion caves, tafoni, lava caves and ice caves. The majority of the karst caves are found in Nordland County in metacarbonates in Caledonian nappes. Approximately 50 caves have been surveyed to more than 1 km in length. At least 6 cave systems reach a length of more than 5 km. There are several caves with exciting archaeological and paleontological finds in Norway. The Norwegian National cave and karst database will aid us to achieve a better understanding of karst processes and caves in Norway. Further, it will likely be beneficial for nature management, research, teaching, tourism, and areal planning.

Key words: database, caves, karst, karst forms
Ključne besede: podatkovna baza, jame, kras, kraške oblike

Karst denudation measurements on North Dalmatian plain using rock tablet method

Meritve kraške denudacije na Severnodalmatinski zaravni z uporabo apnenčastih tablet

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Abstract
Weathering processes affect carbonate rocks exposed to natural environment (on surface or buried under soil cover), resulting in formation of different karst morphologies, and controlling surface denudation. To quantify these processes different methodological approaches can be used, among which rock tablet method is one of the most comprehensive. North Dalmatian plain is one of the most emblematic parts of Dinaric karst and its development has been attributed to corrosional planation process. However, it has not been measured locally. Thus, to determine the speed of karst relief formation and surface denudation in this area we used rock tablets method. Actual weathering was measured using rock tablets of several local lithologies, while "standard" Lipica rock tablets were used to measure potential weathering rate. Rock tablets have been exposed to natural environment at the surface, but as well buried in cambic soil profile at 50 cm depth for a period of one year. Average values measured on the surface were from 4.96 to 5.44 mm/a for local lithologies and 5.9 mm/a for Lipica tablets. At the same time, values measured in the soil were from 1.62 to 2.73 mm/a for local lithologies and 3.64 mm/a for Lipica tablets. Results show significant difference of values measured at different settings and highlight importance of using local lithologies when measuring denudation rates of a certain area.
Acknowledgements: This research is a part of the research project "Inter-comparison of karst denudation measurement methods" (KADEME) (IP-2018-01-7080) financed by Croatian Science.

Key words: rock tablets, weathering, denudation, karst, North Dalmatian plain
Ključne besede: apnenčaste tablete, preperevanje, denudacija, kras, Severnodalmatinska zaravan

Metagenomic insight into microbial communities of two pristine Karst aquifers

Metagenomski vpogled v mikrobne združbe v dveh neoporečnih kraških izvirih (Slovenija)

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Abstract

Groundwaters represent about ninety-five percent of global liquid freshwater. Although they provide an important source of drinking water all around the world, microbiological aspects remain poorly understood. Understanding of composition, function and dynamics of native microbial communities in pristine groundwater reservoirs is important for water management and minimization of the pressure on underground ecosystems.

Krajcarca spring in Zadnjica Valley and well in Idrijska Bela were identified as karst water sources with minimal human impact. We analysed samples from a time-series of 14 months - a number of physical and chemical parameters (n=21) were monitored and large volumes of water (100 l/filter) were filtered to obtain measurable quantities of DNA from different size fractions (>5 µm, >0.45 µm and >0.1 µm). With a metagenomic approach we provide a deeper insight into composition and functional potential of microbial communities of these water sources in association with basic environmental factors. Data analysis showed some significant differences in microbial communities between the two sampling sites and between different size fractions. Changes in microbiomes (bacterial and archaeal communities, functional profiles) are correlated with different environmental factors. Furthermore, we provide basis for massive assemblies of available cave shotgun sequencing to metagenome assembled genomes in the future.

Key words: karst aquifers, environmental factors, shotgun sequencing, microbiome
Ključne besede: kraški vodonosnik, okoljski faktorji, sekvenciranje “shotgun”, mikrobiom

Imaging solution pipes - case study from Miocene calcarenites in Poland

Izris korozijskih cevi - študija primera na miocenskih kalkarenitih na Poljskem

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Abstract
Solution pipes are karst geomorphological features formed in carbonate rocks with matrix porosity, extensively described from calcarenites in the eogenetic stage of their diagenesis. The pipes appear as tubular vertical or near-vertical cavities and vary in size; depths between 1 m to 4 m and diameters between 20 cm to 80 cm are most common.
The occurrence of pipes in particular areas indicates the phenomena of water focusing, which is important from environmental and climatic perspectives. The important components here are pipe distribution and morphology, but their visual exposures are limited due to sediment and vegetation cover. Cliff faces offer a glimpse into their interior through the 2D vertical cross-section, but their true spatial distribution and 3D view are missing. On the contrary, the eroded coastal landscapes give 2D horizontal cross-section and distribution, but their vertical morphology and their depths are missing. Similar situation appears in anthropogenic exposures such as road cuttings and quarries.
We tested two methods, the ground penetrating radar (GPR) and magnetic gradiometer, as prospective methods to image the pipes in a non-invasive way. The measurements were carried out in a grid of fresh exposure of the Miocene calcarenite with the visual presence of solution pipes near Smerdyna (southeastern Poland). GPR radargrams showed several sections with attenuated GPR reflections, more precisely, they correspond to the clayey material filling the pipes. Due to the high iron content in the filling medium, the magnetic effect was also noticeable. The iron filling is variable in the investigated pipes, some of them showing a considerable content. In these areas, the magnetic anomalies on the gradiometer data are very clear. In the rest of the sampled pipes, the iron content is too low for effect to be noticeable in the magnetic method results. Both methods therefore proved convenient to detect the pipes, but with certain limitations, related mostly to unclear detection of pipes' depths, and reliability on the mineralogy, geochemistry and texture of solution pipe fill.

Key words: solution pipe, karst, geophysical method, ground penetrating radar, magnetic gradiometer
Ključne besede: korozijske cevi, gefizikalne metode, georadar, magnetni gradiometer

Driving mechanisms and spatiotemporal variations of radon concentration in Modrič Cave (Croatia)

Pogonski mehanizmi in časovno prostorske spremembe, ki vzdržujejo koncentracije radona v Modriča pećini (Hrvaška)

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Abstract
Emission of radon (as radioactive gas) within the karst underground appears to be a health hazard in show caves, but its origin from the deeper Earth's crust without any surface input, makes it eligible for the reconstruction of cave ventilation patterns based on the spatiotemporal variation of its concentration. We conducted integrated measurements of radon concentrations at several locations in Modrič Cave - shallow horizontal show cave located in the foothill of Velebit Mountain (Croatia). Measurements were performed by means of passive SSNTD LR115 type II detectors (Dosirad, France) from 2018 and are still ongoing. The detectors were exposed from July to October 2018, from October 2018 to March 2019, from March to July 2019 and from October 2019 to March 2020, which covers summer–autumn, autumn–spring and spring–summer periods. The highest radon concentrations were measured in summer–autumn period and they were 2.8 ± 0.6 times (in average) higher than in the autumn–spring period. In right passage of Modrič Cave, the radon concentrations were usually higher than in the left passage and this difference was statistically significant ($p=1.3\cdot10^{-5}$, df=33) at the significance level of 0.05. Presumably, the reason is different fissure architecture of the overlying bedrock. The highest radon concentration of 10.6 ± 1.1 kBq/m^3 was measured in summer–autumn period of 2018. Observed high radon concentrations during this period are indicator of poor cave ventilation caused by decreasing differences between cave and outside temperature during the late summer/early autumn. For better insight in this topic, the regular three months periods of exposure of passive detectors were established from March 2020 and, in addition, continuous radon measurements in both channels are performed by using semiconductor detector TSR3 (Tesla company, Czech Republic).

Key words: radon concentration, spatiotemporal variations, Velebit Mountain, Modrič Cave, Croatia
Ključne besede: koncentracija radona, spremembe v času in prostoru, Velebit, Modriča pećina, Hrvaška

Riverine carbonate system, CO_2 partial pressure and CO_2 emission from a subtropical karst river network, South China

Rečni karbonatni sistem, parcialni tlak in emisije CO2 iz mreže subtropskih kraških vodotokov, Južna Kitajska

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Abstract

Understanding the CO_2 emissions from low-order river and stream is of great significance to the global carbon budget and climate change research. We sampled and analysed the runoff chemical composition in multiple sections (139 sections) along the mainstream and tributaries of the Lianjiang River (LR), a second tributary of the Pearl River flowing through a karst area in South China, and systematically studied the riverine carbonate system using the CO2SYS program. The CO_2 formation in river water were analysed, the CO_2 degassing flux was calculated and the significance of CO_2 degassing was evaluated. The pCO_2 in the Lianjiang River Network (LRN) in non-flood and flood seasons was 1282±1030 and 1390±949 µatm, respectively. The pCO_2 spatial patterns in the mainstream and main tributaries were represented as "lower in the upstream and higher in the lower reaches" owing to the various riverbed gradients. Furthermore, the pCO_2 declined with the increase of stream order from the perspective of river network, which in the second-order stream was 1.77 and 2.13 times of those for the fourth-order stream in flood season and non-flood season, respectively, the difference of pCO_2 distribution at different river orders is related to the contact level between the channel segment and terrestrial ecosystem. The pCO_2 in the LRN was mainly dominated by the riverine carbonate system with a contribution rate of more than 60 %. Influence of biological aerobic respiration on pCO_2 was relatively weak and is slightly notable in high-order streams in flood season. As a typical subtropical karst river, the LR was characterized by a low-level carbon source compared with global rivers, which results in an opposite conclusion to the traditional view. Therefore, the comprehensive identification of CO_2 outgassing flux in mesoscale karst river networks is extraordinarily necessary in accurately evaluating the carbon budget on a global scale.

Key words: karst river, carbonate system, CO_2 emission, biological aerobic respiration, the Lianjiang River

Ključne besede: kraški vodotok, karbonatni sistem, emisije CO_2, biološka aerobična respiracija, reka Lianjiang

Significance and comparison of sediments of Northern Velebit deep caves, Dinaric karst, Croatia

Primerjava sedimentov in njihov pomen v globokih jamah Velebita, Dinarski kras, Hrvaška

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Abstract
Caves formed in karst cavities are often trapping big amounts of different kinds of sediments. Cave sediments can be very useful for the determination of conditions and processes that were present at the time of their deposition. They are usually well preserved so they can give us a lot of information about changing of the conditions over a long period (sometimes even over a few million years). In this research, two caves were chosen for sediment analysis. Both caves are located in the northern part of Velebit Mountain, named Nedam and Ledena jama. Nedam recently became Croatia's fourth deepest pit with depth of 1021 m. Ledena jama is 536 m deep pit that is significant by the permanent ice between depths of 50 and 160 m, and is located in a paleoglacier valley. Nedam is located on steeper and more inaccessible karst terrain. The entrances are at different altitudes - at 1420 m for Nedam, and at 1235 m for Ledena jama. That altitude difference and different terrain morphology (paleoglacier valley vs. steep karst), suggest that interesting differences in the sediments studied may be present. Sediment samples were taken at 50 m depth in Ledena jama, and at 100 m depth in Nedam. The analyses made on the samples were the determination of mineralogical composition - identification of clay minerals by X-ray diffraction analysis, separation of light and heavy mineral fraction, and observing under the microscope. From this analysis we can deduce the province of the sediments, and some conditions that were present during their deposition. The mineral composition of the samples from both pits was compared.
This work was done in collaboration with Speleological Society Velebit, Northern Velebit National Park and Department of Geology, Faculty of Science, University of Zagreb.

Key words: Dinaric karst, sediments, deep caves, mineralogy
Ključne besede: Dinarski kras, sediment, globoke jame, mineralogija

In situ formation of cryogenic calcite on seasonal ice in Snežna jama

In situ nastanek krigenega kalcita na sezonskem ledu v Snežni jami na planini Arto

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Abstract
Cryogenic Cave Carbonates (CCC) are minerals that form by the segregation of solutes during the freezing of calcium bicarbonate solutions in ice caves. Here we describe in-situ precipitation of fine CCC on the surface of ice stalagmites, stalactites and lakes in Snežna jama (Slovenia). Samples of ice with CCC have been transported to the lab in frozen state and examined under a SEM using in-chamber low-vacuum sublimation of ice fragments. The studied CCC are flaky particles detached from each other, that form thin whitish crusts on the surface of ice and accumulate as loose powdery deposits when the ice melts. Flakes are 50 to 200 mm in diameter and around 20 mm thick having a flat (outer?) side and drusy crystals on the other side, often showing rosette morphologies, with a fibrous radial distribution of crystals. XRD analysis revealed that the CCC are composed mainly of calcite and smaller amounts of aragonite. Two main types of crystal habits have been observed under SEM, sometimes coexisting: rhombohedral single crystals or complex morphologies consisting of stacked rhombohedra, and small smooth spheres, 1–5 mm in diameter, resembling vaterite, a metastable $CaCO_3$ polymorph.
Such mineral paragenesis indicates possible early transformation of vaterite to calcite in the presence of liquid water. Our ongoing research has been aimed at understanding the relative influence of freezing segregation, melting-and-refreezing, evaporation and ice sublimation processes in the genesis and mineralogical evolution of CCC. Detailed chemical analysis of minerals, ice and water has been performed, complemented by experimental cryogenic mineral precipitation.

Key words: cryogenic carbonates, cave ice, mineral transformations, Snežna jama
Ključne besede: kriogeni karbonati, jamski led, preoblikovanje mineralov, Snežna jama na planini Arto

Geochemistry of Snezhnaya cave system (Western Caucasus, Bzybsky Ridge)

Geokemične značilnosti jamskega sistema Snežnaja (Zahodni Kavkaz, Bžipski hrbet)

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Abstract
Snezhnaya cave system is the largest karst cavity of Bzybsky massif (Western Caucasus) with a length of 32,136 m with total amplitude of 1760 m. The upper part of the system up to the depth of 450–600 m is embedded in massive and thick-layered limestones and barrem dolomites, and the lower part is in alluvial breccia of the Lower Neocomian. The most common secondary minerals of the cave are calcite and Mg-containing calcite, aragonite, gypsum, and hydromagnesite. Celestine and strontianitis were also noted at one locality. Dolomite, barite, apatite, goethite, pseudorutil are observed in leaky crust samples in form of inclusions, as well as quartz, clay minerals, biotite, plagioclases, xenotime, zircon, and monazite, which are impurities captured by calcite crust during the growth. This paper discusses the regularities of rare elements and petrogenic components redistribution during the formation of the secondary sediment of various types in a cave. The chemical composition of the host rocks and secondary mineral formations was determined by the silicate and spectral analysis methods. The aggregates of gravitational crusts formed in the flooded parts of the cave with the active influx of the feed solution are considered to be the most chemically pure. In calcite of corallite crusts, which were formed during the less active supply of the solution and the movement of water by thin films under the action of capillary forces, a large amount of impurities is observed, which are probably caused by an admixture of clay captured by mineral aggregates during growth. In the sand and clay deposits, almost the whole spectrum of rare elements accumulates, except for Mo, Sn, and Pb, and all petrogenic components except with CaO, MgO, and CO_2, which are removed due to the dissolution of the calcite and dolomite component of the host rock.

Key words: karst, mineralogy, geochemistry, Western Caucasus
Ključne besede: kras, mineralogija, geokemija, Zahodni Kavkaz

Tidal karst notches as indication of Holocene sea levels in peninsular Malaysia

Plimne kraške zajede kot indikator holocenske gladine morja na Malezijskem polotoku

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Abstract

Evidence of mid-Holocene highstand of sea level due to post LGM flooding of the Sunda Shelf have been reported in Peninsular Malaysia, with the maximum occurring at 4400 years BP. Among this evidence is erosional sea notches preserved on 7 karst towers, located up to about 4.9 m above current mean sea level and in between 7 to 18.86 km away from the present day shoreline at the north of the peninsula. These notches are believed to be formed in a stable geological condition. Therefore, these notches have not been influenced by tectonic uplift or submergence. Many retain a single stack of nip, indicating a steady lowering/rising of sea levels. A few shows a stack of nips that may indicate the gradual episodic rising/lowering of the sea levels. Preliminary observation shows the notches to retain the morphology of the rising levels, and this may indicate a slow rising that gave enough time for the formation of the nips and faster retreat of the shoreline.

Key words: holocene sea levels, karst notches

Ključne besede: gladina morja v holocenu, kraške zajede

New findings of the water snail of the genus Emmericia in the karst springs of Herzegovina

Nova odkritja vodnih polžev iz rodu Emmericia v kraških izvirih Hercegovine

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Abstract

The area of the Dinaric Karst is inhabited by four species of the genus Emmericia: *Emmericia patula*, *Emmericia narentana*, *Emmericia expansilabris* and *Emmericia ventricosa*. Pavle Radoman wrote in detail about their distribution and mutual biogeographical relations. *E. patula* inhabits a narrow coastal belt in the Gulf of Trieste (locus tipicus), Rječina near Rijeka, the lower reaches of the river Zrmanja and in the immediate hinterland from Split to the mouth of the Neretva. *E. narentana* inhabits only a narrow area of the lower reaches of the Neretva. *E. expansilabris* lives in the area from Pelješac to the Bay of Kotor. *E. ventricosa* lives in the area of karst poljes, in the upper course of the river Cetina, Vrljika near Imotski, the river Lištica (Mostarsko blato), and on the left bank of the Neretva (river Buna and Bregava, only near Stolac) and in the area of Popovo polje (Trebišnjica river around Trebinje and to Bileća). The peculiarity of the biogeography of this genus is the pronounced non-mixing of certain species within certain areas.

Thanks to the project "The distribution, population status and threats to biodiversity of freshwater snails family hydrobiidae" funded Crytical Ecosystem Partnership Fund (CEPF) have discovered a new location for the type *E. ventricosa* (Trebinje, in three springs connected with the cave Vruljak; Vrioštica spring in Vitina) and *E. patula* (Boksića, Sv. Ivan and Bilo springs on the northwest side of Mostarsko blato). New findings of the species *E. patula* in Mostar mud show that it does not stand as *E. ventricosa* claims that there is no mixing of species of the genus Emmericia within certain areas. *E. patula* is also a new species for Bosnia and Herzegovina.

Key words: water snails, Emmericia, *Emmericia patula*, karst springs, Bosnia and Herzegovina

Ključne besede: vodni polži, Emmericia, Emmericia patula, kraški izviri, Bosna in Hercegovina

The use of new technologies for understanding structural geology and hydrogeology of the karst unsaturated zone

Uporaba sodobne tehnologije za prepoznavanje strukturnih geoloških in hidrogeoloških značilnosti v nenasičenem delu krašnega vodonosnika

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Abstract

The objectives of the study are to evaluate relationships between the surface and subsurface karstification and the flow directions of the infiltrated water. The study focuses on the Tiha Jama, the initial parts of the Planina Cave, and the surface above it, where geological structures are heavily impacted by karstification. The studied area is located in SW Slovenia, above the southern edge of the Planina Polje, and consists of highly karstified lower Cretaceous carbonate rocks that were strongly affected by tectonic deformation. To reach the objectives of the study a detailed structural geological map of the cave and surface was made. In order to obtain more karst structural information and not only those obtained by conventional geological mapping techniques, modern land surveying methods were used, such as: digital elevation model of the surface made from airborne LiDAR data provided by Surveying and Mapping Authority of the Republic of Slovenia; a drone ortophoto map of the surface and drone photogrammetric model of the entrance rock face to the cave; detailed point cloud data of the cave and the parts of the surface acquired by 3D terrestrial laser scanner. The use of modern land surveying methods proved to play a vital part in obtaining additional karst structural geological information; the information that would have otherwise been missed or overlooked, especially in a cave environment with poor visibility (big cave chambers, high humidity). The resulting maps allowed prediction of the primary drainage pathways in the upper part of the unsaturated zone of the karst aquifer.

Study is performed within the programme Karst Research (P6-0119), doctoral thesis (2020–2024), project ForKarst - Infiltration processes in forested karst aquifers under changing environment (J6-8266), 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: Planina Cave, geological structure, unsaturated zone, drainage pathways, 3D terrestrial laser scanner, drone

Ključne besede: Planinska jama, geološka struktura, nenasičena cona, smeri pretakanja, 3D terestični laserski skener, brezpilotni letalnik

What can patterned ground in karst caves tell us about Arctic carbon cycle?

Kaj nam lahko sortirana tla v kraških jamah povedo o ogljikovem ciklu na Arktiki

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Abstract

One of the most distinctive periglacial landscape landforms is patterned ground. Patterned ground has also been reported from karst caves in temperate climates. We are studying patterned ground movements and temperatures in two karst caves Ledenica pod Hrušico and Barka in Dinaric Mountains, Slovenia.

Both caves are relatively short (around 50 m) and 20 m deep and lie at 800 and 1100 m elevation. Patterned ground can be found in side passages that contain a mixture of fine sediments and limestone debris. Twelve 20–50 cm wide stripes of coarse limestone debris developed on an inclined slope in Ledenica pod Hrušico Cave and characteristic sorted circles with diameters ranging between 40 to 70 cm formed in Barka Cave.

Several freeze-thaw cycles occur at the sediment ground surface in winter due to cave temperature fluctuations. The cold climatic conditions that result from cave morphology sustain lower ground temperatures in summer and cause freeze-thaw cycles in winter, which result in frost heaving that causes sediment sorting. Cave air temperature measurements show that surface cold air pool in the cave Ledenica pod Hrušico is stable whole year round, whereas the cold air pool in the cave Barka is disrupted during stronger wind due to the cave's morphology.

Frost heave and needle ice length up to 10 cm were observed during freezing conditions in both caves. Gravel and sand present on patterned ground enables tracking of ground movements with surface from motion technique (SfM). Absence of snow and vegetation makes karst caves unique places for monitoring of ground movements caused by ground freezing. Sorted patterned ground in karst caves can thus help to reveal cryoturbation mechanisms that are responsible for large organic carbon storage in soils underlain by permafrost and what will be a faith of this organic matter under the warming climate.

Key words: patterned ground, ice caves, carbon cycle, Dinaric karst
Ključne besede: sortirana tla, ledene jame, ogljikov cikel, Dinarski kras

Cold active lipases from Scarisoara Ice Cave and their applicative potential

V mrazu aktivne lipaze iz ledene jame Scarisoara in možnost njihove uporabe

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Abstract
Psychrophilic microorganisms can produce highly efficient cold-active enzymes to ensure their optimal growth in such harsh conditions. Their high activity at low temperatures, low energy consumption and fewer harmful by-products represent economic and ecological advantages. Among extremozymes, lipases constitute widely applied catalysts in various industries. In search of novel reservoirs of cold-active enzymes, we investigated the lipolytic activity of 7 bacterial strains isolated from ice deposits accumulated in Scarisoara Ice Cave, Romania, and cloned and characterized two lipases from the *Psychrobacter sp* cave isolate.
A preliminary API ZYM test indicated the presence of variable lipase activity of these bacteria. In addition, fluorescence tests using Muller-Hinton growth media enriched with olive oil, grape seed oil and thistle oil showed extracellular lipase activity of these strains able to hydrolyse the indicated substrates after 7 days of incubation at 15 and 25 °C, with a preference for the olive and grape seed oils.
Genome sequencing of Psychrobacter sp revealed two genes coding for lipases (Lip-2 and Lip-3) that were cloned in pHAT2 and expressed in *Escherichia coli*. Structural analyses of the protein sequences showed conserved sequence elements of cold-active lipases. The recombinant enzymes were purified by affinity chromatography. Functional characterization of both the bacterial extracellular factions and purified Lip-2 and Lip-3 currently underway indicated the catalysts of this cave bacterial isolate as promising catalysts for enhanced products obtained by derivatization processes in the oil industry.
Funding: UEFISCDI PN-III-P2-2.1-PED-2019-2461

Key words: cold-active lipases, ice cave isolates, *Psychrobacter sp*, recombinant enzymes
Ključne besede: v mrazu aktivne lipaze, izolati ledenih jam, Psychrobacter sp, rekombinantni encimi

Ancient antimicrobial resistance in Scarisoara ice cave

Pretekla antimikrobna obstojnost v ledeni jami Scarisoara

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Abstract

Although the unique physiology of cold-environment microbiomes revealed promising leads for the discovery of new bioactive compounds, the antibiotic resistance and antimicrobial potential of bacteria isolated from perennial ice caves is largely unexplored.

Our study focused on the characterisation of bacterial strains isolated from a 13,000-years old ice core chronosequence of Scarisoara Ice Cave, Romania. The 68 bacterial isolates provided the first isolated bacterial strains from this perennial ice accumulated since Late Glacial period, and the first culture-based evidence of the existence of bacterial resistome and antimicrobial compound production from this type of icy environment. Bacterial strains isolated from 28 core ice samples on R2A media were identified by 16S rRNA gene sequencing and tested by the Kirby-Bauer method for both the antibiotic susceptibility and antimicrobial activity.

Bacterial cave isolates belonged to the four major phyla ubiquitous to frozen environments Actinobacteria, Proteobacteria, Firmicutes and Bacteroidetes, and showed an extended resistance profile to 28 different antibiotics. 11 strains tested for antimicrobial activity against 22 human pathogens, showed a potential for developing novel antimicrobial strategies.

The large antimicrobial resistance spectrum and the prevalence of multidrug resistance phenotype for the retrieved bacterial strains along the ice core constitute novel leads for understanding the evolution of environmental resistome, and provided promising candidates for obtaining new active biomolecules and valuable cold-active biocatalysts.

Key words: antimicrobial activity, antibiotic resistance, perennial ice cave, bacterial isolates
Ključne besede: antimikrobna aktivnost, antibiotska obstojnost, trajna ledena jama, bakterijski izolati

Czech karst as a part of Prague in last 20 years

Vloga češkega krasa oz krasa na območju Prage v zadnjih 20 letih

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Abstract
The article will be oriented on development in the Czech (Bohemian) Karst in the southwestern part of Czech main town (Prague/Praha) area in last 20 years. The reason for it is, that we create there a Sustainable Development Plan for all area of Protected Landscape Area Czech Karst and now we can do the score, what was true and what was false in the last 20 years. All impacts on this area will be visible in the map of landscape prognosis, where we planned with local Mayors development in year 2001. We think, that the direct impact of Prague development (as an Capital of Czech Republic) is according to pressure of new developments in the surrounding of Prague and also to needs of Metropolitan City (food, building materials, store capacities, etc.). Question is if the Nature protection by law was appropriate defence against them. Second question is, if the Prague City as the Capital has some other possibilities to development in surrounding.

Key words: city development, metropolitan region, sustainable development plan, possibilities of development, development prognosis, protected landscape area
Ključne besede: razvoj mesta, metropolitansko območje, trajnostni razvojni načrt, možnosti za razvoj, prognoza razvoja, zaščiteno območje

Healed speleothems in the Demänová Cave System (northern Slovakia)

Zapolnitveni speleotemi v jamskem sistemu Demänova (severna Slovaška)

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Abstract
The healed speleothems, sparsely mentioned in the literature, have been noted in the one of the side passages of the Slovakian Demänová Cave System. Most commonly, the speleothem healing process occurs within columns and it is undoubtedly related to the brittle deformations. The renewal of the calcium carbonate crystallization controlled by the fractures led to the formation of different cave forms, namely: (i) the sub-vertical ridges, (ii) sub-horizontal ridges, and (iii) helectites. The morphology of the sub-vertical ridges and helectites confirms that they were fed by the water migrating within the fractures. In contrast, the development of the sub-horizontal ridges results from the gravitational water flow down the surface of the columns. Independently to the mechanism of water supply the precipitation of calcite mainly proceeded close to the fracture mouths, where degassing of CO_2 out of the water was the most efficient. The composition of $\delta^{18}O$ of host speleothems and their healed parts is comparable and falls in a narrow range between -8.16 and -6.65 ‰ V-PDB. This result is coherent with the $\delta^{18}O$ values of other stalagmites occurring in the Demänová Cave System. Contrarily, the significant diversification of $\delta^{13}C$ values has been observed between each type of a speleothem healed part and its substratum. The mean $\delta^{13}C$ value of the former is -7.78 ‰ V-PDB, while the mean $\delta^{13}C$ value of the latter is -4.80 ‰ V-PDB. The depletion of $\delta^{13}C$ value is the most plausibly caused by crystallization in different environmental conditions.

Key words: speleothem, fracture, stable isotopes, paleoenvironment
Ključne besede: speleotem, razpoka, stabilni izotop, paleookolje

Emergency response strategies for hazardous materials releases in karst

Strategije odzivanja na izredne razmere pri izpustu nevarnih snovi na krasu

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Abstract

Karst terrains and their underlying aquifers are noted as being highly vulnerable to contamination from a wide range of anthropogenic sources and activities. Worldwide, karst aquifers are important water supplies for municipalities, agricultural, and industrial users. In addition, they provide habitat for many unique and endangered species.

The release of hazardous materials within karst groundwater basins can and has resulted in serious contamination of groundwater resources and ecologies, municipal water supplies, and springs. This presentation will discuss strategies to protect karst aquifers through an integrated planning approach at the local, regional and national level. Components of a comprehensive strategy including data collection related to groundwater quality and quantity; delineation of groundwater flowpaths, basin boundaries, and groundwater velocities; identification of potential contamination sources; recommendations on monitoring parameters and frequency; coordination for the response to hazardous materials releases; and zoning and land use restrictions.

Key words: emergency response, hazardous materials, karst, groundwater

Ključne besede: odziv na izredne razmere, nevarne snovi, kras, podzemna voda

Karst relief denudation based on limestone tablets weight loss (Slovak karst)

Analiza kraške denudacije na osnovi izgube teže apnenčastih tablet (Slovaški kras)

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Abstract

Denudation rate depends on the amount of factors such as climatic conditions, chemical reaction of soil, quantity of precipitation and their chemistry, average temperature, the amount of CO_2 in the soil but also the properties of a karst rock (chemical purity etc.). Our research is based on method of Ivan Gams and measurable results of limestone tablets weight loss at two experimental sites of the Slovak Karst. On Silica and Jasov Plateau was monitored weight loss in the 3 months intervals from December 2016 until present. We used two different types of tablets (from the Lipica quarry in Slovenia and from Slovak karst since 2018) in three different positions - on the surface and at a depth of 20 and 50 cm. To measure the weight loss we used KERN ABT-NM analytical scales together with study and measurement of different factors that affect it.

We have been statistically processed and compared with values measured in various methodologies from other karst areas. In addition, we have tried to explain how individual higher mentioned factors for chemical denudation on the plate surface are affected. There are no significant differences in denudation rate (DR) between experimental sites. Lowest DR was measured on the surface. The highest DR was recorded in the Jasov Plateau at a depth of 50 cm by 3.40 %, but on the Silica Plateau at a depth of 20 cm and 3.62 % (at a depth of 50 cm it was 2.62 %).The most significant factors was rainfall and evaporation; temperature and biological (organic) activity too.

Key words: Slovak karst, carnation rocks, chemical denudation, limestone tablets, weight loss method

Ključne besede: Slovaški kras, karnacijka kamnina, kemična denudacija, apnenčaste tablete, metoda z izgubo teže

The influence of caves as an extreme environment on the physiological functions and mental state of individuals

Kraške jame kot ekstremno okolje, ki vpliva na fiziološke funkcije in mentalno stanje posameznikov

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Abstract

Various research in the caves are aimed at improving the physical and mental health of adults and children. Caves represent an extreme environment that opens the possibility of training persons from different professions in connection with high-stress and risk related activities that can hardly be simulated. An example of good practice is astronaut training program CAVES conducted by the European Space Agency (ESA) since 2011. It focuses primarily on the specificity of environmental conditions and expeditionary aspects based on teamwork and problem solving in the extreme environment. In our research we focus on individuals and wonder how an environment and activities in caves affect the physiological and psychological characteristics of human subject. We suggest continuous monitoring via smartwatch of individual physiological functions for the entire period of stay in the cave and assessment of the psychological state. We want to compare a change in these variables to the same functions in habitual activities and the environment gathered with health app. The deep pits on Velebit Mt. (Croatia) represent a selection of unique surrounding suitable for exploration. Our preliminary study shows a discrepancy between the measured physiological parameters and the personal experience of individuals. This confirms that a cave is a suitable environment for monitoring the effects of extreme external factors on the individual. It also indicates the importance of examining the psychological aspects of humans. The average calorie consumption per hour is extremely low while the measured temperature is lower relative to surface activities. By collecting data, we contribute to the knowledge how stressful and long-lasting efforts affect the functioning and condition of the organism. It is important to distinguish the purely physical fitness acquired through standardized surface programs from the physical functioning in the cave in which the psychological aspect plays a significant role.

Key words: caves, physiology, psychology, extreme conditions, health app, monitoring
Ključne besede: jame, fiziologija, psihologija, ekstremne razmere, aplikacija o zdravju, monitoring

Hydrological and physical-chemical processes and its controlling effect on the karst landscape in the Peruaçu river canyon, Cavernas do Peruaçu National Park, Minas Gerais, Brazil

Hidrološki in fizikalno kemični procesi in njihov učinek na kraško pokrajino kanjona reke Peruaçu, Cavernas do Peruaçu National Park, Minas Gerais, Brazilija

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Abstract
The karst canyon of the Peruaçu river is occupied by carbonate outcrops of the Bambuí Group, presenting a significant set of large dimension caves within the limits of the Cavernas do Peruaçu National Park, located in the north of Minas Gerais, Brazil. The region is one of the most stunning karst landscapes in Brazil and has worldwide significance. Studies addressing hydrology in karst environments are essential for understanding the physical-chemical processes of karst features. The authors carried out a bibliographic review and field research to monitor water flow and water bodies level for the research. Statistical analysis took place in order to organize the data better. The results show that the interruption of the water flow may be establishing favourable conditions for the dissolution of the rock, promoting the opening of alternative channels with the consequent drainage of water, which contributes to the alteration of the karst landscapes in the region.

Key words: karst landscape, hydrology, groundwater carbonate dissolution, Peruaçu river, Brazil
Ključne besede: kraška pokrajina, hidrologija, raztapljanje karbonatov, podzemna voda, reka Peruaçu, Brazilija

Map of karst phenomena of Natividade and Chapada da Natividade, Tocantins, Brazil

Zemljevid kraških pojavov območij Natividade in Chapada da Natividade, Tocantins, Brazilija

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Abstract
From the perspective of karst geomorphology, this research aims to contribute to the karst knowledge production about the relief in the municipalities of Natividade and Chapada da Natividade, southeastern Tocantins. The research characterised the main karst features of the region, pointing to the stage of landscape conservation and its tourist potential. An exploratory map of karst phenomena (1:50,000) was elaborated. The exploratory map was made using a specific methodology based on several bibliographies. Images from the ALOS satellite, Palsar sensor, satellite Sentinel 2A, MSI sensor, and fieldworks throughout the research areas were important to reach a good result. Finally, it was understood that the karst of Natividade and Chapada da Natividade contains geological, hydrogeological, geomorphological, geotouristic, educational and cultural potential. Therefore, more scientific research is necessary to understand the regional karst better and allow its responsible use.

Key words: mapping, karst, Tocantins, Brazil
Ključne besede: kartiranje, kras, Tocantins, Brazilija

The role of gravitational movements and active tectonics in the Driny Cave development in the Malé Karpaty Mts. (the Western Carpathians)

Vloga gravitacijskih premikov in aktivne tektonike na razvoj jame Driny v Malih Karpatih (Zahodni Karpati)

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Abstract

The Driny Cave is situated in the Malé Karpaty Mts. (MK), which belongs to the most tectonic active regions of the Western Carpathians in Slovakia. MK also represents one of the most seismoactive regions of the Western Carpathians too. The cave developed in the top part of the Driny hill that was affected by large slope deformation, corresponding to the ridge gravitational spreading. A range of geological, geophysical, and geomorphological data from the cave as well as from the close vicinity of the cave is being compared to results of the long-term fault slip monitoring, which has been organized in the cave since 2005. The role of the active tectonics, as well as the recognized gravitational deformation in the Driny Cave development, is discussed and presented here.

Key words: Driny Cave, Western Carpathians, active tectonics, slope deformations, monitoring
Ključne besede: jama Driny, Zahodni Karpati, aktivna tektonika, deformacije pobočij, monitoring

What is needed for improving the reconnaissance karst potential mapping of British Columbia, Canada

Kaj je potrebno za izboljšano kartiranje potenciala za nastanek krasa v Britanski Kolumbiji, Kanada

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Abstract
Approximately 10 % (or 100,000 km^2) of British Columbia (BC) has bedrock units with the potential to develop karst. This potential karst occurs in all five physiographic regions of BC, which closely correlate to the five geologic terranes forming the Canadian Cordillera. The geology, geomorphology hydrology, and ecology of the karst landscapes vary across the BC's land mass, nearly all of which was glaciated. Forested karst occurs throughout the different biogeoclimatic regions of BC varying from the cool and moist forests of the west coast to the drier interior forests and the colder northern boreal forests. Thicker glacial deposits overly parts of the interior of BC and likely form 'covered karst', while further inland, there are examples of stripe karst in thin and steeply dipping limestone (marble) layers. Extensive alpine and sub-alpine karst occurs in the Rocky Mountains to the east within gently dipping limestone and dolostone units.
A reconnaissance "karst potential" map for British Columbia's was developed in 1999 based on the available digital bedrock mapping data. An algorithm was designed to predict the likelihood of encountering karst in each of 7,658 mapped polygons, plus their potential to develop karst. There was little to no ground verification. Despite these limitations, these polygons remain the current digital karst potential mapping layer used in BC. While more recent digitized bedrock data could help to refine the boundaries of the karst potential polygons, they would yield only incremental improvements as to whether karst is present in a polygon or information on the regional variations of karstification. Integrating remote sensing tools such as LiDAR and high-resolution satellite imagery with targeted field verification is needed to enhance the existing provincial 'karst potential' data layer, so that they might be more informative and useful to the end users.

Key words: British Columbia, karst potential, mapping
Ključne besede: Britanska Kolumbija, potencial za kras, kartiranje

Croatian coastal karst - treasury of karst features, yet just a piece of the global jigsaw

Hrvaški obalni kras - zakladnica kraških pojavov, ki predstavlja le del celotne sestavljanke v svetu

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Abstract

More than 8000 m thick carbonate succession deposited from Upper Palaeozoic to Palaeogene reworked by intensive tectonics mostly related to the Alpine orogeny, its subsequent karstification and final interaction with changing Quaternary sea level, created along the eastern Adriatic coast one of the most distinctive karst landscapes. Highly indented coast hosts variety of completely or partly submerged karst features of different origin - some of them being simply drowned, and some of them have evolved and changed due to the sea water intrusion. However, due to the different genesis, lithology and sea water dynamics they are barely comparable with similar features in global perspective. For example, Croatian anchialine caves are hydrogeologically comparable to cenotes, but they differ remarkably by the origin and the shape. Similarly, definition of blue holes (Mylroie *et al.* 1995) practically fits to the description of some Croatian submerged caves, yet substantial difference exists when considered thoroughly. Also, Croatian islands' karstification can hardly fit to the well known Carbonate Island Karst Model (Mylroie & Mylroie 2007). Furthermore, submerged speleothems and their usefulness for the sea-level change reconstructions depend on fresh and sea water mixing patterns, and Croatian submerged speleothems typically end either covered with marine biogenic overgrowth or corroded due to the mixing corrosion. Meanwhile, carbonate encrustation known as phreatic overgrowth on a speleothem (POS), that is usually reported from Spanish submerged caves (e.g. Tuccimei *et al.* 2010), has not been common in Croatian submerged karst until recently discovered POS-like features (Lončar & Kovač Konrad 2020). All these findings underline once more the necessity of independent regional studies with full consideration of local hydrogeological and biogeochemical settings.

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Key words: coastal karst, anchialine caves, submerged speleothems, Eastern Adriatic, Croatia

Ključne besede: obalni kras, anhialne jame, potopljeni speleotemi, Vzhodni Jadran, Hrvaška

Changes in the hydrogen sulfide content of Hévíz thermal lake

Spremembe v vsebnosti vodikovega sulfida v termalnem jezeru Héviz

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Abstract

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 cold component of the spring waters is supposed to come from the aquifer of the nearby Keszthely Mountains, while the warmer component originates from the Transdanubian karst system. 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 due to decades of mining activity, a significant decrease in the karst water levels was observed in the area affecting 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.

Although the hydrogen sulfide concentration of the lake was regularly recorded in the recent years, the applied sampling techniques did not guarantee the preservation of the dissolved gases in the samples, and no information is available on the individual springs. We have tested several sampling methods implemented by scuba divers, and a range of analytical methods were also evaluated to find the best combination that gives reliable information on the sulfide content in the shortest time possible. A technique involving sampling with syringes pre-filled with a reagent mixture giving a colour reaction with sulfides was developed, providing a semi-quantitative information at the time of sampling. As the reaction takes place immediately, control and re-sampling is possible, eliminating the need of additional dives in case of sampling errors. Besides hydrogen sulfide, other sulfur species and dissolved oxygen concentrations were also recorded during the year 2020. Annual variation in the hydrogen sulfide content of the individual springs was observed.

Key words: karst water, Lake Hévíz, hydrogen sulfide, spring cave
Ključne besede: kraška voda, jezero Héviz, hidrogeni sulfid, izvirna jama

Regional undulations: an ultimate stage of the karst landscape?

Regionalne undulacije: zadnja faza v razvoju kraškega površja?

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Abstract
The term regional undulations is introduced to describe the occurrence of karst surface features with clear identity but presently not completely explainable origin. They were evidenced by manipulation of the DTM on Krk Island in Croatia while delimiting individual entities of the karst surface. Regional undulations appear as a gently undulating, unexpectedly regular, surface characterized by smooth elevations and intermediate depressions with a wavelength of several kilometres. Even though presumed that the basic framework of undulations was guided by some kind of regional structural pattern, low, rather constant slope angle, and mirror geometry of negative and positive segments imply that presently individual undulations are quite equilibrated features. Not regarded how old they might be, if compared to the other surface features of karsts of the middle latitudes reported up to now, their size indicates a pretty long time necessary for their formation. Regional undulations may actually represent a morphological manifestation of the ultimate stage of surface karstification, similarly as a featureless plain represents the ultimate stage in the fluvial systems. In the other words, they may be a realization of the, pure karst model, close to steady-state, stage. The distribution pattern of undulations as noticed on Krk Island has not been evidenced elsewhere in the wider region. At other locations, surface features of the same scale may take different and locally specific sizes, geometries and distribution. To examine the validity of the concept of regional undulations, this contribution aims to encourage the discussion and expand the range of research on this topic. Despite not yet entirely defined mechanisms that result in the formation of regional undulations, its established existence pointed out several size and time ranges of karstification.

Key words: karst, geomorphology, regional undulations, temperate karst
Ključne besede: kras, geomorfologija, regionalne undulacije, zmeren kras

Active water cave Vodna jama v Lozi and Loza Unroofed Cave - a case of morphogenesis in the Slavina Corrosional Plain (SW Slovenia)

Aktivna Vodna jama v Lozi in brezstropa jama v Lozi - primer morfogeneze na Slavenskem ravniku (JZ Slovenija)

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Abstract

The Slavina Corrosional Plain is a levelled karst area located between Postojna and Pivka Basin, Karst Plateau, and Vipava Valley, developed in Eocene, Paleocene, and Cretaceous Limestone. The northern part was influenced by allogenic waters, forming a distinctive contact karst geomorphology, among which caves are present, extending towards the south. Vodna jama v Lozi is a 7.7 km long active water cave (between 550 and 470 m a.s.l.). On the surface, an unroofed cave filled with sediments appears (between 630 and 580 m a.s.l.), named Loza Unroofed Cave. Extending at least 4.3 km on the karst surface, it represents the longest known and studied unroofed cave in Slovenia, classified as a Valuable Natural Feature. The distinctive relict cave channel without a ceiling is up to 10 m deep and 30 m wide. A geomorphological map was produced by LiDAR imaging, cartographic measurements, and sediment sampling. The sedimentary methods and X-Ray Diffraction (XRD) were used to determine the origin of sediments. By the analyses, we could prove that the sediments in the Loza Unroofed Cave were brought into the cave by an allogenic river(s) sinking into the Slavina Corrosional Plain from the North or north-west part of the Postojna Basin. Furthermore, we assume regarding its position, sediment contents, and direction of water flow, to be a precursor of Vodna jama v Lozi, now an active epiphreatic cave about 100 m deeper.

Key words: active water cave, unroofed cave, epiphreatic, morphogenesis, X-Ray Diffraction (XRD), Slavina Corrosional Plain

Ključne besede: aktivna vodna jama, brezstropa jama, epifreatika, morfogeneza, difrakcija rentgenskih žarkov (XRD), Slavenski ravnik

Water flow in karst soil: implementing preferential flows in one-dimensional model

Pretakanje vode skozi kraška tla: ponazarjanje preferenčnih tokov z enodimenzionalnem modelom

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Abstract

Due to high secondary porosity, karst areas are characterized by rapid water infiltration into the underground. Therefore, soil cover plays an important role since it is the first media that controls the amount and quality of water on its path to the aquifer. To better understand processes that impact water distribution and transport through soil cover, one-dimensional model at daily resolution was developed, which simulates water content at 6 levels in a 50 cm deep soil. The study site is located in central Spain (40°9'15"N, 5°4'20"W) and is characterized by red soil rich in iron minerals that is half meter thick and overlies metamorphosed carbonates. At a soil monitoring station, sensors are measuring soil water content every three hours, at depths of 10, 20, 30, 40 and 50 cm. Amount of precipitation, temperature, relative humidity, air pressure, wind velocity and direction are recorded every 10 minutes at a meteorological station installed at a study location. To determine basic soil properties, laboratory analyses were performed. Model is developed by using modified water balance equation, where assumed initial soil water content, precipitation, actual evapotranspiration and percolation are used as input parameters, while modelled soil water content represents the output parameter. Preliminary results show that preferential flows are important mechanisms of water flow through karst soil, which implies that water is rapidly and almost directly infiltrated from the soil surface to deeper soil sections. Correlation coefficients show strong positive relationship between measured and modelled results. Once the model will be completed, simulated soil water content and temperature records will be used as input parameters for CO_2 concentration and transport model.

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Key words: hydrological model, karst soil, preferential flows, soil moisture

Ključne besede: hidrološki model, kraška tla, preferenčni tokovi, vlaga v prsti

Advanced approach in evaluating the cave pollution in Slovenia

Napredni pristop pri proučevanju onesnaženosti jam v Sloveniji

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Abstract

Karst caves in Slovenia are defined as natural values of national importance. They are owned by the state and protected by the Cave Protection Act. The lack of municipal waste management and general economic development after WW2 led to an increase in the amount of waste. As such, caves were used as a convenient place for waste disposal. By deteriorating the quality of groundwater, the pollution primarily affects the diverse and vulnerable underground habitats. Moreover, the decrease in water quality can affect the health of the local population. Despite the legal protection and enhanced environmental awareness the pollution of caves is continuing.

In Slovenia, cave pollution has been partly studied at the local level. Though, international literature refers to the topic only in studies of the pressures on the karst environment. Our research focuses on cave pollution on a regional scale, where we studied the condition of caves in 17 selected Slovenian regions. For this purpose, we relied on data from the Cave Registry, where we obtained detailed information about 6965 caves. By establishing the new methodology for processing archival data, we initially obtained 7 main categories and 60 subcategories of cave pollution data. Geographic information systems were used to process the data and followed by the implication of statistical methods.

We found that in the selected sample of caves, 1390 caves or 20.0 % of caves were polluted. Extrapolation of the results to the level of 12.588 registered caves suggests that at least 2512 caves in Slovenia may be polluted.

Key words: geography, environmental protection, karstology, cave pollution, geographic information system

Ključne besede: geografija, varovanje okolja, krasoslovje, onesnaženost jam, geografski informacijski sistemi

The REE and trace elements in karst hydrogeothermal systems of Carpatho-Balkanides, Serbia

Redki zemeljski in sledljivi elementi v kraškem hidrogeotermalnem sistemu Karpato-Balkanidov, Srbija

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Abstract

The thermal waters of the East-Serbian Carpatho-Balkanides (ESCB) have been the subject of various studies, where the agreement on the origin of the elevated temperature and circulation pathways has not been achieved. Hydrogeological systems formed in Cretaceous limestones have been cited as the most significant reservoirs of thermal waters with temperatures up to 40 °C, while the questions about the main karst/fissured aquifer have remained unresolved. The aim of this study was to apply hydrogeochemical analysis of the rare earth elements (REE) and trace elements to give new insight into the genesis of thermal groundwater in complex karst systems. The close examination of the REE patterns revealed that they slightly differ, and led to the separation of three general types of karst hydrogeothermal systems, while the trace elements enabled additional hydrogeochemical fingerprinting. The regional tectonic play the important role in the karst systems formation, distinguishing (1) structures formed in the peripheral part of ESCB, (2) the karst systems in the internal tectonic zone of ESCB, and (3) the complex karst systems related to volcanism. The karst systems of the first group are influenced by the water circulation through deep structures at the contact of regionally important geotectonic units with a specific trace element signature (F, Li, Sr, Rb). The karst systems in the internal tectonic zone are characterized by groundwater circulation through deep fault zones with a long pathway (U, V, Se, Mo, Re, In). The thermal waters of the remaining major karst system clearly showed hydrogeochemical signature genetically related to the Cretaceous volcanic rocks (B, W, Si, Mo, Ga, Ge). The REE patterns and trace elements enabled new insights into the functioning of important thermal karst systems in ESCB.

Key words: thermal water, karst aquifer, REE, hydrogeochemical tracers, geotectonics

Ključne besede: termalna voda, kraški vodonosnik, redki zemeljski elementi, hidrogeokemična sledila, geotektonika

Research possibilities in the Tropical Karst: past, present and future

Možnosti raziskovanja tropskega krasa: preteklost, sedanjost in prihodnost

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Abstract
The bibliography shows several types of karst mainly due to their development conditions, their main characteristics of karstification and their geomorphological features. Tropical Karst hosts some of the most impressive karst features on the surface and the underground, showing a wide variety of landforms. Almost in all tropical regions are the lithological differences and contacts, soil cover, microbiological and biological activity, and climatic conditions that determine variations in morphology. One can see enormous karst towers, cones, dolines, stone forests, tsingy and large cave systems all over the Planet. The South China Karst, the Madagascar Karst, the Yucatan Peninsula, the Caribbean Karst and the Southeast Asian Karst are just a few examples of this worldwide visibility, mainly due to the relative proximity with known research centres. Many of the karst features found in these areas were also develop in Brazil. The country is located in South America, a continent that contains fewer carbonate areas than other tropical regions. However, most of its carbonate karst is situated in the Central Brazilian Plateau, which hosts the largest karst areas in the continent. For this lecture, the focus is the Tropical Karst, its distribution, and its main aspects, especially in Brazil, highlighting the research from the past, present, and future.

Key words: tropical karst, research possibilities, Brazil, Minas Gerais
Ključne besede: tropski kras, možnosti raziskovanja, Brazilija, Minas Gerais

Preliminary results of speleothem U-Th dating and paleoclimate reconstruction from Garganta del Dino Cave (Ecuador)

Prvi rezultati paleoklimatskih rekonstrukcij glede na U-Th datacije v jami Garganta del Dino (Ekvador)

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Abstract
Speleothems were collected from several caves in the Amazonian and the Pacific karst areas of Ecuador, as part of a project dedicated to study the paleoclimate record along the South American equator that includes also paleoclimate study of tree-rings as well as cave and precipitation monitoring.
Sample preparation and all analyses (stable isotopes and U-Th dating) were carried out at the ICER Centre, Institute for Nuclear Research, Debrecen. For the U-Th analysis, chemical preparation to separate U and Th fractions from the carbonate matrix was carried out in a Class 1000 clean laboratory. Samples were spiked with a 229Th-233U–236U tracer and measurements of isotope ratios (234U/238U, 230Th/238U and 230Th/232Th) were carried out on our recently installed Neptune Plus MC-ICP-MS.
U-Th ages were obtained for 11 samples, and stable isotope composition ($\delta^{13}C$, $\delta^{18}O$) was determined for 110 samples, all sampled along the growth axis of a stalagmite (Dino 1) from Garganta del Dino Cave, located near Mera, in the Amazonian part of Ecuador. One age, that was out of stratigraphic order, was excluded, and an age-depth model was constructed in StalAge, covering the period of 6.87 to 5.10 ka BP. The stalagmite had a relatively fast growth rate (0.2–0.5 mm/yr). δ18O values ranged from -6.0 to -4.5 ‰ VPDB, and $\delta^{13}C$ values from -6.6 to -2.0 ‰ VPDB. Our monitoring in the area shows the influence of the amount effect on the precipitation $\delta^{18}O$ values, with seasonality corresponding to the influence of the Intertropical Convergence Zone (ITCZ), instead of the South America Monsoon System (SAMS). Preliminary comparison with speleothem records from South America reflecting the SAMS activity and covering the same period show comparable trends, suggesting that the study area during Middle Holocene was dominantly under the influence of the SAMS.
This research was supported by the GINOP-2.3.2-15-2016-00009 project.

Key words: U-Th dating, speleothem, paleoclimate, Holocene, Amazon, Ecuador
Ključne besede: U-Th datiranje, speleotem, paleoklima, Holocen, Amazonija, Ekvador

Morphogenesis research as basis for conservation and interpretation of karst landscape in the area of West Medvednica Mt. (Croatia)

Raziskava morfogeneze kot osnove za ohranjanje in interpretacijo kraške pokrajine na zahodnemu delu Medvednice (Hrvaška)

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Abstract
The aim of the research is to contribute to the knowledge of surface and underground karst relief in the area of West Medvednica Mt. (Croatia) with the purpose of understanding its morphogenesis and improve its conservation and interpretation. This includes general and specific morphometric analysis, comparison of relief with geological structure of the selected area and geospeleological analysis. A special emphasis is placed on the caves Bijele sige and the Velebitaška jama in order to contribute to their evaluation and protection. The pits were endangered, in particular the Bijele sige where we found anthropogenic materials of human origin. The best way to protect nature is through education, and in order to be able to perform it well, it is necessary to collect data and present it in a professional and interesting way to different target groups. Many people are not aware of the natural values of Medvednica Mt., especially related to the geodiversity of above-ground and underground karst phenomena. Apart from the largest cave in this area - Veternica cave, there are many other interesting caves on Medvednica. Documenting the natural values of these pits and the surface area gives rise to the idea of preparing educational materials for a broader educational program.

Key words: geomorphology, geospeleology, karst, Medvednica
Ključne besede: geomorfologija, geospeleologija, kras, Medvednica

Regional water balance analysis of karstic areas by remote sensing

Regionalna analiza vodne balance kraških območij z uporabo daljinskega zaznavanja

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Abstract

Recent global karstic potable water analyses have shown that despite their unstable hydrological regimes and higher vulnerability to pollution, karstic aquifers represent a significant share of water supply where they are widely present. Sustainable management is needed to prevent their overexploitation or depletion since the future projections predict increased demands and additional natural and anthropogenic stresses. Continuously measured variables can provide useful research options to study and understand the water balance of aquifers, which improves the knowledge needed to effectively manage the water sources, particularly in regional aquifers such as Dinaric karst.

Since 2002, GRACE (Gravity Recovery and Climate Experiment) satellite has been acquiring precise data on the Earth's gravity through an innovative system measuring the distance between two instruments during their path around the Earth which changes due to the Earth's gravity. These measurements are the basis for the most precise geoid model yet, however they also enable research of the processes that affect the gravity field in smaller time scales, which include the water mass movements of the planet. Analysis of groundwater variability in a karstic-fractured aquifer of Dinaric karst is thus possible for a continuous 19-year period. Monthly averaged total water storage variability derived from GRACE data is available from three different data analysis centres at 1 and 0.5 degree spatial resolution which offer a precision of 1 cm liquid water equivalent thickness at 300 km^2. Preliminary data analysis for the mascons covering the Dinaric karst shows the storage variability between -32 cm and +26 cm with an average range of 43 cm relative to the average of the 2004–2009 period without a prominent long-term trend. The data offers the possibility of identifying areas of Dinaric karst with different patterns of groundwater variability which could improve the water balance monitoring of an important international water source.

Key words: Dinaric karst, karstic aquifer, water balance, storage, GRACE, remote sensing

Ključne besede: Dinarski kras, kraški vodonosnik, vodna bilanca, skladiščenje, GRACE, daljinsko zaznavanje

Rockfall dynamics in caves: Velebit Mt., Croatia

Dinamka podorov v jamah: Velebit, Hrvaška

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Abstract
Studies have named geologic structure, type of water recharge, and changes in base water level to be main controlling factors of speleogenesis. The complexity of karst cave systems is even more increased by a large number of fractures and cavities in karst landscape being enlarged by meteoric water dissolution. Such speleogenesis is made possible by carbon dioxide being absorbed from air and soil. Contrarily, so called "boulder caves" originated by rockfall and debris accumulation were given their own lithological and morphological cave category as pseudokarstic caves. Such natural processes of sudden rockfall, other than water erosion, frost weathering and temperature change, is even more common in non karst cave systems. However, occasionally observed rockfall in karst cave systems is yet to be assigned a quantitative value when it comes to cave formation. An ongoing study in Slovačka pit (Northern Velebit, Croatia) is yet to yield results necessary for understanding rockfall dynamics in karst cave systems.

Key words: cave dynamics, rockfall, karst caves, speleogenesis
Ključne besede: dinamika jam, podor, kraške jame, speleogeneza

General characteristics of karst aquifers in Greece

Splošne značilnosti kraških vodonosnikov v Grčiji

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Abstract
The aim of this study is to describe the general characteristics of the karst aquifers in Greece. Karst in Greece presents specific characteristics compared to other Mediterranean karst, because a large part of Greece territory emerged recently e.g. after Middle Miocene-Pliocene, affected by neotectonic activity. The Messinian crisis of salinity had as result the development of karst phenomena below the present sea level and produced the most original features of karst in Greece.
The karst aquifers of Greece are developed within carbonate sedimentary (limestone, dolomite) and metamorphic rocks (marbles). Both are karstified, forming excellent aquifer systems with commonly high yield boreholes and large storage capacity. The hydrogeological behaviour of carbonate rocks is controlled by tectonic deformation, which favours infiltration (coefficient of infiltration ranges between 40–55 % of the annual precipitation) and karstification, which quickly decreases with depth. The karst aquifers discharge through springs that are submarine, coastal brackish, inland freshwater, and thermal springs due to the volcanic activity and tectonic structure of Greece.
Based on pumping test analyses, it is concluded that the hydraulic parameters of the karst aquifers range within a large scale of values depending on karstification, tectonics and stratigraphy. High values of transmissivity and specific capacity are recorded in the upper stratigraphically levels of the karstic aquifers or along the faulted zones. The majority of karst systems are of good water quality and quantitative status; poor water quality status is recorded in coastal karst aquifers (mainly in islands) due to seawater intrusion phenomena. As karst water is an important natural resource contributing significantly to water supply for drinking and irrigation use, as well as very vulnerable to external pollution from anthropogenic activities and climate changes, the protection and the sustainable management of karst aquifers is a matter of first priority.

Key words: karst water, hydraulic parameters, springs, carbonate rocks, Greece
Ključne besede: kraška voda, hidravlične lastnosti, izviri, karbonatne kamine, Grčija

Connecting the dots - the inter-relationship between sinkholes, uvalas and conduits in evaporite karst at the Eastern Dead Sea shore, Jordan

Povezovanje točk - medsebojna povezava med vrtačami, uvalami in kanali v evaporitnem krasu vzhodne obale Mrtvega morja, Jordanija

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Abstract

Karst landscapes are characterised by enclosed topographic depressions of variable scale and morphology, the most common of which are sinkholes (dolines). Certain larger karst depressions that display gentler slopes and more complex three-dimensional shapes are termed uvalas. The developmental relationship between sinkholes, uvalas and subsurface drainage is debated, however, mainly because long developmental timescales in limestone karst impede direct observations of landscape evolution.

This work describes the rapid development of uvalas, sinkholes and conduits in an evaporite karst setting on the eastern shore of the hypersaline Dead Sea from 1992 to 2018, in response to the anthropogenically-forced decline in the Dead Sea level. Remote sensing data and field observations show that sinkholes and uvalas form in a very close spatio-temporal relationship. While sinkhole development is initially clustered, the uvalas develop around such clusters; the two are structurally distinct both in space and time. Additional field observations, electrical resistivity tomography (ERT) and self-potential data from the head of a groundwater-fed surface stream channel within one uvala point to concentrated, multidirectional water flow in conduits located in the shallow subsurface (< 25 m depth). Further ERT surveys from within the uvala show anomalies that are coincident with the depression axis and that we interpret to represent subsurface water flow.

Accordingly, we interpret the primary process of uvala formation here to be subsidence (sagging) in response to distributed dissolution and physical erosion within a mechanically unstable subsurface volume (groundwater conduit network). Sinkholes, on the other hand, are interpreted as discrete subsidence responses to highly localised material removal within that volume (e.g. single void collapses). Our multi-disciplinary approach therefore leads us to a refined conceptual model of the processes forming uvalas and sinkholes in this evaporite karst setting, and an improved understanding of the nature, occurrence, and genesis of uvalas in karst systems generally.

Key words: evaporite karst, geomorphology, uvala, sinkhole
Ključne besede: kras v evaporotih, geomorfologija, uvala, vrtača

Facilitating the use of subterranean biodiversity data in nature conservation - examples from Slovenia and Bosnia and Herzegovina

Vspodbujanje uporabe podatkov o podzemni biotski raznovrstnosti pri varovanju narave - primeri iz Slovenije in Bosne in Hercegovine

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Abstract

Reliable knowledge of species distributions is a prerequisite for assessing human impacts on the viability of species and their habitats, which in turn form the basis for successful conservation strategies. Inventorying subterranean habitats is challenging: species are rare, habitats are difficult to access and species identification is time-consuming. Most of the subterranean species are narrowly distributed and are therefore highly endangered. Information on subterranean species is scattered across different sources, while conservation measures and monitoring crucially depend on standardized and retrievable data. An example of such a database is SubBioDB, an integrative database on the distribution of subterranean species, mainly covering Western Balkans. SubBioDB supported the development of two ongoing regional projects focusing on hotspots of subterranean biodiversity in the Dinarides. The project Life NarcIS - Nature Conservation Information System in Slovenia (funded by LIFE Programme of the European Union; 2020–2024) will establish an information system that will serve as a "one-stop-shop", to disseminate data on habitats, species distributions and especially nature conservation documents. As one of eight partners, we participate with data and knowledge on subterranean species. The project SubBIOCODE - Developing new tools for rapid assessment of subterranean biodiversity in Bosnia and Herzegovina (funded by Critical Ecosystem Partnership Fund; 2019–2022) is implemented in the Trebišnjica river catchment. In partnership with the Center for Karst and Speleology, we aim to improve the collection and accessibility of data on subterranean species, identify conservation priorities and train conservationists in the region. Both projects share a common overarching goal: to slow down the extinctions and improve conservation of subterranean species in both global hotspots of subterranean biodiversity. Such a modular interlinked database system that collects and delivers high-quality data could be implemented elsewhere and holds the promise of transboundary natural heritage management despite economic, cultural and legal differences.

Key words: subterranean biodiversity, database, nature conservation, monitoring

Ključne besede: podzemna biotska raznovrstnost, podatkovna baza, varovanje narave, monitoring

International Year of Caves and Karst - Karst, Caves, and People Worldwide

Mednarodno leto jam in krasa - kras, jame in ljudje po svetu

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Abstract

The purpose of the International Year of Caves and Karst is to present phenomena to people all over the world, and that people would know what karst and caves are, how they were formed, how they function, and also to be aware of their vulnerability. At the same time, to show the diversity of karst and caves according to various geological settings and climate. The development of karst landforms is limited to areas where are present relatively soluble rocks such as carbonate rocks or evaporites, but the "Classical" karst is karst formed in carbonate rocks. Many variations of karst landscapes are located in different climatic zones around the globe, with different temperatures, the amount of precipitation, soil, and vegetation. The availability of water is the most important climatic factor for karst development. Karst occurs in an arid and extremely cold environment, but its development is slow. On the other hand, in a humid tropical climate, the dissolution processes are much faster. During history, karst was never densely populated, because of lack of water and soil. There were bigger settlements close to karst springs, and also caves and cenotes were used as a source of water. With the growing settlement of karst landscapes, people start interfering with it and changing it, whereby the natural balance. People and their way of life and often reckless land development pose a serious threat to nature. Groups of individual karst pollutants are settlements, industry, agriculture, transport, and constructions. Karst is vulnerable due to a thin cover layer of the soil, rapid water infiltration, rapid groundwater drainage through open channels and, the potential spread of contamination in different directions, as well as occasional long-term retention of harmful substances. To minimize human impacts in karst areas, it is necessary to educate the inhabitants of karst areas on general threats to the underground as well as specific to their region.

Key words: karst, caves, people, IYCK 2021

Ključne besede: kras, jame, ljudje, mednarodno leto jam in krasa 2021

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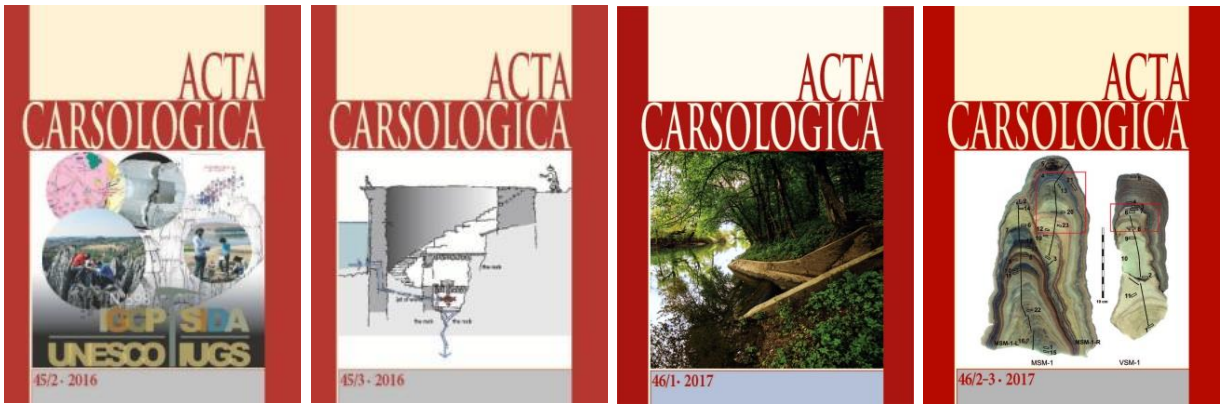
Acta Carsologica publishes original research papers and reviews, letters, essays and reports covering topics related to specific of karst areas. These comprise, but are not limited to karst geology, hydrology and geomorphology, speleology, hydrogeology, biospeleology and history of karst science.



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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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