KARST RESEARCH INSTITUTE ZRC SAZU

24th INTERNATIONAL KARSTOLOGICAL SCHOOL
"Classical Karst"

PALEOKARST

ABSTRACTS & GUIDE BOOK

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Postojna, 2016

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CONTENTS

GENERAL INFORMATION

PROGRAMME

Monday, June 13th, 2016

8.00–13.00	**REGISTRATION**	**Cultural Centre Postojna**
9.00–11.00	**OPENING SESSION**	**Cultural Centre Postojna**
9.00–9.20	**Opening Ceremony**	
9.20–10.10	**Keynote lecture** Andrea Mindszenty: *Superimposed karst events reflecting a tectonic story. The case of Halimba (Hungary)*	
10.10–11.00	**Home lecture** Bojan Otoničar: *Paleokarsts of SW Slovenia and NW Croatia (introduction to the field trips)*	
11.00–11.30	*Coffee break*	
11.30–13.30	**SESSION 1**	**Cultural Centre Postojna**
11.30–12.00	**Invited lecture** Armstrong Osborne: *Palaeokarst, an inside view*	
12.00–12.30	**Invited lecture** Pavel Bosák: *Amalgamation of paleokarst surfaces: from depositional to inter-regional paleokarst*	
12.30–12.50	Eglantine Husson, Séranne, M., Camus, H., Fondecave-Wallez, M.-J., Melinte-Dobrinescu, M.-C., Combes, P.-J., Peybernes, B., Couëffé, R., Dörfliger, N.: *Sedimentary record of paleokarsts: a patch on uncomplete continental stratigraphic records. Case study from Cretaceous to Neogene paleokarsts in Southern France*	
12.50–13.10	Rosario Ruggieri, Maniscalco, R.: *Paleokarstic features of the Hyblean Plateau (SE Sicily)*	
13.10–13.30	Andrea Mindszenty: *Blue-hole-type pond sequences recording internal transgression over karstic carbonate terrains at times of relative sea-level rise*	
13.30–16.00	*Lunch break*	
16.00–17.30	**POSTER SESSION**	**Karst Research Institute**
18.00–22.00	Ice breaker and Unresolved Mysteries of (paleo)karst	

Tuesday, June 14th, 2016

8.30–10.30	**REGISTRATION**	**Cultural Centre Postojna**
8.30–11.30	**SESSION 2**	**Cultural Centre Postojna**
8.30–9.00	**Invited lecture** Roman Aubrecht: *Mesozoic and Cenozoic paleokarst events and related structures in the Western Carpathians*	
9.00–9.30	**Invited lecture** Adrijan Košir: *Paleokarst-calcrete associations: the role of vegetation, climatic factors and process rates*	
9.30–10.00	**Invited lecture** Mihovil Brlek: *Fossil rocky-shores, submarine and polygenic discontinuity surfaces: characterization, eustatic and tectonic implications*	
10.00–10.30	*Coffee break*	

10.30–10.50	Andrzej Tyc: *Relict shafts – significant features of palaeosurface morphology of the Częstochowa Upland (S Poland)*	
10.50–11.10	Nadja Zupan Hajna, Mihevc, A., Pruner, P., Bosák, P.: *Several million years old cave sediments as a part of ongoing karstification period*	
11.10–11.30	Solbakk Terje, Aizprua, C., Johansen, S., Tore Amund, S.: *Pitfalls when interpreting karst from seismic images. Examples from the Norwegian shelf*	
11.30–13.00	*Lunch break*	
13.00–20.00	Late Cretaceous paleokarst of SW Slovenia and NE Italy	**Afternoon field trip (A)**

Wednesday, June 15th, 2016

8.30–10.20	**REGISTRATION**	**Cultural Centre Postojna**
8.30–11.40	**SESSION 3**	**Cultural Centre Postojna**
8.30–9.00	Tihomir Marjanac: *Conceptual response of cave systems to relative changes of sea-level.*	
9.00–9.30	Kelsey E. Budahn, Sasowsky, I. D., Quick, T. J.: *Verifying the origin of late stage conduit modifications by high resolution meteorological monitoring in active corrosion sites*	
9.30–9.50	Magdolna Virág, Mindszenty, A., Kele, S., Czuppon, Gy., Surányi, G., Braun, M., Palcsu, L., Futó, I., Hegedűs, A., Kiss, K., Szieberth, D., Leél-Őssy, Sz.: *Study of speleothems and other thermal-karst features in the caves of Rózsadomb (Budapest, Hungary)*	
9.50–10.20	*Coffee Break*	
10.20–10.40	László Palcsu, Vasić, Lj., Milanović, S., Túri, M., Rinyu, L.,Koltai, G., Gessert, A.: *Why ^{39}Ar dating is a necessary and indispensable tool in karst hydrology*	
10.40–11.00	David Domínguez-Villar, Krklec, K., Cheng, H., Edwards, R.L.: *Dating an episode of paleo-condensation corrosion in Eagle Cave (Spain)*	
11.00–11.20	Krklec Kristina, Domínguez-Villar, D.: *The role of denudation in forming unroofed caves, the case of Eagle Cave system (Spain)*	
11.20–11.40	Closing remarks	
11.40–13.00	*Lunch Break*	
13.00–20.00	Late Triassic, Late Jurassic and Late Cretaceous paleokarsts of the western part of central Slovenia	**Afternoon field trip (B)**

Thursday, June 16th, 2016

7.30-19.30	Forebulge related Late Creatceous to Palaeogene paleokarst of Istria (SW Slovenia and NW Croatia)	**Whole-day excursion (C)**
20.00–	**Reception at the Karst Research Institute**	

Friday, June 17th, 2016

8.30–18.00	Ljubljanica karstic river basin	**Whole-day excursion (D)**

Lunch

- Lunches are not organized on excursions and during the session days with exception on a *Whole-day excursion (C)*.
- 80- to 90-minute lunch breaks are in the schedule during the session days.

Excursions

- register **for each excursion** at the registration desk;
- bus departure for the field trips is from the parking place at the central Postojna Bus station;
- walking shoes and field clothes are recommended, swimming suit is optional on excursion C;
- take care for additional information and changes regarding the bus departures;
- drinking water will be available on all busses;
- **insect repellents** are recommended (we will be walking in the areas populated with **ticks** (*Ixodes ricinus*) that transfer mainly lyme desease and tick-borne meningitis;
- on the excursion C a short refreshment in the Adriatic sea will be possible **ON YOUR OWN RISK**;
- **participation on the excursions is at your own risk;**
- **make sure that you have valid travel documents for traveling in Italy and Croatia. Both countries are, like Slovenia, EU members; however, Croatia is not within the Schengen zone.**

Lectures

- PowerPoint presentations should be given to organizers at the break before Session starts.

Posters

- **Leave posters at registration desk on Monday before the lunch break**,
- stand by your poster during the poster sessions.

INVITATION TO A SPECIAL SESSION: UNRESOLVED MYSTERIES IN (PALEO)KARST

(Scheduled Monday, 13.6.2016)

This year's school will be as always a great opportunity as a meeting point between experienced and new researchers from different parts of the globe.

The last years, a Special Session on Mysteries in Karst science was held, and it was quite successful, in that some answers could be found, and others are actively investigated at the moment.

Usually talks in schools and congresses deal with progress of ongoing research and with their results. This session, however, has the aim to present the still-unresolved problems and to promote and stimulate research! In opposition to many other scientific branches, karstologists most often try to collaborate in order to resolve problems. This session should therefore promote further the world-wide collaboration.

Because there are no results, talks usually are short, but because questions are formulated, discussion should be longer. Therefore, talks are limited to about 5 minutes, while discussions may last 10–15 minutes.

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

With best regards,
Philipp Häuselmann

MAP OF POSTOJNA

Map of the town centre with important places:
1 – Karst Research Institute ZRC SAZU, Titov trg 2
2 – Start of field trips. Bus station, Titova cesta 2
3 – Kulturni dom (Cultural Centre of Postojna), Gregorčičev drevored 2

Places to eat:
4 – Proteus: restaurantd with local and "global" food and daily menu
5 – Bar Bor: restaurant, simple but good local food, also serves daily meals
6 – Čuk: restaurant at the sport park, pizzeria, good pasta, local and global food
7 – Minutka: restaurant with pizza, pasta, Balkan food and daily menu
8 – Štorja pod stopnicami: local and "global" food and daily menu

ABSTRACTS

* In alphabetical order

Mesozoic and Cenozoic paleokarst events and related structures in the Western Carpathians

Roman Aubrecht
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In the West Carpathian zone called Pieniny Klippen Belt, the oldest paleokarst features are related to the Middle Jurassic rifting and rising of the so-called Czorsztyn Swell. This was accompanied by breakage (neptunian dykes), emersion and erosion of new lithified sediments and forming the toe-of-slope megabreccias. There is an interesting cave-dwelling fauna of ostracods Pokornyopsis feifeli Triebel, descendants of which still inhabit submarine caves in tropical seas. Further drowning of the Czorsztyn swell led to deposition of the Rosso Ammonitico facies, with local occurrences of stromatactis mud-mounds. Stromatactis structures were enigmatic for over a century but at one of the sites the participants will have a chance to see that stromatactis are just cavities after collapsed siliceous sponges.

Later, on the Szorsztyn Swell there was also an Early Cretaceous emersion which resulted in expressive paleokarst karren surface. The emersion period started in Hauterivian and ended in Albian with sudden flooding (ingression) with deposition of red pelagic marls. Therefore, until recognition of the paleokarst features, this break in sedimentation was considered to be caused by submarine non-deposition and erosion.

In the Central Western Carpathians, an older period of emersion was related to the Mid-Cretaceous crustal shortening and nappe stacking. The nappe stacking resulted in emersion and karstification of the highest nappe surfaces, forming paleokarst surface depressions filled with bauxites and breccias with fossil Terra Rosa and fresh-water cyanophyte limestones resting on the unconformity surfaces.

A younger, Neogene erosional and karstification phenomena in the Central Western Carpathians are best manifested along the former, Miocene eastern shoreline of the Vienna Basin. They are represented by Middle/Upper Badenian and earlier, Eggenburgian transgressive surfaces along the eastern shore of the Vienna Basin. Paleokarst phenomena, such as clefts and caves were initially filled with sinters, as well as by terrestrial sediments locally with rich fauna. The erosion and karstification phase was followed by the Middle/Late Badenian marine transgression.

Keywords: Western Carpathians, paleokarst, neptunian dykes, collapse breccias, stromatactis

Lokvarka Cave (Croatia) microclimate and dripwater settings: Implications for comprehensive speleothem paleoclimate records interpretation

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There are many systematic studies which emphasize the importance of understanding cave atmosphere and hydrology in order to select suitable stalagmites for paleoclimate analyses. In order to collect data which are important for reliable and confident interpretation of Lokvarka Cave speleothems palaeoclimate records cave monitoring program (surface and cave air temperature, relative humidity, dripping rates, precipitation and drip water stable isotope composition) was established through one-year period (November 2014–November 2015).

Lokvarka Cave is situated in the Lokvarka stream blind valley side, in Gorski Kotar area, the narrowest part of the Dinaric mountain range, at an altitude of 780 m a.s.l. It is a complex cave which consists of three main levels formed in lower Jurassic limestone. Depth of the cave is 277 m and length is 1200 m. Broader area of the Lokvarka Cave is characterised by Cfb climate, with high values of annual precipitation (>3000 mm) while MAAT recorded during 1981–2014 period is 8.3 °C.

Monitoring sites were situated at the depth of 40 m and 50 m in respect to entrance elevation. Estimated thickness of limestone overlay is about 80–90 m. On both sites, data loggers for measurements of cave air temperature, relative humidity and drip rates were installed. External air temperature and relative humidity were measured for the purposes of comparison with cave air properties and composite monthly meteoric water samples were collected in the house yards 2.5 km from the cave, while daily precipitation data are provided by CHMS for the meteorological station Delnice (6 km from LOK).

During the given monitoring period mean cave air temperature was in the range between 7.3 and 7.7 °C. Relative humidity of the cave air was between 99.9% and 100%. Mean annual air temperature and relative humidity in front of the cave were 9 °C and 85.1%. Both cave dripping sites display fracture-flow regime with fast response to rain events. Local meteoric water line $\delta^2H = 7.31 \times \delta^{18}O + 12.03$, and *d*-excess of 17.9‰ suggests that monitored area is influenced by cool North Atlantic and warm and wet eastern Mediterranean air masses. $\delta^{18}O$ and δ^2H weighted means of collected drip water are close to the precipitation weighted means, but positioned slightly towards more positive part of LMWL, notwithstanding that the seepage of the water prevails in colder part of the year. Inter-annual $\delta^{18}O$ variation of 8.6‰ in precipitation has been reduced to 1.3‰ and 0.3‰ at the drip sites which is in concordance with their fracture-flow drip regimes.

Obtained values indicate that Lokvarka Cave has stable cave atmosphere suitable for equilibrium deposition of calcite in terms of constant air temperature and relative humidity and therefore is appropriate for further paleoclimate studies.

This monitoring program was performed within the project 1623 Reconstruction of the Quaternary environment in Croatia using isotope methods - REQUENCRIM financed by the Croatian Science Foundation.
Keywords: Lokvarka Cave, paleoclimate, Gorski Kotar, variations of $\delta^{18}O$ and δ^2H in cave drip water, local meteoric water line

Amalgamation of paleokarst surfaces: from depositional to inter-regional paleokarst

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Karst evolution is particularly dependent upon the time available for process evolution and on the geographical and geological conditions of the exposure of the rock. The time scale for the development of karst features cannot be longer than that of the rocks on which they form. The longer is the time, the higher the hydraulic gradient and the larger the amount of solvent water entering the karst system, the more evolved is the karst. In general, stratigraphic discontinuities, i.e. intervals of nondeposition (disconformities and unconformities), directly influence the intensity and extent of karstification. The higher the order of discontinuity under study, the greater will be the problems of dating processes and events. The order of unconformities influences the stratigraphy of the karst through the amount of time available for subaerial processes to operate. Karst forms of individual evolution stages (cycles) can be easily destroyed by erosion, denudation and abrasion without the necessity of the destruction of the whole sequence of karst rocks. Temporary and/or final interruption of the karstification process can be caused by the fossilisation of karst due to loss of its hydrological function (metamorphism, mineralisation, marine transgressions, burial by continental deposits or volcanic products, tectonic movements, climatic change etc.). The introduction of new energy (hydraulic head) to the system may cause reactivation of karstification reflected in the polycyclic and polygenetic nature of karst formation. Results of paleokarst evolution are best preserved directly beneath a cover of overlying deposits, i.e. under sediments, which terminated karstification periods or phases. The longer the stratigraphic gap the more problematic is precise dating of the age of the paleokarst, if it cannot be chronostratigraphically proven. Therefore, ages of paleokarsts has been traditionally assigned to time just at or shortly before the termination of the stratigraphic gap.

Stratigraphic discontinuities usually hide 5 to 90 % of geological time (time not recorded in any correlated sediments) depending on the geotectonic and paleogeographic position of depocentres and distance from the mailand, i.e. on disconformity/unconformity type and order. The mainland, if repesents the cratonic area (like e.g., Scandinavian Shield), records only ca 5 to 15 % time in correlate cover sediments, i.e. 85 – 95 % time is hidden and available for karstification, while in younger platforms (like some European epi-Variscan ones) the recorded time is 12 to 45 %. Sedimentary cover on platforms (like e.g., East European Platform) records ca 50 to 60 % of time. Distant parts of stable continental margins, except of submatine erosion, cover usually more than 80 or 90 % of there evolutions, which is about identical with orogeneic belts (e.g., Inner Carpathians), with some exceptions for individual tectonic units. On the contrast, some recent and fossil carbonate platforms show time recorded in sediments in a frame of only 5 to less than 10 % due to complex eustatic conditions and a high proportion of carbonate dissolution during depositional and early digenetic stages. Therefore the cross-section from active depocentres to old shields shows successive evolution and amalgamation of discontinuities from the 5th up to 1st orders expressed in time not-recorded in correlate sediments. While products of short-lived karstification on shallow carbonate platforms can be preserved by deposition during the immediately succeeding sea-level rise, products of more pronounced karstification can be destroyed by a number of different geomorphic processes. The longer the duration of subaerial exposure, the more complex are those geomorphic agents. Another problematic feature of karst records is the reactivation of processes, which can degrade a record by mixing karst fills of different ages.

Keywords: paleokarst, subaerial exposure, stratigraphic discontinuities, stratigraphic gap, amalgamation of paleokarst surfaces

Fossil rocky-shores, submarine and polygenic discontinuity surfaces: characterization, eustatic and tectonic implications

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Discontinuity surfaces (or discontinuities) resulting from breaks in sedimentation and representing hiatuses independent of their duration are common features in the sedimentary record (Clari *et al.* 1995; Hillgärtner 1998). Such surfaces are useful marker horizons for correlation of stratigraphic sections and are highly applicable in carbonate sequence stratigraphy (e.g., Wright 1994; Cachão *et al.* 2009; Buatois and Mángano 2011; Schwarz and Buatois 2012). Besides subaerial exposure surfaces, which are commonly distinguished from other discontinuity surfaces by a variety of palaeokarst and palaeosol features (Esteban and Klappa 1983; James and Choquette 1984; Wright 1994; Otoničar 2007; Brlek *et al.* 2014), several other types of discontinuity surfaces, such as fossil rocky-shores represented by unconformities and basal conglomerates, as well as composite and marine omission surfaces, can be recognized in the geological record and a clear distinction can be made from subaerial exposure surface based on the criteria given below.

The transition between land and sea is the most abrupt and coextensive ecological boundary on Earth (Johnson and Baarli 2012). Overall, intertidal rocky shores may account for more than 33 per cent of the world's present shore (Johnson 1988a), but they may have been more or less abundant during the past (Johnson 2006) representing a marine habitat of long temporal persistence (Johnson 1988a, b). The presence of marine trace fossils on a hard substrate, such as borings (*Trypanites* Ichnofacies with common elements of the *Gastrochaenolites-Entobia* assemblage; Bromley 1994; de Gibert *et al.* 2012) at the unconformity surface or as direct encrustations on it, are the best evidence for the existance of a rocky shore (Johnson 1988a, 2006; de Gibert *et al.* 1998, 2012; Domènech *et al.* 2001; Santos *et al.* 2011; Johnson and Baarli 2012). Such trace fossils are also significant in reconstruction of the palaeoenvironments related to sedimentary discontinuities (Bromley 1975; Cachão *et al.* 2009; Santos *et al.* 2010). Identification of rocky shores (colonised by boring and encrusting organisms due to their reduced or null sedimentation rates) in the geological record is very important because they represent major transgressive surfaces and provide crucial information about palaeoshorelines and ancient sea-levels (de Gibert *et al.* 1998, 2012; Domènech *et al.* 2001; Santos *et al.* 2008; Johnson *et al.* 2011, 2012). They also give information needed for palaeoenvironmental and tectonic reconstructions (Cachão *et al.* 2009; Santos *et al.* 2010), including e.g., tectono-eustatic movements deduced from fossilized marine tidal notches (developed by bioerosion in the intertidal zones of rocky coasts) found raised above or submerged below the water line (e.g. Mediterranean region; Spampinato *et al.* 2014; Surić *et al.* 2014; Boulton and Stewart 2015; Mourtzas *et al.* 2015). Some ancient rocky-shore deposits involve a basal conglomerate associated with an unconformity (Johnson 1988b; de Gibert *et al.* 1998; Domènech *et al.* 2001; Santos *et al.* 2008, 2011; Johnson and Baarli 2012).

The unconformity between the Mesozoic basement and the overlying Middle Miocene (Badenian) deposits (which belong palaeo-geographically to the south-western margins of the Central Paratethys, and geotectonically to the Pannonian Basin System) in the NE Mt. Medvednica (N Croatia) is marked by basal Badenian conglomerates (Brlek *et al.* 2016). The Upper Cretaceous limestone lithoclasts occurring in basal conglomerates show abundant truncated *Gastrochaenolites* and *Entobia* borings (represented by an *in situ* rocky substrate community of bivalves and sponges, respectively), with *Gastrochaenolites* being the dominant ichnogenus (Brlek *et al.* 2016). *Gastrochaenolites-Entobia* ichnofossil assemblage related to the *Entobia* subichnofacies and in turn assignable to the *Trypanites* Ichnofacies, is very typical of Neogene rocky shores (Santos *et al.* 2011). This association characterizes littoral rockground environments indicating wave-cut platforms and marine flooding surfaces (transgressive surfaces) with a low or null rate of sedimentation. Erosion of a pre-existing Mesozoic basement rocky shore during a marine transgressive phase in these high-energy littoral conditions, which formed basal conglomerates analysed here, is also evidenced by truncation and the occurrence of *Gastrochaenolites* borings on all sides of limestone clasts (Brlek *et al.* 2016). The transgressive phase correlates to the main Badenian transgression in the Central Paratethys (*Orbulina suturalis* Zone, the 3rd order sequence TB 2.4) (Brlek *et al.* 2016).

The significance of substrate-controlled trace fossil suites and calcretes for genetic interpretations of discontinuity surfaces has been emphasized by many researchers (e.g., Bromley 1975; Wright 1994; Hillgärtner 1998; Schwarz and Buatois 2012). Marine omission surfaces are clearly marked by substrate-controlled trace fossil suites (Bromley 1975; Knaust *et al.* 2012; Savrda 2012; Schwarz and Buatois 2012), with progressive hardening of the substrate demonstrated by cross-cutting vertical relationships between the pre-lithification *Glossifungites* Ichnofacies (firmgrounds) and the post-lithification *Trypanites* Ichnofacies (hardgrounds) (Bromley 1975; Savrda 2012). In addition, authigenic marine mineralization (e.g., phosphorites and glauconites) also reflect sedimentary condensation and is often associated with marine omission surfaces (e.g., Bromley 1975; Odin and Fullagar 1988; Föllmi 1996, 2016). Composite (polygenic) surfaces, which record both marine omission and subaerial exposure stages (Sattler *et al.* 2005; Rameil *et al.* 2012), are also commonly marked by substrate-controlled trace fossil suites and calcretes (e.g., Wilson *et al.* 1998), and indicate the complexity of hiatal surfaces in carbonate rock successions (Rameil *et al.* 2012).

Several firmgrounds and composite surfaces were recorded in the Upper Cretaceous platform carbonate successions in central Dalmatia, Croatia (Adriatic-Dinaridic Carbonate Platform, ADCP) (Brlek *et al.* 2014). *Thalassinoides* (probably *T. paradoxicus*) box-work burrow systems of the substrate-controlled *Glossifungites* Ichnofacies characterize the documented firmgrounds and the composite (polygenic) surface (Brlek *et al.* 2014). Rhizogenic laminar calcretes developed subsequently inside burrows of the composite surface through diagenetic overprint of marine sediment that passively infilled the burrows (Brlek *et al.* 2014). The formation of the firmgrounds was probably caused by cessation of precipitation and/or deposition of calcium carbonate due to relative sea-level fall, with development of some firmgrounds probably correlative with the regionally recorded Upper Campanian Event that represents a global eustatic sea-level fall *sensu* Jarvis *et al.* 2002 (Brlek *et al.* 2013). However, the recorded trace fossils associated with the composite surface indicate that this surface developed through both submarine firmground and subaerial exposure stages probably caused by several episodes of regression and transgression (Brlek *et al.* 2014), and exemplifies the general complexity of hiatal surfaces in shallow-marine carbonate successions (Rameil *et al.*2012).

Keywords: rocky-shore deposits, discontinuity surfaces, firmground, polygenic surfaces, trace fossils

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Verifying the origin of late stage conduit modifications by high resolution meteorological monitoring in active corrosion sites

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Cave passage morphologies provide important, and occasionally conclusive, information regarding speleogenetic mechanisms. However, recent work from several locations indicates that relatively late stage corrosion activity can confound the interpretation of genesis (phreatic, vadose, epigene, hypogene) for presently inactive (or paleokarst) cave passages. In order to improve fidelity of interpretation for these settings, it is important to identify active caves that can serve as analogs. This can allow more robust analysis of prior environmental conditions such as water table positions, connections to the surface, etc. High-resolution microclimate monitoring stations were set up in caves along a small limestone ridge on the eastern edge of the Iberian Chain, Spain, in March 2016. The site was chosen because the caves show evidence of active condensation corrosion through corroded walls and coralloid deposition, in the apparent absence of thermal or sulfidic conditions. Three stations were deployed in Cueva del Muerto, and one in Cueva del Pastor. The monitoring was designed to measure microclimate parameters necessary to understand the temporal and spatial variability of cave microclimate. Each station is equipped with three temperature sensors, one barometric pressure sensor, and one relative humidity sensor. A telescoping PVC pipe design was constructed as a base so that the temperature sensors would be spread out from floor to ceiling of the passage (up to 6.3 m), as well as (where applicable) measure cave wall temperature. The loggers and sensors were developed at the University of Akron using a combination of custom made and stock devices. A temperature sensor resolution of +/-0.001° C was set and calibrated, in order to measure small differences in temperature from floor to ceiling. Initial data indicate a current maximum difference in temperature from floor to ceiling of 0.595° C, with an average of 16.12° C. Wall temperature sensors were drilled up to 20 cm into the limestone cave walls, and show a bedrock average temperature of 16.19° C. Seasonal variability is expected to play a role in the activity of corrosion in this cave, which is configured with a single top entrance. Microclimate data will be collected over the course of one year at a minimum of 30-minute intervals in order to examine the temporal control on active condensation processes.
Keywords: speleogenesis, meteorology, Spain, instrumentation, temperature

Dating an episode of paleo-condensation corrosion in Eagle Cave (Spain)

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Eagle Cave is a small tourist cave from central Spain. In this cave, aragonite speleothems frequently show a distinctive red/orange colour with unusual blunt edges, exposed laminations and occasionally large holes through them. On the other hand, white calcite speleothems show more traditional shapes and textures. The later speleothems clearly postdate the former aragonite speleothems, and both speleothem stages are easy to identify. Fresh cuts of aragonite speleothems show that the red/orange colour is just a thin coat on their surface. During the first stage, the environmental conditions favoured aragonite precipitation of speleothems. However, a later event caused condensation corrosion all over the cave, partly dissolving speleothems. Low relative humidity during this period favoured the advection of aerosols (mostly clay-size oxide particles) that coated cave walls and speleothems. This sudden environmental change is likely the result of a significant collapse that dramatically changed the cave ventilation. At some point the cave environmental conditions changed again and speleothems were formed once more. Change in speleothem mineralogy from aragonite to calcite indicates that ventilation did not return to the initial conditions and cave CO_2 was likely higher. U-Th

dates of four different speleothems were obtained for samples above and below the "red layer" that indicated the collapse. The cave collapse occurred soon after 60 ka BP and open conditions lasted only some thousand years. This collapse story is in agreement with the record of multiple collapses of different magnitudes within the cave and with the karst record at the surface where unroofed caves are found.
Keywords: condensation corrosion, cave collapse, cave ventillation, U-Th dating, speleothems

Linear forms in surface karst of Mt. Miroč, eastern Serbia – Imprints of former streams or something else?

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Surface karst of Mt. Miroč (eastern Serbia) is developed mostly in Upper Jurassic limestones. Dolines are the dominant surface karst features in the present morphology, while fluviokarst is well developed along the lines of contact between carbonate and non-carbonate rocks. Fluviokarst is represented mostly by blind valleys, which bring seasonal and/or permanent allogenic input of water into karst. However, even in the surface morphology of central karstic parts away from the contacts, certain linear forms resembling dry valleys can be recognized. The recognition of such forms has been done using GIS software and spatial analysis on digital terrain model of Mt. Miroč. Acquired results show the existence of linear network forms on surface karst. The question arises whether these linear forms are the imprints of former surface streams or their origin is different. Geological settings indicate that the Upper Jurassic limestones previously had a cover of Lower Cretaceous sandstones, shales and marls (in normal superposition), which was subsequently washed away. We discuss the possibility that the Cretaceous cover in the previous phase of morphogenetic evolution enabled the existence of normal surface river network which was subsequently imprinted on carbonate base and transferred to the underground.
Keywords: surface karst morphology, fluviokarst, surface streams, GIS, Mt. Miroč

Sedimentary record of paleokarsts: a patch on uncomplete continental stratigraphic records. Case study from Cretaceous to Neogene paleokarsts in Southern France

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Continental erosion and weathering destroy parts of the stratigraphic record. Analyses of the sedimentary filling of paleokarsts help completing the geological record of regions that have been submitted to post-depositional, long-term, continental evolution.

Jurassic carbonate platform of Languedoc (South of France) has undergone several karstification phases from Cretaceous to Neogene. Later incision of canyons through the carbonate massifs allows to observe paleokarsts over 400 m depth, within the massifs.

Paleokarsts are partly filled with sediments. Some have yielded marine bioclasts (echinoderms, radiolars), foraminifera and nannofossils; others are composed of polygenic detrital sediments, including sources from the upstream Paleozoic basement (Cevennes). The age of the filling of successive paleokarsts can be constrained by structural relationships and by biostratigraphy.

These findings suggest 1) the marine elements of the karstic filling relate to a Late Cretaceous to Early Paleocene interval, while 2) the Paleozoic basement-sourced-sediments were trapped in the karst during Miocene to Present.

Karstic sediment containing Early Paleocene foraminifera and nannofossils are found in paleokarsts cavities distributed across the entire thickness of the carbonate massif (≥350m). This requires base-level lowering and associated karstification, followed by base-level rise and karst filling of at least 350 m amplitude, respectively. The time interval corresponding to the occurrence of foraminifera and nannofossils in karsts covers 10 Myrs;

surprisingly, no equivalent marine sediments are preserved on the surface. In addition, analyses of the different forams species suggests several (up to 3) distinct karstification and marine filling cycles. Finally, sedimentological facies analysis of the karst filling reveals the following succession of processes: low energy settling of mudstone, high energy reworking, transport and deposition of silts and sandstones within the karst system.

Integration of geological, paleontological and sedimentological data, leads to a polyphase scenario in response to repeated base-level variations, more than 350 m amplitude. Such an amplitude excludes eustacy, and the improbable repeated sequence of uplift and subsidence rules out tectonics, as driving forces for base-level change, respectively. We propose that the high-amplitude base-level changes results from a succession of desiccation-flooding events of an endorheic, silled, basin during Early Paleogene.

The later detrital assemblage sourced in the Cevennes occurs on perched paleosurfaces and in karst cavities across the whole 350m-deep canyon walls. When found on paleosurfaces, they correspond to the south-flowing Early Miocene fluvial drainage, and can be correlated downstream with the marine, well dated, Early Miocene, sediments. When found within the karst cavities, they correspond to successive base-level surfaces connected to the progressive incision of the canyon. This canyon incision is coeval with a Late Miocene uplift of the hinterland.

Keywords: paleokarst, karstic sedimentary process, geodynamics, base level, Paleocene, Miocene

Surface water and groundwater interactions in a shallow karst aquifer, Thala karst area, North-Estonia

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Tuhala karst area is situated in Northern Estonia, on the lower course of the Tuhala River, which drains the Mahtra wetlands. Upper-Ordovician carbonate rocks outcrop in the area, covered by a 2–5 m thick layer of poorly permeable glacial till (K=0.001 m/d). Tuhala karst area is best known for a temporary karst spring, called the Witch's Well that offers a peculiar sight to thousands of enthusiasts as it overflows during favorable hydrological conditions. This study aims to gain new insights into the operation of the Tuhala karst system, with emphasis on the Witch's Well. To fulfill the aim, water levels and discharges were observed in seven monitoring points and three quantitative groundwater tracing tests were conducted from October 2014 to February 2016. Study results suggest direct hydraulic link exists between the recharge and discharge areas. Despite the relatively moderate hydraulic gradient (0.003–-0.004) groundwater travels rapidly (V_{max}=500-673 m/h) through the densely fractured karst system, where well-developed conduits serve as preferential flow paths. During low to medium-flow conditions, groundwater preferably discharges in the Veetõusme spring group, whereas the Witch's Well group remains static despite being hydraulically linked to the system. Significant outflow in the Witch's Well group is established when the threshold piezometric groundwater levels 55.5 and 56.39 m asl in the springs are exceeded (which correspond to discharges of 2.4 and 3.97 m^3/s and water levels 58.67 and 59.23 m asl in the recharge area). Although the operation of the karst system is primarily dependent on the hydrological conditions in Tuhala River, a significant interaction with the adjacent aquifer is evident in many aspects.

Keywords: karst aquifer, tracer test, water level-discharge relation, surface-groundwater interaction

The role of denudation in forming unroofed caves, the case of Eagle Cave system (Spain)

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Denudation plays important role in evolution of cave systems and can lead to exposure of cave passages to the surface and formation of unroofed caves. In the area of Eagle cave, in central Spain, collapse breccias and flowstone speleothems exposed at the surface indicate the existence of unroofed caves. Their formation is the result of bedrock thinning above caves, triggering the collapses of their ceilings. We consider two end-member hypotheses that may explain this thinning: (1) a progressive denudation at the surface or (2) the collapse of blocks from cave ceilings. In order to evaluate the importance of denudation in the formation of unroofed caves at this site, we buried rock tablets for a year, at the depth of half meter, on top of the cave. Measured denudation rate was 1.75± 0.66 µm/yr, and different local lithologies did not show different weathering. Even if denudation rate could have been higher in the past, fluvial dissection rates are two orders of magnitude higher, causing dissolution of bedrock under the existing caves enabling new collapses. Alternatively, the fall of blocks inside the cave galleries is potentially a more efficient process for the progressive thinning of the cave ceiling before collapse. Therefore, the formation of unroofed caves is likely to be the result of thinning of cave ceilings dominated by collapses from inside the cave.
Keywords: unroofed cave, denudation, rock weathering, rock tablets

Paleokarst-calcrete associations: the role of vegetation, climatic factors and process rates

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Paleokarsts and calcretes are two groups of major macroscopic products of meteoric diagenesis. Although generally considered to represent contrasting styles of diagenetic processes in the vadose zone, ancient (epi)karst features and calcretes are often associated in carbonate depositional successions. Modern surface and shallow subsurface karst on carbonate rocks as well as the buried ancient karst systems are characterized by dissolutional features generally developed under prevailing humid climatic conditions and predominance of dissolutional weathering. In contrast, calcretes are typically considered as an indicator of 'arid' (semiarid to subhumid) climate, characterized by precipitation of secondary calcium carbonate in soils or within shallow, near surface vadose diagenetic environment. This paleoclimatic generalisation has been often used in the interpretation of paleoexposure surfaces in stratigraphic sequences. However, many calcretes form by predominance of biologically induced processes, particularly precipitation of calcium carbonate within the root systems of higher plants and associated microorganisms in soils. In its broadest definition, the depth of soil is defined by the rooting depth of plants, and this zone generally overlaps with the epikarst. We will show that certain examples of paleocalcretes, associated with paleokarst, reflect specific biological processes responsible for the precipitation of secondary carbonates rather than specific paleoclimatic conditions. Furthermore, occurrence of calcretes within a zone of prevailing dissolutional regime is less contradictory when we examine rates of carbonate dissolution in karst and the precipitation rates typical for biogenic calcretes.
Keywords: paleokarst, biogenic calcretes, plant roots, calcification

Archaeological sites as an indicator of environmental changes - examples from Northern Dalmatia

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This study presents a multidisciplinary research implemented in Geographic Information System (GIS) environment in order to investigate the palaeo-hydrography in Northern Dalmatia. The aim was to correlate archeological and geomorphological markers in order to corroborate present findings on Croatian coastal evolution during and after Roman period. Among many archeological sites in the wider area; roman villa, salt pond and medieval church from the Privlaka peninsula together with roman aqueduct and 9th century church from Vransko polje (near Biograd) have been chosen as a case study sites. The approach proposed here combines the results obtained by different remote sensing images (DOF) with the data obtained from historical maps and recent archeological field surveys using ArcGis software. Archeological sites in the research area were mapped in details and georeferenced. In the execution of the DEM the topographical plans (Croatian base maps) at a 1:5000 scale were used. ANUDEM method of interpolation was applied for the isolines and elevation points interpolation. Archeological sites were vectorised from Digital ortophoto map at a 1:5000 scale and excavation documentation was also integrated.

Changes of hydrographic characteristic e.g. sea level rise, groundwater level and marshlands changes have been reconstructed on both sites. These findings corroborate the submersion of at least 1.5 meters in Northern Dalmatia (Zadar) region during post roman time which is revealed based on archeological relics and geomorphological markers. This research illustrate importance of integrating geographical data base (mapping, spatial analysis, paleogeographic reconstructions) and archeological data (placement of sites) in a GIS offering a better interpretation of the relationships of sites, their structure and their formation as well as environmental change. As such it represents a useful starting point that can be implemented by further, more detailed, studies aimed to better understanding of the landscape evolution and the possible relationship with archaeological sites.

Keywords: geoarchaeology, environmental change, sea level rise, GIS, Northern Dalmatia, Croatia

Conceptual response of cave systems to relative changes of sea-level

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Relative sea-level changes must have profound effects on karst processes. As the sea-level rises or falls, so does the base-level, and that is what leaves its mark in cave systems. In caves, we can often see sediments with complex history of deposition and erosion. Usually, these are attributed to changes in hydrological regime within a cave, or to climate changes. But, how the fluctuating sea-levels may have influenced subterranean terrestrial environments? As the relative sea-level falls or rises, it also drives falls or rises of the base -level, but also causes seaward or landward translation of the graded profile of fluvial systems.

The relative rise of sea-level causes landward translation of the graded profile, which causes creation of new accommodation space in the lower part of fluvial systems, but also "negative" accommodation space (erosion) in their upper parts. This is recorded by headward erosion which creates debris for deposition in available accommodation space, also underground, and accretion of fluvial systems. Caves will be filled with sediments, some completely. The opposite process, relative sea-level fall will cause seaward translation of the graded profile, which will cause creation of "negative" accommodation space and erosion in the lower part of alluvial systems, but also creation of new accommodation space in the upper part of the profile. This would be a trap for debris and will be recorded as aggradation of alluvial fans, but downstream the alluvial systems will be sediment-free and subjected to erosion, also underground. In caves this would cause erosion of older sediments, and deeper incision of hydrologically active cave channels.

As the relative sea-level oscillates in rhythm of Milanković's cycles, the cave sediments will gain complex history of repeated depositional and erosional episodes, which can be correlated with terrestrial and marine records of global sea-level change.

Keywords: sea-level change, eustasy, graded profile, accommodation space, base-level change

How to measure the passage of time in karst?

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The only way of documenting the time is by monitoring karstification and measurement of its products. Subaerially exposed limestones are 'decorated' by various types of grikes which generally follow the rule: the larger – the older, but how old? In stabile climate it should be easy to associate the size of karren with its age, provided we know the mass of dissolved calcite. Kamenitzas are common all over the karst world and document the volume of dissolved calcite, so it should be possible to use them as a proxy for dating of the exposed surfaces. We have tested the possibility of determining the age of kamenitzas as a function of limestone dissolution rate and their volume.

In our experiment we have: a) measured the volume of several closed kamenitzas, b) analyzed mineralogical composition of their substrate, and c) calculated minimal age of kamenitzas as a function of their volume and dissolution rate of limestone. The type of limestone is determined by calcimetry and XRD analyses of insoluble fraction, whereas the limestone dissolution rate was measured at various localities by other researchers by dissolution of 'standard' limestone tablets. To account for difference of local limestone and 'standard' tablets, we have tested their solubility under controlled laboratory conditions.

Smaller kamenitzas were apparently formed in more-or-less stabile climatic conditions, in considerably shorter time compared with very large kamenitzas which must have been formed in time spans when climate change provided significant influence on the rate of their growth. Theoretically a kamenitza of 100 cm^3 was formed by dissolution of 271 g. of calcite in 5.593,2 years at dissolution rate of 0.,04845 g/y [1]. Consequently, measured small kamenitza on Rab Island with volume of 837,4 cm^3 would be formed in 46.839,5 years. However, it is very unlikely that the corrosion started in Late Pleistocene at the time of very low temperature and CO_2 levels [2]. Consequently, extrapolation of modern corrosion rates to geological history is misleading, and relationship of karstification with paleoclimate should be further studied.

Keywords: karstification, grikes, limestone dissolution, paleoclimate, dating

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Superimposed karst events reflecting a tectonic story.
The case of Halimba (Hungary)

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Karst bauxites are soil-derived sediments deposited over humid tropical karst terrains. When occurring in the stratigraphic record they are tale-tellers of past events of karstification jointly controlled by climate and tectonics. Lithofacies of karst bauxites shows strong correlation with the morphology of the underlying karst. Deep sinkholes – obviously formed in the vadose zone – are usually filled by thoroughly oxidized, deep-red, intensely leached, hematite-rich weathering products, whereas shallow (uvala- or polje-like) karst-forms are filled by less thoroughly leached, pale-colored material often with siderite, pyrite or other minerals of divalent iron. It is reasonable to think that the common factor controlling both the lithofacies of the karst-fill and karst morphology is hydrology, i.e. the elevation of the karst terrain above the water-table (Fig. 1). The concept of high-level and low-level karst and the response of karst terrains and their karst-fill to tectonic uplift and subsidence is discussed and demonstrated with the fossil example from the Transdanubian Range (TR), Hungary. Karst bauxites of the TR occur at major regional unconformities of Albian, Santonian and Paleocene/ Eocene age. Vertical and lateral facies relationships of bauxites, their karstic, partly dolomitic bedrock and the covering limestones and siliciclastics were studied in outcrops and in boreholes.Field observations were supported by micro-petrography, stable isotope geochemistry and fluid inclusion studies (Mindszenty *et al.* 2000).

The results fully supported earlier paleogeodynamic hypotheses (e.g. Tari 1994) according to which subaerial exposure in the TR was brought about in the Cretaceous by foreland-type flexural deformation (Fig. 2). Karstification proved to be most intense on the supposed apex of the forebulge where the unconforimities merge. Topographic changes, resulted by the migration of the forebulge, are clearly reflected by the superposition of the various karst-bauxite lithofacies, the calcite-cements in the underlying karst and the diachronism of burial of the bauxite-covered surface.

Keywords: multiple karst, bauxite, tectonics, Cretaceous, Hungary

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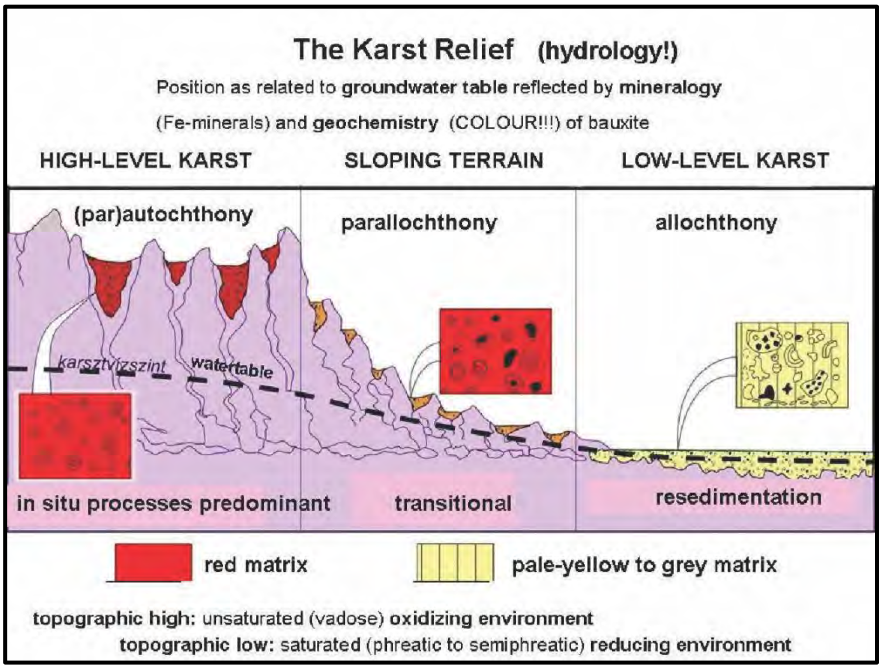

Figure 1

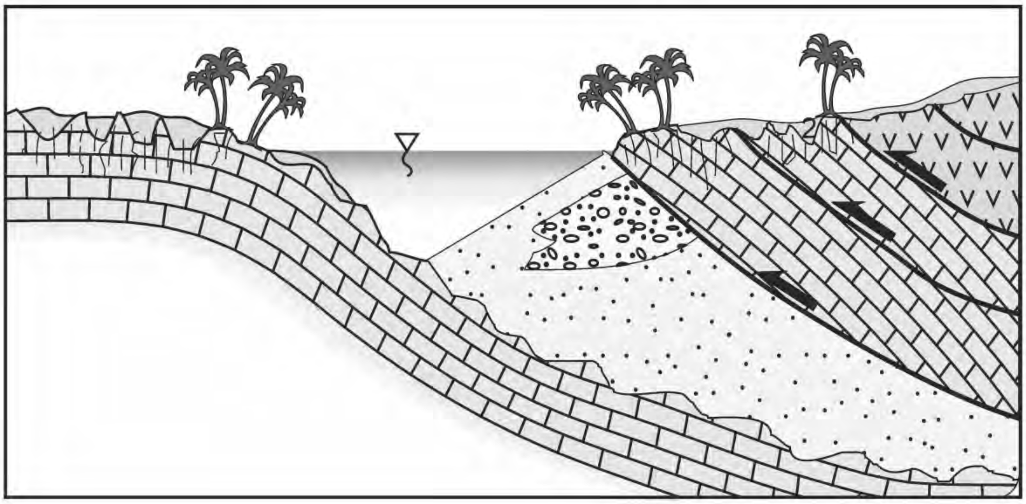

Figure 2

Blue-hole-type pond sequences recording internal transgression over karstic carbonate terrains at times of relative sea-level rise

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In low-relief carbonate islands of the Bahamas vadose-zone karst features (including dolinas and also underground passages) of Pleistocene age are currently being filled up by fresh-water as on relative base-level rise they slowly pass from the vadose into the phreatic zone of the meteoric lens (e.g. Watlings' Blue Hole on San Salvador, or the Blue Hole of Eleuthera – eg Bourrouilh 1974, Mylroie & Carew 1995 *et al.*) Depending on their elevation above sea-level, many of those inland blue-holes exhibit a salinity which qualifies them as brakish or even already marine (Whitaker and Smart 1990). Rasmussen and Neumann (1988) described a Holocene karstfilling sequence from above the large shallow Pleistocene karst depression of the Bight of Abaco. By studying this sequence they realized that the evolution of the initial freshwater pond above this karst depression into brakish and then hypersaline facies was the joint result of an „internal” transgression facilitated by the excellent underground karstic porosity and by an efficient topographic barrier on land along the platform-periphery (Rasmussen 1989). Karst porosity provided for unhampered inflow of -waters from underneath, whereas the topographic barrier prevented the area from immediate overland transgression up to a point. Finally, rising sea level reached the barrier and the original fresh-water pond (an inland blue-hole) became flooded and converted into a true marine blue-hole. This internal transgression was characterized by a transition from fresh water to brackish and hypersaline and than to frankly marine facies without desiccation features or evaporites normally associated with the extensive supratidal zone expected in the case of overland flooding of smooth ramps. In the case of the overland transgression a shallow tidal flat is established which is intermittently exposed and submerged as the slowly advancing sea-front occupies a relief-less flat coastal morphology. So the antecedent karst topography seems to play a fundamental role in controlling the anatomy of the filling sequence.

Similar to the Bight of Abaco case, transgressive sequences beginning with Characean-rich freshwater sediments gradually giving way upwards to brakish/schizohaline and then to frankly marine deposits were reported also from several Mesozoic/Tertiary karst-bauxite occurrences of the Mediterranean (Bignot *et al.* (1985).Carannante *et al.* (1994), Durn *et al.* 2003 etc.) suggesting that the internal transgression is the norm rather than the exception when relative sea-level rise affects a highly dissected, mature karst topography.

Details of blue-hole sequences from above an Italian and a Hungarian occurrence are compared with the Bigth of Abaco case and the differences and similarities between the „empty” Pleistocene blue-holes of the Bahamas and the bauxite-filled Mesozoic/Tertiary paleo-blueholes are pointed out.

Keywords: palaeo-blue-holes, internal transgression, karst bauxitesit

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The unroofed caves in Bosnia and Herzegovina

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After many research of unroofed caves in Slovenia and a lot of research papers which have become available, in recent years we have started paying more attention to the phenomena which indicate existence of these karst forms in the relief. Although our research doesn’t include the whole state's territory, at the present time we can discuss about three types of phenomena.

Many unroofed holes and a few caves filled with sediment have been noted during building of new roads, id est. their expansion in the territory of Trnovo municipality (Igman, Crna rijeka). In the profile of those roads, many clusters of flowstones have also been noted that probably originate from destroyed speleological objects (Igman, Stijene quarry near Vareš).

In the Podvelež area, a few flowstone clusters have been noted, visible at the very surface of the terrain, which occupy an area of a few tens of square metres.

The third phenomenon has been spotted on the Google maps, in the area south of Stolac. It is a number of abnormal green spaces which definitely aren’t karst sinkholes or basin. They are sometimes standalone, in the shape of elongated ellipses, and sometimes in very irregular shapes which additionally continue one onto the other.Traces of flowstone have been found in the terrain and are often surrounded by the stone dry walls. It is obvious that they originate from those surfaces and those they then got into the wall by purification. These flowstones are known by local people under the name ‘Rabbit’s salt’.

Keywords: unroofed caves, traces of flowstone, Sarajevo area, Podvelež, Bosnia and Herzegovina

Palaeokarst, an inside view

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Palaeokarst deposits are most commonly found in excavations, drillholes and naturally exposed at the Earth’s surface. Some caves however intersect palaeokarst deposits. This occurs in large hypogene caves in the USA, thermal caves in Hungary and in many caves in eastern Australia. Palaeokarst deposits in caves often form parts of the cave wall with wall sculpturing continuing unaltered across the palaeokarst-bedrock boundaries. A range of palaeokarst deposits is exposed in caves including; filled tubes, walls composed of flowstone, large-scale bodies, breccia pipes, dykes, volcaniclastic palaeokarst and crystalline palaeokarst. As well as being exposed in cave walls, palaeokarst deposits can wholly or partly form speleogens. Caves can also intersect fragments of older caves producing palaeokarst speleogens such as bridges and pseudonotches. Records of geological events not preserved elsewhere can be found in palaeokarst deposits in caves. These can be difficult to correlate with conventional geological histories. It is important to be able to distinguish between palaeokarst deposits, relict sediments and phantom rock. Relict sediments can be distinguished from palaeokarst deposits because relict sediments are bounded by cave walls while palaeokarst deposits form cave walls. Palaeokarst can be distinguished from phantom rock, as palaeokarst is unconformable with the bedrock, with structures in the bedrock not continuing across the boundary into the palaeokarst. Bedrock structures and textures do continue across the boundary between unaltered bedrock and phantom rock. Similarly, cave sediments are unconformable or disconformable with the bedrock while phantom rock is conformable with bedrock and contains bedrock structures and textures. It has been difficult to explain why palaeokarst occurs in some caves and not others. It is better to consider where palaeokarst deposits do not occur in caves or sections of caves. Palaeokarst deposits do not occur in caves that contain large perennial streams and/or have undergone large-scale vadose fluvial development capable of escaping from the bounds of structural guidance, such as the caves in the Classical Karst.

Keywords: palaeokarst, caves, relict sediments, phantom rock

Paleokarsts of SW Slovenia and NW Croatia (introduction to the field trips)

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During the Mesozoic in the area of present day W Slovenia and NW Croatia dominantly shallow-marine carbonate platforms thieved on the top of Adria microplate. During the geologic history the Adria and the superimposed platforms constantly have been changing their position and character in relation to geotectonic events and episodes at plate's boundaries and to climate conditions. It was important if the carbonate **platforms** were isolated or attached to direct influence of continental depositional systems. During these processes not only characteristics of the carbonate platform's depositional systems have been changing periodically but also their diagenetic evolution, including karstification.

In general, the gross architecture, lithological/structural characteristics, and the evolution and the longevity of the uplifted area with subaerially exposed carbonate platform are mainly dependent on its geotectonic position regarding to plate boundaries, former geodynamics and consequently topography of the area, especially of the carbonate platform. Although important for the appearance of the karstic landscape, the effects of other variables, such as climate and ground water level, may be just superimposed on certain geotectonic framework. Each karstic landscape carries its specific geotectonic signature which can be read from and explained with specific evolution of karstic features and a karst system as a whole.

Although minor stratigraphic gaps, denoted by paleokarstic landscape with more or less limited spatial extend, are relatively common throughout geological history of the discussed area we will mainly focus on major paleokarstic periods interrupting carbonate successions occasionally from Middle/Late Triassic boundary till Palaeogene. They were developed during different tectonic regimes apparently in a bit different climate although tropical/subtropical wet conditions with indicated seasonality prevailed. All described paleokarsts or subaerial exposures of carbonate platforms were tectonically induced although eustatic sea-level fall and specific climate change may have influenced a character and perhaps even extend and time span of certain paleokarstic landscapes. The time of the different uplifts is correlated with events/episodes on the adjacent plate boundaries of the western Tethyan domain (traditional "orogenic phases") and global eustatic curve.

For further explanations see field trip's guide book where discussed paleokarsts are described more in details.

Keywords: Paleokarst, SW Slovenia and NW Croatia, geodynamic evolution, carbonate platform, eustasy

Paleokarst and Caves of Velebit Mt., Dinaric karst of Croatia

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Great majority of Dinaric karst Caves probably have their origin within very long continuous phase of karstification which have lasted without major interruptions from the uplift of Dinaric Mountains till nowadays. Major structural formation of the Outer (Western) Dinaric mountain belts started during upper Eocene and lasted through Oligocene and lower Miocene. Tectonically active period, with several modification of deformation characteristics and intensity have been active till present. Therefore, time span for speleogenesis of Caves in Dinaric Karst is potentially very long. Tectonic activity of the area, together with pronounced climate and sea level changes during last two MY resulted in frequent changes and adjustments of cave morphology. This can be observed in majority of Dinaric karst larger caves.

In the Caves of North Velebit Mt. vertical shaft and meander morphology of vadose origin is largely prevailing, which points to single continuous phase of their speleogenesis. However, origin of large chambers, which are found in some of the Caves is not clear. They are strongly modified by collapse processes, and are possibly inherited features from the former phases of karstification, later incorporated to present caves. Other possible fragments of paleo cave levels above present epiphreatic zone are very scarce and uncertain.

In the contrast to North Velebit Caves, in the most southern part of Velebit Mt. some of the largest known Dinaric karst multilevel caves are present. They are of complex origin with few paleo(epi)phreatic levels, connected with the surface by the younger invasive vadose shafts. However, detailed study of speleogenesis chronology of the Velebit Mt. Caves haven`t been conducted yet, which can be stated also for the rest of Dinaric karst area in Croatia.

Paleokarst in “sensu stricto” of Dinaric karst area probably cannot be associated with the features originated within the long, but generally continuous karstification phase which lasted approximately last 35 MY. Older karstification period was present during upper Cretacious and Paleocene period, when carbonate rocks of Dinarides was first time emerged and subjected to karstification. Upper Cretacious – Paleocene karst in Croatia was studied mainly with the purpose of bauxite ore exploration and exploitation. Due to the latter strong tectonic deformation of the area, it can be supposed that only very small fragments of caves and other karst features could be preserved from that period.

Keywords: caves, paleokarst, Dinaric karst, Velebit Mt., Croatia

Part of research of Velebit Mt. Caves was done under projects Physical Research of Active and Paleoenvironmental processes in Caves of Dinaric Karst (SLO-CRO, PMF ZG-IZRK SAZU) and Exploration of deep pits of Northern Velebit (Northern Velebit National Park and Croatian Environmental protection and energy efficiency Fund).

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Why ^{39}Ar dating is a necessary and indispensable tool in karst hydrology

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About 25% of global population depends partially or entirely on drinking water supply provided by karst aquifers. As karst aquifers are highly vulnerable to surface contamination, their hydrological studies are of paramount importance. Dye tracing tests are widely used to investigate the hydrological properties of a karst system and the residence time of the karst water, if the transit time is expected to be up to a few months. Numerous methods are available to study the age distribution of karst water bodies, if they are characterised by longer residence times. All these methods work in different time ranges. To investigate the past few decades, tritium, $^{3}H/^{4}He$, SF6, CFC’s, ^{85}Kr age determination methods are frequently used to calculate the time elapsed since recharge. On the other hand, ^{14}C seems to be the only tool for studying water bodies having residence times of a few thousands or few tens of thousands of years. However, piston flow movement of groundwater occurs very rarely in karst aquifers longer than a few months. Rather, hydrodynamic dispersion and mixing are significant along the flow lines of karst water. Hence, based on isotope analyses there are cases when young (<70 years), not too old (few hundred years) and old (thousands of years) components are present in a groundwater system. The more age indicators we know, the more precisely we can determine the mixing ratios of the components of different ages (for example with lumped parameter modelling). While there are tools for 0 to 70 years and for thousands of years, for the time scale of 100–2000 years ^{39}Ar dating is the only available method for the time being. ^{39}Ar is a cosmogenic isotope with a half-life of 269 (±3) years. The activity concentration of atmospheric argon is about 1.5 mBq/dm^{3}ArSTP, it dissolves into groundwater during recharge. Along the flow line, its activity is decreasing due to the radioactive decay. Knowing the activity of the atmospheric and the dissolved argon, the "age" can be calculated. Nevertheless, due to the tremendously complicated analytical requirements ^{39}Ar dating is performed only in a few laboratories worldwide.

In our presentation, different methods of age determinations using environmental tracers will be delineated. The details of the analytical procedure to determine ^{39}Ar/Ar will be also shown. Additionally, a few case studies from karst regions, such as Mecsek Mts. (Hungary), Jasov Plateau (Slovakia), Beljanica-Kucaj Karst (Serbia), will provide examples for determining residence times. Tritium and stable isotope time serious show no seasonality in the Slovak Karst indicating that either recharge water has a longer residence time in the karst or due to the various lengths of the flow lines mixing might occur even in the epikarst. Tritium values are varying around 7 TU confirming this latter theory. A similar situation can be seen in the Mecsek Mts. Tritium is about 6-7 TU, while ^{3}H/^{3}He, SF6 and ^{35}S apparent ages point out a mean residence time of less than 3 years. In the Beljanica-Kucaj, both tritium and radiocarbon can be found in all samples showing a linear trend in tritium with decreasing ^{14}C. Yet, even if the radiocarbon is less than 25 pMC tritium is above 1.5 TU, indicating the presence at least two component: a fresh tritium bearing component, and an old one having a radiocarbon age of older than 2500 years. Therefore when a wider time frame encompassing more than a few decades are expected, argon dating could contribute to the better understanding of the age distribution of different components in the karst aquifer.

Keywords: karst hydrology, residence time, environmental tracers, ^{39}Ar dating

On a hunt for microbes, their metabolic potential and impact in pristine karst environments: a case from Idrijska Bela well, Slovenia

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Water plays a crucial role in karst formation and its evolution, and does not represent solely a milieu for chemical reaction and a mode for matter transport, but also a habitat for microorganisms. In subsurface, groundwater microbes are abundant and generally play an active role in biogeochemical cycles. In comparison to planktonic (non-attached) microbes, the microbes attached on rocks and sediments have a greater impact on physical properties of environment. To characterize environment and metagenome of pristine groundwater microbial community, Idrijska Bela well in the Belca Valley (Idrija) was sampled. A 120-m deep well in Upper Triassic dolomite supplies water with a constant discharge of 10 liters per second (temperature 9.4 °C, pH 7.91, electric conductivity 345 µS/cm, total hardness 179.7 mg/l $CaCO_3$, alkalinity 180.7 mg/l $CaCO_3$, chlorides 1.4 mg/l, nitrates 6.3 mg/l, o-phosphates 0.02 mg/l, sulphates 1.3 mg/l) which had stable isotopic composition in early spring and at the beginning of summer, i.e. δ^2H -53.7/-53.3, δ^{18}O -8.58/-8.52 at the end of March and beginning of July 2015, respectively. Water from the well contained on average 3.0×10^3 cells per ml with low percentage (≤ 0.05 %, very rough estimate) of non-fastidious cultivable microbes. First colonies were observed on nutrient rich agar media (nutrient broth soyotone yeast extract, Luria Bertani, trypticase soy) after five weeks of cultivation at 18 °C, whereas eight weeks were needed to observe visible colonies on nutrient limiting media (tap water agar and tap water agar supplemented with 1% of pyruvate). The restriction profile of fosmid libraries indicated diverse metabolic potential of captured metagenomics DNA. The exact role of microbiome functional genes in the low energy aquifer and its effects on subsurface biogeochemical processes and environmental parameters is currently being mapped in two wells over the course of the seasonal extremes.

Keywords: karst, groundwater, metagenomics, microorganisms

Hydrochemical and isotopic analyses of water samples from (non-)karstic and (partly) thermal wells and springs in NW-Slovenia

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The presented poster gives a first overview of the hydrochemistry and isotopic ($\delta^{18}O$ and $^{\delta}2H$) composition of selected wells and springs in NW-Slovenia. It emphasizes the geothermal pattern of heat flow and temperature in the deep underground in the western part of Slovenia.

In two sampling campaigns in the years 2013 and 2014, water samples (n = 82) from (partly) thermal wells and (partly) subthermal karstic and non-karstic springs were taken and analyzed. The water sampling points are located in the vicinity of Upper Carniola in North-West Slovenia. The investigated area is placed on the transition from the Dinaric karst of inner Slovenia towards Prealps.

Near Koper and in the central part of Slovenia (near Ljubljana) temperatures in 1.000 m depth are expected to be around 30 to 40°C. In the eastern part of Slovenia temperatures in 1.000 m depth are expected to up to 70°C. This work focused on the area in between, where temperatures in 1.000 m are expected to be around 20–30°C (www.geo-zs.si).

Lapanje & Rman (2009) classify thermal and thermomineral waters in three types: 1) Warm springs with fissure porosity, which emerge at the intersection of fault zones and drain the carbonate-aquifers. This leads to the low mineralization with Ca-Mg-HCO_3-type waters and temperatures of 20–50°C. Locally SO_4-ions occur due to gypsum or anhydrite dissolution. 2) Aquifers in sedimentary basins with intergranular porosity. The predominant water type is Na-HCO_3. 3) Aquifers in the basement of sedimentary basins with fissure porosity in different Mesozoic and Cenozoic carbonate rocks, waters mostly of the Ca-Mg-HCO_3-type and with low mineralization and almost no CO_2. Nonthermal springs and wells drain the uppermost aquifers and are influenced by surface processes (like meteoric precipitation) (Lapanje & Rman, 2009).

Waters from analyzed thermal wells have mean outflow temperatures of 22.5°C, obviously influenced by heat flow in the deep underground. Thermal water was tapped directly by deep boreholes (Cerkno borehole, 2.000 m, Placer *et al.* (2000)) or indirectly by shallower boreholes (Bled Hotel, around 600 m, Nosan (1973)). Hydraulic connection may be existent at shallow boreholes (probably draining the deep (non-/karstic) aquifer). Waters from karstic springs have mean temperatures of 8.8°C, which are characteristic for near surface karstic groundwaters. Subthermal springs have mean temperatures of 14.2°C, probably yielding deeper groundwater through fissures and large faults. The non-thermal wells have mean temperatures of 10.1°C. Depending on the borehole casing, inflow of groundwater varies through depths and results in mixed waters at wellhead.

Almost all waters are Ca-Mg-HCO_3-type waters. In the area of Rovte, wells have higher sulfate concentrations up to 740.6 mg/l. "Kisli studenec" (subthermal spring) has the highest electric conductivity (1995 µS/cm) and therefore highest mineralization. In the Rovte area, isotopic analyses ($\delta^{18}O$ and $\delta^{2}H$) showed that on the one hand waters from karstic springs are (directly) influenced by meteoric waters (high isotopic variability: e. g. Podklanec with $\Delta\delta^{18}O = 0.96$ and $\Delta\delta^{2}H = 9.02$, n = 7). On the other hand thermal and non-thermal wells are probably mixed in the underground (low isotopic variability: e. g. Rodolfov Mlin with $\Delta\delta^{18}O = 0.57$ and $\Delta\delta^{2}H = 1.13$, n = 7). Remaining data (Cerkno and Kranj area) shows similar results, but with less quantity (n < 5).

Keywords: hydrochemistry, thermal wells and springs, NW-Slovenia

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Paleo-Karstic features of the Hyblean Plateau (SE Sicily)

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The Hyblean Plateau of southeast Sicily represents the northern leading edge of the African foreland in the central Mediterranean. During the late Miocene (Messinian) large areas of the plateau were prone to emergence, and widespread subaerial exposure took place with intense karstic dissolution on oligo-miocene carbonate rocks and messinian evaporites. The onset of modern karstic phenomena in the Hyblean Plateau started at that time, when the combined effects of isostacy, tectonics, volcanism, and the Messinian drawdown event took place. The general southward tilting of the plateau, and toward the ESE in the Siracusa area in recent times (Bonforte *et al.*, 2015), have strongly controlled the evolution of karstic phenomena. Marine conditions never again fully inundated the Hyblean region, although the return of deep-water marine conditions in the Early Pliocene did permit marginal flooding by chalks of the Trubi Formation (Grasso *et al.*, 2000). Several gypsum outcrops show karstic features filled with Trubi chalks in Rosolini, Mineo and Licodia Eubea areas, thus postdating the Messinian karstic event (Maniscalco, 1999; Grasso *et al.*, 2002). Along the Syracuse coastal area, major karstic features are located along fault planes that act as preferential drainage for groundwater circulation. Messinian limestones are intensively fractured and filled with Pleistocene (Emilian) calcarenitic deposits, the result of a marine transgression of the area (Maniscalco & Stamilla, 2000). During the rest of Pleistocene, the plateau was subjected to local glacio-eustatic regressive-transgressive events coupled with the regional uplift of the area, that determined the formation of an epikarstic system with two main karstic levels preserved at the present day. The two karstic levels can be respectively correlated with the Early and Middle Pleistocene regressive-transgressive events (Grasso *et al.*, 2000; Ruggieri & Grasso, 2000). Phreatic hydrological paleo-morphology and terraces are also correlatable to the above eustatic events. On the western flexured margin of the plateau, beneath the front of the Gela Nappe in the Vittoria-Acate area, the karstic features are buried at about 80 m depth and are linked with the Early Pleistocene lowstand event, that predated the filling of the structural depression of the Vittoria Plain. On the eastern side of the plateau, karstic features are younger (Tyrrhenian age), being widespread in the area between the mid-Pleistocene paleoshoreline and the modern one at a depth of 20 m and a distance from the coast of about 100 m (Ruggieri, 1997, 1998).

Keywords: karst, paleokarst, Sicily, Hyblean Plateau, messinian evaporites

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Pitfalls when interpreting karst from seismic images. Examples from the Norwegian shelf

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How do we infer karst bodies and karst imprints when interpreting seismic data, and how do we validate them for hydrocarbon exploration? The Barents Sea area of the Norwegian shelf have recently seen the emergence of a new offshore hydrocarbon exploration play. This play focus on karstified carbonates, confirmed by two discovery wells 7120/1-3 (Gohta) and 7220/11-1 (Alta) (www.npd.no). Karst features in the nearby area have earlier been inferred on seismic (Hunt *et al.* 2003) and was one of the targets for an unsuccessful exploration well 7220/6-1. The carbonate reservoir rocks in question were deposited in Late Carboniferous to Permian times on the paleo Loppa High and was later subaerially exposed into Early Triassic time (Smelror *et al.* 2009).

Recognizing karst from seismic images can be a pitfall that may have consequences in e.g, hydrocarbon reservoir exploration. There seems to be an *a priori* approach to karst identification on seismic; if the carbonate rocks have been subaerially exposed, then the seismic responses found near this unconformity – circular features with dim amplitude, low coherence/variance (3D), sag structures (2D/3D), scours (3D) – are often interpreted as karst features. When going through existing literature on karst derived from seismic observations, there are multiple papers identifying karst features from such seismic responses (Hunt *et al.* (2003), Vahrenkamp *et al.* (2004), Ahlborn, Stemmerik and Kalstø (2014) and others). These morphological expressions seems to be referred to as karst features without ruling out other explanations for origin. Other geologic non-karst processes can explain these seismic features, for example as of fluvial origin. It is the authors view that there seems to be a need for a validation tool of karst features and on how to distinguish those from seismic isomorphs. This will be a useful approach when exploring buried and presumed karstified (paleokarst) carbonate reservoirs.
Keywords: karst, hydrocarbon exploration, seismic morphology

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Microclimate and dripwater hydrology in Nova Grgosova Cave (Croatia) – results from one-year monitoring for paleoclimate study

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Nova Grgosova cave is located in Otruševec village in Samobor hills fluviokarst unit (NW Croatia). The cave was discovered in 2004 during construction works. Before that, there was no natural entrance to the cave. Few years after the discovery, due to the speleothem richness, it became a show cave. It is 97 m long and 14 m deep simple cave developed in intensively karstified Neogene lithothamnium limestone. It consists of two chambers connected with narrow, partially artificially widened passages. According to the geomorphological position, passage morphology and recorded fluvial deposits, in the past it was a ponor of a nearby stream. Considering hydrological zoning important for speleothem deposition, microclimate and dripwater hydrology and chemistry, the cave today extends in epikarst zone. The entrance is at 240 m a. s. l. and limestone overlay above the cave is 5–10 m thick. The area has temperate humid climate with warm summers (Cfb type after Köppen-Geiger climate classification system). Mean annual air temperature in Samobor climatological station (ca. 3 km to the SE) for the 1981–2013 period was 11.2 °C. The highest mean monthly temperature occurs in July (21.7 °C), and the lowest one in January (0.5 °C). The mean annual precipitation is 1076 mm. Most of the precipitation occurs during the summer and early autumn (September 116 mm). The lowest amounts occur

during the winter (February 57.4 mm).The monitoring program, a precondition for the speleothem-based palaeoenvironmental study took place from November 2014 to November 2015 and included high-resolution logging of surface and cave air temperature, relative humidity and drip intensity. Mean annual air temperature and relative humidity in front of the cave were 11.4 °C and 82.5% and in the cave 11.2 °C and 99.9%. In the cave, three drip sites located at the distances of less than 7 m, showed quite different discharge regime illustrating characteristic triple-porosity (conduits, fracture and matrix). According to flow regime characterized by the relationship between mean discharge and discharge variability, two of them were classified as seepage and one as seasonal drip class. Isotopic composition of the meteoric precipitation ($^{\delta 18}$O and $^{\delta 2}$H values and their relationship) reveals the vapor source region. Nova Grgosova cave local meteoric water line ($^{\delta 2}$H = 7.1 × $^{\delta 18}$O + 7.9) lies above the global meteoric water line ($^{\delta 2}$H = 8 × $^{\delta 18}$O + 10), and precipitation δ18O-δ2H pairs plot between eastern Mediterranean MWL and western Mediterranean MWL, but closer to the western one. It shows the influence of transitional zone with mixing influence of cooler North Atlantic and warmer and wetter eastern Mediterranean air masses. Seasonal amplitude of cave precipitation $^{\delta 18}$O is 0.3–0.6‰ and $^{\delta 2}$H 1.0-2.7‰ in drip water. Mean weighted $^{\delta 18}$O and $^{\delta 2}$H values are slightly more negative than the precipitation means suggesting prevalence of the winter precipitation. Longer measurements should verify these preliminary results, but it seems that this cave is promising site for paleoenvironmental reconstruction.

Keywords: microclimate, hydrology, stable isotopes, Nova Grgosova Cave, Croatia

Monitoring and sampling were conducted within the project 1623 Reconstruction of the Quaternary environment in Croatia using isotope methods funded by the Croatian Science Foundation.

Characterization of Modrič Cave (Croatia) hydrological and geochemical settings as prerequisit for the palaeoenvironmental studies

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Uniqueness of each particular cave system, in terms of depth, morphology, aquifer characteristics, climate region etc., requires establishment of cave monitoring program as prerequisite for reliable and confident interpretation of speleothem palaeoclimate records. In order to reconstruct Quaternary changes in the littoral Croatia, Modrič Cave has been chosen as one of the potential sites. We have selected three drip sites in deep cave interior, collected associated speleothems for U-Th dating and the stable isotope analyses, and commenced data logging and water sampling. After the one-year monitoring (Nov 2014 – Nov 2015), we collected preliminary data on cave and surface air temperature and relative humidity, stable isotopic composition of the precipitation and dripwater, and response of cave drip intensity to rain events, which provided insight into the cave microclimate settings, karst aquifer architecture and geochemical processes.

Stable mean annual cave air temperature (16.4 °C) that closely reflects mean annual surface air temperature (16.1 °C), and relative humidity of 100% year-round, appear to be appropriate conditions for the calcite precipitating at or near isotopic equilibrium with drip water, which is essential for the reliable interpretation of speleothem isotopic signals. However, additional analyses on modern calcite, as well as Handy tests on fossil spelean carbonate should approve these assumptions.

Drip sites with uniform and constant drip intensities have been practically unresponsive to rain events i.e. independent of major showers or prolonged dry periods, displaying seepage flow. Such hydrological regime already point to the good homogenization of the water within the aquifer, and additional proof lies in the isotopic composition of rain and drip water. Seasonal variations of rainwater $^{\delta 18}$O and $^{\delta 2}$H values with amplitude of 6.8‰ and 45.2‰, respectively, are attenuated to dripwater range of only 0.2‰ and 0.9‰, respectively. Apparently, the residence time of the water in the epikarst and karst aquifer is long enough to practically completely diminish atmospheric seasonal variations and detect multi-annual climate trends.

Isotopic composition of the meteoric precipitation (in particular, $^{\delta 18}$O and $^{\delta 2}$H values and their relationship) reveals the vapour source region. Modrič local meteoric waterline ($^{\delta 2}$H = 6.8 × $^{\delta 18}$O + 5.5) lies above the global meteoric waterline ($^{\delta 2}$H = 8 × $^{\delta 18}$O + 10) with lower slope and intercept, indicating the primary evaporation in the vapour source region and secondary evaporation during the rainfall, as expected in this Mediterranean coastal site. However, mean d-excess of 12.5‰ has shown mutual influences of the Atlantic and Mediterranean air masses, but it has been unexpectedly low. Prolonged monitoring campaign should verify

these findings, but based on these preliminary data, it is likely that Modrič Cave stalagmites, with the U-Th ages between 340 ka and the Recent, would enable trustworthy palaeoenvironmental reconstruction.
Keywords: cave monitoring, stable isotopes, palaeoenvironmental changes, Quaternary, Croatia

This monitoring program was performed within the project 1623 Reconstruction of the Quaternary environment in Croatia using isotope methods financed by the Croatian Science Foundation.

Rise of cave air temperature in Postojnska jama and Predjama

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Postojnska jama and Predjama are subject to environmental monitoring in order to see the impact of tourism on karst caves. Since 2009 basic meteorological monitoring (air T and air pressure) is taking place at more locations. Predjama receives about 6,000 visitors per year while Postojnska jama welcomes about 670,000 visitors per year. Hourly collected air temperature data show a slight rise of average annual cave air temperature since 2009 in both caves. Air temperature increase is even more pronounced in 2014 and 2015. At Velika Dvorana chamber in Predjama, summer air temperature in the period 2009 to 2013 did not exceed 9.5 °C, but in 2014 and 2015 it was almost 10 °C. Average annual cave air temperatures at Velika Dvorana are: 6.83 °C (in 2010), 6.67 °C (in 2011), 6.56 °C (in 2012), 6.88 °C (in 2013), 7.95 °C (in 2014) and 7.41 °C (in 2015). Because Predjama is not a highly visited show cave, we contribute the rise of almost 0.5 °C to outside cave climate conditions. The monitoring location at a side passage of Lepe Jame (Postojnska jama) showed more stable climatic conditions as the second monitoring site in Lepe Jame, which is near the visitors' path. Anyway, at the side passage also a small air temperature increase was observed. Average annual cave air temperatures at Lepe Jame side passage are: 10.13 °C (2010), 10.1 °C (2011), 10.31°C (2013), 10.37 °C (2014) and 10.52 °C (2015). At Postojnska jama, visitors' impact on cave air temperature cannot be excluded as in the case of Predjama. However, the rise of cave air temperature in Postojnska jama for the period 2009 to 2015 strongly depends on exterior air temperature increase.
Keywords: cave air temperature, meteorological monitoring, Postojnska jama, Predjama, Slovenia

Geotectonic constrains on possible karstification periods and some paleokarst examples from Macedonia

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Karst in Macedonia is developed in various types of rocks, ranging from Precambrian and Paleozoic marbles, Mesozoic limestones, dolomites and evaporites to Cenozoic limestones, tufaceous limestones, travertines and tufas. Latest karstification period has started as early as Early Pleistocene after the draining of the Neogene-Quaternary lakes and the onset of fluvial drainage (current erosional cycle). While this is true for the karst terrains covered by the extent of the Neogene-Quaternary lacustrine systems, other areas might have received continuous karstification at least since Late Cretaceous, with the onset of the Laramide orogeny, and some since older Mesozoic or even Late Paleozoic. Based on the stratigraphy of karst rocks and the geotectonic evolution in Macedonia, a framework for possible karstification periods has been conceptualized, separately for the main pre-Cenozoic tectonic units in Macedonia, as they all underwent through somewhat different evolution. Possible old karstification periods (paleokarst) range from 8 in the Vardar Zone, 6 in the West-Macedonian (and Cukali-Krasta) Zone, 4 in the Pelagonian Massif, and 2 in the Serbo-Macedonian Massif (and Kraishte Zone), with also a range of 2 to 4 probable continuous karstification periods, yielding relict and active karst with different timespan (to present). Additionally, within this framework, some paleokarst examples from different geotectonic units will be presented.
Keywords: paleokarst, Macedonia, karst periods, conceptual framework

Relict shafts – significant features of palaeosurface morphology of the Częstochowa Upland (S Poland)

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The Kraków-Częstochowa Upland is a well-known example of relict karst sensu P. Bosák *et al.* (1989). The north part of this region, called Częstochowa Upland is an area of occurrence of moulding sands (kaolinized sandy-clayey sediments, resembling Rudice type deposits). These sediments were covered palaeosurface of the Upland and were redeposited in Paleogene and Neogene to depressions, small surface features and caves.

Shafts as relicts of Paleogene (?) surface morphology of the Częstochowa Upland are presented in this contribution. They are of different size (up to 4 m of diameter and up to 25 m of depth), different position in local geomorphology and some of them are still filled with sediments. Both, morphogenetic and speleogenetic factors of their origin and evolution are discussed. Detailed geomorphological and geological studies (sedimentological and mineralogical among them) of these significant features, as well as their spatial distribution within the area were performed.

Keywords: shafts, relict karst, moulding sands, Częstochowa Upland, Poland

Study of speleothems and other thermal-karst features in the caves of Rózsadomb (Budapest, Hungary)

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Szemlő-hegy Cave, belonging to the hypogenic cave system of Rózsadomb, is currently situated in the vadose zone (165 to 215 m a. s. l.). It is supposed to have formed under phreatic conidtions, its present position being the result of tectonically controlled uplift of the area in Pleistocene times. Molnár János Cave, being part of the same cave system is currently located in the phreatic zone at and below the local base level (7 to 137 m a. s. l.) and large parts of its passages are filled by thermal water. The study of Molnár János Cave is considered as a good analogue which may help to improve our understanding thermal-water related paleokarst phenomena in the now-dry caves of Rózsadomb.

For comparison, speleothems and water samples were collected from the passages of both caves. Detailed mapping, macroscopic and microscopic observations, XRD, SEM, trace elements, U/Th and stable isotope analyses permitted to distinguish several groups of the speleothems. Hydrogeochemical analyses of water-samples from the Molnár János Cave were also undertaken.

In both caves, exposed by the passages, there are NE-SW and NW-SE oriented fractures partially filled by calcite, minor barite and pyrite obviously pre-dating cave-formation. Since the cave system is thought to have developed in Pleistocene times, this fratcure-filling paragenesis must be of pre-Pleistocene age. Among the speleothemes grown on the walls and on the floors of the thermal caves, phreatic calcite crust, cave raft, cave coralloid/popcorn, aragonite needle/frostwork, gypsum crust, Mn-oxides, Fe-oxides and in their pores and - in contact zones of gypsum crust and carbonate – small crystals of barite, dolomite, other high-Mg-carbonates, celestite and sepiolite were identified.

In Mid Pleistocene times, as Szemlő-hegy Cave gradually moved from the phreatic to the vadose zone, isolated few meters-deep thermal-water pools established in the bottom of its corridors. Because of evaporation and CO_2 degassing from the lukewarm water surface, condensation-corrosion started in the upper parts of the corridors and resulted in the formation of spheroidal niches. At the same time, apparently, in the lower reaches of the cave, around the phreatic/vadose interface, precipitation of thermal-water speleothems of variegated morphologies were formed.

Keywords: thermal-water related paleokarst phenomena, speleothem, Szemlő-hegy Cave, Molnár János Cave, Buda thermal karst

Opportunistic pathogens of the cave salamander *Proteus anguinus*

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Proteus anguinus or cave salamander, is an extraordinary amphibian species, the only vertebrate in Europe living permanently in the dark underground waters of Dinaric Karst of Slovenia and Croatia. Proteus is a world-famous model for troglobionts, the longest-living amphibian, a flagship species of the subterranean world and a Slovenian national symbol. Amphibian species are unusually vulnerable to a variety of threats. According to the Global Amphibian Assessment, the populations of 43% of amphibian species are in decline, and 32% are threatened. Several factors, including climate change and pollution of their habitats are involved. Another important factor is the perturbation of natural cycles of infection with pathogens due to long distance dispersal of inocula. Besides fungal diseases like chromomycosis, phaeohyphomycosis, and zygomycosis, the main threat for amphibians that has evolved recently is the fungal disease known as chytridiomycosis, followed by saprolegniosis, as well as bacterial and viral infections. The unique adaptation to cave waters makes Proteus susceptible to any damage of this fragile environment. Also, the animals are especially vulnerable and prone to infections in artificial environments, where animals are kept in a confined space for scientific, touristic, and recovery purposes as well as future breeding and re-vitalisation projects. There are no published data on microbial infections of Proteus in Slovenia in their natural or artificial habitats. Here we report the results of the first observations of contaminated Proteus eggs from Postojna cave. We have observed a diversity of opportunistic potentially infectious organisms on the outer jelly coats of Proteus eggs.
Keywords: Proteus, opportunistic pathogens, fungi, bacteria, artificial environments

Several million years old cave sediments as part of ongoing karstification period

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Systematic research of cave sediments in Slovenian caves in the last 20 years with different dating methods (paleomagnetic studies, U series dating, paleontology, palynology,…) showed that the sediments are much older than was originally assumed, as identified age cover not only the entire period of the Pleistocene but also the Pliocene and even reach into the Miocene.

The majority of dating of karst sediments has been carried out in south-western Slovenia (i.e. in the north-western part of the Dinaric karst), and at some sites of Alpine karst. More than 3500 samples were taken and analyzed in 42 different profiles in caves and on the karst surface. Studied were sediments from present relict and active caves. Magnetostratigraphy data and the arrangement of obtained magnetozones often indicated ages of sediment fill over 1.77 Ma and even over 5 Ma. Results were in some sites calibrated by U-series dating, paleontological, biological and geomorphological analyses. Although certain cave sediments are several million years old, they are not paleokarst sediments, because they belong to the one ongoing karstification period without any interruption of marine transgression. Distinct phases of massive deposition in caves with still preserved sediments were dated to about 5.4–4.1 Ma (Miocene–Pliocene), 3.6–1.8 Ma (Pliocene) and Quaternary, following the cessation of Miocene deposition in the Pannonian Basin in the central, E and SE Slovenia and post-Messinian evolution in the SW and W Slovenia. These sedimentation phases in underground suggest climatic changes on the surface with possible flood events and/or changes of the tectonic regimes during Neogene and Quaternary.

The evolution of the caves in Slovene karst took part within one karstification period, which began with the regression of Eocene sea and exposing of limestones at the surface within complicated overthrusted structure, which formed principally during Oligocene to early Miocene.
Keywords: karst sediments, relict karst, paleomagnetic dating, Slovenia

GEOLOGY OF THE SLOVENE KARST REGIONS AND STRATIGRAPHIC POSITIONS OF ACTUAL AND POSSIBLE PALEOKARST PHENOMENA (A BRIEF OVERVIEW)

GEOLOGY OF THE SLOVENE KARST REGIONS AND STRATIGRAPHIC POSITIONS OF ACTUAL AND POSSIBLE PALEOKARST PHENOMENA (A BRIEF OVERVIEW) (after Otoničar *et al.*, 2016)

Bojan Otoničar

Geological characteristics of Slovenia in a great extent arise from its geotectonical position between African and Eurasian plates or intermediate Adria-Apulian microplate. Here three major geotectonic units meet – the Alps, the Dinarides and the Pannonian basin with their specific geological evolution resulting also in somehow different character and abundance of carbonate rocks and related karst. Southern Alps and Dinarides are separated from Central Alps (i.e. Eastern Alps) by pronounced Periadriatic fault (Fig. 1).

In Slovenia, majority of karstic terrains are located in Dinarides and Southern Calcareous Alps in western half of Slovenia (Fig. 1). In Dinarides, carbonate rocks occupy mainly its western and southwestern part or fold-and-thrust belt of the External Dinarides, while in the Southern Calcareous Alps compose major part of Julian Alps, Kamnik-Savinja Alps and Karavanke Mt. or its S- to SE-verging fold-and-thrust-belt (Fig. 1).

The oldest carbonate rocks that crop out in Slovenia are Lower and Middle Devonian bedded deeper marine and predominantly massive reef limestone in Southern Karavanke Mt. At the end of Devonian reef limestone was uplifted and allegedly karstified although no compelling evidence has been submitted yet. Of the same age are patches of slightly metamorphosed limestone in Slovenian part of the Eastern Alps, while ages for marbles in metamorphic complex of the same geotectonic unit have not yet been properly dated.

In the Southern Alps, Carboniferous and Permian carbonate sequences that alternate with clastic rocks on metric and decametric scales reflect highly irregular post-Variscan topography of sedimentary basins and different morphology of carbonate platforms at the western edge of Paleo-Tethys. From nearby Carnian Alps, in geotectonic and partly also environmental conditions comparable to those in Karavanke Mt., Lower Carboniferous paleokarst is reported (Schönlaub *et al.*, 1991). Already in the Middle Permian first post-variscian extensional tectonics caused »*swells and grabens*« morphology (Neubauer *et al.*, 2000) with localised karstified subaerially exposed carbonate areas.

In the Upper Permian relatively unified shallow marine carbonate platform was established over western part of present Slovenia and also further towards south (i.e. Dinarides in Croatia) and northwest (i.e. Italian Southern Alps). Between Middle Triassic and Lower Jurassic this extended epeiric carbonate platform was dissected in extensional tectonic regime and in the area of central part of the western and central Slovenia (in recent position) so called deeper marine "Slovenian Basin" ("i.e. failed rift") was formed separated southern Adriatic Carbonate platform (AdCP) from northern Julian Carbonate Platform (JCP). At marginal parts of the basin "*horst and graben*" relief and halfgrabens occurred during Middle Triassic and at the beginning of Upper Triassic (Šmuc & Čar, 2002; Celarc *et al.*, 2013). Horsts and uplifted parts of halfgrabens may contain paleokarstic fetaures adjacent to neptunian dykes (see Celarc *et al.*, 2013). Tectonically uplifted parts of previously dolomite dominated Anizian carbonate platform on the southern side of the incipient Slovenian basin gave rise to formation of talus carbonate breccia and sandstone as well as local paleokarstic surfaces (Čar, 2010). While JCP was drowned till the Middle Jurassic, which deposits are recently presented in the External Dinarides, thrived till the end of Mesozoic.

Due to general compressional tectonic regime or tectonic activites at plate boundaries a few regional paleokarstic periods interrupted shallow marine carbonate deposition of otherwise passive margin AdCP since Middle Jurassic till Late Cretaceous (see field trip B). In the External Dinarides, the Mesozoic shallow marine deposits of AdCP are overlain by Maastrichtian to Eocene shallow to gradually deeper marine limestone of the synorogenic carbonate platform and prograding hemipelagic marl and deep-water clastics (flysch). At the periphery of the foreland basin, carbonate successions of the AdCP are separated from the overlying deposits of the synorogenic carbonate platform by paleokarstic unconformity (Otoničar, 2007) (see field trips A and C). In Slovenian basin mixed siliciclastic and deeper marine carbonate sediments had being deposited during the Mesozoic.

In the Karst Dinarides the entire Upper Carboniferous to Eocene carbonate succession could exceed thickness of 8000 m, while Lower Jurassic (final stage of the formation of the AdCP) to Eocene from 3500 to 5000 m (Vlahović *et al.*, 2005). The most pronounced carbonate formations in Slovenian part of Southern Calcareous Alps belong to bedded Upper Triassic “Main” dolomite (up to 1400 m) and “Dachstein” limestone (up to 1700 m) where local syndepositional paleokarst commonly occur.

Compressional tectonics related to closures of the nearby small oceanic basins of the western extension of the Neo-Tethys dominated the area since Middle Jurassic culminated in the Upper Cretaceous to Eocene foreland basins formation and especially in the final uplift of Dinaric range during the Oligocene and Miocene. In Slovenia, during this time some intermontane basins had been partly filled by carbonate coarse-grained clastics, while in the surrounding of forming extensional Pannonian basin in the Middle Miocene small cold water carbonate platforms (ramps) with “foramol” community thrived. Locally paleokarst with bauxite deposit underlay Oligocene deposits. Quaternary fluvioglacial coarse-grained material deposited in intermontane depressions of NW Slovenia (i.e. Northern part of Ljubljana Depression) is commonly highly calcareous and indurated in carbonate conglomerates.

The Paleogene to recent thrust belts along the Adria margin (northern part of the Adria-Apulian microplate) include Dinaric thrust systems, the South-Alpine thrust system and Dinaric faults. The Dinaric thrust systems of the External Dinarides are post-Eocene, representing a NW-SE striking fold-and-thrust belt that can be followed from the Istria peninsula towards central Slovenia (Vrabec & Fodor, 2006) (Fig. 1). The S- to SE-verging fold-and-thrust-belt of the Southern Alps formed younger (post-Upper Miocene) than Dinaric and are in part thrusted over it. Dinaric faults cut and displace both Dinaric and South-Alpine fold-and-thrust structures. Many Dinaric faults, including the prominent Idrija Fault (Fig. 1), formed as dip-slip normal faults and were only later dextrally reactivated (Vrabec & Fodor, 2006). An important role in tectonics of Slovenia has played about 30° counter-clockwise rotation of the Adria since the late Miocene to Pliocene based on paleomagnetic data (Márton *et al.*, 2003).

In geotectonic sense Slovenia that lies on the NE edge of the Adria has moderate historic and recent seismicity. Dinaric dextral shear zone (*sensu* Poljak *et al.*, 2000) with majority of Slovene karst area corresponds to External Dinarides and includes a wide area between Raša Fault on the SW and Stična Fault on the NE. The zone consists of NW-SE oriented Dinaric faults with right-lateral horizontal displacements. The most prominent structure is Idrija Fault (Fig. 1).

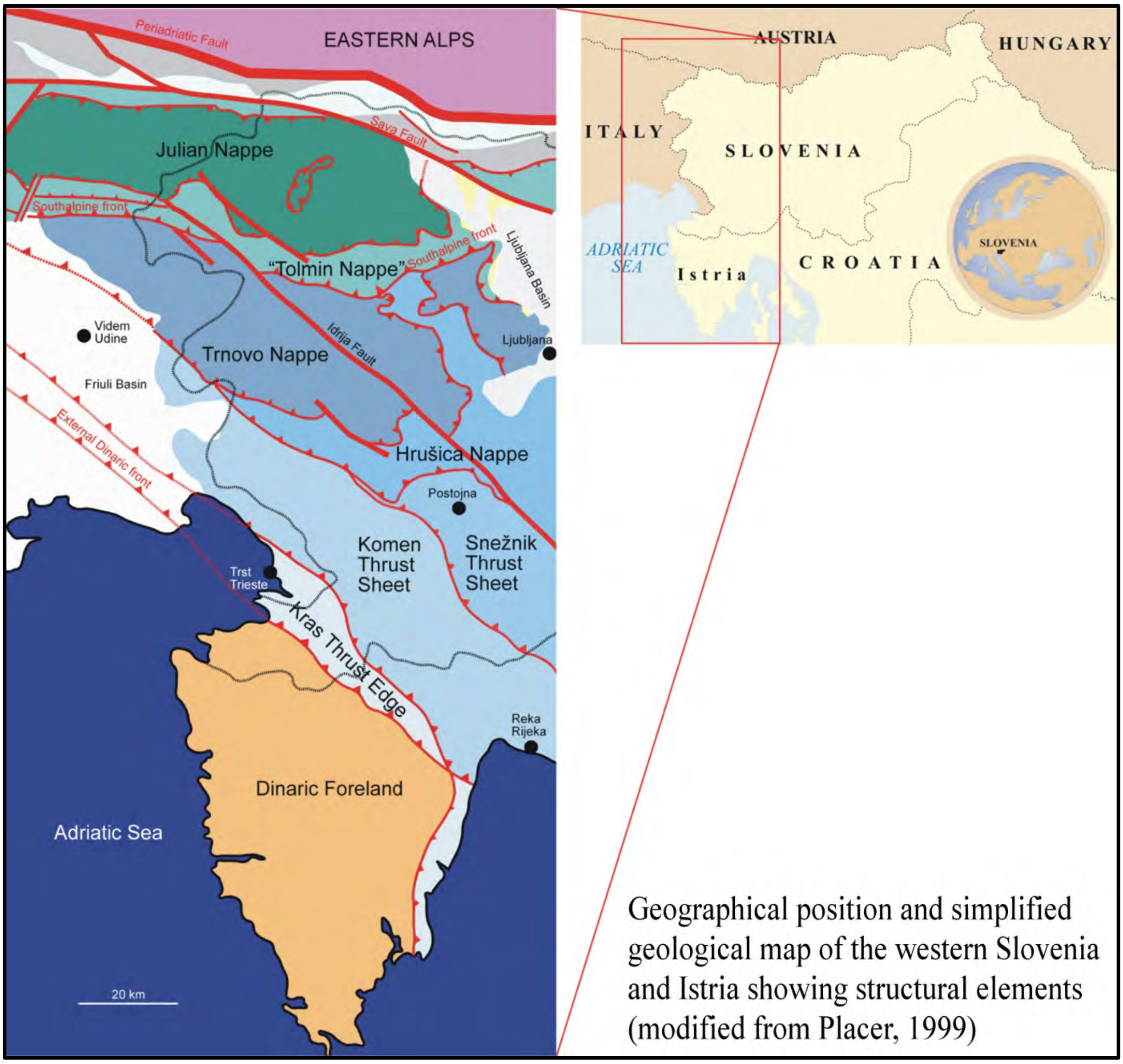


Figure 1: Geographical position and simplified geological map of the western Slovenia and Istria showing major structural elements (modified from Placer, 1999).

FIELD TRIPS

STRATIGRAPHY AND EVOLUTION OF THE FOREBULGE RELATED PALEOKARST – INTRODUCTION TO EXCURSIONS A AND C

Bojan Otoničar

In the SW Slovenia and NW Croatia (Istria) a regional unconformity separates passive margin shallow-marine carbonate successions of different Cretaceous formations from the Upper Cretaceous to Eocene palustrine and shallow marine limestones of the synorogenic carbonate platform (Fig. 2). The latter containing the Liburnian Formation, Alveolina-Nummulites Limestone and intermediate Trstelj Formation that represent the Kras Group (Košir, 2003) (Fig. 2), which corresponds to the lower unit of the underfilled peripheral foreland basin stratigraphy (i.e. the lower unit of the "underfilled trinity" of Sinclair, 1997). Thus the unconformity represents a megasequence boundary and typically separates the underlying passive margin carbonate succession from the overlying deposits of the synorogenic carbonate platform at periphery of the foreland basin (Košir & Otoničar, 2001). The synorogenic carbonate platform was finally buried by prograding hemipelagic marls (i.e. the middle unit of the "underfilled trinity" of Sinclair, 1997) and deep-water clastics (flysch) (i.e. the upper unit of the "underfilled trinity" of Sinclair, 1997) (Fig. 2).

The unconformity is expressed by an irregular paleokarstic surface, locally marked by bauxite deposits (see below).

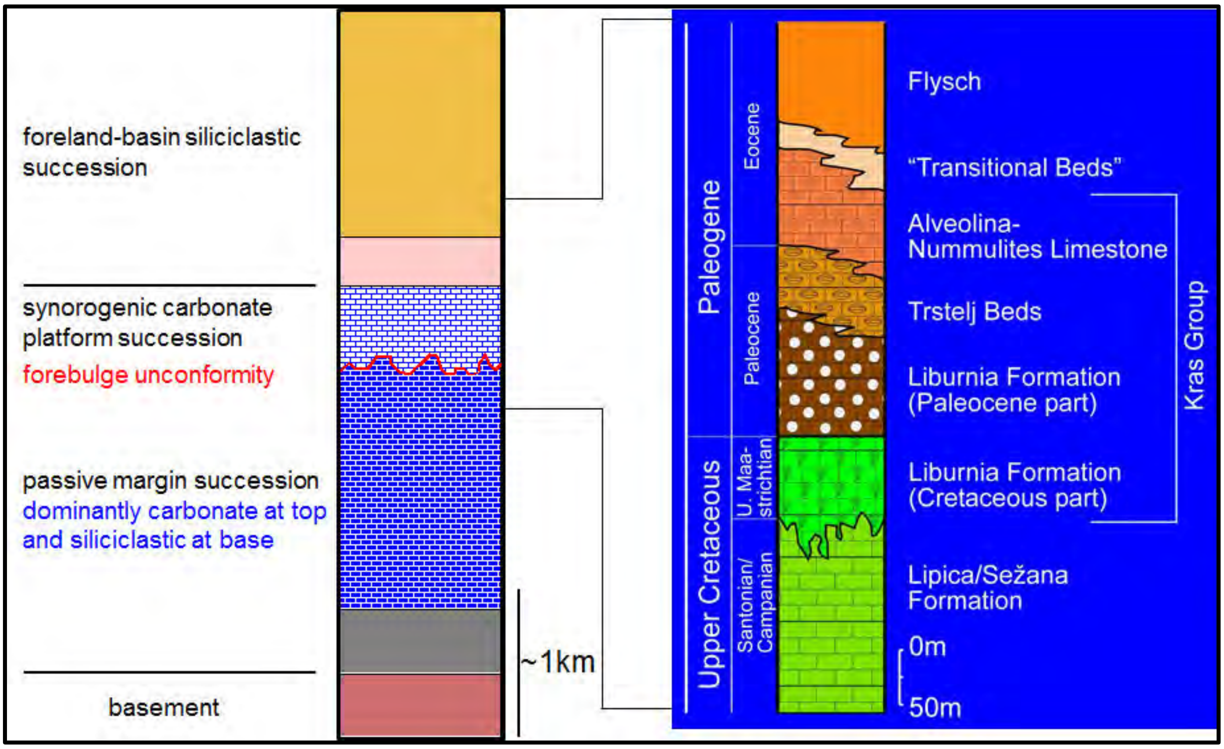


Figure 2: Generalised lithostratigraphic column of the Upper Cretaceous to Eocene succession of rocks in the Kras and the Matarsko podolje regions, SW Slovenia showing major lithostratigraphic units (after Košir, 2004).

Tectonically, the discussed area corresponds to the External Dinarides and the Dinaric foreland (Placer, 1999) although the flysch-related sediments can be followed across these two units to the Southern Alps (Fig. 1). The unconformity and the overlying carbonate successions of the Kras Group correspond to the most external thrust unit of the Dinaric fold and thrust belt – the northwestern External Dinarides in southwestern Slovenia, Italian part of the Kras plateau and northeastern Istria, and to more stable foreland domain of the Dinaric mountain belt in other parts of Istria (Fig. 1).

The nappe structure of northwestern part of the External Dinarides comprises five successively lower and younger thrust units from northeast to southwest: Trnovo Nappe, Hrušica Nappe, Snežnik Thrust Sheet, Komen Thrust Sheet and Kras Thrust Edge (Placer, 1981, 1999, 2004) (Fig. 1).

The External Dinarides and the Dinaric foreland correspond to the northwestern part of the Cretaceous Adriatic Carbonate Platform and the Upper Cretaceous-Eocene synorogenic carbonate platform which occupied northeastern part of the Adria microplate s.s. (Fig. 3). In the Cretaceous the area of present day Southern Alps was a part of deeper marine realm which comprised the Slovenian Basin formed in the Middle Triassic (Cousin, 1981; Buser, 1989) and the area of former Julian Carbonate Platform which was drowned in the Lower and Middle Jurassic (Cousin, 1981; Buser, 1989). The geologic and paleogeographic situation started to change severely in the Late Cretaceous (see below). It is important to note, that the described region is recently confined from the north side by the Periadriatic fault zone, from the west by the deposits of the Southern Alpine Molasse Basin and from the south and southwest by the Adriatic Sea and its sediments (Fig. 1).

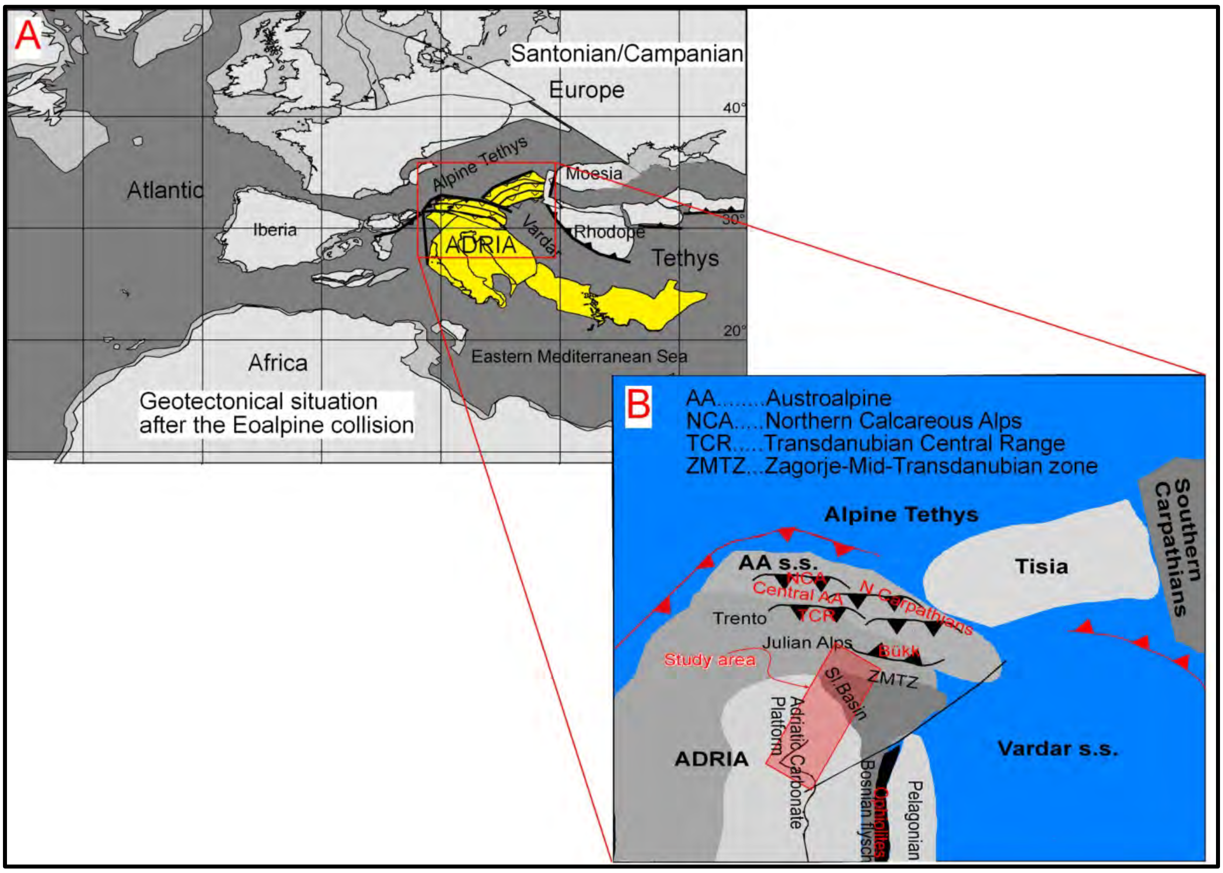


Figure 3: A) Paleogeographical map showing major geotectonic units at Santonian-Campanian boundary in western Tethys and central Atlantic (modified from Neugebauer *et al.*, 2001). B) Geotectonic and paleogeographic units of Adria microplate and adjacent areas.

Besides the research on paleokarst-related phenomena, the study of sedimentary successions of the host rock in which the paleokarstic features occur and those that overlie the paleokarstic surface is of crucial importance to understand the uplift of substantial part of the Adriatic Carbonate Platform above the sea-level in the Late Cretaceous and Paleogene. To explain the mechanisms that govern the uplift, regional (Western Tethys) and global geotectonic and eustatic conditions should be taken into consideration.

The age of limestones that immediately underlie the unconformity and the extent of the chronostratigraphic gap in southwestern Slovenia and Istria systematically increase from northeast towards southwest (Figs. 4a, b), while the age of the overlying limestones decrease in this direction (Fig. 4c). In western part of Istria the orientation of the isochrones is slightly different and shows a dome-like topography of the forebulge. The isochrones represent a statistic result acquired by kriging. The data were provided from 36 geological profiles from the karstic regions of southwestern

Slovenia, both Slovenian and Croatian part of Istria peninsula and the area between Trieste bay and Italian-Slovenian border in northeastern Italy (red dots on Fig. 4).

The youngest rocks below the unconformity belong to Campanian and occur in the central and northern part of the Kras (Karst) plateau (the Komen thrust sheet) (Fig. 1) (Jurkovšek *et al.*, 1996; Venturini *et al.*, 2008; Dalla Vecchia, 2009) and close to Postojna (the Snežnik thrust sheet) (Fig. 1) (Šribar, 1995; Rižnar, 1997) in southeastern Slovenia, while the oldest one, Valanginian and Hauterivian in age, crop out in the western part of Istria (Matičec *et al.*, 1996) (Fig. 4a).

The beds that cover the unconformity correspond to different ages, litofacies, members and formations. As mentioned above, the age trend of the immediate cover is opposite to that of the footwall. In this case the oldest rocks occur in southwestern Slovenia and NE Italy (between Trieste and Gorica/Gorizia) and belong to the youngest stage of the Late Cretaceous - the Maastrichtian or even Late Campanian – Early Maastrichtian (Venturini *et al.*, 2008; Dalla Vecchia, 2009). Towards southwest, in general, progressively younger deposits onlap the paleokarstic surface (Fig. 4c). With regard to described situation, the chronostratigraphic gap increases considerably from few Ma on the Kras plateau (southwestern Slovenia) to more than 80 Ma in western Istria (Fig. 4b).

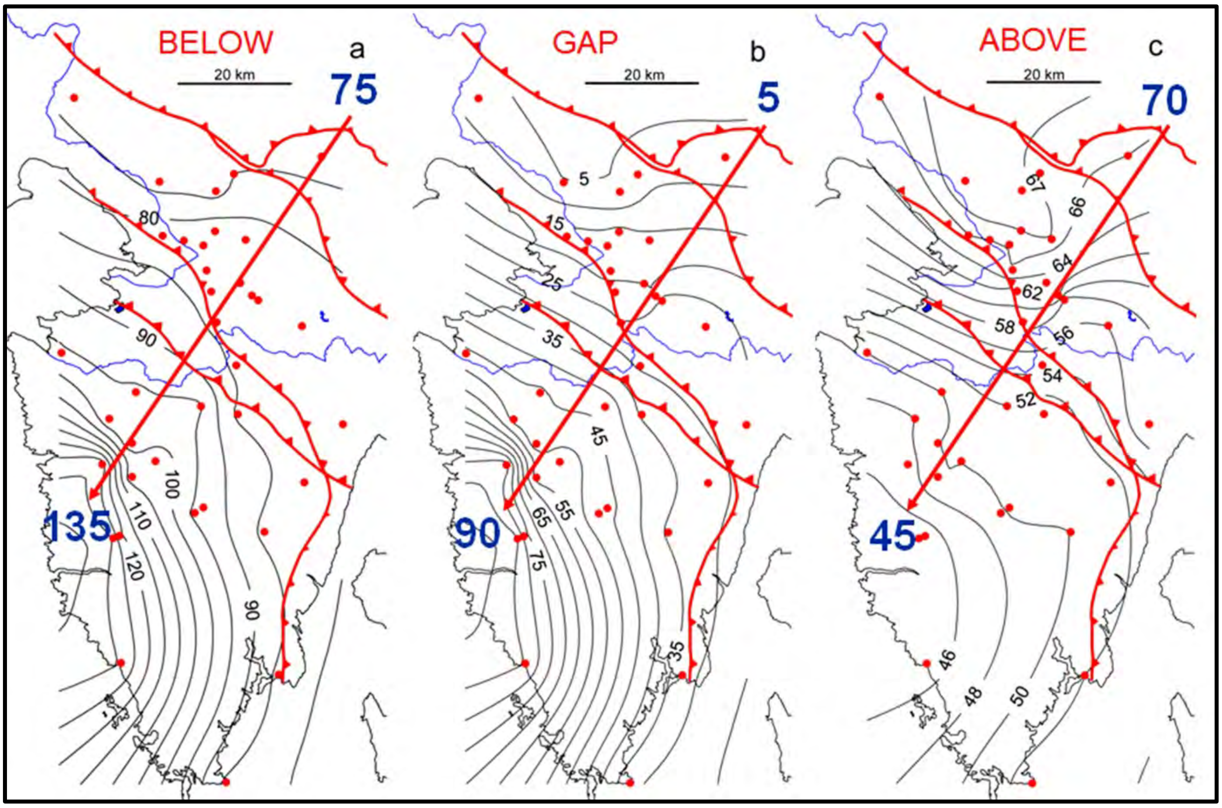


Figure 4: Isochrones (in millions of years) of the carbonate rocks directly underlying the paleaokarst surface (a), the extent of the chronostratigraphic gap (b), and the carbonate rocks directly overlying paleaokarst surface (c). The figures also show the main structural characteristics of the area and the locations of the geological profiles considered.

The lithofacies of the lower part of the cover sequence (The Liburnian formation) frequently show features typical of subaerial exposure surfaces, including calcrete, pseudomicrokarst, brecciated horizons and karstic surfaces. Locally, the lowermost subaerial exposure surface of the Liburnija Formation, which shows karstic topography of decimetric amplitude, and the main paleokarstic surface form a composite unconformity. In western Istria, where the chronostratigraphic gap is the most extensive, the foraminiferal limestones frequently lie directly on the paleokarstic surface (Matičec *et al.*, 1996). The thickness of the Kras Group generally decreases from northeast toward southwest, although significant deviations may occur (Fig. 5).

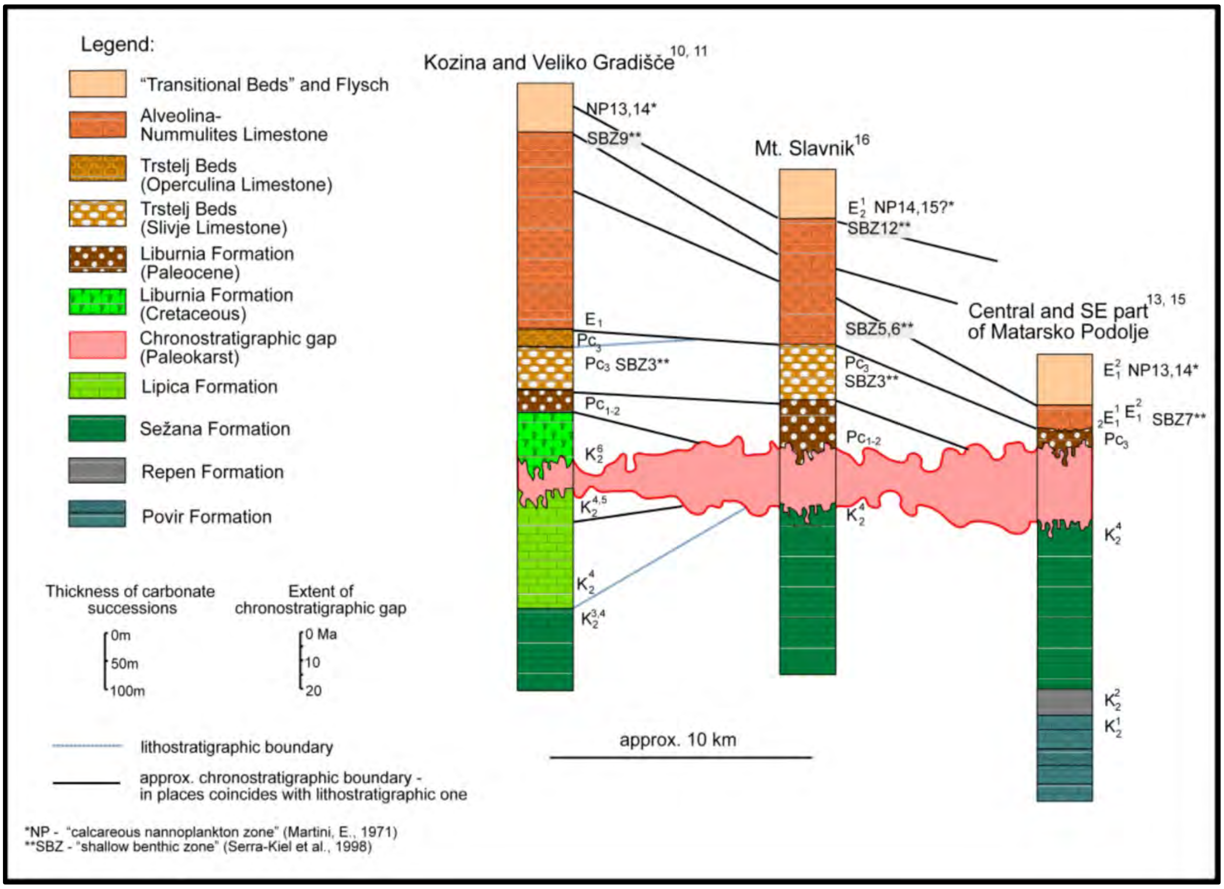


Figure 5: Lithostratigraphic columns of three locations in the Matarsko podolje and on Mt. Slavnik. Despite the proximity of the locations, we can observe considerable differences in the thickness of the lithostratigraphic units and the range of stratigraphic gaps.

The point where the unconformity pinch-out towards the foreland basin occurs somewhere between the northeastern part of the Kras plateau on the Komen Thrust Sheet and some 10 km (approximately 25 km in original position – see Placer, 1999) distant Mt. Nanos on the Hrušica nappe (Fig. 1). From this point on towards the foreland basin, the uplift of the forebulge did not take place because the area was so close to the orogene that experienced only a subsidence. Here, the sedimentary succession of the Adriatic Carbonate Platform gradually passes into progressively deeper-marine carbonate succession of synorogenic carbonate platform. Namely, on the Mt. Nanos at Campanian-Maastrichtian boundary, the deepening of the shallow marine carbonate platform without any evidence of preceding emersion is documented (Šribar, 1995; Jež & Otoničar, 2010; Jež, 2011) (see field trip B).

Further towards the northeast, in the Julian Alps (the eastern part of the Southern Calcareous Alps) and in the most northern part of recent Dinaric mountain belt in western Slovenia and northeastern Italy (the Trnovo Nappe), the turbiditic siliciclastic sediments (flysch) started to deposit in Campanian and Maastrichtian over the rocks of different lithology, age and origin (Pavšič, 1994). Flysch often overlies deeper marine pelagic marls of "scaglia" type and alodapic carbonates, which were receiving the material from Adriatic Carbonate Platform. The oldest pelagic marls (pre-flysch deposits) which overlie the Upper Cretaceous shallow marine carbonates of the northeastern margin of the Adriatic Carbonate Platform also belong to Maastrichtian. Similar as for chronostratigraphic gap, the pelagic marls and flysch deposits are also diachronous over the area.

The synorogenic carbonate and siliciclastic deposits of other parts of External Dinarides (e.g. Dalmatia) are younger than these described here. They started to deposit not before Eocene and probably represent deposits of different foreland system or at least of different segment of the one described here.

Systematic trends expressed by isochrones showing the age of the carbonate rocks that immediately under- and overlie the paleokarstic surface (Figs. 4a, c), and consequently, the extent of the chronostratigraphic gap (Fig. 4b), can be explained mainly by the evolution and topography of peripheral foreland bulge (the forebulge) (Fig. 6).

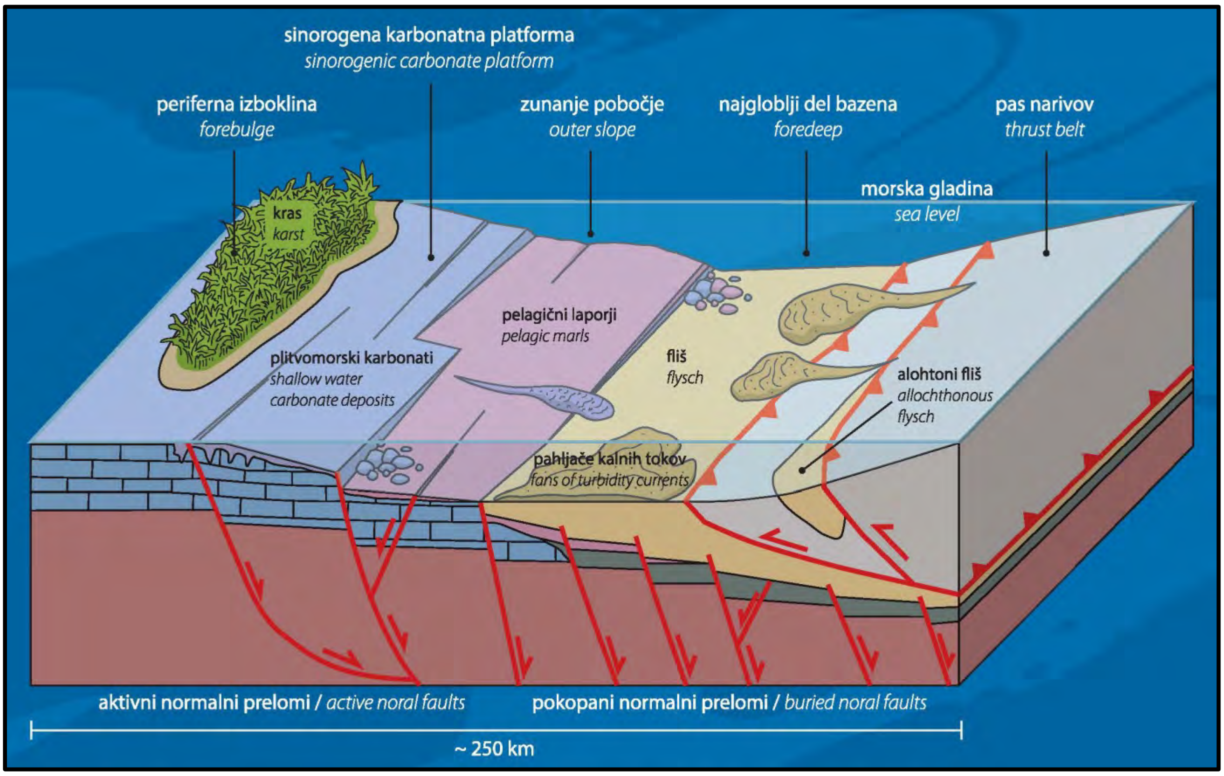


Figure 6: The schematic block diagram of the foreland basin system shows the position of the orogenic wedge, the deep-marine section of the foreland basin (the foredeep) and the peripheral bulge (the forebulge). The model also shows the distribution of macrofacies before the completion of tectonic plate convergence (adapted from Bradley & Kidd, 1991)

When the foreland continental lithospheric plate is vertically loaded by the fold and thrust belt, it responds with flexure. In front of the evolving orogen an asymmetric foreland basin is formed; the deepest part of the basin (the foredeep) is located adjacent to the orogenic wedge (Fig. 6, 7). Because of the isostatic rebound on vertical loading of the lithosphere, the opposite side of the basin (opposite to the orogenic wedge) is instantaneously upwarped and the bulge with subtle relief is formed, the peripheral bulge or the forebulge (Figs. 6, 7). The bulge is especially well expressed in early, flysch stage of the foreland basin evolution (Crampton & Allen, 1995). While the wavelength of the deflection is approximately the same for both, foreland basin and peripheral bulge, the amplitude of the basin subsidence is typically much greater as the uplift of the bulge (Crampton & Allen, 1995; Miall, 1995). If the conditions are suitable, synorogenic carbonate platforms with distinctive ramp topography may colonise the gentle slope of the forebulge toward the foredeep (Dorobek, 1995).

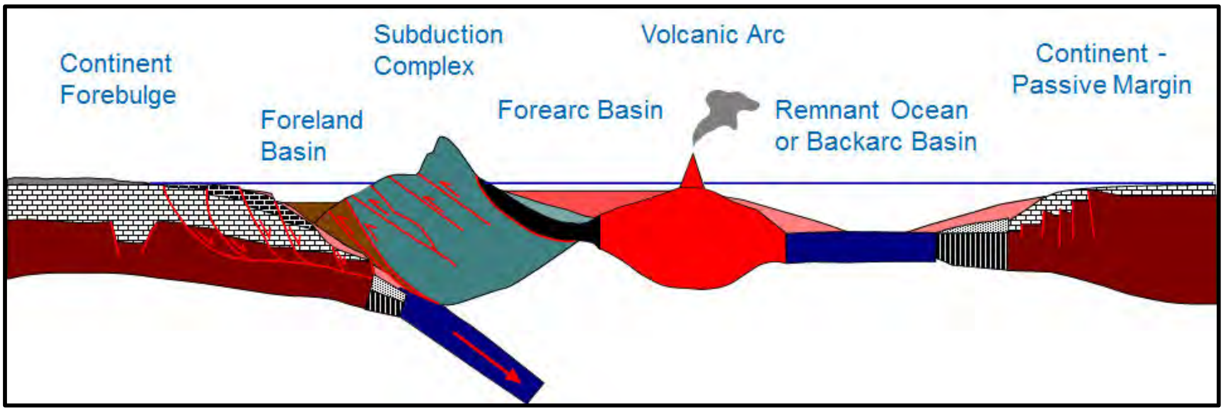


Figure 7: Specific evolution of karstic and paleokarstic systems is in a great extent dependent on different geotectonical settings where particular carbonate region occurs. Among others, paleokarsts may occur in carbonate sequences related to the evolving peripheral bulges.

Significantly, as the whole complex of the orogenic wedge advances forelandward, the flexural profile produced by the orogenic wedge advances with it. Topography of the forebulge is controlled by numerous factors, among which the rigidity of the foreland lithospheric plate and the rate of emplacement of the load are the most important (Allen & Allen, 1992; Dorobek, 1995; Miall, 1995). An expected maximal height of the forebulge above the sea level (if the foreland plate is at or close to sea-level prior to flexural loading) would be in the range of up to a few tens to few hundreds meters (Crampton & Allen, 1995; Miall, 1995). According to topography of the forebulge, the rate of erosion and the style of migration of the orogenic wedge, the area of maximal denudation should occur in the central part of the region, which is over-passed by the bulge (Crampton & Allen, 1995). In addition, non-flexural deformations (e.g. reactivation of pre-existing heterogeneities, enhanced deflections because of horizontal in-plane stresses…) and inherited topography may significantly influence the evolution and topography of the forebulge (Allen & Allen, 1992; Dorobek, 1995; Miall, 1995; Crampton & Allen, 1995).

According to the stratigraphic position of the pinch-out line where unconformity reduces to conformity, the age of the oldest pelagic marls, the age ot the oldest turbiditic siliciclastic flysch and trends of unconformity related isochrones elsewhere (Figs. 4a, b, c), it is suggested that northern part of the Adriatic Carbonate Platform had thrived more or less prosperously till the end of Campanian, when an initial uplift of the forebulge occurred. The carbonate sediments that had originally been deposited till that time, and are now missing in carbonate successions immediately below the unconformity, had been erased during the paleokarstic period by the karstic denudation processes.

According to topography of the forebulge and advancing nature of the foreland geodynamic complex as a whole, the most extensive denudation is expected in the central area over which the forebulge migrates. The western part of Istria, where the chronostratigraphic gap is the largest and the beds immediately below the unconformity are the oldest (Figs. 4a, b), most probably corresponds to this zone. However, in an ideal conceptual/mathematical model of the forebulge unconformity, the amount of erosion should remain more or less constant over vast area in the central part of the region over-passed by the bulge, and decreases on its distal slope towards back-bulge basin (Crampton & Allen, 1995). Instead, in western Istria the isochrones of the beds underlying the unconformity show distinctive condensation compared to situation in northeastern Istria and southwestern Slovenia (Fig. 4a). I suggest that this is not the result of rapid increase of the amount of footwall eroded but rather of denudation of primarily much thinner Cretaceous carbonate successions in western Istria (see Matičec *et al.*, 1996), partly because of repeating emersions throughout the Cretaceous (Velić *et al.*, 1989) and partly because of reduced accommodation space of Cretaceous shallow marine environments. Evidence of considerable Late Jurassic and Cretaceous land areas in the vicinity of western Istria (probably offshore form its recent west coast), came also from dinosaur record (footprints and bones) (Dalla Vecchia *et al.*, 2000; Mauko & Florjančič, 2003;

Mezga *et al.*, 2003) and distribution of sedimentary facies of the adjacent peritidal to deeper marine environments of intraplatform basins (Tišljar *et al.*, 1995; 1998).

It is also possible that the central zone of the forebulge and the slope towards back-bulge basin in their final position occurred offshore of recent Istrian west coast. However, we should be aware that the Late Cretaceous Adriatic Carbonate Platform was surrounded from the western side by deeper marine interplatform basins (Vlahović *et al.*, 2005) what might considerably affect the appearance of the forebulge and the back-bulge area.

Although the “abnormal thickness” of denuded stratigraphy in western Istria is mainly the result of previous sedimentary history, some uncertainties may also arise from differential uplift/subsidence of certain parts of the forebulge. Evidence for differential subsidence along reactivated ancient tectonic structures is for example well documented in carbonate successions of the Kras Group, where the thickness of chrono- and lithostratigraphic units may vary considerably over short distances (Fig. 5).

In conclusion it is suggested that the denudation exposed the oldest carbonate rocks in the western Istria partly because of specific evolution (migration) and topography of the forebulge and partly because of primarily thinner carbonate successions in this part of Istria compared to more northeastern parts of the investigated area.

The rate of transgression over the paleokarstic surface is expressed by the isochrones of the strata that onlap the unconformity (Fig. 4c). While the large scale diachronism of the onlapping strata shown in Figure 4c is the result of specific large-scale topography and migration of the forebulge as a whole, local smaller scale spatial differences in the onlap pattern (not observable in Figure 4c) may be due to shorter oscillations of relative-sea level and deposition over topographically irregular paleokarstic surface (e.g. dolines, shafts… – a “blue hole phase” of the transgression).

Evolution of phreatic caves below a forebulge unconformity (Fig. 8)

In modern exposed carbonate platforms and young carbonate islands laterally extensive but vertically restricted caves with irregular walls and discrete horizons of spongy porosity are mainly characteristics of phreatic diagenetic environments related to fresh water lenses (Mylroie & Carew, 1995a, b). In the discussed area, the phreatic caves are frequently completely filled with deposits originated in a vadose zone, like flowstone and bauxite, or they had been opened to the paleokarstic surface by complete denudation of the ceiling (i.e. unroofed caves of Mihevc, 2001). In addition to pedogenically altered carbonate rocks immediately below the paleokarst surface, also cave infilling deposits often comprise pedogenic features. Caves with deposits that show no apparent origin in the vadose zone are usually smaller and situated deeper below the paleokrast surface. Yet internal deposits, usually silty carbonate material and coarse-grained cements, yield isotopic signatures heavily influenced by meteoric waters. Some cave deposits show alternating deposition of detrital sediments, cements, and speleothems interrupted by episodes of chemical and mechanical erosion that may be the result of oscillations in relative sea-level, and consequently underground water table, and/or hydrogeochemical conditions in the fresh/brackish lens. While in general, a major part of the phreatic cavities had been subsequently emplaced in the vadose zone prior to submergence and burial apparently this occurred in oscillatory manner.

According to the proposed simple model for dissolutional/infilling evolution of phreatic caves related to fresh/brackish water lenses in a forbulge setting (see above and Fig. 8) all those phreatic caves uplifted and infilled in vadose or epiphreatic zones should be formed below the flank of the forbulge facing the back-bulge area. However, short-term sea-level oscillations, which have been recognized from subaerial exposure surfaces in carbonate succession that immediately overlie the paleokarstic surface and may be superimposed on long-term relative sea-level trends, should influenced also the position of fresh/brackish water lens below uplifted part of the forebulge. Consequently, a relative underground water table fall of just few meters would expose for example at least caves from the upper part of the lens to the vadose zone where they could be easily filled with flowstone and sediments form the paleokrastic surface, especially if the vadose zone is relatively thin with well-developed interconnected subsurface vadose cavities (channels, pits, shafts, root casts…) that may transport vadose and pedogenic products underground. If we suppose that at least most extended paleokarstic caves originated close to the margin of the uplifted forebulge (i.e. flank margin caves of Mylroie & Carew, 1995a, b or Quintana Roo- type caves of Smart *et al.*, 2006) or were situated at the interface between phreatic in vadose zones (i.e. banana holes of Harris *et al.*, 1995) then the paleokarstic surface was probably quite close to the phreatic caves, which could also increase the filling of these caves.

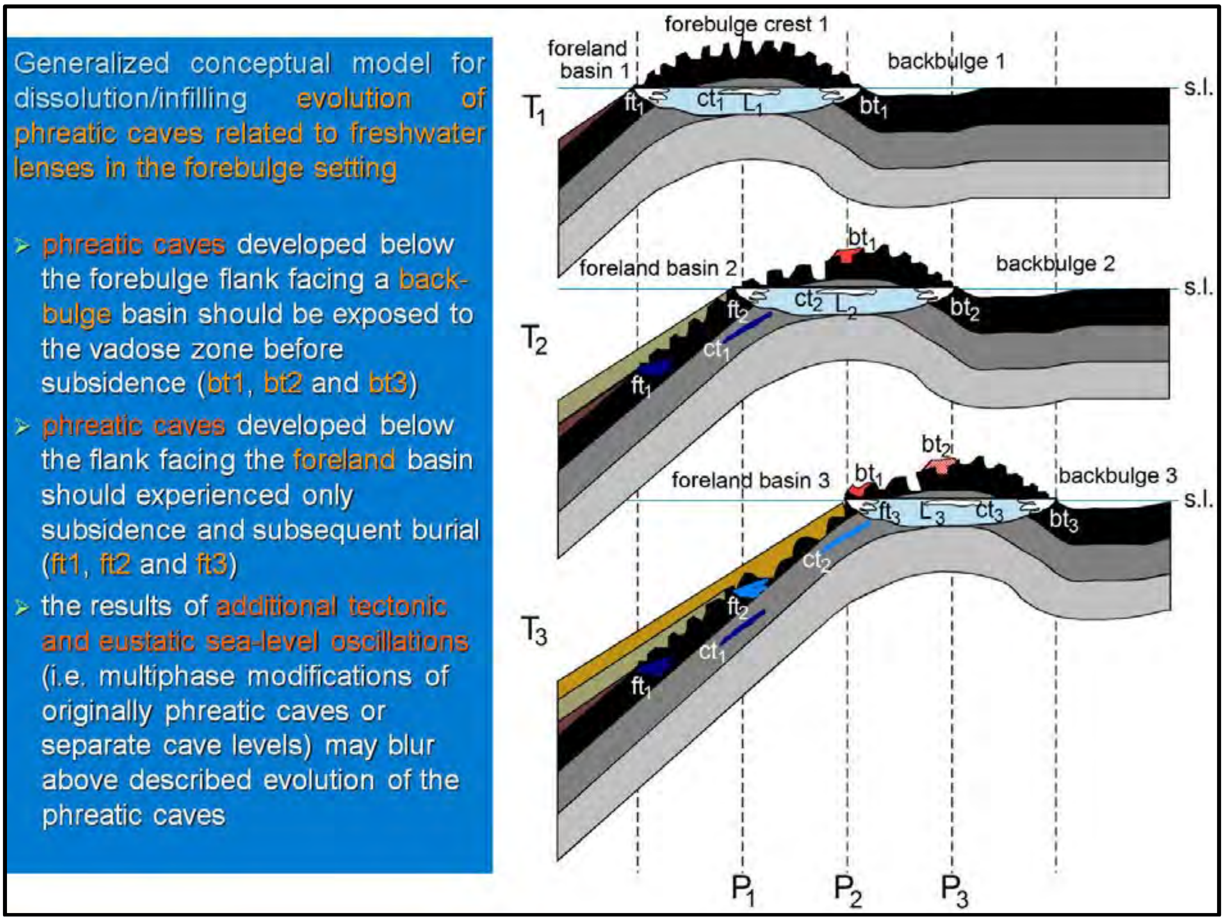


Figure 8: Successive sketches of the evolution of phreatic caves related to forebulge migration (see text for explanation; extreme vertical exaggeration in comparison to horizontal distances). Grey to black colored strips represent passive margin carbonate platform sequences, while stipple marked strips show different generations of underfilled foreland basin deposits (e.g. synorogenic carbonate platform). (T_1, T_2, T_3) - geomorphological characteristics of the forebulge complex in three successive time-snaps; (P_1, P_2, P_3) – position of the forebulge crest at different times; (ft) – flank margin or coastal caves developed below the flank facing the foreland basin; (Bt) – flank margin or coastal caves developed below the flank facing the back-bulge area; (ct) – caves developed in the upper part of the fresh/brackish water lens (i.e. banana holes by Harris *et al.*, 1995) situated below the crest of the forebulge; (L) – fresh/brackish water lens.

Besides eustatic sea-level oscillation, processes at plate boundaries and rheological/structural characteristics of foreland plate itself may cause somewhat shorter term relative oscillations of underground water table. The extent and hydrogeochemical conditions of the fresh/brackish water lens may also change without relative sea-level oscillations, either by climate changing or diagenetic/karstic evolution of the aquifer (see Mylroie & Carew, 1995b).

Because of the specific diachronous nature of karstified unconformities, direct comparison between paleocave levels among different locations even if they occur at the same depth below the paleokarstic surface is impossible.

Afternoon field trip **(A):**

LATE CRETACEOUS PALEOKARST OF SW SLOVENIA AND NE ITALY

(*Paleokarstic pits/depressions filled with deposits that contain vertebrate (dinosaur and crocodile) bone remains and teeth*)

Tuesday, 14.6.2013, 13.00–20.00

Stops:

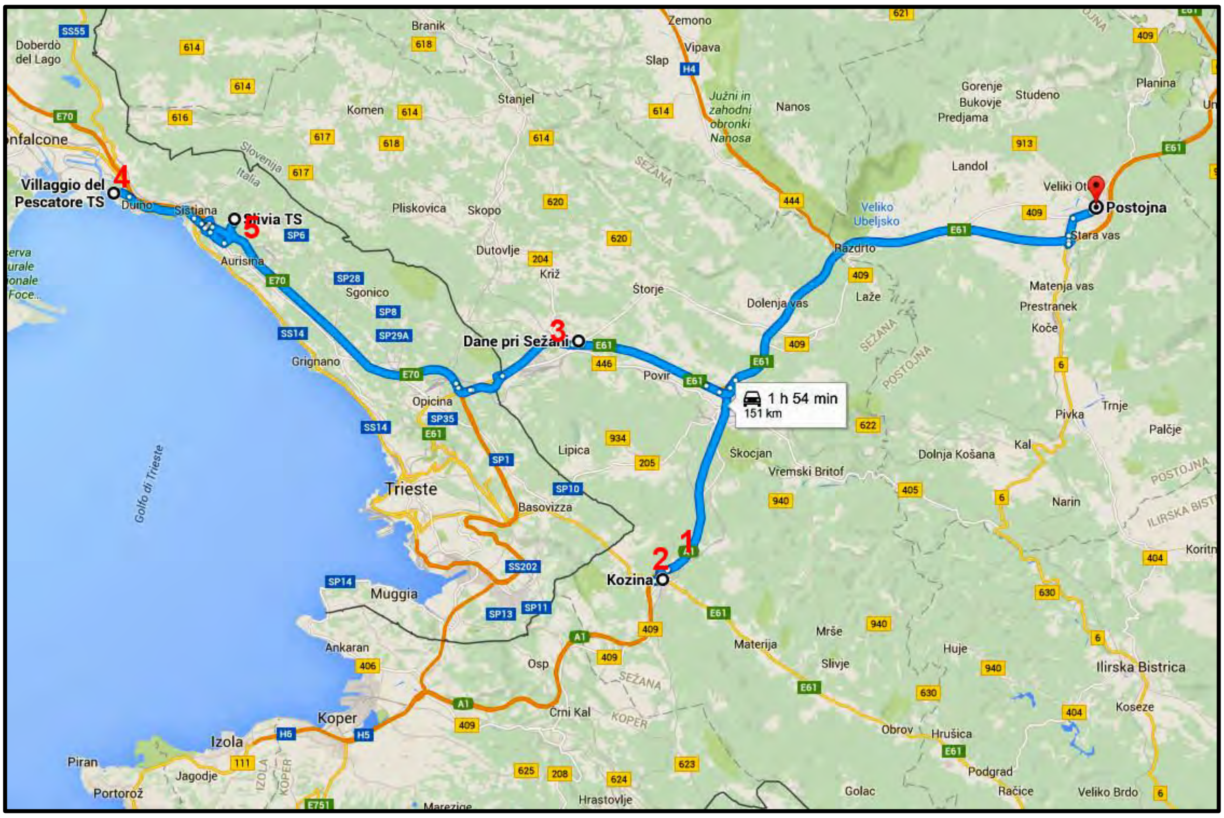
1 – Kozina (relict vs. paleokrastic caves; geology and geomorphology of the area);

2 – Kozina (motorway road-cut; paleokarstic surface between Santonian and Maastrichtian carbonate successions; paleokrastic pit filled with breccia that contains dinosaur and crocodile bone ramins and treeth);

3 – Sežana (motorway road-cut; phanton karst vs. paleokrast; dissolution of Albian(?) to Lower Cenomanian Ca-evaporites, dedolomitization);

4 – Devin/Duino (Ribiška vas/Villagio di pescatore), Italy: paleokarstic(?) depresion filled with blue hole related deposits where a few almost completely preserved dinosaur and crocodile sceletons were excavated; excavated ahreological cave;

5 – Slivno/Slivia, Italy: abandoned quarry of Late Createaceous (?Paleogene) coarse-grained breccia body – a paleokarst collaps doline or something else?



KOZINA (No. 1 & 2): THE 75 MA LONG HISTORY OF KARSTIFICATION OF UPPER CRETACEOUS AND LOWER PALEOGENE LIMESTONES AT KOZINA

Bojan Otoničar

From the time of their sedimentation until today, the Upper Cretaceous and Lower Paleogene limestones of the wider Kozina area underwent karstification over several karst periods and phases. Due to denudation the epikarst (sensu Klimchouk, 2000) moves down the transverse profile of the karst system, through the traces of former karst periods and phases (*sensu* Bosák *et al.,* 1989). The most distinct paleokarst surface and related subsurface features of the area in question were formed during above discussing uplift and subaerial exposure of the Adriatic Carbonate Platform in the Upper Cretaceous and Lower Paleogene. The paralic carbonate sequences that cover the paleokarst surface were also occasionally subaerially exposed, as evidenced by the appearance of specific karst and paleosol features. The old traces of cavernosity of the present-day karst aquifer can be observed in the form of "unroofed caves" and old caves right underneath the current karst surface. Even though the area in question was definitively formed during the post-collision tectonic phases/episodes of varying intensity and although the tectonic processes were "disturbed" by the external, mainly climate-based influences (e.g. the Messinian crisis), the characteristics of the present karst system mostly result from karstification that took place in the course of gradual uplifting of the territory, most notably during the post-Miocene underthrusting of Istria under the External Dinarides.

While constructing motorways in the region, the excavation of roadcuts revealed the upper part of the vadose zone, the epikarst, in several places. Lengthy denudation combined with simultaneous spatially and temporally uneven tectonic uplifting of the area brought the traces of various karst phases of the active karst aquifer and of the paleokarst (*sensu* Osborne, 2000) closer to the present-day karst surface. The research covered the relatively shallow motorway cuts in the vicinity of Kozina, where it is possible to see the intertwining of karst features that developed through the geologic history in greatly differing climate, geotectonic, geochemical and hydrologic conditions, as well as in lithologically different rocks which, by the time they became subjected to the karstification, passed over different stages of diagenesis and structural deformations.

Our primary focus will be on two different, relatively extensive karst systems that underwent karstification for several millions of years. The older of the two systems developed in a warm tropical climate of the Upper Cretaceous, in diagenetically immature carbonates located relatively close to the sea level (eogenetic stage), while the other system developed in the tectonically active period extending from Miocene to present-day, in diagenetically mature and structurally deformed carbonate rocks in a constantly changing climate (telogenetic stage).

Kozina (No. 1): Relict (roofless) caves
(from Bosák *et al.*, 2000)

The karstification of the region is typified by the presence of old caves partly crossed by younger shafts. The shafts are related to a drop of piezometric level, which lies now about 200 m below the surface. Some shafts are empty and others are filled with young (Pleistocene) sediments. Valley systems on the surface of the Karst were once believed to represent primary river valleys, as they contain remains of fluvial sediments. Latest interpretations, however, indicate that fluvial sediments are the fills of fossil caves, not the remains of surface fluvial systems (*cf*. Mihevc 1998, 1999 a, b, c). The paleofill of the caves appeared at the surface due to erosion and/or chemical denudation of the limestone. Such caves are called denuded, roofless or unroofed caves.

Construction of the motorway and regional roads from Divača to Klanec (SW Slovenia, Classical Karst, Matarsko podolje) uncovered a number of fossil caves (Fig. 9 left) and unroofed caves (Fig. 9 right). One of them was located to the NE of the village of Kozina, close to the present main road from Ljubljana to Koper in a road-cut made during construction of the highway from Divača to

Klanec. The fossil channel was unroofed with remains of collapsed roof only in the upper part. It formed a mild depression in the field. The sedimentary profile in the cave was about 5 m high. It was composed mostly of sandy sediments of light brown to ochreous colour with clayey and silty intercalations. Sediments contained dynamic structures and textures (lamination, cross-lamination, etc.). Erosional surfaces divided the profile into individual sequences. In total 38 samples were taken from the profile, only one of them was cemented. The rocks showed low or medium magnetisation. The profile contains inverse and normal polarity magnetozones. The character of distribution of magnetozones is similar to the nearby Divača profile (fossil cave in road cut at Divača). The age of the profile at Kozina is older than the Bruhnes/Matuyama boundary (0.78 Ma). From the arrangement of individual magnetozones, it can be stated that the sediments are older than the top of Olduvai chron (1.77 Ma), as the magnetostratigraphic profile at Kozina terminates by a reverse polarised magnetozone and contains two normal polarised zones.

The profile can be correlated with the Divača profile, not only from the palaeomagnetic point of view, but also from lithological point of view. We suppose, as at Divača, that the cave formed in the Messinian speleogenetic epoch and its fossilization was connected with rapid base level uplift after refilling of the Mediterranean basin by water. If this hypothesis is close to reality, the fossilization process can be dated from about 5.2 Ma up.

Figure 9: Left: Crosscut of relict filled cave with only about 1–2 metre thick roof; near Kozina village (motorway is under construction). Right: An old roofless cave marked only by thin layer of highly calcareous cave sediments and flowstone (Road-cut in Kozina village).

Kozina (No. 2): Late Cretaceous paleokarst

In Kozina, surface and subsurface karst features occur (Fig. 10). Traces of subsurface paleokarst features are located just below the paleokarst surface, in the Upper Santonian shallow-marine subtidal limestones of the Lipica Formation (Fig. 10); in some places, they are manifested as two originally more or less horizontal reddish strips measuring up to one metre in width, with secondary dissolution vugs and caves (Figs. 10, 11).

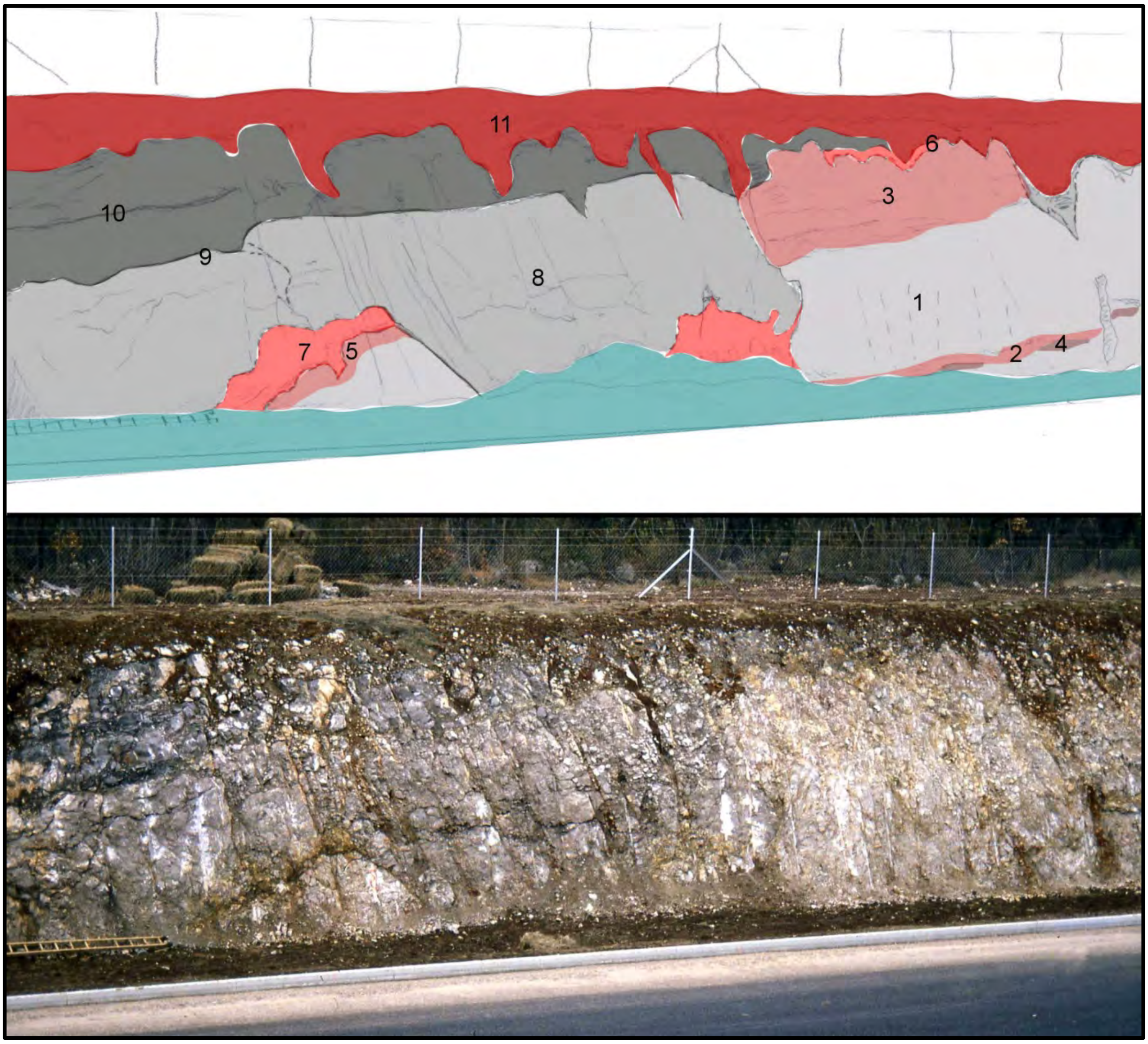


Figure 10: The profile along the Divača-Kozina motorway section. Legend: 1 limestones of the Lipica Formation (Upper Santonian); 2 bottom red horizon; 3 upper red horizon, direct base of the paleokarst surface; 4 series of horizontal centimetre todecimetre-scale cavities, filled with brown silt; 5 paleokarst surface, contact area between the altered limestones of the Lipica Formation and the weathered zone; 6 amalgamated paleokarst surface; 7 weathered zone: bauxite, calcite-bauxite-clayey sediments and breccias; 8 limestone of the Liburnian Formation, lithofacies of brackish closed bays/lagoon; 9 micropaleokarst surface in the Liburnian Formation; 10 pedogenically modified palustrine limestone (pseudo-microkarst features); 11 present karst surface and soil.

The millimetre- to centimetre-scale vugs were later filled with several generations of meteoric cements alternating with muddy to silty calcareous sediments (Figs. 11 (left); 12A, B). Directly under the paleokarst surface and even on it, remains of larger caves filled with sediments (Fig. 11 right) or flowstone can be found. Flowstone (Figs. 12C, D) indicates precipitation in the vadose zone, while the frequent presence of calcite rafts (Fig. 12D) and, in some places, of cave pearls points to the precipitation from the cave pools of the epiphreatic or vadose zone. The karst surface approaching to the phreatic caves is also seen in the intense filling of caves with soil products (ferruginous-bauxite material), selectively leached cements, fossils and flowstone as well as carbonate micrite and silt (Fig. 13). Cave sediments also occur frequently as clasts in paleokarst breccias (Figs. 13A, B) deposited at the bottom of paleokarst depressions (Fig. 13A).

Figure 11: Left) The interwined system of small channels/vugs created through non-selective dissolution of diagenetically immature limestones is filled by geopetally deposited red micrite and coarse-grained sparite; Right) A horizon of narrow voids and seems filled with yellowish-brown sillty to sandy carbonate deposit (max. thickness of the horizon is app. 0.4 m) (Kozina).

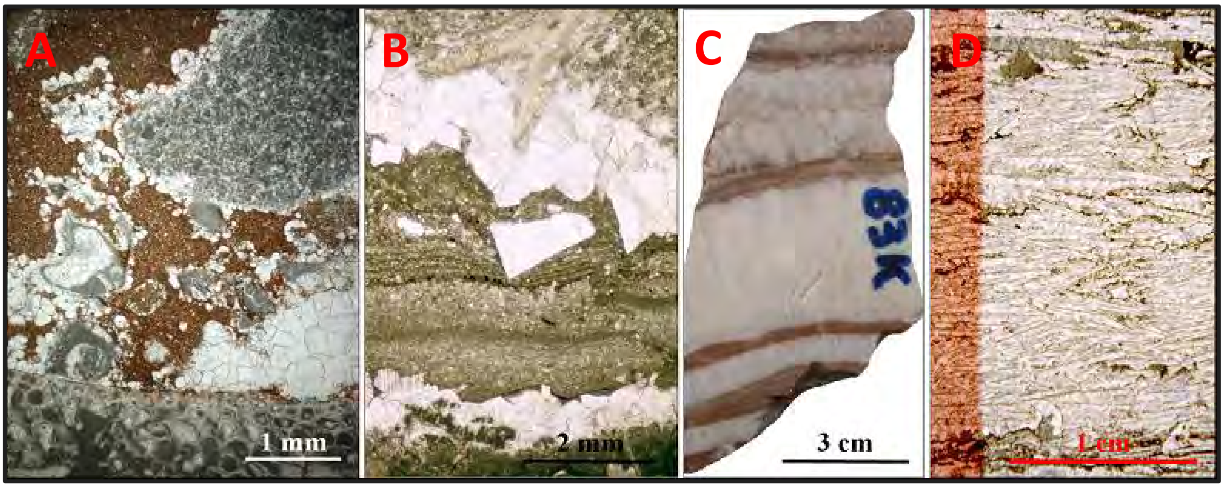


Figure 12: A) Irregular dissolution vug filled with reddish silty calcareous material. Note patchy distributed neomorphic calite and secondary dissolution vug filled with equant calcite spar; B) Dissolution vug enveloped by meteoric sparite and filled with laminated light brown calcite silt as well as individual grains of sand-grained calcite crystals; C) Alternation of white flowstone and red carbonate micrite/siltstone. D) Calcite rafts that underwent secondary cementation. The primary intergranular pores that, in places, underwent a secondary enlargement through dissolution are filled by sparite and a yellowish-brown silty sediment.

The presence of boehmite can be observed among the bauxite minerals; the purest bauxites contain around 80% of it, while the clay minerals contain the greatest weight percent of kaolinite (up to around 10%) (Fig. 14). Bauxite is usually the last sediment to have filled the remains or the newly formed pores both in the host rock and cave sediments.

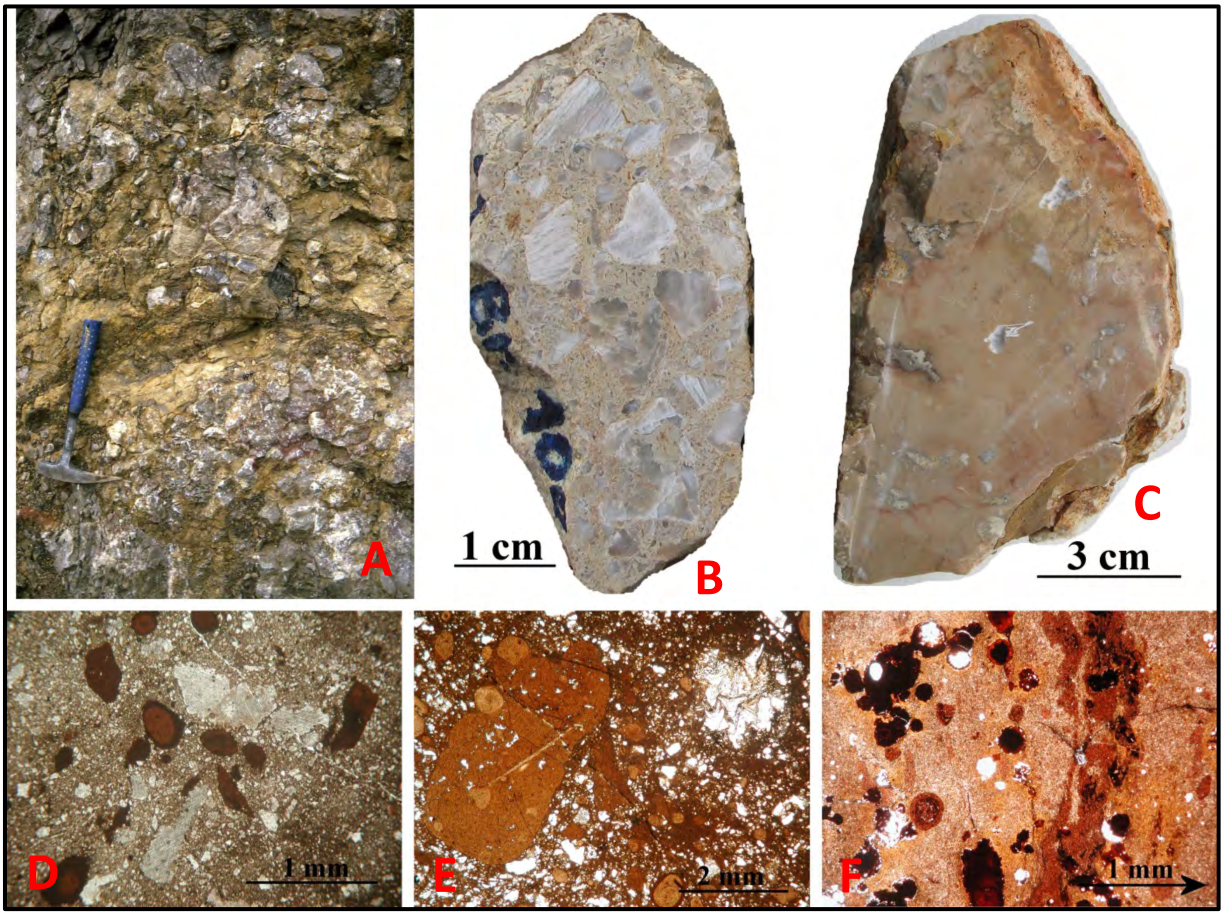


Figure 13: A) Weathered zone; pedogenic-karstic breccia – modified limestone clasts of the Lipica Formation and of flowstone in the calcite-bauxite-clay matrix. B) Fine-grained breccia that fills smaller vadose channels below the paleokarstic surface. Crystalline calcite clasts derive from flowstone disintegrated on the karstic surface C) Subcutaneously(?) modified limestone of the immediate base of the paleokrastic surface. Note multiple staining phases, neomorphism, dissolution and filling. D) Sandy calcareous siltstone with ferrigenous-bauxitic peloids and ooids as well as bioclasts of echinoderms and rudists. E) Calcareous-clayey-bauxitic sandstone with sparse larger bauxitic intraclasts. Note basuxitix-ferigenous peloids and ooids as well as calcite grains heavely recrystalized host rock limnestones and flowstone(?) F) Replacement of bauxitic and kaolinitic matrix and ooids with ferigenous oxides. Some hematite and boehmite ooids (peloids) were formed in-situ by replacement of kaolinitic matrix.

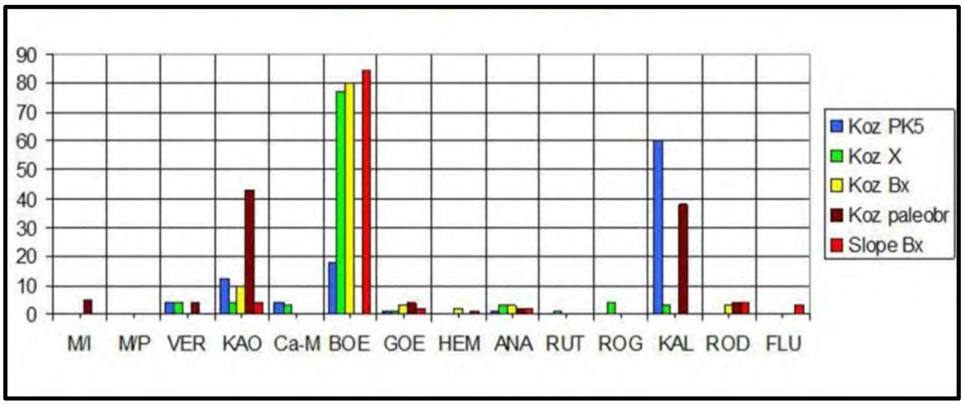


Figure 14: Mineral composition of bauxite and bauxitic-clayey sediments at Kozina and Slope villages. Legend: M/I - muscovite/illite, M/P - muscovite/paragonite, VER - vermiculite/chlorite, KAO - kaolinite, Ca-M - Ca montmorillonite, BOE - boehmite, GOE - goethite, HEM - hematite, ANA - anatase, RUT - rutile, ROG - hornblende, KAL - calcite, ROD - rhodochrosite in FLU – fluorite. All samples are related to the main paleokrastic period except “Koz. Paleobr.” which represents regolithe horizon in Lower part of the Liburnian Formation.

In two-dimensional motorway cuts, the paleokarst surface is manifested in the form of pocket-like and gently undulating depressions measuring a few decimetres to several metres ("*potholed paleokarstic depressions*" and "*hummocky paleokarstic depressions*" *sensu* Vanestone 1998) (Fig. 15A), and larger, distinctly irregular depressions (Fig. 9) and shafts measuring a few metres (Fig. 15B, C) to as much as several tens of metres in size.

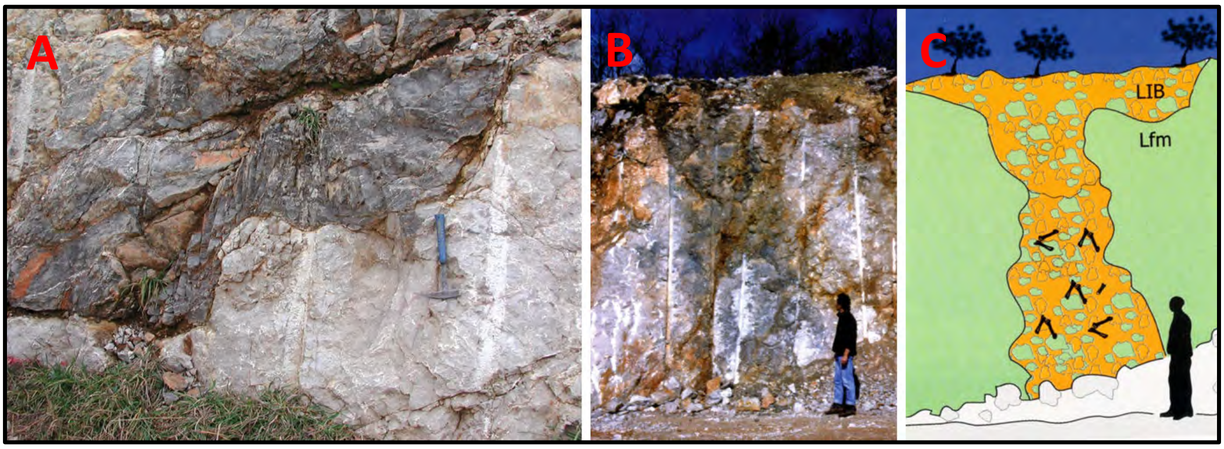


Figure 15: A) The undulating paleokarst surface separates the Upper Santonian light grey shallow marine massive limestone of the Lipica Formation and Maastrichtian dark grey plustrine limestone of the Liburnija Formation; motorway road-cut at Kozina village. B, C A) paleokarst shaft filled with breccia, in which remains of fossilvertebrates were found, i.e. the teeth and crushed bones of dinosaurs and crocodiles (the Maastrichtian) (from Košir *et al.,* 1999)

Depressions are filled/covered with paralic carbonates (Fig. 15A), while "ferruginous-bauxite-carbonate" sediments and karst breccias (Figs. 10, 13 A) often directly overlie the paleokarst surface. The highly unevenly thick, non-homogeneous clast- and matrix-supported breccias are up to a little more than a metre thick (Fig. 10). The matrix is mostly "ferruginous-bauxite-calcite", while grains of crystal calcite are also frequent (Fig. 13). In some spots, directly under the paleokarst surface, it is possible to observe up to a few decimetres wide and up to several metres deep dissolution-enlarged subvertical vadose fissures filled with "ferruginous-bauxite-carbonate" sediments.

Biodiagenesis

Certain cements in breccias exhibit characteristics typical of biodiagenesis (Fig. 16) which is the result of the activities of various microorganisms in the vadose diagenetic zone (Jones & Khale, 1985). Due to various pedogenetic, diagenetic and biodiagenetic processes as well as due to the similar colouration of the matrix, weathered clasts and the host rock, it is often difficult to draw a boundary line between the individual component parts of breccias.

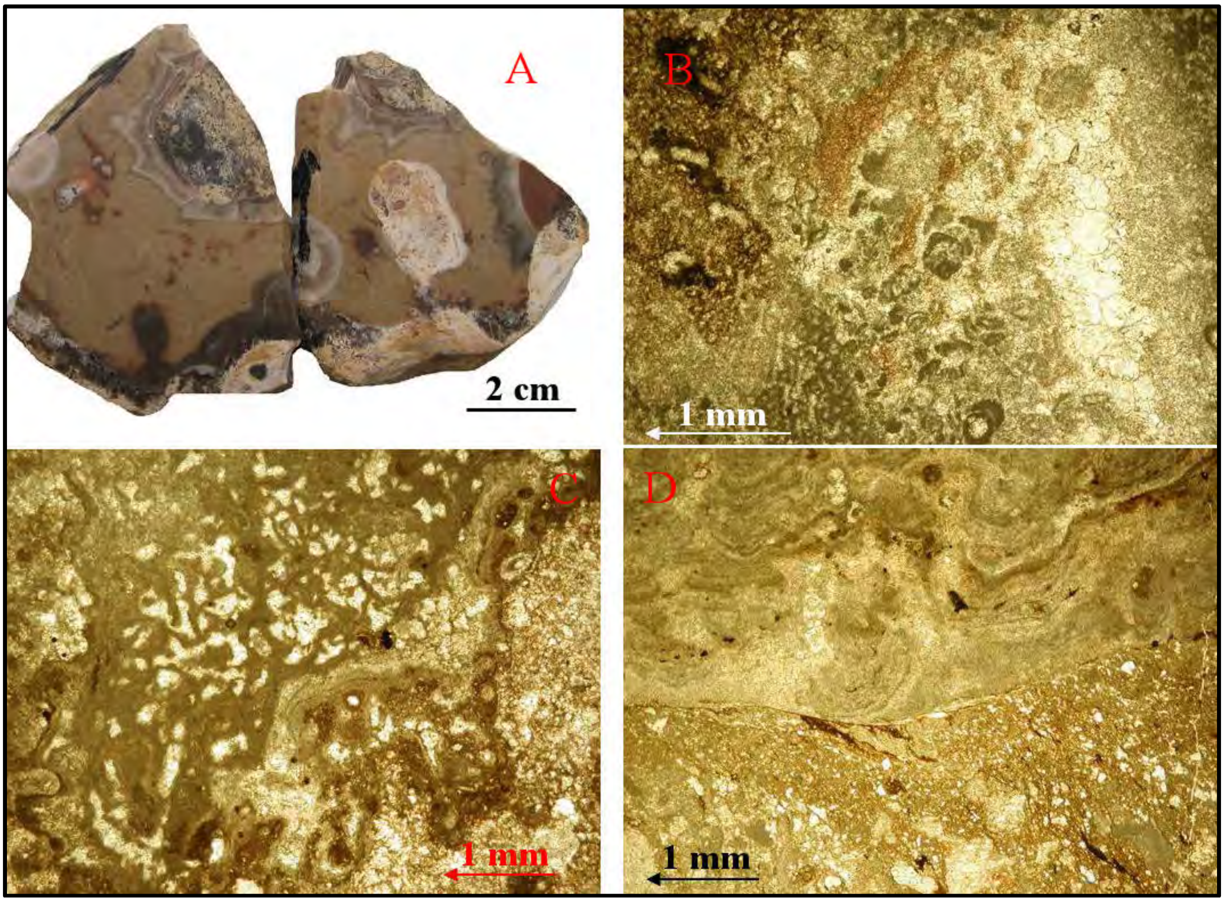


Figure 16: Biodiagenesis: A) The clast of pedogenic-karstic breccia indicates several generations of dissolution and filling. The dark brown border is the result of biodiagenetic processes; B) Part of biodiagenetic rim built of brown microsparite to clotted micrite. Altered rim pass over to relatively well preserved host rock, what is reflected in different preservation level of the foraminifera test (lower left corner of the photommicrograph) C) The neomorphised host rock (microsparite) transitions (right corner of the photommicrograph), via the belt of brownish microsparite or clotted, partly laminated micrite, into a belt of fibrous micrite arranged into an alveolar-septal structure. D) Erosional contact between biodiagenetic rim (microstromatolites) and brown sandy-silty deposit representing a matrix of the breccia.

Stabile isotops ($\delta^{13}C$ and $\delta^{18}O$ values of paleokarst related deposits and the host rock)

In general, a variety of cave infilling deposits and the amount of surface derived material decrease with the distance from the paleokarstic surface. Below the paleokarstic surface $\delta^{13}C$ and $\delta^{18}O$ values of cavity deposits usually exhibit good correlation with trend significant for meteoric diagenesis (Fig. 17).

Similarly, the vadose channels and voids are also filled with sediments and flowstones, but they usually differ from those of phreatic cavities in higher content of noncarbonate material, lower $\delta^{13}C$ values of carbonate material and more distinctive pedogenic modification of the cave deposits.

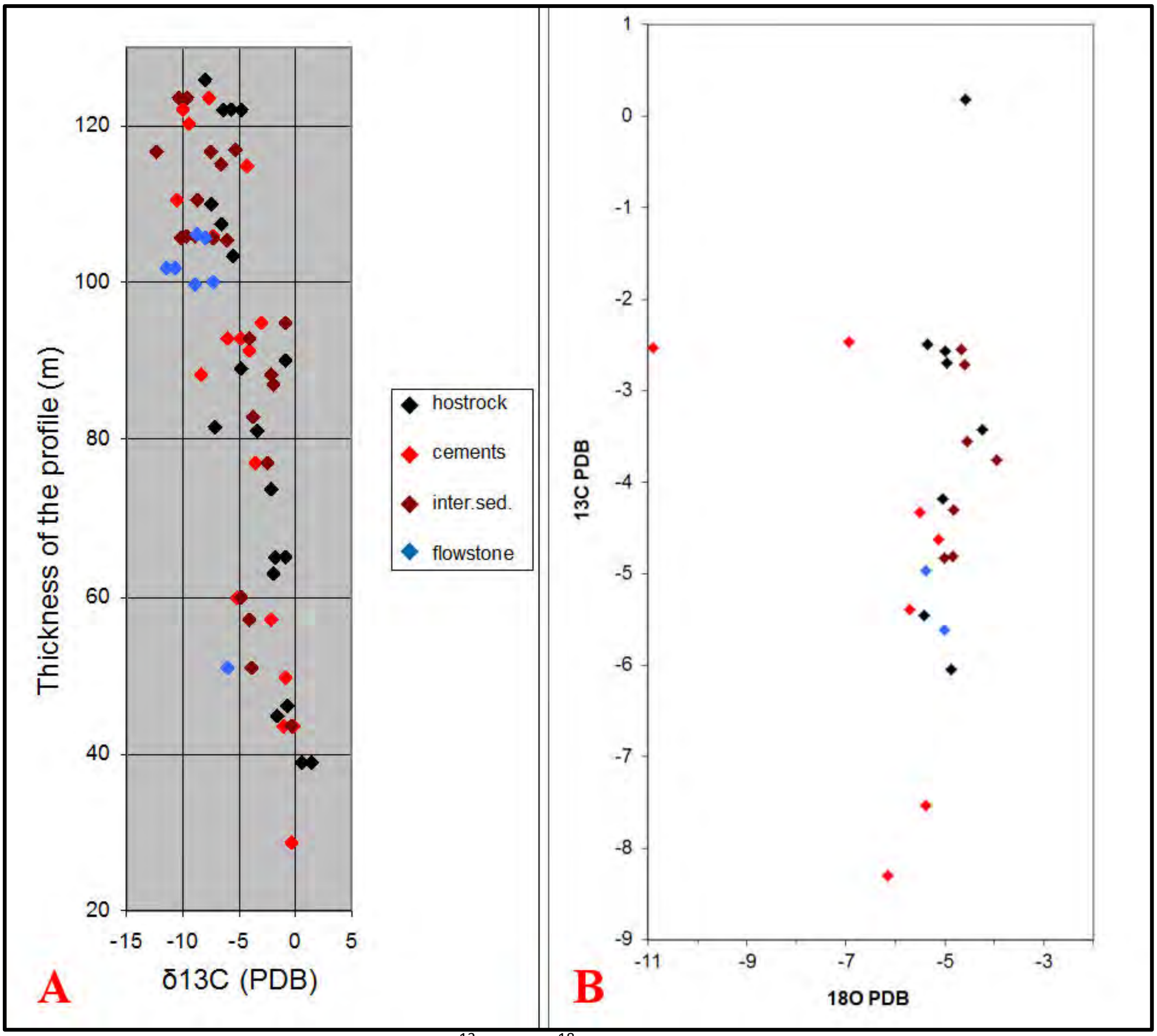


Figure 17: Below the paleokarstic surface $\delta^{13}C$ and $\delta^{18}O$ values of hostrock, cements, flowstone and internal sediments exhibit good correlation with trend significant for meteoric diagenesis (meteoric calcite line of Lohmann). A) Podgrad profile; B) Kozina motorway road-cut.

Diagenesis of the host rock *(Fig. 18)*

Carbonate sediments below the paleokarstic surface have been subjected to numerous diagenetic alternations in various diagenetic environments from time of their deposition till present. However the most important for today's diagenetic appearance is emplacement of carbonates in meteoric diagenetic environment soon after their daposition or in eugenetic stage of diagenesis.

In carbonate rocks immediately below the paleokarstic surface differences in diagenesis are observable already in the field (i.e. different staining and recrystalisation of certain parts of the bedrock below the paleokarstic surface, patchy development of secondary porosity…)(Fig. 11, 12 left). The most completely developed and expresed paragenetic sequences can be observed in moulds of primarely aragonitic parts of rudist shells and theirs intraskeletal pores, biuturbation burrows and secondary dissolutional vugs (Figs. 11 left, 12A, B, 18). Depending where the samples were taken (because of unhomogeneous nature of diagenetic alternation of the rock) but as much as twelve early diagenetic phases has been detected in places (Fig. 18).

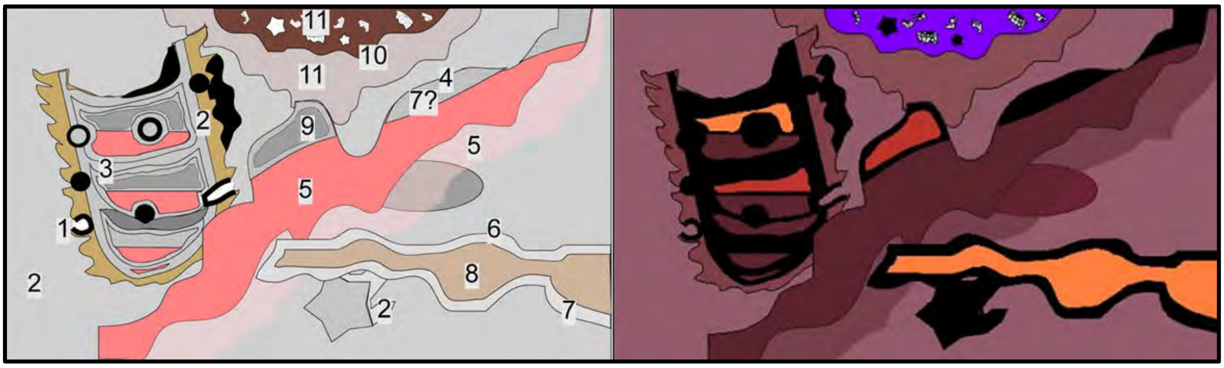


Figure 18: An idealized succession of the main diagentic phases of the upper part of carbonate sequence below the paleokarstic surface at Kozina village (see Fig. 10) – under transmitted light (left) and under cathodoluminiscence (right).

Paleokarstic pit cave with dinosaur remains

(compiled from Debeljak et al., 1999, 2002; Košir et al., 2000; Otoničar, 2006)

During motorway construction a diverse assemblage of terrestrial vertebrates was discovered in a road cut at Kozina village (Figs. 15B, C). Numerous teeth and fragmented bone remains occur in polymict breccia that fills a paleokarstic shaft or pit cave (Fig. 19). This distinctive vertebrate assemblage comprises dinosaurs and crocodiles and in traces indistinctive remains of fishes, amphibians and other reptiles (Debeljak *et al.* 1999; 2002).

Vertebrate remains have been found in a poorly sorted, coarse-grained matrix to clast supported limestone breccia that infills a larger-scale, up to 4 metre wide, paleokarstic pit cave of irregular shape which extends more than 10 metre downwards from the paleokarstic surface (Figs. 15B, C, 19A). The breccia is composed of angular to subrounded clasts of limestone with rudist fragments (typical lithologies of the Lipica Formation that underlies the unconformity) and clasts of dark grey and pedogenically modified limestones, characteristic of the Liburnian Formation, which overlies the unconformity. Vertebrate remains and breccia clasts of the overlying Liburnian formation are missing only in the lowermost part of the pit.

Abundant 0.1 mm to 10 cm long bone fragments and teeth are embedded in matrix consists of silt- to sand-sized carbonate particles and subordinate clayey material, ferruginous ooliths and pyrite. The breccia generally exhibits a chaotic fabric, yet grading and preferred (bedding-parallel) orientation of elongate bone fragments and clasts as well as indistinct dish-like stratification occur in places. The fabric and the composition of the cavity-infilling material as well as the structure of the vertebrate fauna (see below) suggest that the vertebrate assemblage represents an allochthonous (transported) thanatocenosis.

The age of the vertebrate-bearing deposits has not been determined directly. According to regional geological data (Jurkovšek *et al.*, 1996, 1997; Otoničar, 2006), the total gap expressed by the paleosurface and paleokarst-related deposits at Kozina may range from Late Santonian to Late Maastrichtian (Figs. 4, 5).

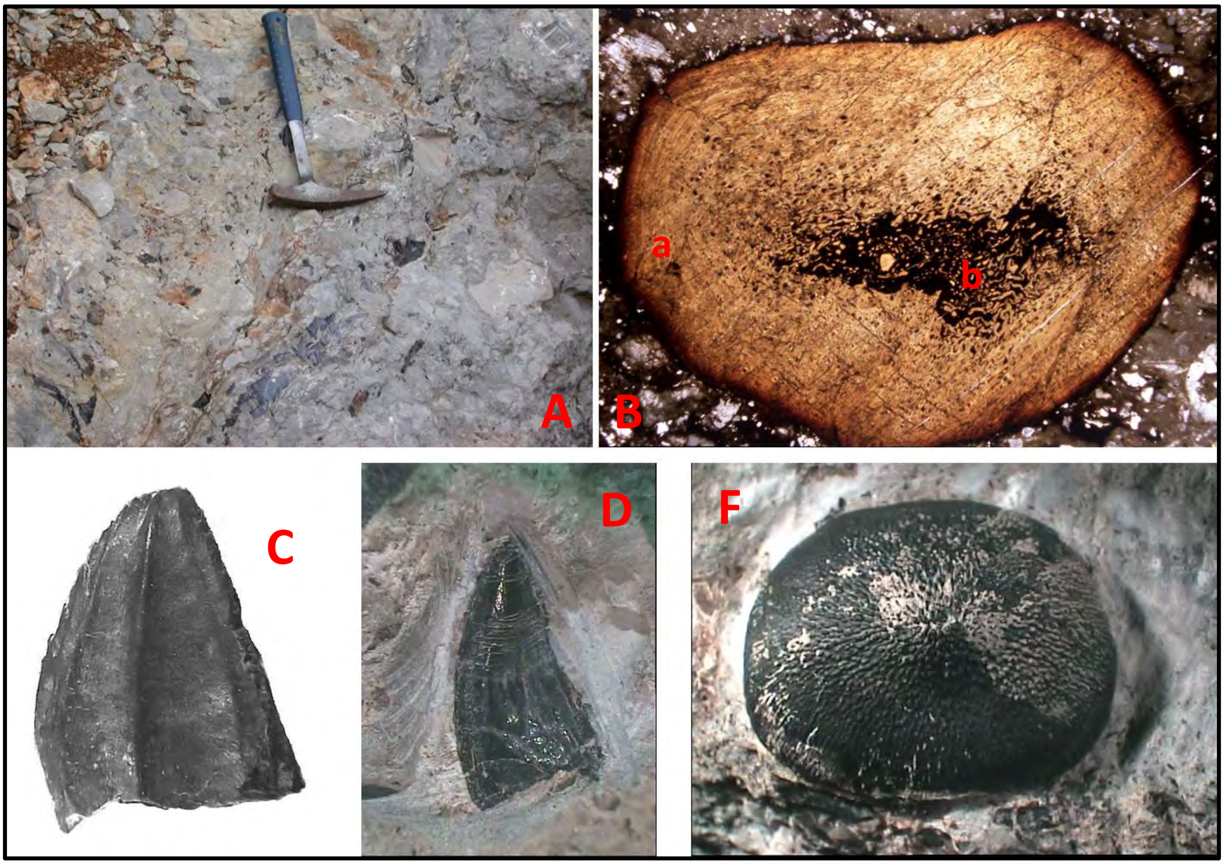


Figure 19: A) Mainly dinosaurian bone fragments in breccia that infills a paleokarstic pit cave; motorway road-cut at Kozina village. B) Cross-section of a limb bone: a –compact bone; b – cancellous bone. Note annual growth layers (a). C) Hadrosaur tooth with characteristic ridge in the middle (side view),and enlarged papillated lateral margin. D) Dromaeosaurian tooth. Carnivorous dinosaurs had blade-like teeth with typically serrated lateral margins to shred meat fibers. F) Button-shaped crocodilian tooth. Such *durophagous* teeth were specialized for crushing turtle armours and hard moluscan shells.

Overlying Liburnian Formation

The facies and sedimentary successions of limestones of the Liburnian Formation, which deposited over the markedly uneven karst surface, change quickly in the lateral direction or limestone of certain facies is spatially highly restricted (Fig. 10). The oscillating transgression over the paleokarst surface is indicated by the sedimentary succession arranged in the shallowing upwards cyclical parasequences (Fig. 20A). The limestone is frequently interwoven with rhizolithes and pseudo-microkarst voids (*sensu* Freytet & Plaziat, 1982) (Figs. 20A, B) that show the breccia-like and "pseudo-breccia-like" texture (Fig. 20C). In the bottom few metres of the succession, only one cycle ends with a "true" paleokarst surface (Figs. 20A, D, E) covered with regolith (Fig. 20D), which also includes karst pockets that are up to a few metres deep ["*pit cave*" or "*dissolution pit*" (*sensu* Mylroie & Carew, 1995)] (Fig. 20E).

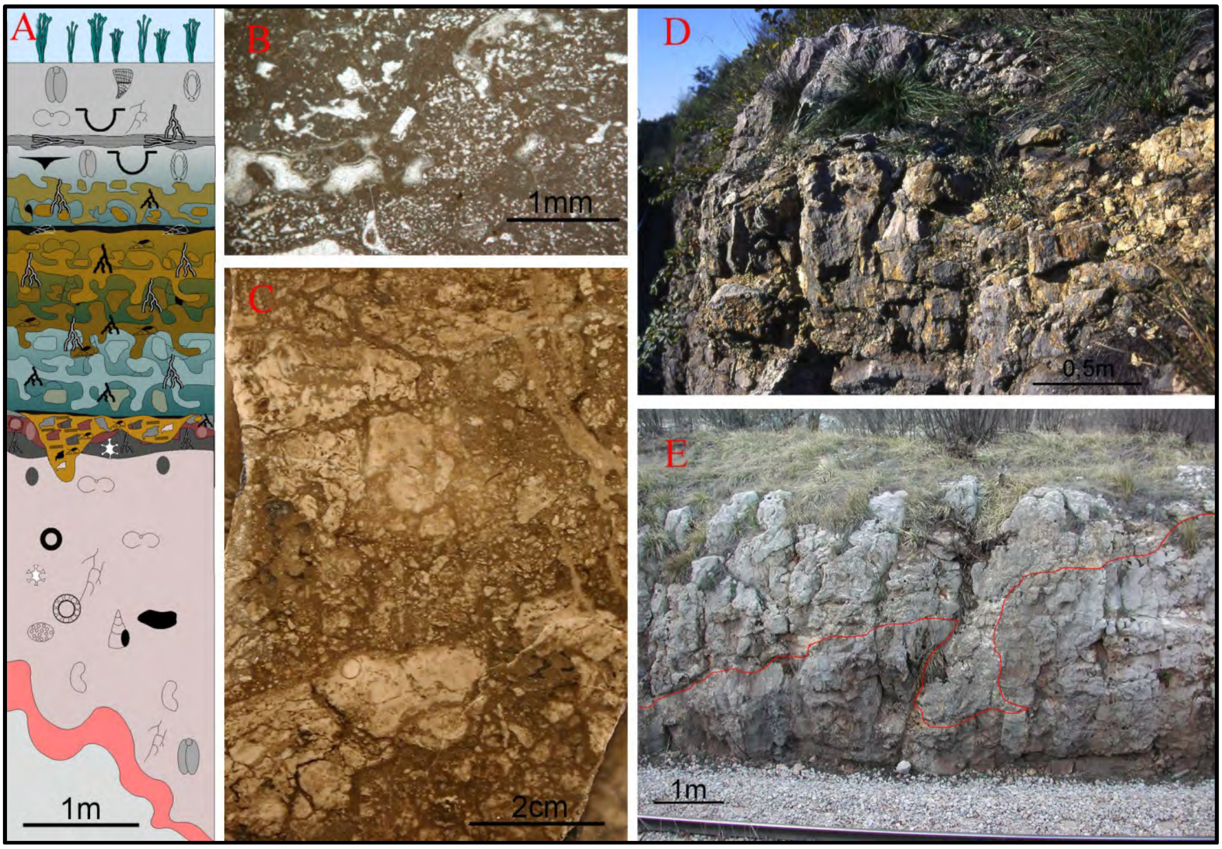


Figure 20: A) A short geological profile of the direct cover of the paleokarst surface (bottom left corner) shows micrite limestones which, together with foraminifera in the bottom part, show at least a limited influence of seawater in a sedimentation environment. Higher up, the micrite limestones underwent several phases of pedogenic modification, and at least one rather prominent paleokarst surface interrupts them; B) Pedogenically modified micrite with typical rhizolits; C) Breccia-like or pseudo-breccia-like texture of pedogenically modified limestone with several centimetre-size nodules; D) Regolith, with matrix which, in addition to the calcite grains, is abundant in kaolinite (>40 wt.%), but does not contain bauxite minerals, covers the paleokarst surface in the bottom part of the Liburnian Formation, only a few metres above the main paleokarst surface; E) A fairly dynamic paleokarst surface in the bottom part of the Liburnian Formation (see A and D) with a karst pocket.

Discussion

As it was already mentioned above, in the area of the Julian Alps, the Slovenian Basin and the northern part of the AdCP, a collision in the area north-east of the present Periadriatic Lineament caused the creation of a synorogenic sediment system with a foreland flexure basin and the related peripheral bulge as well as the intermediate transitional (i.e. inflection line) area as early as the Upper Cretaceous (Otoničar & Košir, 2002, Otoničar, 2007). The primary, probably Upper Campanian, uplift of the peripheral bulge placed shallow-marine, diagenetically immature and unaltered carbonate sediments, which were deposited in the internal parts of the northern section of the AdCP (Fig. 21), into the area of the meteoric and mixed diagenetic environment (Otoničar 2006, 2007). Here, they were subjected to hardening (neomorphism, cementation) on the one hand, and selective dissolution (formation of vadose and phreatic channels/vugs) on the other (Otoničar, 2006). During these processes, porosity decreased, while the karst system's permeability increased (Fig. 22A).

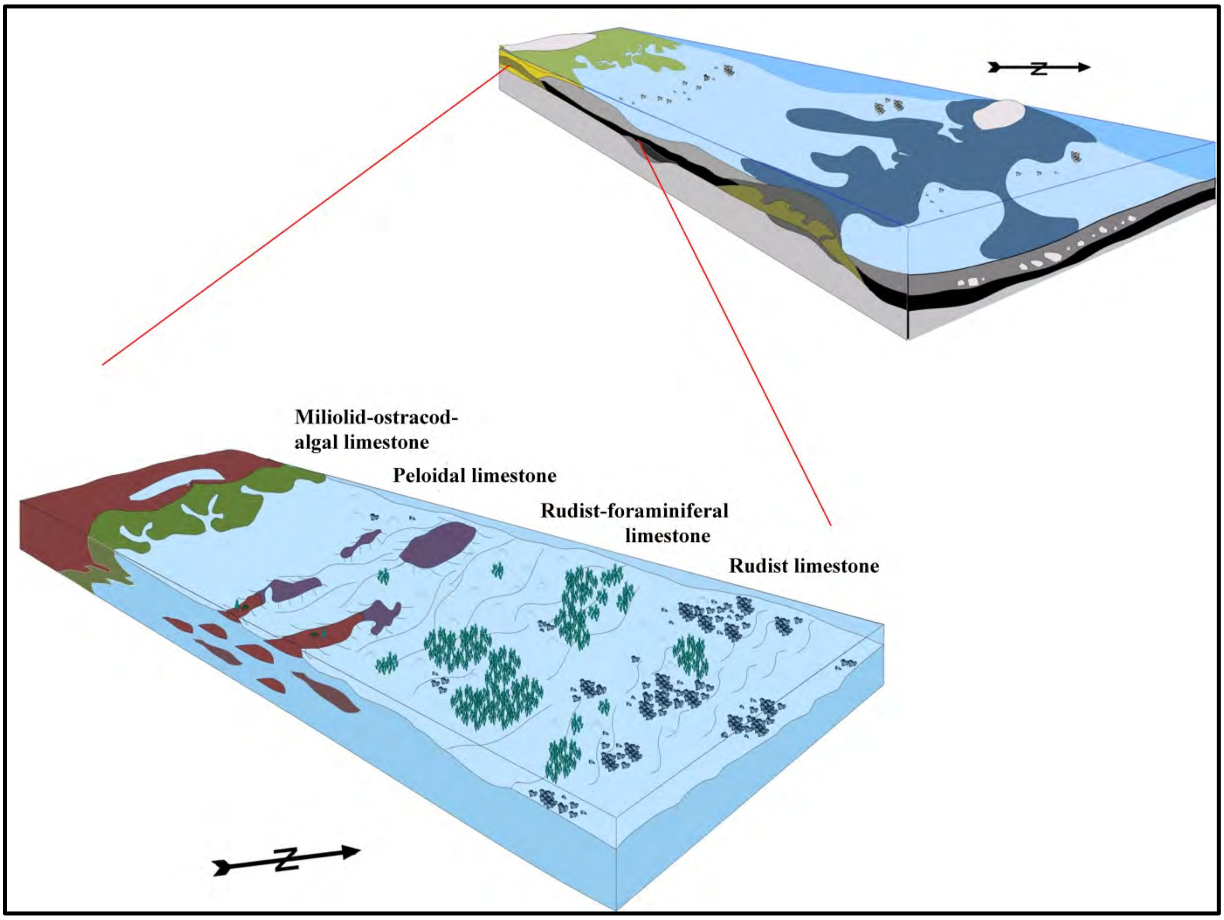


Figure 21: Idealised depositional model of the AdCP in the area of present-day SW Slovenia and Istria (Coniacian–Santonian).

The creation of the secondary dissolution porosity, the reddish rock (from oxidation of iron sulphides), and occasional precipitation of carbonates and pyrite could be the result of reduction/oxidation processes that take place in the mixed zone area (Stoessell, 1992). On the other hand, the reddish colourations directly under the paleokarst surface could be the result of the fine soil material infiltrating the porous carbonate (Foos, 1991; Rossinsky & Wanless, 1992).

Diagenetic and speleogenetic features of the area in question indicate processes that took place in the young limestones that experienced only early diagenetic alteration prior to karstification, mainly in the meteoric and mixed meteoric/marine diagenetic environment. In view of the overall extensiveness of otherwise low and preferentially horizontally oriented (originally) in-filled cavities or horizons of smaller, connected vugs, along with general geological characteristics (dip similar to layers below the paleokarst surface, characteristics of sediments and cements of fills etc.), we suggest that dissolution took place in the area where the meteoric and seawater mixed on the periphery of freshwater lenses during the eugenic stage of diagenesis (*sensu* Choquette & Pray, 1970). With continuous uplifting of the area, the caves were placed into the epiphreatic and/or vadose zone, where they were gradually filled with sediments and flowstone. Meanwhile, the upper parts of the carbonate aquifer were constantly exposed to karstification and the lowering of the karst surface, which brought the partly filled underground karst caves closer to the surface. Simultaneously with the lowering of the karst surface and the formation of karst features, pedogenic modification of the residual and eolian transported sediments took place along with the formation of the ferruginous-bauxite soil which was occasionally resedimented into unfilled parts of paleokarst cavities and surface depressions, karst pockets and widened fissures. On the one hand, the carbonate micrite and silt, which often fill large parts of cavities, represent undissolved or neomorphically altered original carbonate sediment which bears great geochemical similarities with the neomorphised host rock; on the other hand, they represent flowstone disintegrated by weathering, especially calcite rafts. As the karst surface was getting closer to the phreatic caves, which were either partly or entirely filled, the ceilings of these caves disintegrated completely; the blocks formed during this process "floated" in the cave or surface kars related sediment. In the course of surface processes of weathering and pedogenesis, the blocks became rounded, recrystallized and coloured. At the same time, the paleokarst surface under the soil was subjected to subcutaneous karstification. Geomorphologically, the disintegrated caves were probably expressed as somewhat oblong, more or less shallow depressions, i.e. denuded or unroofed caves (*sensu* Mihevc, 2001; Knez & Slabe, 2002). Breccias, which cover parts of irregular paleokarst relief, also frequently resulted from the disintegration of caves and cave deposits on the paleokarst surface or directly beneath it, which is especially obvious in places where the clasts are also formed of flowstone.

Bauxites indicate the humid tropical or subtropical climate during karstification and the processes of pedogenesis that lasted at least a million years (Birkeland, 1984). Such climate can also be inferred indirectly, as the warm-water carbonates were still deposited on the submerged parts of the platform.

Although lenses of freshwater undoubtedly existed under the fairly extensive karst land in the hinterland of sedimentary environments, where the carbonate sequences of the lower part of the Liburnian Formation were deposited, the sedimentological and paleontological characteristics (e.g. foraminifera) of the limestone directly above the paleokarst surface indicate, at least in the Kozina area, at least some marine influence. Thus we suggest that the sediments of the lower part of the Liburnian Formation were deposited in peripheral marine to brackish, possibly (in some places) also freshwater environments of closed lagoons that were partially marshy (i.e. paralic environments) (Fig. 22).

The quick lateral and vertical alteration of the facies of the lower parts of the Liburnian Formation (Fig. 20) can be explained by the oscillating transgression over the markedly uneven karst surface (Fig. 22A). Some spatially very restricted lithofacies (only a few m^3 to a few tens of m^3) represent sediments of karst depression fills during the "blue hole" transgression phase (*sensu* Durn *et al.,* 2003) (Fig. 22B). Considering the entire area of the northern part of the AdCP (SW Slovenia and Istria), the paleokarst surface is covered with carbonates of the Liburnian Formation of the Maastrichtian age (Drobne, 1977; Jurkovšek *et al.,* 1996; Otoničar, 2006, 2007) only in the Kras and in the vicinity of Kozina. Only here was thus possible, in relation to the discussed "main" paleokarst period, for some paleokarst pockets and shafts to be filled, in the initial transgression phase, with breccia that contained among other vertebrate remains also crushed dinosaur bones and teeth (Fig. 10). We suggest that the remains of fossil vertebrates, together with sediments that overlie the paleokarst surface and clasts of the host rock, were resedimented in some paleokarst pockets and shafts from the nearby freshwater and/or brackish marshes that were located between the karst mainland and the sea (Figs. 22B, C).

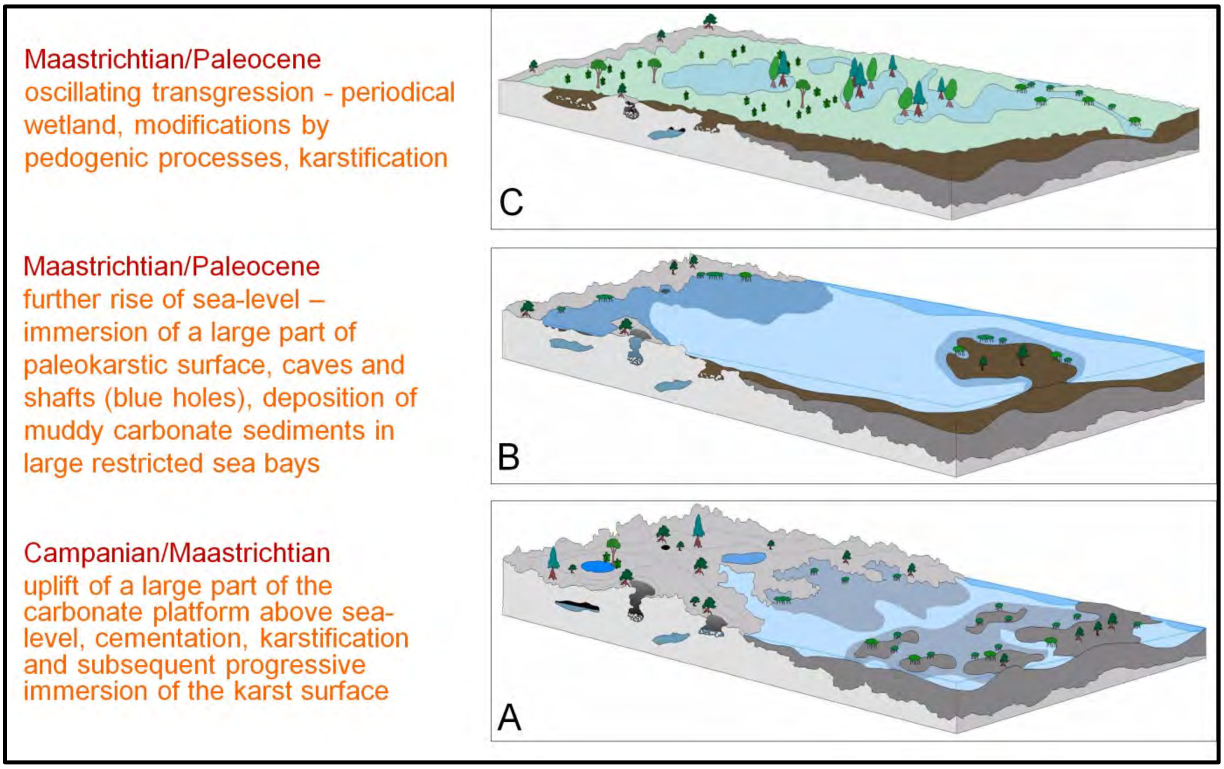


Figure 22: Evolution of the paleoenvironment between the Campanian/Maastrichtian and the Paleocene in the area of the present-day SW Slovenia and between Trieste and Gorica/Goricia in NE Italy. The paleokarst surface that developed on the peripheral bulge is covered by palustrine carbonates of the synorogenic carbonate platform.

SEŽANA (No. 3): HYPOGENICALLY-FORMED DEDOLOMITE BODIES IN THE MID-CRETACEOUS DOLOMITE OF THE POVIR FORMATION (KRAS, SLOVENIA)

Andrea Martín-Pérez, Adrijan Košir & Bojan Otoničar

Extensive road-cuts in Cretaceous carbonate succession exposed along the motorway near Sežana (Kras, Slovenia) revealed remarkable, decametre-size yellow to red rock bodies crosscutting dark grey bedded dolomite and forming sheet-like structures parallel to the bedding. The bodies appear to be limited to the massive and laminated bituminous dolomite of the Albian-Cenomanian Povir Formation and form a 3-dimensional network pattern, likely predisposed with intersecting vertical fractures and bedding-plane partings (Fig. 23). XRD and petrographic analysis shows calcite composition of the yellow-red rock and indicates its formation predominantly through dedolomitisation and replacement of the host dolomite (Fig. 24). Typically, dedolomites have chalky appearance and high microporosity. Original dolomite shows planar-s textures, either polymodal (Fig. 24B) or unimodal with crystals having cloudy brownish centers and transparent rims. During dedolomitisation this fabric can be partially preserved, where the rims of the crystals transform into calcite while centers remain dolomitic (Fig. 24C). Partial dedolomitisation can also result in calcite mosaics with relics of grey dolomite rhombs. Total dedolomitisation results in microsparite mosaics (Fig. 24D), which can preserve or not the rhombic morphology of the dolomite precursor. Typically, these calcite mosaics are rich in intercrystalline iron oxides (Fig. 24D). Blocky calcite cements are also abundant. Preliminary informational isotopic analyses of few samples suggest that dedolomitization was taking place in meteoric conditions. The stratigraphic unit of bituminous dolomite with dedolomite is underlain by a thick succession of dolomite, interbedded with irregular, several metres thick beds of dolomite breccia.

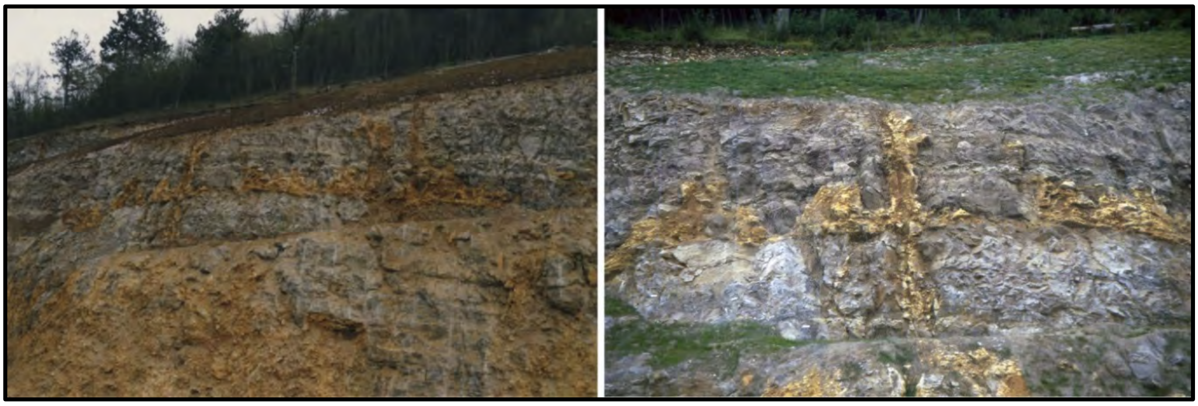


Figure 23: Phantom karst exposed in a motorway road-cut near Sežana (Kras). Brownish stained portion in otherwise gray dolomite part of the Povir Formation represets dedolomite or calcified dolomite. Note local criss-cross nature of dedolomite body following fissures and bedding plane partings (upper part of both figures).

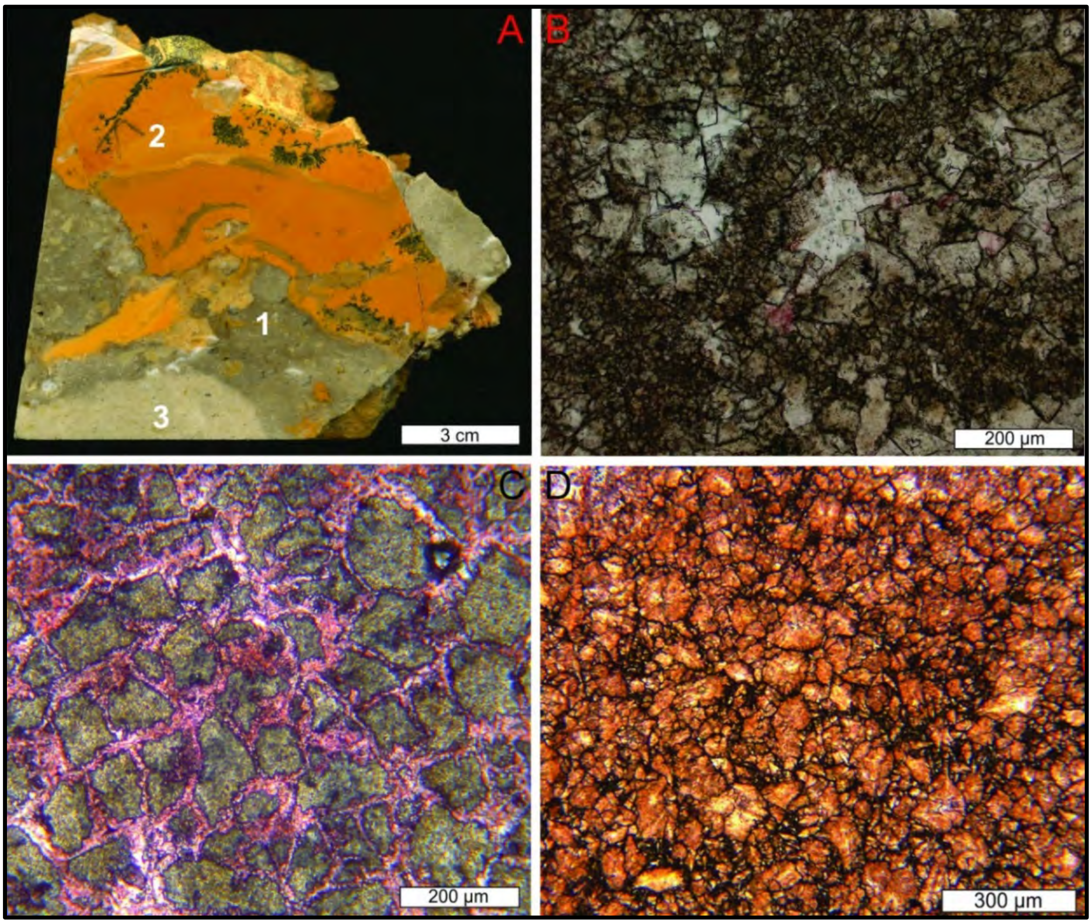


Figure 24: A) a cut slab of dedolomite sample, where different textures and mineralogies are visible; B) original grey dolomite; C) partial dedolomitization, which affects rims of rhombic dolomite crystals (pink); D) total dedolomitisation, resulting in yellow rock formed by calcite mosaics rich in intercrystalline iron oxides.

Composition, structure and geometry of the breccia beds indicate that they most probably formed by the collapse associated with dissolution and complete removal of evaporites (Ca sulphates), originally present in the dolomite succession. We hypothesise that the dedolomite and collapse breccia are two closely related phenomena, namely, that the dedolomitisation resulted from upward recharge of Ca sulphate-rich solution formed by dissolution of evaporates in meteoric conditions.

RIBIŠKO NASELJE/VILLAGGIO DEL PESCATORE NEAR DEVIN/DUINO (No. 4)
Bojan Otoničar

When researcher gave a name to well preserved filled Upper Cretaceous paleokarstic cave found in cliffs of Devin/Duino "The cave of the last dinosaur" (Cucchi *et al.*, 1984) I suppose they didn't have a clue that small old quarry less than some 2 km from there hiding a few completely preserved dinosaur and crocodile skeletons (Fig. 25). Even more, although dinosaurs were not found in a cave that would serve them as a shelter, the founding is at least indirectly related to paleokarst. Namely vertebrate remains were found in a lens of well-bedded, black limestone, 10 meters-thick and 70 meters long, of the upper Campanian-Paleocene Liburnian Formation embedded in coarse-grained breccia of the same formation (Figs. 26, 27). It should be stressed that the lens of the Liburnian Formation here represents a patchy erosional remain of palustrine sediments that were deposited over an irregular paleokarstic relief developed on adjacent Campanian limestone, probably preserved because of its position in paleokarstic depression (a blue hole deposite?)(Fig. 26B). Bones were found on different levels within the lens (Dalla Vecchia, 2009) (Fig. 26B), which supposed to be formed in less than 10,000 years (Arbulla *et al.*, 2006 after Dalla Vecchia, 2009). The occurrence of the foraminifer Murciella *cuvillieri* immediately below the bone bearing lens, its range, and the stratigraphic framework of the Karst Plateau, and presence of the alligatoroid Acynodon, suggest a Late Campanian to Early Maastrichtian age of the lens of the Liburnian formation (Dalla Vecchia, 2009).

"The Adriatic-Dinaric Island had a maximum estimated sur face approximately 100,000 km^2 (based on Camoin *et al*., 1993), comparable to that of Cuba today. All individuals represented in the sample are much smaller than average North American adult hadrosaurids (Weishampel *et al*., 1993) and lack evidence of osteological immaturity suggestive of a juvenile condition. This small size might plausibly be due to insular dwarfism (e.g., Azzaroli, 1982; Lomolino, 1985), a phenomenon already observed in other insular dinosaurs (Jianu & Weishampel, 1999; Dalla Vecchia *et al.*, 2001)." (Dalla Vecchia, 2009)

For further reading on dinosaurs see Dalla Vecchia (2009) and references therein.

Figure 25: Left: Replica of Skeleton of a hadrosauroid dinosaur, *Tethyshadros insularis* Dalla Vecchia, 2009, from the Liburnian Formation (late Campanian-early Maastrichtian) of Ribiško naselje/Villaggio del Pescatore in the Trieste Province of northeastern Italy - one of the most complete dinosaur fossil ever found. Right: reconstruction of the late Campanian-early Maastrichtian palustrine depositional environment of the lower part of the Liburnian formation.

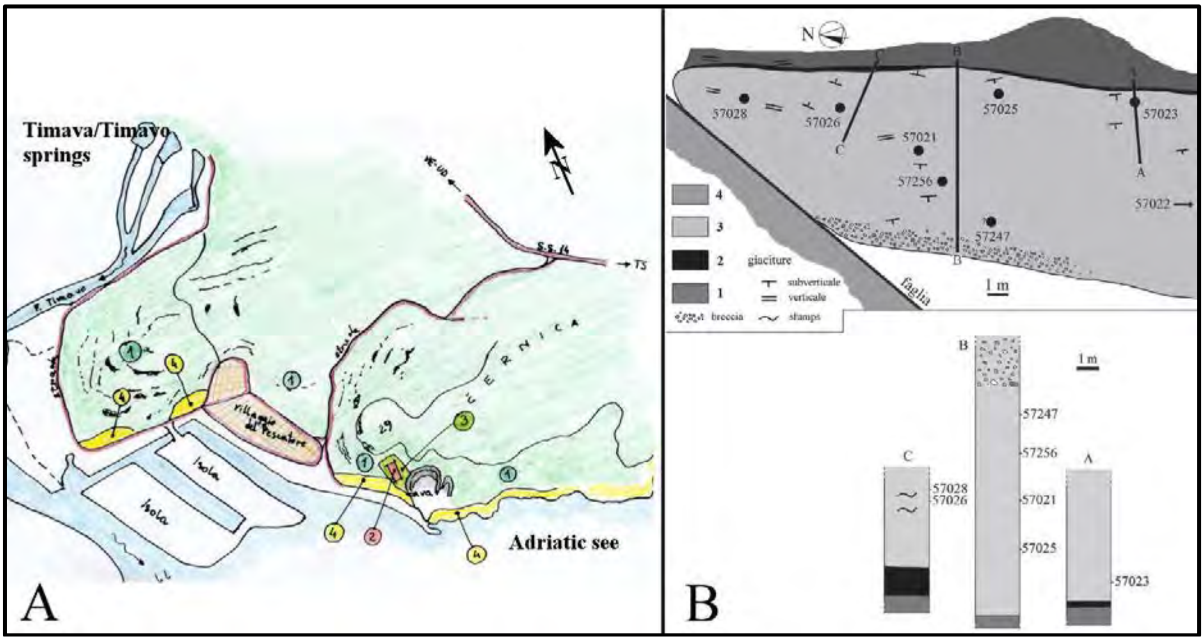


Fig. 26: A) The geologic sketch of the Ribiško naselje/Villaggio del Pescatore area (Paolo Sossi). Legend: 1) gray limestone with rudists fragments, 2) black laminated limestone, 3) breccia with centimetre scale clasts, 4) limestone with briozoans, echinoderms and foraminifera Keramospherina tergestina. B) The topographic and stratigraphic position of some tetrapod remains excavated at the Ribiško naselje/Villaggio del Pescatore site (Dalla Vecchia, 2008). Legend: 1) "basal” dark gray limestone, 2) transitional bed, 3) black laminated limestone (“laminites”); 4) gray limestone with fragments of rudist bivalvs.

Figure 27: A) Ribiško naselje/Villaggio del Pescatore dinosaurian site. A) Late Campanian-early Maastrichtian laminated to thin-bedded black micritic limestone of Liburnian Formation where dinosaur and crocodile skeletons were found. B, C and D) rather limited thin-bedded black limestone body is surrounded by chaotic

clast and matrix supported coarse-grained breccia with clasts of Liburnian Formation and those derived from lithologies below the paleokarstic surface. Note clast with bauxitic deposits that fill small paleokarstic voids (C). Predominantly highly irregular clast are immersed into micritic matrix resemble palustrine deposits of the Liburnian Formation.

SLIVNO/SLIVIA (data from our own observations and from Venturini & Tentor, 2010) (No. 5)
Bojan Otoničar

Two kilometres north of Nabrežina/Aurisina near Slivno/Slivia village a few relatively small abandoned quarries occur (Fig. 28). There a coarse-grained densely packed chaotic polymictic carbonate breccia had been exploited as architectonic stone (Fig. 29). In the area of Slivno/Slivia two breccia body occur, bigger being app. 450 m long, 200 m wide and up to few tens of metres thick. The breccia is overlying Upper Cretaceous rudist limestone or Aurisina Limestone Formation (Cenomanian/Turonian-Lower Campanian) but according to geological map not its uppermost part. Where visible, the contact between breccia and underlying rudist limestone could be described as relatively sharp angular unconformity. It has been suggested that according to apparent stratigraphy the breccia is situated more than 600 m below the paleokarst surface visible near Nabrežina/Aurisina (see Fig. 28). Clasts in breccia belong to lithologies of different stratigraphic levels of the Aurisina Limestone Formation which predate paleokarst period (Coniacian to Lower Campanian) but also to Liburnian Formation which postdate paleokarst period (Upper Campanian/Lower Maastrichtian) (Fig. 29). Lithologies related to paleokarst, like reddish stained limestone of underlying Aurisina Limestone Formation (Fig. 29D) and bauxite, are also presented. No clasts composed of Tertiary lithologies have been proven.

The origin of breccia has been interpreted as collapse breccia related to formation of syndepositional (Maastrichtian) tectonically controlled basins of limited size (i.e. "pull apart" s.l.) in extensional tectonic regime (Venturini & Tentor, 2010). Faults supposed to be later repeatedly reactivated what is the reason for present position of the breccia (Venturini & Tentor, 2010). The same authors claim that breccia or tectonically controlled small basin were formed during the same tectonic event and on similar way than "depression" with breccia and black laminated limestone with vertebrate remains in Ribiško naselje/Villaggio del Pescatore.

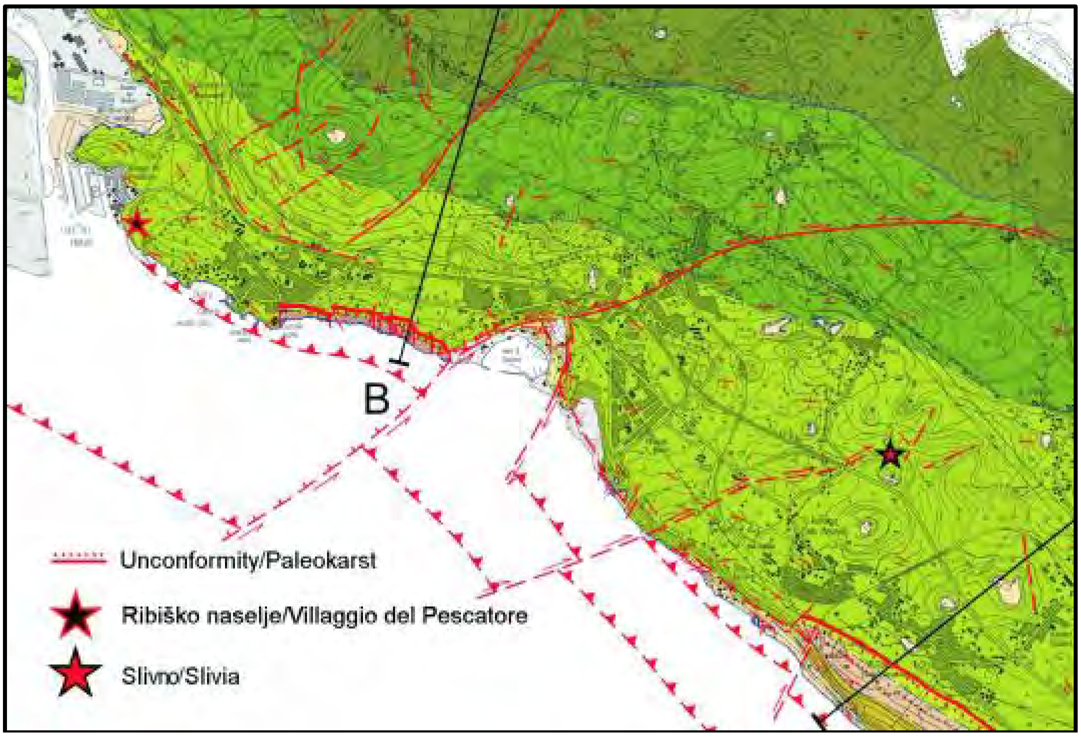


Figure 28. Geological map of the area between Nabrežina/Aurisina and Ribiško naselje/Villaggio del Pescatore. Light green area below the unconformity and with the marked field trip locations (stars) belongs to Aurisina Limestone Formation, while narow light green area above the unconformity to Cretaceous part of the Liburnian Formation (Carta Geologica del Carso Classico 1:50.000; Lizzi *et al.*, 2008).

Figure 29. Slivno/Slivia quarry: Polimictic coarse-grained clast supported chaotic breccia with limestone clast mainly derived from formation immediately below the paleokarstic surface. However some clast belongs to the palustrine limestone of the Liburnian Formation. A) A natural outcrop of the Slivje/Silvia breccia, B) Artificially cutted wall of the quary. Note chaotic distribution od clast of different size. C) Contact between clast are mainly stilolitic. D) Reddish stained clast suggesting modification under subaerial exposure conditions (i.e. paleokarst).

Afternoon field trip **(B):**

LATE TRIASSIC, LATE JURASSIC AND LATE CRETACEOUS PALEOKARSTS OF THE WESTERN PART OF CENTRAL SLOVENIA

(Paleokarsts of the marginal parts of the Adriatic carbonate platform)
Wednesday, 15.6.2016, 13.00–20.00

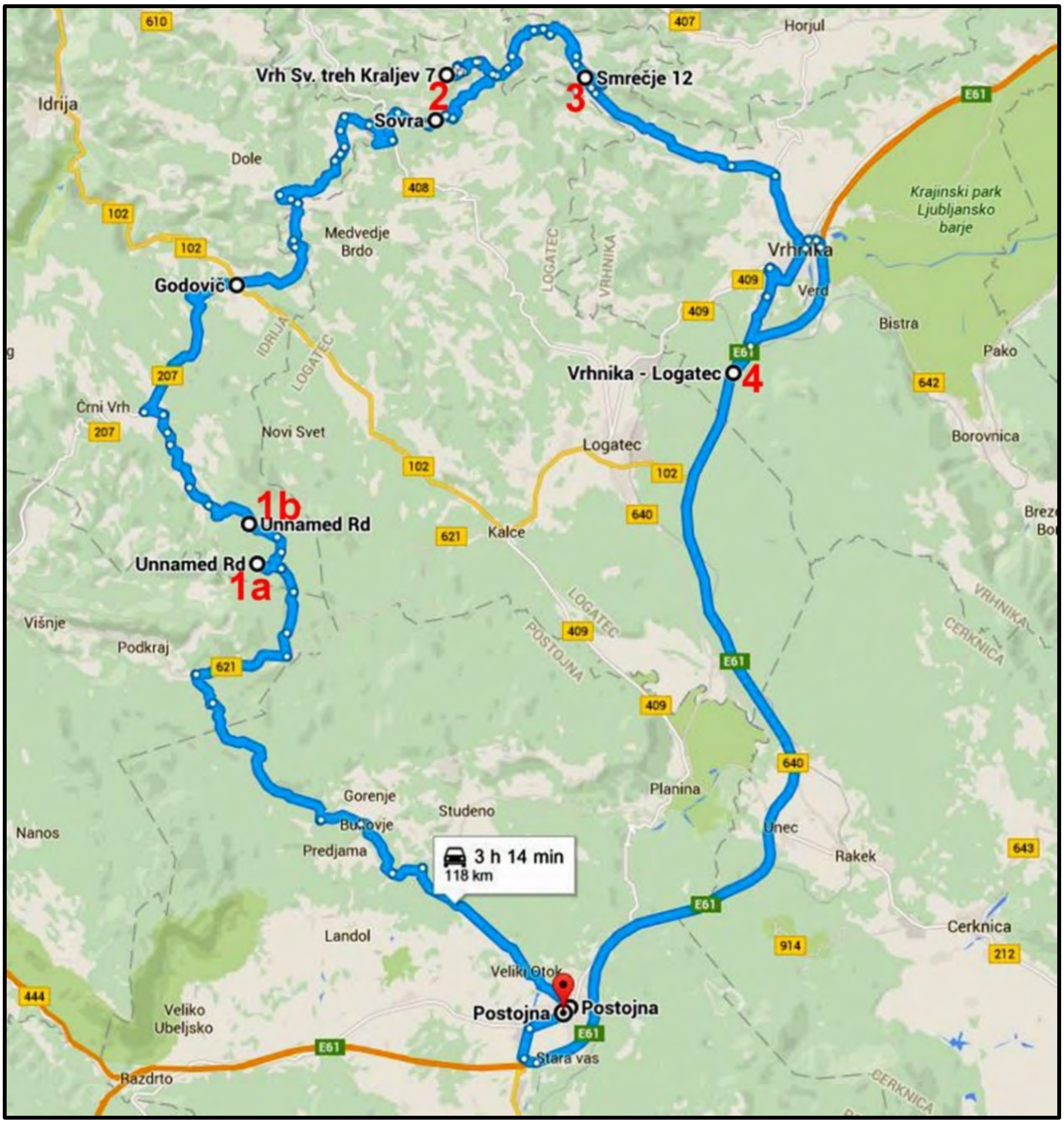
Stops:

1 –Nadrt (geology and geomorphology of the area; paleokrast surface that separates Upper Cenomanian from Coniacian (Lower Santonian?) carbonate successions denoted by bauxite deposit, small exploration pit;

2 – by the roadside: Rodolfov mlin well with sulphuric water outflow (geology, hydrogeology and speleology of dedolomite related spelogenesis);

3 – Podlipa/Smrečje (geology of regional Late Triassic paleokarst with bauxite deposits separates Ladinian/Cordevolian inner platform dolomites and marginal reef limestones from Julian/Touvalian marine to brackish(?) siliciclastic deposits (sandstons and claystones localy containing coal seems and dark-grey limestone lenses and horizons);

4 – Vrhnika/Štampetov most (Kimmeridgian regional paleokarst with bauxite deposits).



GEOLOGICAL SETTING OF NADRT AREA (HRUŠICA PLATEAU, W SLOVENIA) (No. 1)

Jernej Jež & Bojan Otoničar

Nadrt area is located in a central part of Hrušica high karst plateau in the Western Slovenia. The entire plateau is composed of Mesozoic carbonate rocks and Paleogene siliciclastic flysch. Tectonically, the area belongs to the Hrušica nappe (Fig. 1), the most extended thrust unit of the northwestern External Dinarides (Placer 1981, 1998). Rocks of Hrušica plateau and adjacent Nanos plateau are separated by a major NW-SE trending strike-slip Predjama fault, while from north-eastern side Hrušica is cut by Idrija fault. In the central part of the plateau - the Nadrt area over a 1000 m thick Cretaceous shallow-water carbonate succession was deposited (Buser *et al.*, 1967; Jež & Otoničar, 2010; Jež, 2011). Beds are folded to syncline gently dipping toward north-west (Placer, 1981).

This part of the External Dinarides corresponds to the northern part of the Cretaceous passive margin Adriatic Carbonate Platform (AdCP) that occupied the north-eastern part of the Adria microplate. With regard to lithofacies characteristics and their stratigraphic position, 1200 m thick Albian to Campanian carbonate successions of the Nadrt and adjacent areas were devided into eight lithostratigrafic units (Jež, 2011) (Fig. 30). In time and space, shallow marine lagoon and peritidal facies of the inner platform/ramp alternate with deeper marine hemipelagic facies of the intaplatform basins.

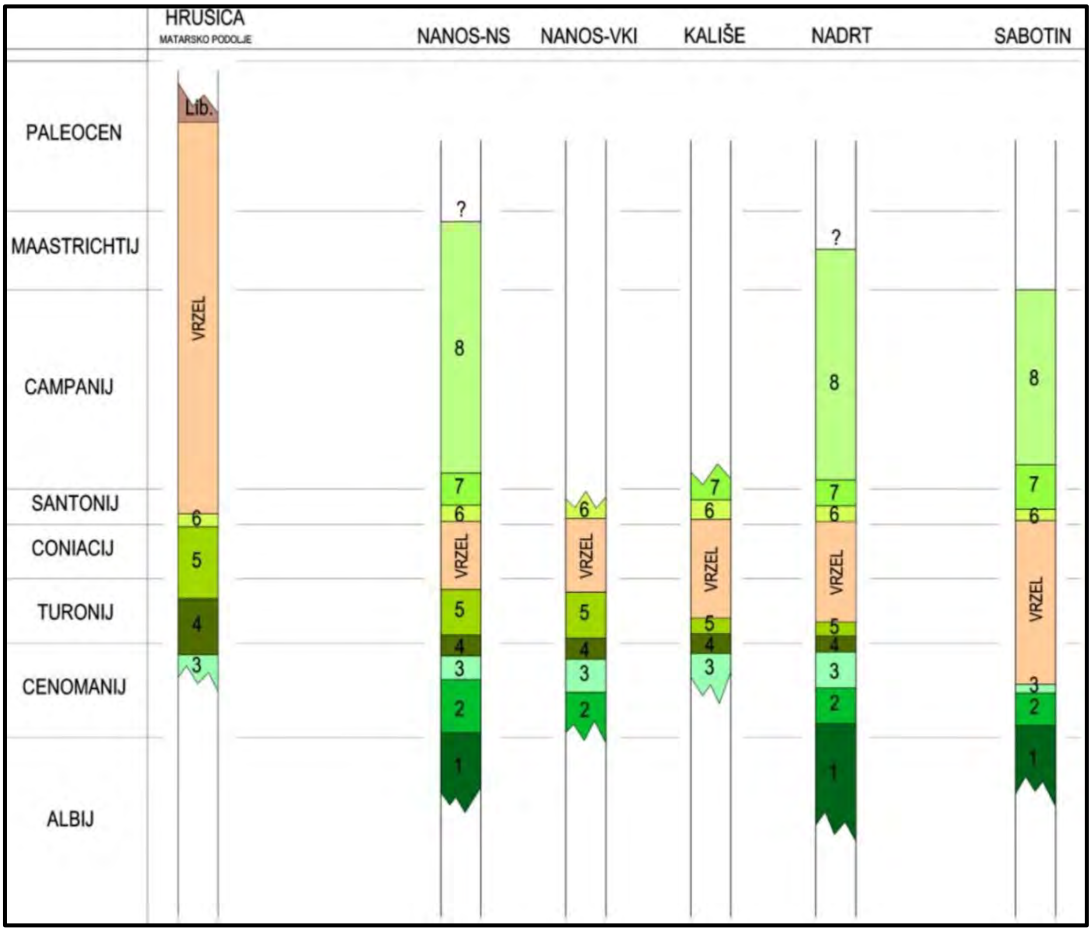


Figure 30: Chronostratigraphic correlation among Upper Cretaceous lithostratigraphic units of the northern part of the Adriatic carbonate platform. Hrušica site (Matarsko podolje area) represents the innermost part of the platform, while the other sites represent more marginal parts. Not significant difference in extension and stratigraphic position of the stratigraphic gap (*vrzel = stratigraphic gap*) occurs among those areas.

Thick, rather continuous, Cretaceous carbonate succession is interrupted by pronounced stratigraphic gap (Fig. 30) denoted by paleokarstic surface (Fig. 31). Karstic phenomena include smaller vadose roots and dissolution channels and vugs and a bit bigger karstic pockets (Figs. 31, 32A, B). All subsurface karstic features and surface features of negative relief had been subsequently filled or covered with yellowish and reddish calcareous sediments, different cements, oolitic bauxite and breccia (Fig. 32). Thickness of oolitic bauxite layers and lenses in Nadrt could reach up to 50 cm. At Nadrt karstic features occur in Middle Turonian bedded biomicritic algal-foraminiferal limestone and they do not penetrate more than 10 meters below the former karst surface.

The same palokarstic unconformitie occurs also in carbonate successions of other tectonic units that represent more marginal parts of mid-Createceous AdCP, but not in its inner part, where even deeper marine intra-platform basins or deep lagoons were formed contemporaneously (Fig. 33). It should be mentioned though that researchers mostly explaining this incipient drowning event of the inner parts of AdCP as a result of Cenomanian/Turonian eustatic sea-level rise and related anoxic event. Here we may even hypothesize that before the platform was subaerially exposed its relief was at least partly increased by diferences in carbonate production between inner and marginal parts of the platform (i.e. empty bucket effect). When the eustatic sea-level fall at the end of Turonian (Haq *et al.*, 1987) the higher parts of the platform at its margin would be exposed while in inner parts shallow marine environments would be re-established what in fact happened (see Gušić & Jelaska, 1990).

However, it seems that the thicknesses and the age of successions that underlay the paleokarstic surface along the platform marginal parts (Jež, 2011) are too diverse – despite of unhomogenous lithology of the underlying formations because of their position on the platform, inherited sub-marine relief and possible differences in denudation rates–that tectonics and related asynchronous relative sea-level fall should be neglected. Nadrt area was most probably exposed before than the Nanos area (south of Nadrt) where youngest carbonate rocks below the paleokarst surface are of Upper Turonian in age. On Mt. Sabotin (northwest of Nadrt) Turonian and also Upper Cenomanian successions are not preserved, suggesting that more marginal areas of the platform were probably even earlier exposed to karstification and denudation (see Figs. 30, 33).

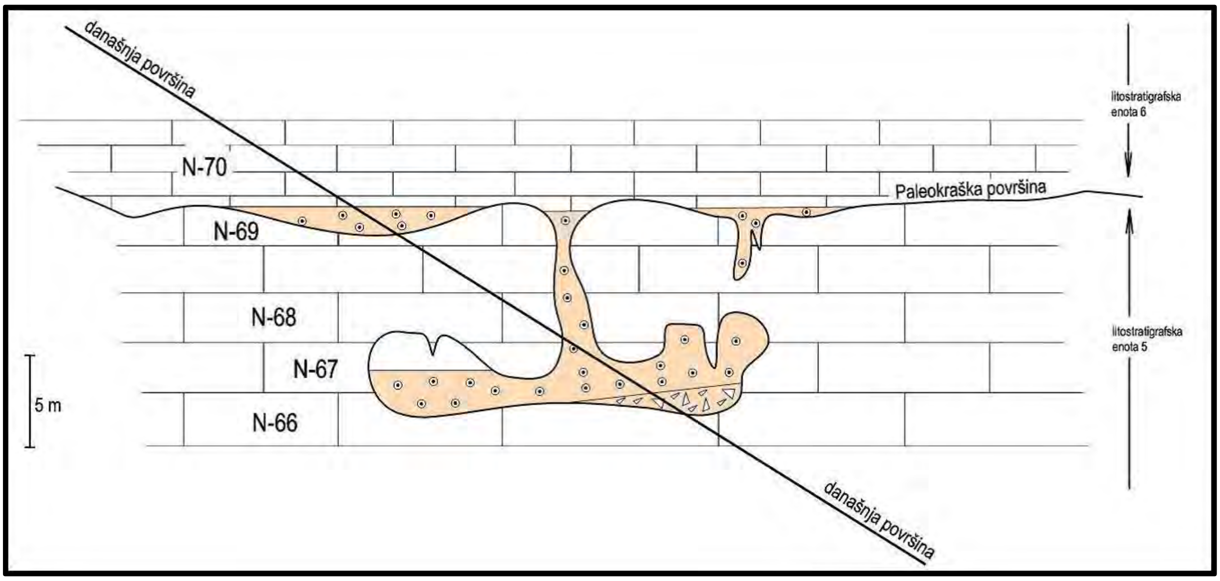


Figure 31: A schematic interpretation of paleokarstic features in limestones of the upper part of the lithostratigraphic unit 5 in Nadrt. Shallow karstic depressions and smaller paleokarstic shafts or pockets are filled with oolitic bauxite, breccia and other paleokarstic deposits. Marks N-66 to N-70 showing position of samples taken for the analyses.

Figure 32: Paleokarst related phenomena of Hrušica Plateau. A) Turonian and Upper Coniacian/Lower Santonian limestones are separated by distinctive paleokarstic surface marked by bauxitic deposits (Podkraj, Hrušica Plateau). Note paleoepikarstic zone crisscrossed by infilled irregular channels (root related?). B) Vadose channel filled with sandy-grained calcareous-bauxitic material (Nadrt, Hrušica Plateau). C) Oolitic bauxite (boehmite) with reddish black hematite in intergranular pores (Nadrt, Hrušica Plateau).

Although subaerial exposure could be the result of sudden eustatic sea-level fall, the chronological and spatial distribution of exposed areas indicates that gradual tectonic uplift of the platform marginal parts was the main controling factor of the relative sea-level fall. The subaerial exposure of the area progressively expanded from northern (marginal) parts toward southern (more inner) parts of the platform (Fig. 33).

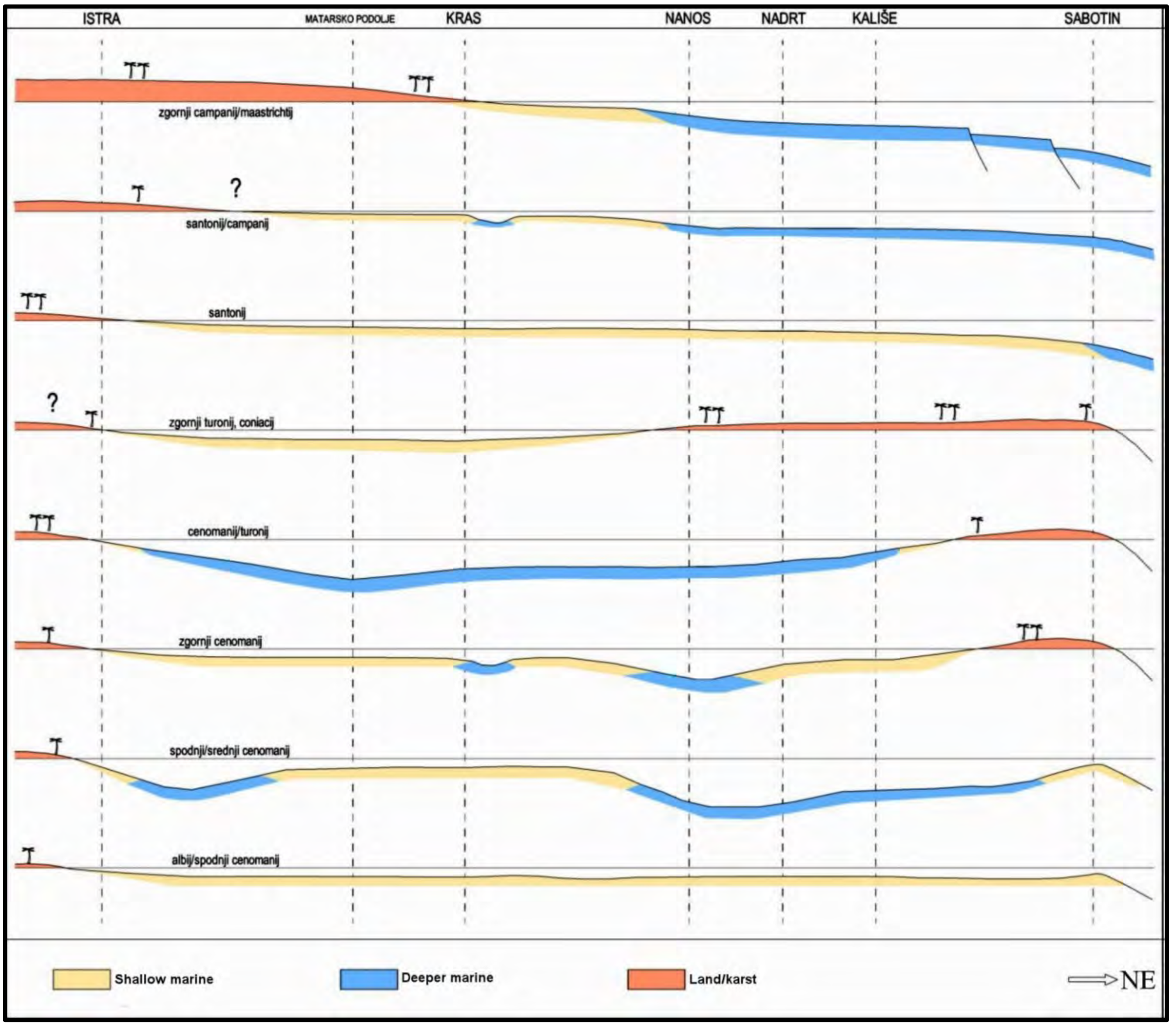


Figure 33: Paleogeographic evolution of the northern sector of the Adriatic carbonate platform between Albian and Maastrichtian presented on cross section over northern part of the platform between Istria and Sabotin (SW towards NE).

Deposition of carbonates within restricted shallow lagoon started with oscillating transgression over paleokarstic surface. In Nadrt, above the paleokarst surface, Early Santonian bioturbated micritic limestone was deposited. According to chronostratigraphic position of the studied sequences transgression was more or less synchronous over marginal parts of platform (Jež, 2011). Later, in the Campanian, more or less grainy biomicritic limestone was deposited in the inner to middle carbonate ramp settings. In the Late Campanian depositional settings were progressively changing (drowning) due to amplified tectonically controled differentiation of the platform topography related to early phases of foreland sedimentary basin formation (Fig. 33).

Although remnants of a bit bigger subsurface cavities or phreatic voids were not found in Nadrt area, cavities of decametric and centimetric dimensions filled with flowstone, calcite cements and calcareous silt were found at Kališe some 10 km east of tha Nadrt site (Fig. 34).

We may conclude that the Upper Cretaceous depositional settings of the northern sector of the AdCP indicate significant differentiation in topography, culminated in development of intraplatform basins on one side and subaerially exposed areas on other. The varied dynamics was mainly a result of regional tectonics and in minor extent eustasy.

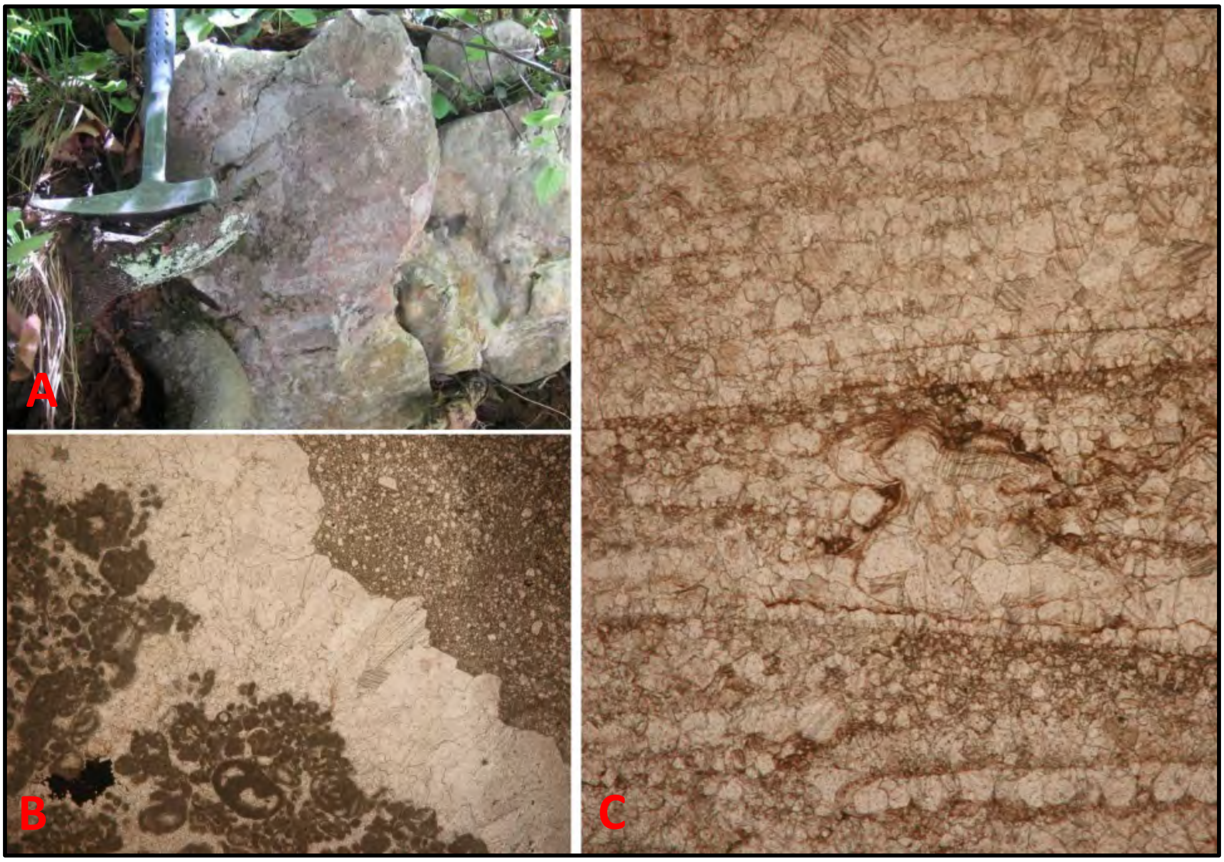


Figure 34: A) Intercalation of reddish stained micite and coarse-grained calcite cements (rafts) represent filled primarely paleokarstic pheratic passage (Kališe). B) Dissolution void in biopeloidal G/P a few meters below the paleokarst surface filled by bladed meteoric calcite spar crust and silty calcareous material (Kališe). C) Re-crystalized calcite rafts with dissolution void filled with calcite spar.

CARBON AND OXYGEN ISOTOPE STRATIGRAPHY OF LATE CENOMANIAN TO SANTONIAN SHALLOW-MARINE CARBONATE SUCCESSION OF MT. NANOS, W SLOVENIA

Bojan Otoničar & Jernej Jež

In the Nanos Mt., the area adjacent to Nadrt, together with geological profiling, we also performed sampling for stable isotope stratigraphy to separate global carbon isotopic excursions from locally induced primary and diagenetic isotopic signals. The aim of the study was to evaluate the curve of $\delta^{13}C$ and $\delta^{18}O$ values taken from Upper Cenomanian to Upper Santonian shallow marine carbonate succession with special respect to sea-level rise at Cenomanian/Turonian boundary. A side, but important, result of the study was detection of distinctive depletion of both, $\delta^{13}C$ and $\delta^{18}O$ values, but especially $\delta^{13}C$ values while approaching Upper Turonian (Fig. 35) suggesting significant meteoric water and soil CO_2 influence in diagenesis. With lithostratigraphic studies we detected a stratigraphic gap between Late Turonian and Late Coniacian/Early Santonian sequences, but with no obvious evidences of subaerial exposure phenomena. On the basis of the isotopic results we focused our field work on a narrow horizon where $\delta^{13}C$ and $\delta^{18}O$ values were most depleted and detected thin lenses of bauxite on centimeter scale.

Distinctive decrease of $\delta^{13}C$, and a bit less obvious decrease of $\delta^{18}O$, values in approximately 60 metres thick horizont below the paleokarstic surface (Fig. 35) could be explained by transition from prevalent marine to dominantly meteoric isotopic signal. More or less constant $\delta^{18}O$ values and distinctly oscillating, but progressely lower $\delta^{13}C$ values within the horizon, fit relatively well with "meteoric calcite line" (*sensu* Lohmann, 1988). Most distinct deviations from abovementioned trend of both $\delta^{13}C$ and in less extent $\delta^{18}O$ values could be explained by stabilization and/or lithification of limestone before main emersion.

Rather low $\delta^{13}C$ and $\delta^{18}O$ values in the first 10 meters above the paleokarstic surface (Fig. 35) still indicate relatively pronounced influence of meteoric diagenesis and/or fresh water inflow to peritidal (palustrine?) depositional environments. Trend of relative sea-level rise is reflecting also in gradual deposition of open marine subtidal limestone and increasing $\delta^{13}C$ and $\delta^{18}O$ values in the upper part of investigated succession (Fig. 35).

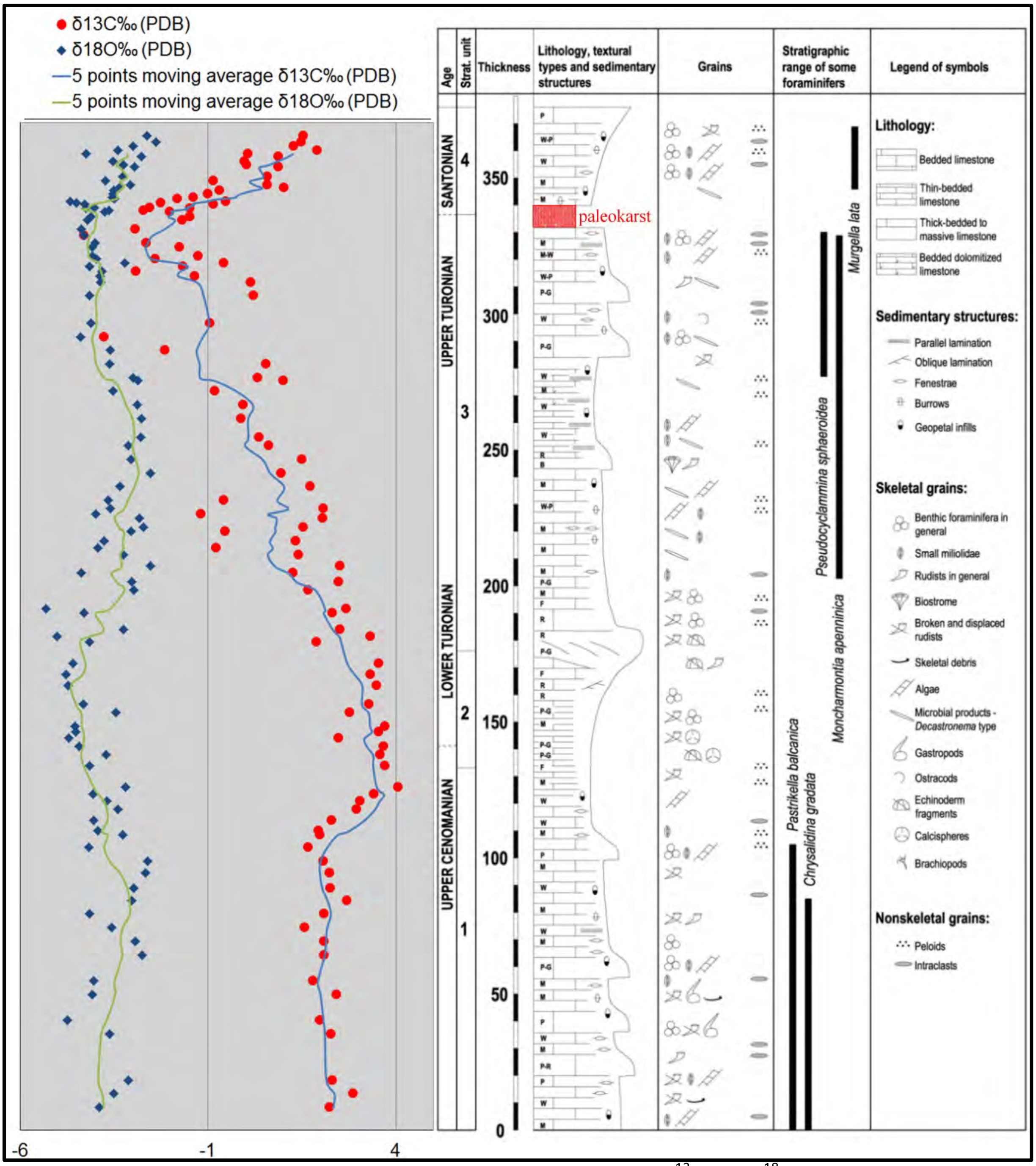


Figure 35: A) Curves connecting five-point running-average values for $\delta^{13}C$ and $\delta^{18}O$ data that correspond to Cenomanian, Turonian and partly Upper Coniacian/Lower Santonian carbonate succession of the Nanos-VKI profile. B) Upper Cenomanian to Santonian shematic lithostratigraphic coloum of the Nanos, Hrušica and Trnovski gozd.

VRH SV. TREH KRALJEV – "*THE THREE HOLY KINGS HILL*" (No. 2): LITHOLOGY CONTROLLED DEEP PHREATIC KARST (HYPOGENE KARST?) (from Otoničar *et al.*, 2016)

Bojan Otoničar

When evaluating potential hypogene caves from the cave maps in the Slovenian cave register, the Vrh Sv. Treh Kraljev – "*The Three Holy Kings Hill*" (VSTK) of the Rovte region, the hilly landscape along the transition between the Dinaric karst of inner Slovenia and the Prealps, attracted our special attention.

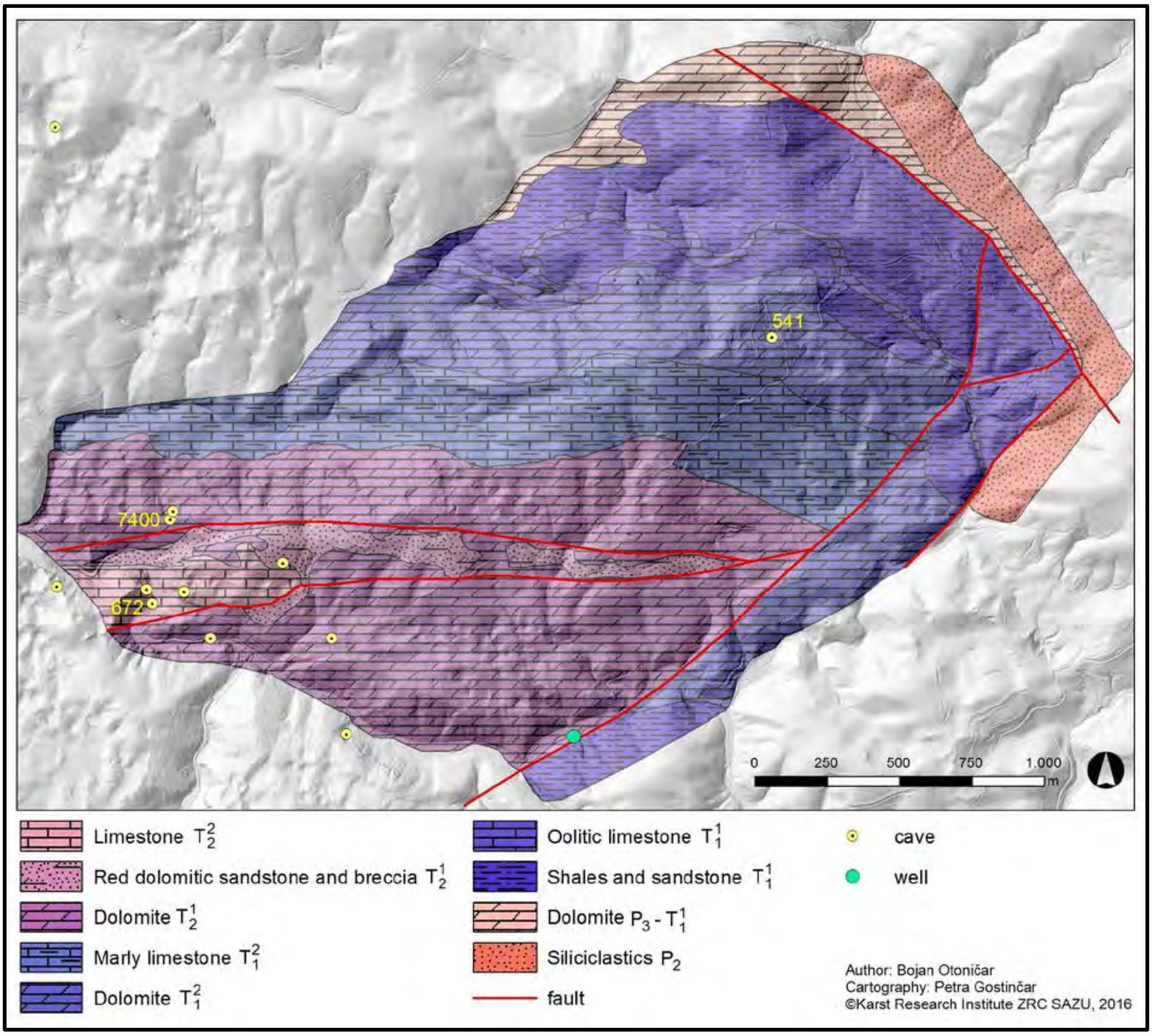


Figure 36: Lithostratigraphic map of the Vrh Sv. Treh Kraljev area with marked cave entrances and sulphate water well.

The VSTK is topographically well expressed and surrounded by four valleys developed mainly along fault lines and on the contact of different lithologies (Fig. 36). Between the faults, the mountain represents a relatively stable block in which the uniform dip of the strata is disrupted only locally by a few limited metre-scale strike-slips along minor local faults.

The VSTK consists of a sequence of Middle Permian to Middle Triassic carbonate and siliciclastic rocks a few hundred meters thick (Fig. 36), with intercalations of evaporates in the subsurface. During the 1960s, drilling for mercury ore at Idrija mine near Rovte Village discovered an evaporate horizon up to 270 m thick that forms up to 59% of the Upper Permian and over 29% of Lower Triassic dolomite succession at depths 130 to 717 m below the surface (Čadež, 1977). There, up to metre-thick lenses of gypsum and anhydrite alternate with dolomite that contains veins and geodes of gypsum.

In the subsurface of the VSTK three caves, between 300 m and 1000 m long, exhibit a ramiform and/or maze-like pattern and other evidence indicating their possible hypogene origin (Fig. 37A). The wall rock of Mravljetovo brezno v Gošarjevih rupah cave is in a great part composed of a yellowish to reddish-brown calcareous deposit in an otherwise Middle Triassic grey dolomite formation (Fig. 37B). It has been found that the yellowish to reddish-brown material consists mainly of calcite (Fig. 37C), while the colour is derived from small quantities of iron hydroxides. It is suggested that calcite was formed by dedolomitization of the host rock as a result of interaction among limestone, dolomite and Ca-sulphate rock in the phreatic zone. "Dedolomite" is the term for calcite forced to precipitate by the dissolution of dolomite and Ca-sulphates. It was revealed from oxygen and carbon isotope composition that dedolomite was precipitated from low temperature meteoric water derived from areas populated by C3 plants.

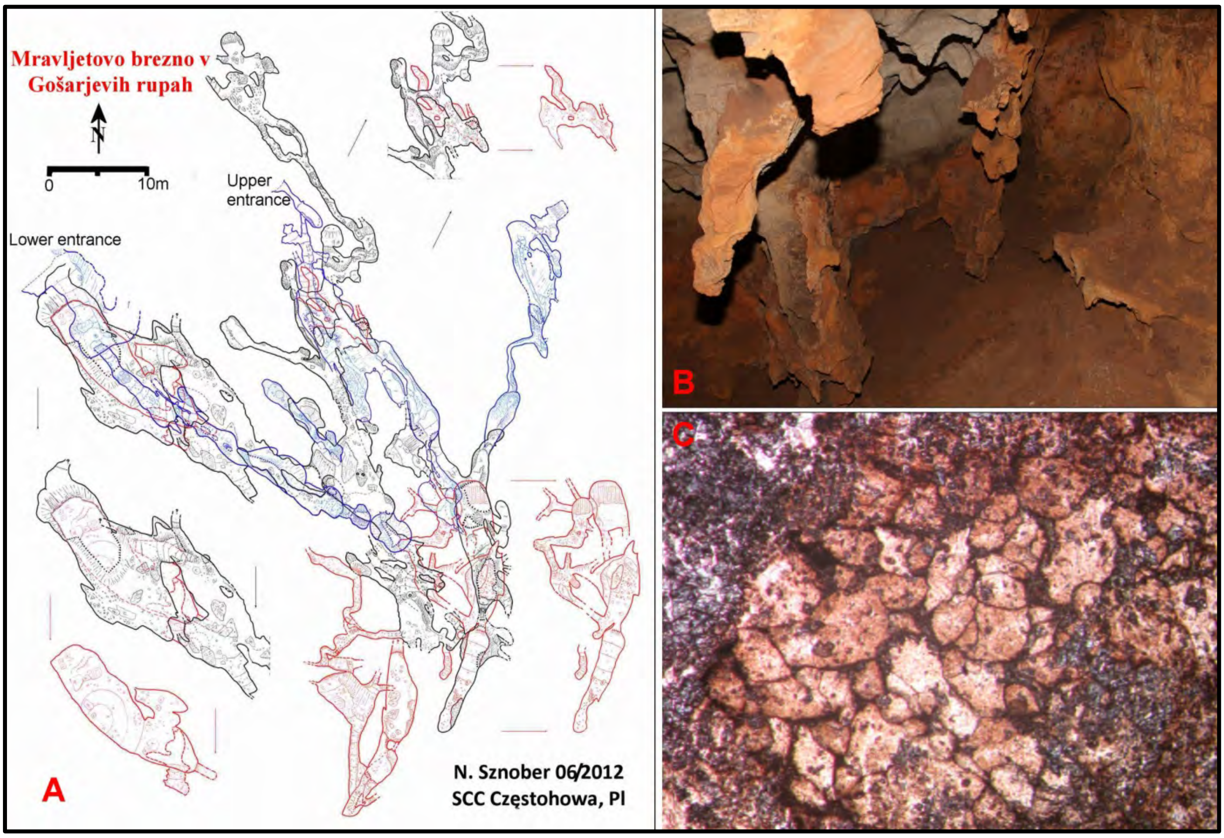


Figure 37: A) Ground plan of the Mravljetovo Brezno v Gošarjevih Rupah cave. Blue = upper level; black = middle level; red = lower level. B) Highly irregular wall rock of the small chamber ceiling in Mravljetovo brezno v Gošarjevih rupah cave. Note pendants and wall rock on the left side containing mainly yellowish brown dedolomite while part of the ceiling is developed in gray dolomite (width of the picture is app. 1.2 m). C) Photomicrograph showing coarse grined equant to pseud-spherolithic calcite crystal mosaic (i.e. dedolomite) replacing finer-grained gray dolomite (note dolomite patches embeded in calcite crystals). Thin-section is stained by Alizarin Red S. (width of the picture is 2.2 mm).

Subsequently the cave was developed in phreatic or/and epi-phreatic conditions almost exclusively by dissolution of the original dedolomite body. Later the cave was reshaped and partly infilled by epi-phreatic streams and their sediment load. Now the cave is in the vadose zone where aggressive water creates localized vadose shafts and downcutting vadose meanders.

In the area, there are three wells a few hundred meters deep that among others cut Upper Permian to Lower Triassic evaporate horizon and discharging sulphate water to the surface, in contrast to normal meteoric waters from a few karstic springs. The chemical analyses of water discharging from the wells indicate still-ongoing dedolomitization deep below the surface (Fig. 38).

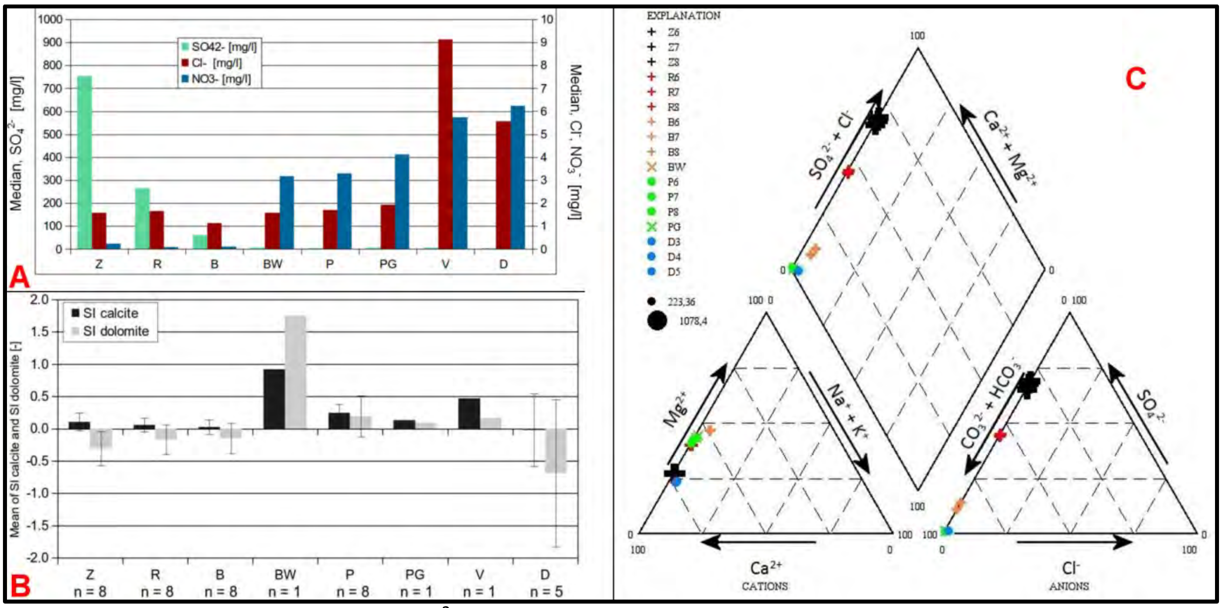


Figure 38: A) Diagram for sulfate (SO_4^{2-}), nitrate (NO_3^-) and chloride (Cl^-) concentrations for the analysed samples [»sulphate« wells: Z, R, B; surface stream: BW; natural springs: P, PG, V, D (see Philipp, 2015 and Otoničar *et al.*, 2016)]. B) Mean with standard deviation of the SI calcite and SI dolomite from wells and springs in the Rovte area. Note the high saturation indices of calcite and dolomite from surface stream BW (due to outgassing of CO_2). C) Hydrochemistry (Piper diagram) of deep wells (Z, R and B) and springs (P, PG and D) in the Rovte area; size of symbols correspond to total dissolved solids.

PODLIPA (No. 3): LATE TRIASSIC PALEOKARST AND RELATED BAUXITE DEPOSITS

Bojan Otoničar

In central Slovenia bauxite deposits that underlie Late Triassic siliciclastics were traditionally interpreted as bauxite that denotes contact or paleorelief separating Lower Carnian ($^1T_3^1$) dolomites and limestones from Middle-Upper Carnian ($^{2+3}T_3^1$) mainly reddish marginal-marine clastics. Although some researcher noticed that bauxite and related deposits (i.e. carbonate and bauxite breccia) fill paleokarstic depressions and that relief on dolomite (up to few metres high pinnacles) differs from that on limestone (subcutaneous karren), they did not really discus their origin neither they defined time span of the stratigraphic gap correctly (Dozet, 2004 and references therein). Celarc (2008) reported on »forgotten« stratigraphic gap below Carnian bauxite in Kopitov grič some 20 km south from the Podlipa location. He suggested that bauxite deposits represent a stratigraphic gap between Ladinian (T_2^2) limestone and dolomite with *Diplopora annulata* algae and Late Carnian or Tuvalian ($^3T_3^1$) clastics. In some areas in Southern Slovenia and NW Croatia Carnian bauxites or clastics overlain even older Middle and also Lower Triassic successions (Celarc, 2008 and references therein). Celarc (2008) suggested that subaerial exposure event was synchronic and related to the late Lower Carnian "Raibl event" in the Southern Alps and western Northern Calcareous Alps or "Reingraben turnover" in the western Northern Calcareous Alps (Schlager & Schölnberger, 1974) – a sudden anoxic event that was followed by strong terrigenous influx triggered by "pluvial event" because of Cimmerian orogeny and consequential changes in the oceanic and climatic (monsoonal) circulation (Simms & Ruffel, 1989). He explained differences in the age of the underlying sequences by differential erosion during the same Carnian subaerial exposure period. However it seems plausible that at marginal parts of the Slovenian basin (i.e. "failed rift" *sensu* Şengör, 1995) and wider southwestern shelf of the opening Meliata-Maliac Ocean (Stampfli & Borel 2002) as an embayment of the Neotethys (e.g., Schmid *et al.,* 2008) topography of the platform was highly irregular and dissected to "*horsts and grabens*" (Šmuc & Čar, 2002; Celarc *et al.*, 2013) where during the Middle Triassic successions of various lithologies and thickness were deposited. For example, in less than 15 km distant Idrija area at least 3 erosional phases, some also with minor paleokarstic relief, occurred but no paleokarst neither stratigraphic gap was documented during Carnian (see Čar, 2010). It is important to note that periods of non-sedimentation and stratigraphic gaps vary considerable over different tectonic blocks and are dependant on tectonic "fate" of the individual block (Čar, 2010).

At abovementioned Kopitov grič, but also in other places along the discussed contact in central Slovenia, bauxite deposits form from a few metres to 10 metres thick lenses (Dozet, 2004). Bauxite texture is commonly oolitic with ferruginous, bauxitic and mixed ferruginous/bauxitic ooids. Few mineralogical and geochemical analyses of bauxite showing that mineral composition of individual bauxite body is variable but in general containing boehmite, as a major mineral but limonite, hematite and quartz are also frequent. Analyses samples show high and highly variable content of silica and Fe_2O_3 what make these bauxites unfavourable for exploration (Dozet, 2004).

In Podlipa location oolitic bauxite and red clastic deposits overlie paleokarstic surface developed on Ladinian (T_2^2) or Cordevolian (${}^1T_3^1$) bedded limestone and dolomitized limestone (Fig. 39). Bauxite was supposedly concentrated/deposited in paleokarstic depressions of medium size (i.e. dolines) (Fig. 39A, C) while ridges are directly overlain by reddish clastics. At the contact below the bauxite, the limestone is commonly highly cavernous, interwoven with channels of decametric dimensions presumably originally filled with bauxitic and siliciclastic reddish material (i.e. subcutaneous karst) (Fig. 39A, B). By the road there are 3 boulders representing cavernous subcutaneous pinnacles excavated from paleokarst surface directly below the bauxite deposit during regulation of pasture (Fig. 39B). In places below the paleokarst surface the limestone is "disintegrated" into *near-situ* karstic breccia with clasts intensively reddish stained. Bauxite gradually passes over to reddish claystone/siltstone and sandstone/fine-grained breccia which include intercalations of dark grey bedded limestone; first limestone lens occurs some 20 to 30 metres above the paleokarstic contact.

In conclusion, the paleokarst here is a consequence of specific tectonically controlled topography of the platform (Fig. 39 E) and pre- late Lower Carnian (T_3^1) eustatic sea-level fall which is documented in most of the carbonate platforms in the Dolomites and in the Northern Calcareous Alps (Bosellini, 1984; Brandner, 1984; De Zanche *et al.*, 1993, 2000; Gianolla *et al.*, 1998). Subsequently a "pluvial event" (see above), which interrupted the general arid climate of the Late Triassic and led to enhanced run-off and accumulation of siliciclastics at the Julian–Tuvalian boundary, establish also conditions for intense karstification and bauxite formation.

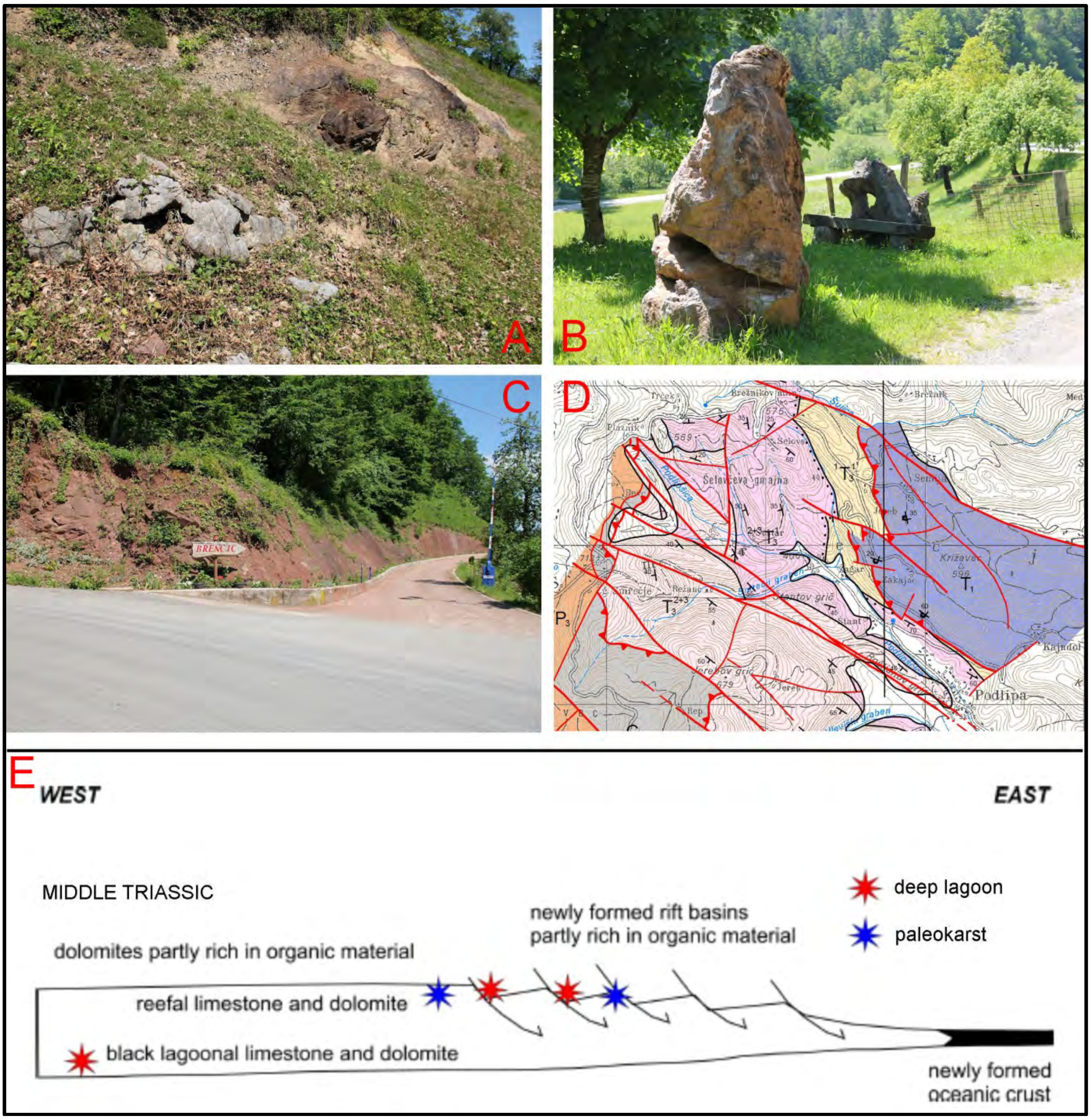


Figure 39: A) Contact between Ladinian/Lower Cordevolian (?) dolomite and Middle to Upper Cordevolian siliciclastics is commonly denoted by irregular paleokarstic surface and bauxite deposits. B) Dolomite boulders dug out during pasture regulation at contact between dolomite and bauxite represents parts of subcutaneous paleokarst surface. Bauxite or other non-carbonate material was washed-out from voids which were possibly partly reshaped during recent karstification period. C) Continuous transition between red oolitic bauxite and siliciclastic coastal (?) deposits. D) Geological map of the area above Podlipa Village (Bavec *et al.*, 2013). E) Simplified cartoon indicate geotectonic/paleogeographic situation before eustatic Cordevolian sea-level lowstand and conterporaneus decreasing of carbonate production.

LATE JURASSIC PALEOKARST WITH BAUXITE DEPOSITS

Bojan Otoničar

From Greece through Montenegro and Croatia to Slovenia the Upper Jurassic carbonate successions are commonly more or less contemporary interrupted by regional unconformity denoted by more or less extended bauxite deposits (see Durn *et al.*, 2003 and references therein). In Slovenia basic characteristics of Upper Jurassic bauxites where studied on Nanos Mt. (Dozet *et al.*, 1993) (Fig. 40A). There Upper Kimmeridgian to Tithonian peritidal limestones slightly discordantly overlaying bauxites and Oxfordian to Lower Kimmeridgian massive to poorly bedded oolitic and peri-reefal open marine limestones. Bauxite deposits are not continuous but occur in lenses, pockets and funnel-like bodies on average 2 to 5 m thick, representing filled paleokarstic depressions. Bauxite deposits are not homogenous but rather distributed in horizons of different colour, texture and structure, most characteristic being bauxitic breccia and dark red oolitic bauxite. Depending on location and horizon mineral composition of bauxites is significantly varying, yet mainly in quantity of main minerals: boehmite, kaolinite, goethite and hematite. In some localities also gibbsite occur (up to 26 wt% of sample). In general bauxites contain relatively high percentage of clay (kaolinite) so commonly it can be classified as clayey bauxites.

Above Vrhnika "oolitic" bauxites separates Oxfordian to Lower Kimmeridgian massive oolitic limestone and Upper Kimmeridgian to Tithonian peritidal and lagoonal bedded micritic limestone. Also here low angle discordance is observable as well as distinctive difference between tectonic structures of under- and overlying sequences (Fig. 40B). Un-homogenous bauxite deposits fill shallow doline-like depressions (Fig. 40B).

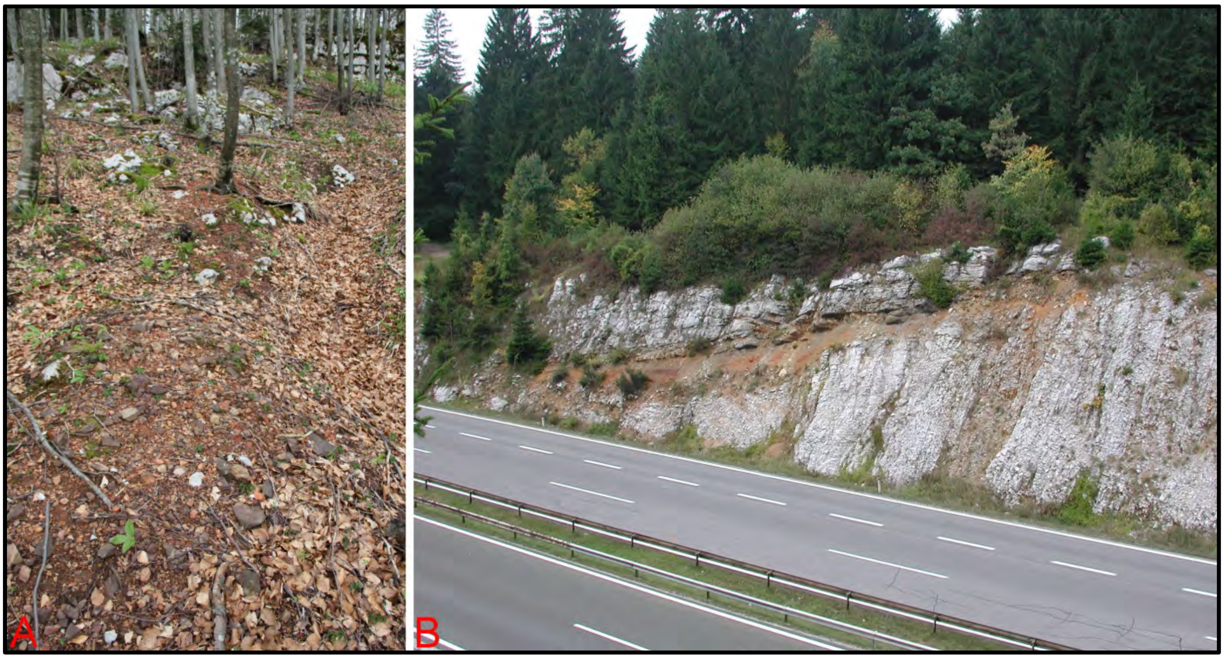


Figure 40: A) Relatively thick Upper Jurassic bauxite lens (Železni klanci; Nanos). B) Paleokarstic surface denoted by bauxite deposit separates Lower Kimmeridgian (Oxfordian?) open marine massive oolitnih limestone from Upper Kimmeridgian inner platform (lagoon) well bedded micritic limestone (motorway Vrhnika–Postojna road-cut; Raskovec above Vrhnika.

Pronounced deviations among trends of carbonate successions of different areas and, more or less, contemporaneous subaerial exposure (stratigraphic gaps) which could not be entirely explained by global eustatic sea-level changes (Haq *et al.*, 1987; Hallam, 2001) are roughly simultaneous with initial phases of ophiolite obduction on to the Adria margin during Late Jurassic (see Schmid *et al.*, 2008) (Fig. 41). On the northern sector of AdCP in places asynchronous tectonically deformed (Strohmenger 1990; Velić *et al.*, 1995) paleokarstic surface with bauxite deposits occur (Buser, 1974;

Dozet, 1994a; Dozet *et al.*, 1993; 1996; Velić *et al.*, 1995, 2002) on one side and deeper marine intraplatform basins on the other (Buser, 1989; Bucković, 1995; Matičec *et al.*, 1997; Velić *et al.*, 2002) (Fig. 42). Evidences of non-uniform subsidence of different parts of the platform arise also from trends and thickness of carbonate successions of the same chronostratigraphical units which are distinctively diverse regarding the area on the platform (Tišljar, 2001; Bucković & Cvetko Tešović, 2003). Locally on the NE margin of the platform non-synchronous stratigraphic gaps without evidences of subaerial exposure phenomena on the underlying commonly Lower Jurassic shallow marine carbonate deposits marked locally with neptunian dykes are overlain by thin sequence of amalgamated deeper marine sediments and thicker coarse-grained clinoform calcareous deposits of prograding carbonate platform suggesting intense tectonic activities during Middle and Late Jurassic.

In conclusion, above described deflections (and also spatially not uniform subaerial exposure of the platform) could be the result of obduction-related events at the margin of Adria microplate (see Schmid *et al.*, 2008 and references therein) that produced horizontal in-plane stresses which may be transmitted many hundreds of kilometres inboard of actual collision (i.e. obduction of ophiolites in our case) (Zeigler *et al.*, 1995) (Figs. 41, 42).

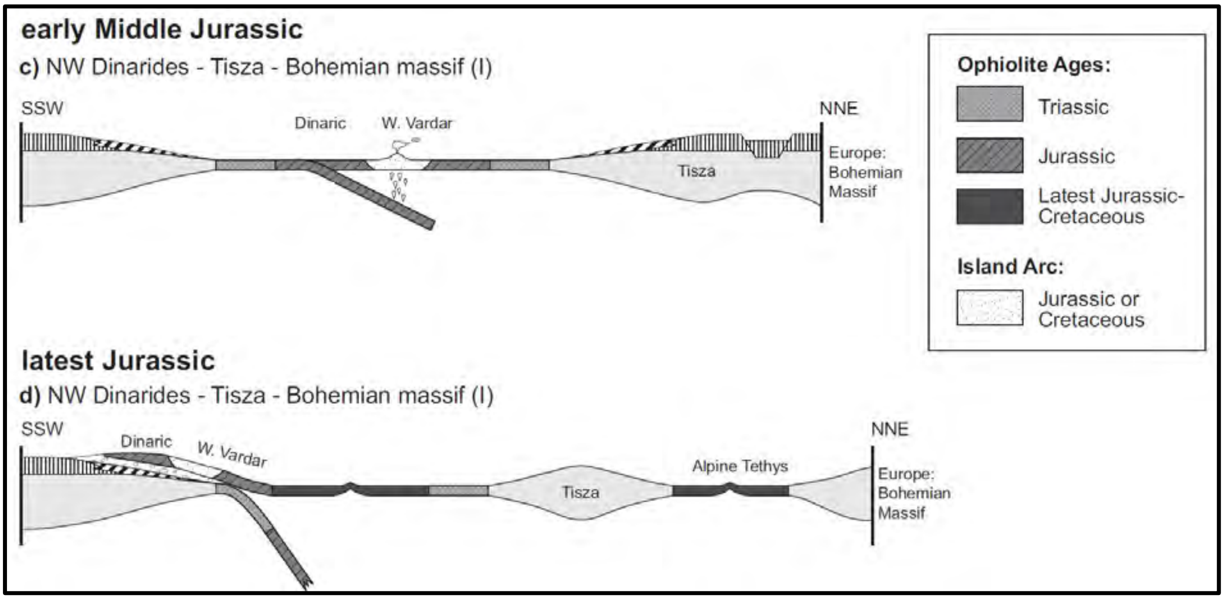


Figure 41: Geotectonic sketch of the NW Dinarides and adjacent areas in Middle and Upper Jurassic (from Schmid *et al.*, 2008).

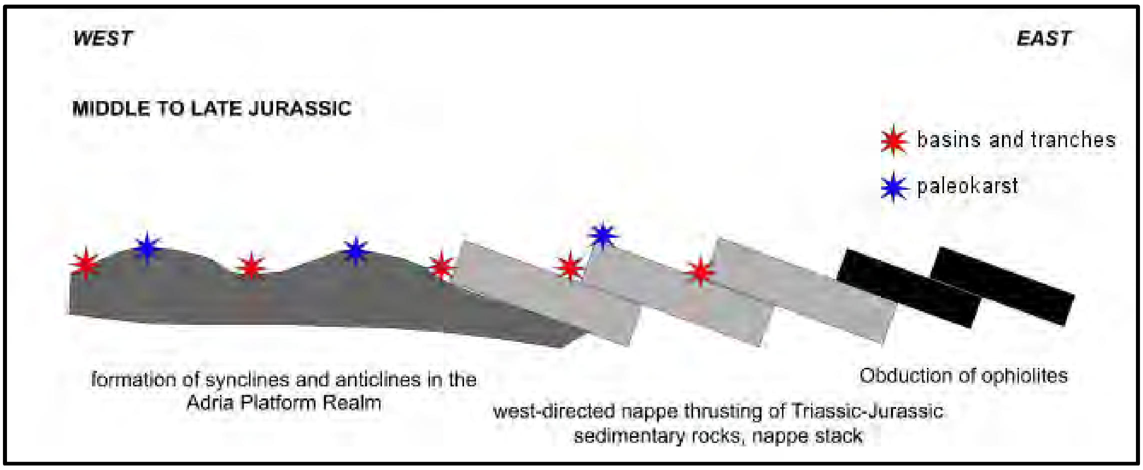


Figure 42: Simplified cartoon indicate processes (i.e. ophiolite obduction) that triggered uplift of certain parts of the Adriatic carbonate platform above the sea-level while others were simultaneously subsided.

Whole-day excursion **(C)**:

FOREBULGE RELATED LATE CREATCEOUS TO PALAEOGENE PALEOKARST OF ISTRIA (SW SLOVENIA AND NW CROATIA)

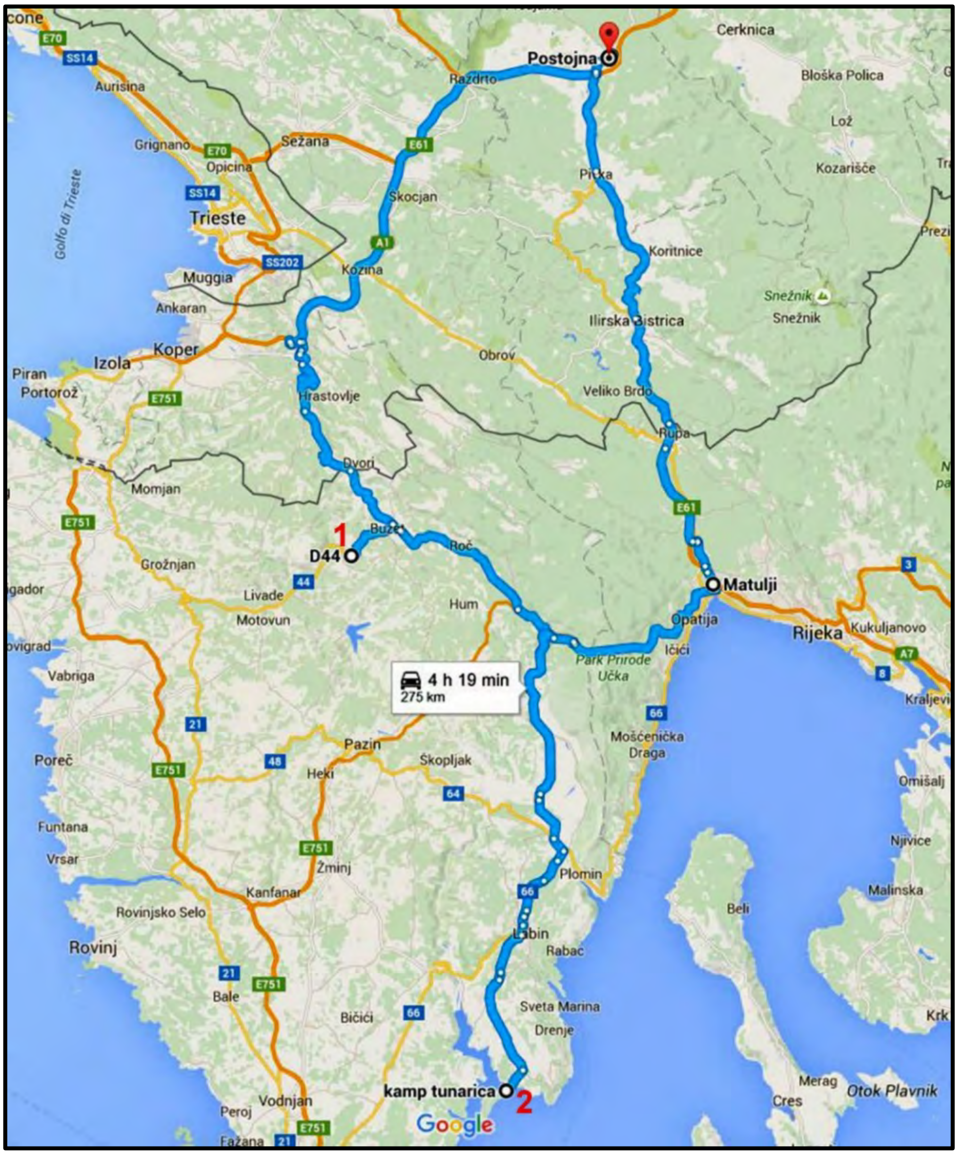
(Outstanding outcrops of surface and subsurface paleokrastic phenomena of the eastern coast of Istria)

Thursday, 16.6.2016, 7.30–19.30

Stops:

1 – Minjera near Buzet, Croatia: general geology of the area; depositional gap between Upper Cenomanian and Upper Paleocene/Lower Eocene carbonate successions; old bauxite mine; pyritized bauxite; saggy structures of blue hole deposits over bauxite pits;

2 – Ubac Peninsula near Koromačno Village, Croatia: a) an unroofed paleokarstic cave filled with flowstone, disintegrated calcite rafts/silty calcareous material derived from the weathered host rock, different types of breccia, bauxitic and clayey material, pedogenically altered cave deposits etc., b) over a kilometre long outcrop along the coast of paleokarstic cave, mostly with denuded ceiling, paleokrastic surface with overlying palustrine deposits (also containing coal seems), bauxite deposits, numerous and various cave related deposits (flowstone, calcareous and bauxitic autochthonous and parautochthonous cave sediments etc.).



MINJERA (No. 1): BAUXITE PITS OVERLAIN BY SAGGY THIN-BEDDED FRESH/BRACKISH WATER LIMESTONE OF "BLUE HOLE" FACIES
Bojan Otoničar

In the area of the Buje Anticline (*sensu* Placer *et al.,* 2010) between Savudrija and Buzet the basement of paleokarst containing peritidal Lower Cenomanian limestones of the stable carbonate platform overlain by the late Lower Cenomanian and the Middle Cenomanian carbonate successions deposited in different depositional environments of the disintegrated carbonate platform (i.e. peritidal limestones to those deposited in various parts of the slightly inclined slope (ramp) of the intraplatform basin or deep lagoon)(Vlahović *et al.,* 1994; Tišljar *et al.,* 1998; Velić *et al.,* 2003; Durn *et al.,* 2003). In such slightly deeper marine environments, finer-grained micritic limestones were mainly deposited, in which cherts are sometimes present (Vlahović *et al,.* 1994). The intraplatform basins were gradually filled by prograding sandy bioclastic bodies advancing towards the open sea. Until the end of the Cenomanian relatively uniform shallow-marine carbonate environments were re-established on a more or less uniform carbonate platform, where light-grey micritic limestones of the mudstone structural type and bioclastic (rudist) floatstones were deposited (Vlahović *et al.,* 1994; Durn *et al.,* 2003).

In Istria the age and, to a large extent, the lithofacies of the directly overlying strata of the paleokarst surface change relatively rapidly and, with some deviations, relatively systematically (Fig. 4; see also chapter: "Stratigraphy and evolution of the forebulge related paleokarst - introduction to the excursions A and C"). Towards the SW or the central section of the west coast of Istria, the limestones of the directly overlying strata are progressively younger – from the Maastrichtian and Palaeocene limestones of the Liburnian Formation in southwest Slovenia, via the Lower Eocene limestones in northwest Istria to the Upper Eocene limestones along the central part of the west coast of Istria. Generally speaking, the thickness of the Kras Group (see Fig. 2), which can only be represented by the Alveolina-Nummulites Limestone, is also thinner in this direction. In the Metković-Mečari profile near Pazin the thickness of the Alveolina-Nummulites Limestone and the "Transitional Beds" between the palaeokarst surface and the flysch is just 20 to 25 m (Tarlao *et al.* 1995). In the area of the Buje Anticline, the lower sections of the palaeokarst surface developed in Cenomanian limestones are covered by Lower Eocene freshwater-to-brackish thin-bedded micritic limestones of the Liburnian Formation of a thickness of up to some tens of metres (Hamrla, 1959; Šinkovec *et al.,* 1994; Velič *et al.,* 1995; Gabrić *et al.,* 1995; Durn *et al.,* 2003). More distinct karst depressions (karst pockets, shafts, etc.) are frequently filled with pyritised bauxite, which was excavated in the valley of the Mirna in several small underground and opencast mines (Šinkovec *et al.,* 1994) (Fig.43). In the limestones of the Liburnian Formation we frequently find relatively thin inclusions of black coal, which has also been mined in Sečovlje (Hamrla 1959, 1986) and Labin.

In the area of Minjera along Mirna river 17 underground historical bauxitic pit mines have been documented (Šinkovec *et al.*, 1994) (Fig. 43A). Bauxite mines actually represent filled paleokarstic depressions with steep sides (shafts, dolines, pits, elongated small canyon-like depression…) (Fig. 43B, C, D) which were commonly related to joint-intersections at rather highly dissected paleokarstic surface, here develop on Upper Cenomanian shallow marine limestone. Paleokarstic surface is overlain by Early Eocene palustrine limestone of the Liburnian formation (Fig. 43E), thus the stratigraphic gap here lasted about 38 Ma (Durn *et al.*, 2003). The depth of the vadose karstic features suggesting at least several tens of metres high amplitude of karstic relief above the sea-level. While Paleogene bauxites of Istria are mainly red in colour with prevailing oolitic intraclastic texture and with less abundant pelitomorphic lithotypes (i.e. "vadose" lithofacies of D'Argenio & Mindszenty with commonly parautochtonous bauxite grains) here central parts of bauxite bodies are dark grey to black (Fig. 43C). During initial transgression when iron oxide phases had not been yet perfectly mineralized and intergranular porosity of soil-derived material was still opened the ore reacted with the reducing stagnant pore waters and alternated "en mass" (Durn *et al.*, 2003) and pyritic (also marcasite) bauxites were formed (disseminated syndiagenetic pyrite). According to

Šinkovec (1994) two phases of pyritisation of bauxite can be recognised. The source of sulphur of the first phase supposed to be organic matter from the hanging wall sediments and for second from the sea-water. Due to recent oxidising processes on the surface and at the contact of bauxite and the host rock where surface water percolates pyrite is oxidised. In the process limonite and sulphuric acid are formed resulting in brownish colour of bauxite (Fig. 43C) and precipitation of gypsum at the limestone walls.

Transgressive sequence over paleokarstic depressions with bauxite deposits begins normally with lacustrine/palustrine facies with abundant coal seems (Fig. 43E), bituminous limestones that passing to brackish, restricted marine and normal marine sediments (Durn *et al.*, 2003). Firs beds over the bauxite depressions are non-tectonically deformed in saggy structure and are laterally limited or discontinues on decametric or even metric scale. They represent a first phase of transgression when fresh or brackish water lens were pushed up from below and formed isolated fresh/brackish-water lakes on marshy karstic landscape in front of the approaching sea (see Fig. 22).

Major mineral phases of pyritic bauxite are boehmite, pyrite, marcasite and kaolinite (for more detailed mineralogical and geochemical data see Šinkovec *et al.*, 1994 and Durn *et al.*, 2003).

Although there are no reports in the literature on subsurface paleokarstic features from the Minjera area, commonly in road-cuts few metres to some 20 metres (very rough estimation) below the bottom of deepest surface paleokrastic depressions decametric to even metric cavities occur filled with reddish stained calcareous sediment and flowstone (Fig. 43 F).

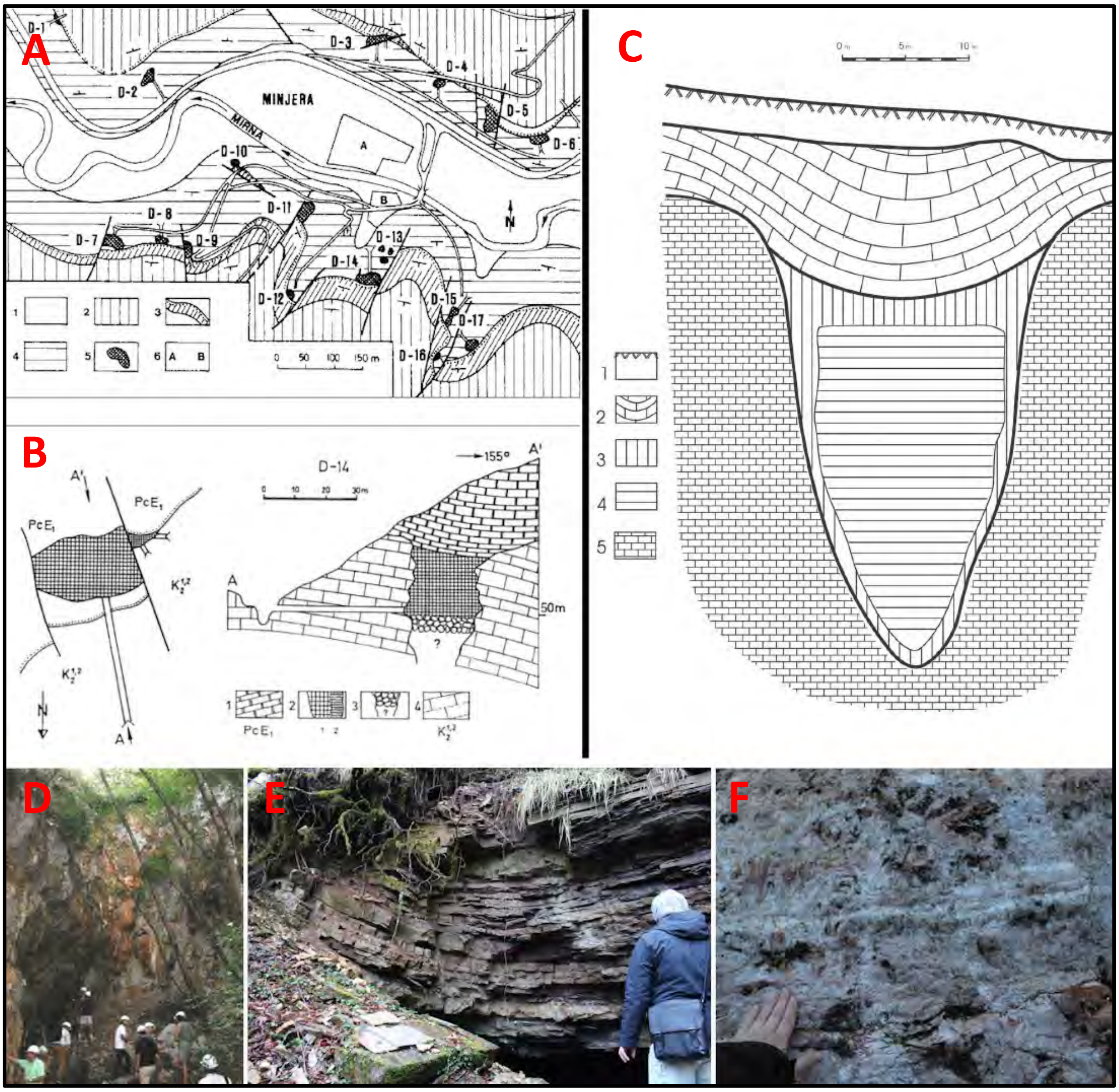


Figure 43: Paleokarst features of Minjera (NE Istria, NW Croatia). A) Geological position of bauxite deposits in Minjera (Šinkovec *et al.*, 1994; Durn *et al.*, 2003). Legend: 1) Aluvium, Holocene; 2) Foraminiferal limestone, Eocene 3) Kozina beds, Paleocene-Eocene; 4) Limestone with rudists, Cenomanian; 5) Bauxite deposits; B) Bauxite deposit D-14 (Šinkovec, 1994 *et al.*; Durn *et al.*, 2003). Legend: 1) Kozina Beds and Foraminiferal Limestone, Paleocene-Eocene; 2) bauxite; 3) collapse structure; 4) Upper Cretaceous limestone. C) Sketch of pyritic bauxite deposit with overlying saggy limestone beds (Šinkovec, 1994 *et al.*; Durn *et al.*, 2003). Legend: 1) sediments and soil, Quaternary; 2) Kozina Beds and/or Foraminiferal Limestone; Paleocene-Eocene; 3) yellowish-red bauxite; 4) grey to black bauxite; 5) Upper Cretaceous limestone. D) Excavated paleokarstic cavity (vadose shaft?) originally filled with bauxite; E) Saggy beds of dark thin-bedded to laminated limestone with coal seams and fossil leaves of higher plants of the Liburnian Formation form immediate cover of bauxite pits – a blue hole event of transgression phase over paleokarstic surface. F) Phreatic(?) cave filled with coarse-grained flowstone (informative isotope analyses shows values comparable to flowstone related to discussed paleokarst (strong influence of soil CO_2 populated with higher plants) but also to recent flowstones from low altitude caves of SW Slovenia (Urbanc *et al.*, 1985): $\delta^{13}C$ (‰)-10,09 and $\delta^{18}O$ (‰)-6,48.

CRETACEOUS–TERTIARY PALEOKARST FROM UBAC PENINSULA (ISTRIA, NW CROATIA): AN EXAMPLE OF PALEOKARSTIC PHREATIC CAVE (No. 2)

Bojan Otoničar & Adrijan Košir

General geology of the area

The area of interest is situated along the SE coast of the Ubac peninsula near the Koromačno village, on the south-eastern coast of Istria peninsula in NW Croatia.

The paleokarstic cave and related deposits presented here denote the unconformity between the underlying Upper Santonian shallow marine and overlying Lower Eocene paralic carbonate successions. The unconformity represents a megasequence boundary and typically separates the underlying passive margin carbonate succession from the overlying deposits of the synorogenic carbonate platform at periphery of the foreland basin (Košir & Otoničar, 2001; Otoničar, 2007, 2008).

Tectonically, the investigated area corresponds to the foreland of the Dinaric fold-thrust belt, which occupied the north-western part of the Cretaceous Adriatic Carbonate Platform and the Upper Cretaceous-Eocene synorogenic carbonate platform (Fig.1).

For more detailed explanation on the geologic evolution of the area see chapter: "Stratigraphy and evolution of the forebulge related paleokarst - introduction to the excursions a and c".

During long lasting subaerial exposure period different surface and subsurface paleokarstic features were developed and successively filled with breccia and other deposits. In the area under consideration carbonate sedimentation was re-established in the lower Eocene. During the transgression, sedimentary processes, facies distribution and stratigraphic units were prominently affected by the underlying karstic topography (a "blue hole" phase of transgression).

Breccia facies as evidence of paleokarstic phreatic cave evolution: from pre-karst to cessation (No. 2a)

Introduction

Some elongated dolines, dry valleys, trenches and similar geomorphic features of the karst surface landscape may represent denuded remnants of former phreatic caves. The recognition of such roofless caves in karstic landscape may significantly improve knowledge of speleological, geomorphological, hydrological and tectonic evolution of karstic regions (Mihevc, 2001). In the SW Slovenia and Istria the major regional unconformity in the Late Cretaceous and Palaeogene is frequently marked by infilled roofless phreatic caves preserved as elongated lens-shaped clastic sediment bodies that occur in otherwise continuous carbonate successions (Otoničar *et al.*, 2003; Otoničar, 2006, 2007, 2008). These sediments often comprise breccias with clasts derived from cave wall-rock and speleothems, immersed into silty to sandy matrix. The matrix is usually composed of calcareous, clayey and ferigenous/bauxitic components in different proportions. Where most of the cave related features had been removed by denudation or outcrops are limited and poorly exposed, remnants of caves are preserved only as patches of untypical lithologies embedded in carbonate bedrock. In this case they may easily be misinterpreted with some other type of clastic or residual deposit.

In addition, a study of diagenetic history of the cave sediments and bedrock may provide an important data on paleohydrology and karstification of the investigated paleokarstic aquifer.

Thus, well exposed features related to denuded roofless phreatic caves offer an opportunity for studying of principles of the paleokarstic evolution of the certain area. The recognition of such phenomena in the rock record may be of vital importance for the interpretation of the nature of paleokarst related unconformities and to understand the evolution of ancient carbonate aquifers and landscapes in general.

Breccia

Coarse-grained breccia bodies which represent the main paleokarstic deposit of the site 2a include various chemical/biochemical and mechanical deposits and residuals which are frequently overprinted by pedogenic modifications. Among chemical/biochemical deposits different *in-situ* and *near-situ* re-deposited speleothems occur. Mechanical deposits are the main constitute of the breccia bodies (Fig. 44), including coarse-grained limestone breccias with calcareous/bauxitic matrix and intercalations of calcareous/bauxitic sandstone and siltstone.

Simultaneously with karst evolution and denudation, subaerial chemical weathering of wind derived non-carbonate material and residue from *in-situ* weathering of carbonate bedrock providing a soil material and its end product – bauxite. Simultaneously with bauxitisation of non-carbonate material, also bedrock carbonates were pedogenically modified.

It is important to note, that in discussed case, the bauxite should be considered mainly as sedimentary rock (mainly parautochthonous), because it was transported from their original site into cave environment.

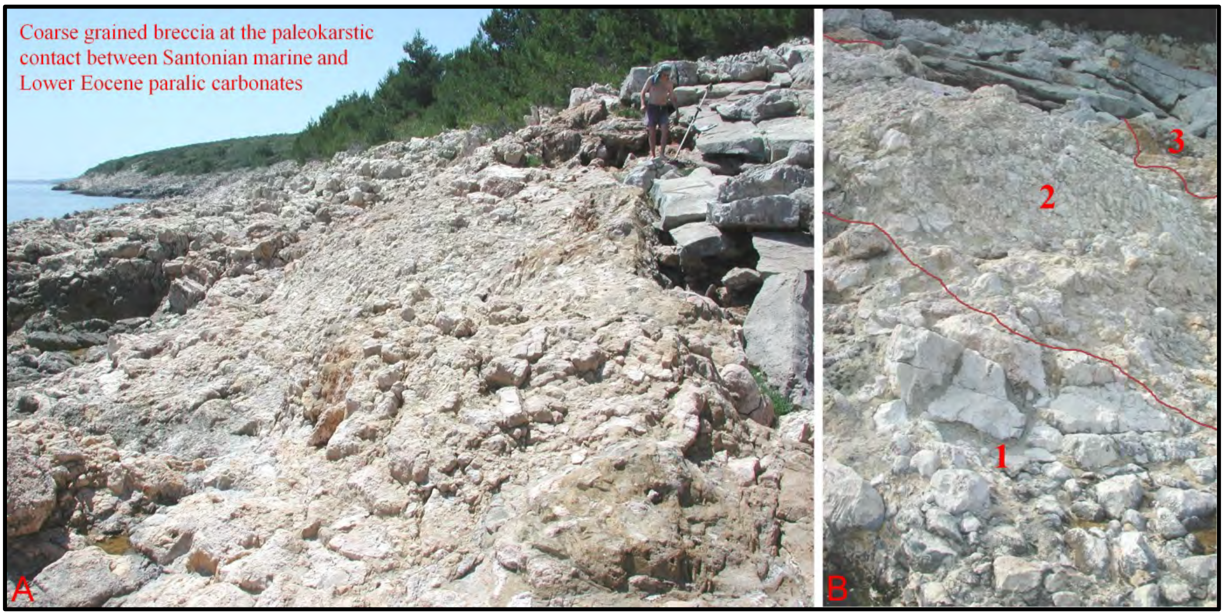


Figure 44: Large originally phreatic paleokarstic cave filled with speleothems and breccia of different generations and origin (Koromačno, Istria Peninsula; NW Croatia). The denudation subsequently exposed partly filled phreatic paleokarstic cave to the paleokarstic surface where new generations of breccia was deposited. In the upper part of both photographs bedded paralic limestones cover the paleokarstic surface, in this case the roofless infilled phreatic cave. Large block in the foreground of the photograph B is approx. 1 m long.

The breccia deposits cross-cut underlying sequence of shallow marine carbonates and underlay a paralic carbonate succession, which after a few tens of metres grades upwards into marine foraminiferal limestone. A contact with the underlying bedrock is sharp, highly irregular and locally expressed by the network of dissolution widened, irregular filled fractures (i.e. "fracture breccia") and channels. At the contact the wall-rock surface is usually slightly smoothened and locally covered with flowstone and oxidised iron-rich crust.

In a ground plane, single breccia bodies extend over a few hundreds square meters and their maximum thickness could exceed 6 meters. In area adjacent to Ubac peninsula a calcareous breccia that separates Cretaceous from Paleogene successions was used as mappable unit on the basic geological map of Yugoslavia in scale 1 : 100 000 and could reach thickness of 15 to 20 metres (Magaš, 1968).

Breccia body could be divided into several breccia and calcareous siltstone/sandstone units. Although different lithologies are not clearly stratigraphically successive, we can roughly differentiate a tree superimposed units of the breccia (Figs. 44B, 45). The thickness of each unit is laterally variable, however the lower being the thickest (up to 4 m) and the upper one the thinnest (up to 1m). The irregular portions of calcareous siltstone/sandstone, which are mainly decametric in scale, are intercalated and dispersed throughout all three breccia units, being the most pronounced between the lower and middle breccia unit. Transitions between the breccia units and between the breccia and the siltstone/sandstone are gradual and indistinct.

All three breccia units have no internal stratification and clasts are more or less chaotic orientated (Fig. 45). Locally in the lower and middle unit, some clasts are indistinctly bedding-parallel orientated.

Fabrics include framework-, matrix- and clast-supported styles, commonly in close proximity. The lower unit comprises the most variable fabric although framework-supported style is the most common (Fig. 45A). Middle unit is predominately clast- (Fig. 45B) and the upper one matrix-supported (Fig. 45C).

Figure 45: A) Framework-supported block breccia forms lower part of disintegrated and collapsed paleokarstic phreatic cave. Note flowstone deposited on blocks and as broken columns/stalagmites. B) Clast- to matrix-supported coarse stone/coble breccia. Note chaotic distribution of in-situ rounded stones/cobles. C) Matrix- to clast-supported conglomerate/breccia forms the uppermost part of described breccia body.

Locally, the siltstone/sandstone portions (the intercalation and the matrix of the breccia) (Fig. 46) include crude stratification and lamination (Fig. 46A). Also where siltstone/sandstone portions do not contain significant lamination constant alternation of grain size, composition and package on decametric scale, suggests some sort of internal stratification. Among other sedimentary structures graded bedding bedding-parallel orientation of elongate particles occur in places. Rarely birds-eye-like porosity, now occluded by drusy mosaic spar, is observed (Fig. 46E).

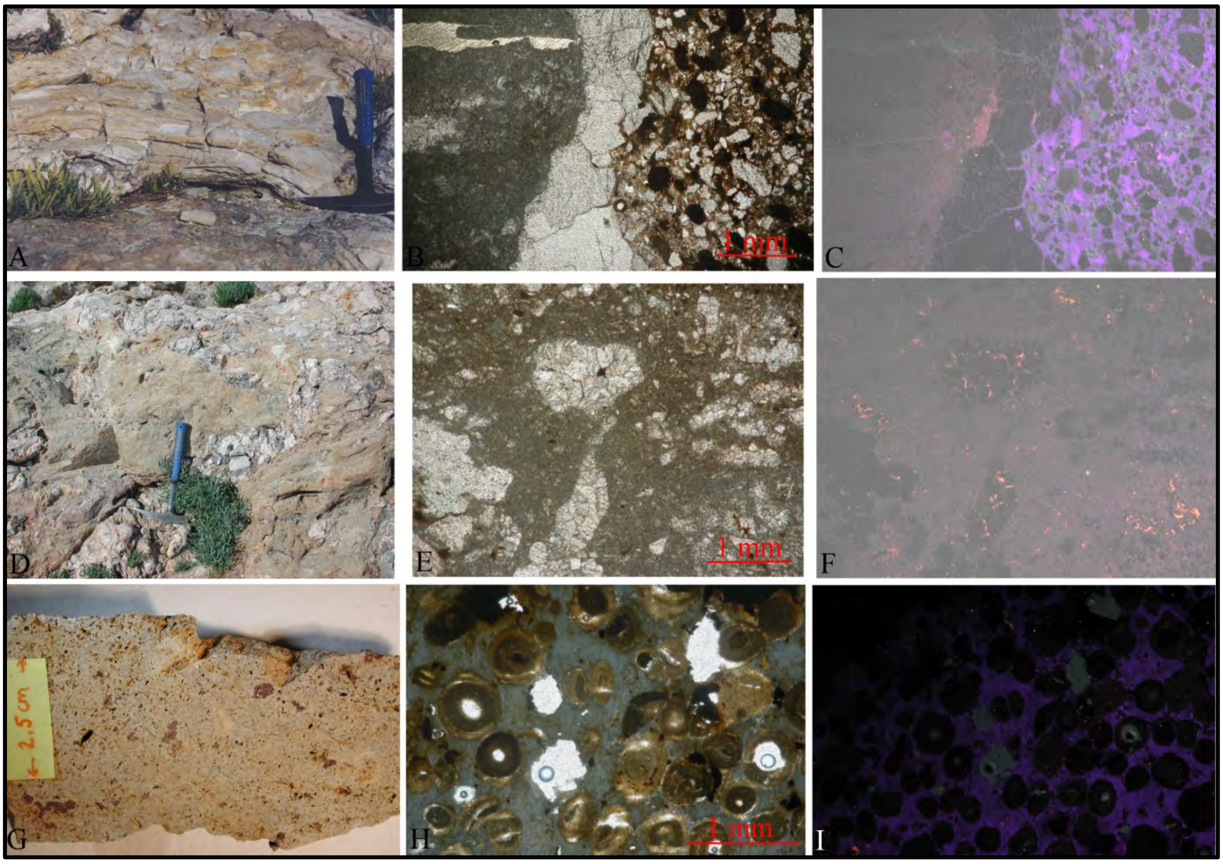


Figure 46: Matrix of framework-supported block breccia suggesting multiple generation of matrix deposition among the breccia clasts. Stratigraphically higher facies are not essentially younger from previous one. A) Laminated sandy sediment deposited in the upper part of the framework-supported breccia. B) and C) Photomicrograph showing a micirtic clast of the breccia with calcite spar rim (left side) embedded in matrix (see figure A). Matrix itself is actually sandstone with calcite (disintegrated sandstone and recrystallized host rock) and bauxitic grains immersed in clayey/bauxitic? matrix. B – transmitted light, C – cathodoluminiscence. D) Picture showing un-homogeneous distribution of clasts and matrix. E, F) In the central part of the framework-supported breccia succession, different types of matrix alternate. Commonly the matrix is composed of calcite micrite including individual grains of sandy-size calcite crystals and may includes secondary dissolution voids filled with calcite spar E – transmitted light, F – cathodoluminiscence. G) In general, the last generation of paleokarstic deposits is commonly composed of bauxite. H, I) Autochthonous to parautochthonous oolitic bauxite. Whole and broken ooides in clayey matrix. H – transmitted light, I – cathodoluminiscence.

Clasts sizes of the breccia are variable but typically range from fine pebble to boulder; cobble size being the most common (Figs. 44, 45). There is significant decrease in clast size from lower to the upper breccia unit (Figs. 44, 45). In the lower unit the size range is the most variable and comprises the whole spectrum from fine pebble to large boulders/blocks, which could exceed one meter in diameter (Fig. 45A). The middle unit comprises the most uniform clast size range, cobbles being predominant (Fig. 45B). Although in the upper unit the clast may vary significantly pebbles are dominant (Fig 45C).

Gravel sorting in poor, but is moderate in the middle unit where breccia is clast-supported and clasts show crude bedding parallel orientation (Fig. 44B – section 2).

Clast shape is variable but slightly elongated form is the most common. Especially in the upper two units, some clasts are highly irregular and contain up to few centimetre wide hollows (Figs. 45B, 47). Most clasts derived from the host limestone are subangular, while calcareous crystal clasts are angular. Degree of roundness is increasing upwards through the breccia profile (Figs. 44, 45, 48).

In composition most of the clasts match with hosting cave limestone lithologies, however speleothem clasts (Fig. 49) are locally abundant. Some speleothem still have preserved original shape (stalagmites, stalactites) while others occur as a part of composite bedrock/speleothem clasts. Some limestone clasts reveal widened joints filled with pedogenically modified carbonate sediment. In the uppermost matrix- to clast-supported conglomerate/breccia grains commonly contain weathered of pedogenicaly or biogenically (lichens?) altered rim (Fig. 48). Clasts of the overlying paralic limestone are absent in the cave related breccia.

Breccia matrix could be considered independently as calcareous/bauxitic sandstone (Figs. 46, 47, 48). Allocheme composition varies from mixtures of sand- to pebble-sized detritic calcareous crystal particles (desintegrated speleothems) (Figs. 46A–F), aluminous/ferruginous oolites, peloids and intraclasts (Figs. 46G–I) and bedrock limestone intraclasts. Alochemes are embedded into silty to clayey matrix (Fig. 46). In the upper part of cave profile first generation of matrix is highly pedogenically modified (Figs. 47, 48). Grains are represented by microcodium particles (Figs. 47a, b), different more or less irregular brown peloids which merge together into clotted micrite (Figs. 47a, b, 48E), bedrock intraclasts and fragments of land snails (Fig. 47c). Porosity between dominantly pedogenically originated grains of clast- to matrix-supported coarse stone/coble breccia (Fig. 45B), primarily probably originated from rhizolithes is occluded by non-luminescent spar (Fig. 47A, B). Last generation of remaining voids filling or locally also a matrix represents a kaolinite violet blue under CL (Figs. 46–48).

Degree of roundness of breccia matrix grains depends on their lithology. Commonly calcite crystals are angular, intraclasts sub-rounded and bauxitic particles rounded (Figs. 46–48). Matrix particle size ranges from silt to small pebble.

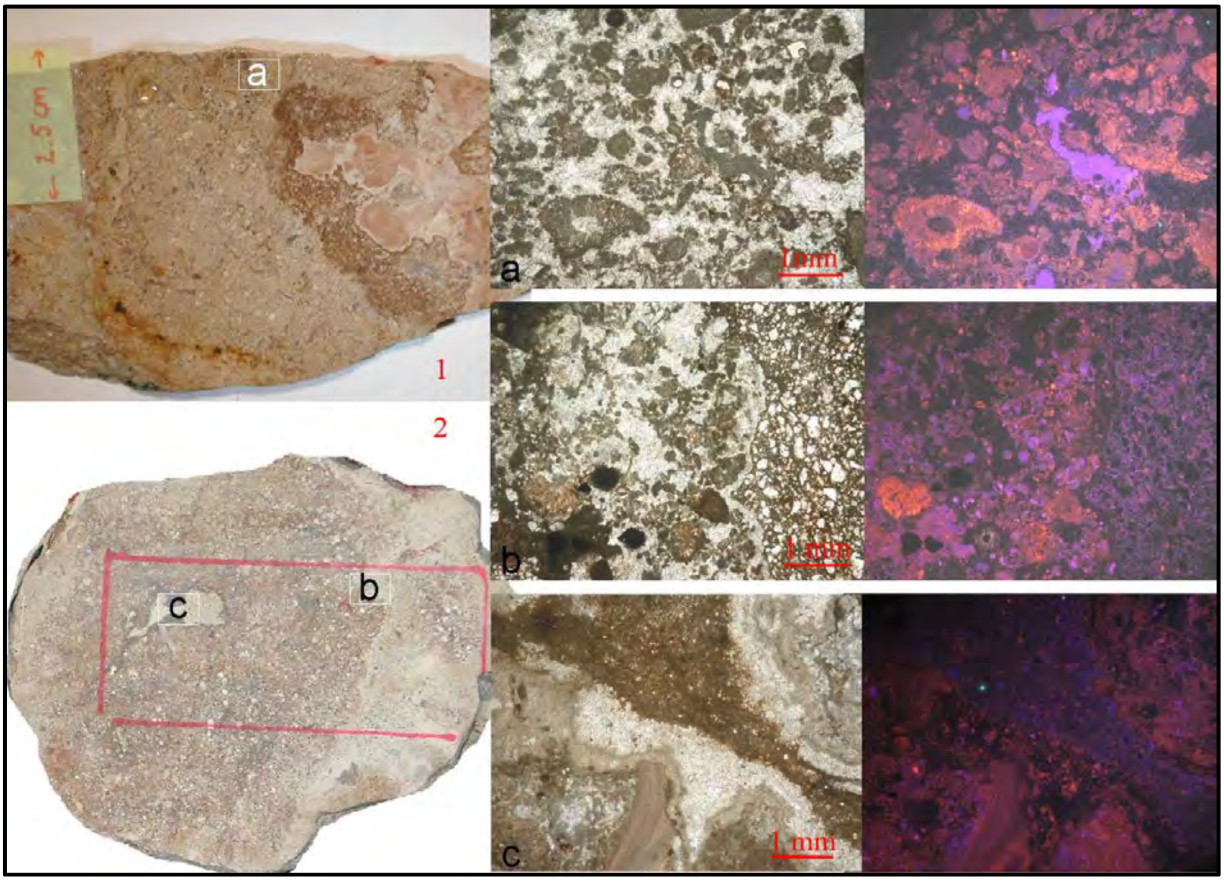


Figure 47: Matrix of clast- to matrix-supported coarse stone/coble breccia. 1) Brown un-homogeneous sandy calcareous matrix. Note highly irregular reddish stained breccia clast with weathered margin and dark brown "reaction rim" in surrounding matrix probably representing selective cementation and ferruginous mineral transformation. a) Grains mainly represent to different stage disintegrated *Microcodium* aggregates, micirtic noduls or peloids and pedogenically altered clotted micritic and clayey aggregates. First generation of

intergranular pores is filled by nonluminescent calcite spar while second generation of pores or remaining pores after first generation of cement are filled by clayey sediment violet under cathodoluminescence. 2) Two generations of matrix, first one similar to one in picture 1, and second one more homogenous and finer-grained. b) Material similar to that in picture 1a with a bit more clayey particles in sharp contact to more homogenous sandstone with nonluminescent angular calcite crystal particles and clayey matrix violet under cathodoluminescence. c) Secondary dissolution void surrounded by biodiagenetic rim (alveolar septal texture, brownish sparmicirte and fine-grained spar calcite) and filled by clayey material and silt-sized calcite particles. Note shell of terrestrial snail in the lower part of photomicrograph.

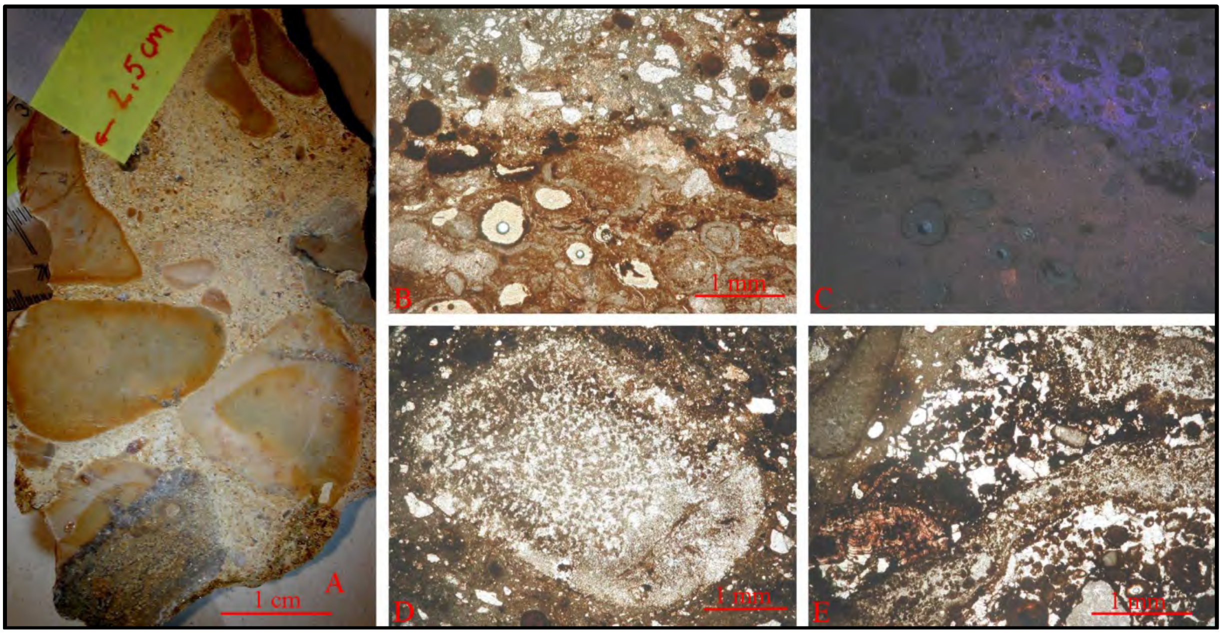


Figure 48: Pedogenically altered matrix- to clast-supported pebble conglomerate/breccia. A) In situ rounded conglomerate/breccia clast of different origin (Upper Cretaceous host rock limestone vs. bauxite) showing high degree of alternation. B, C) Oolitic bauxite clast (dull luminescent)(lower part) and sandy matrix of conglomerate/breccia (upper part) build of angular calcite spar particles and spars bauxite ooids immersed in clay, violet under cathodoluminescence. D) Highly etched/weathered limestone pebble. E) Chaotic structure of conglometrate/breccia matrix related to carbonate pedogenic processes showing multiple episodes of cementation, dissolution, nodule formation and void filling in soil zone.

Calcite Spar (Speleothem)

Speleothem occurs as *in-situ* precipitate and as breccia clasts (Figs. 49, 50). It appears in several types: flowstone (Figs. 49A, 50B), stalagmites (Fig. 49C), stalactites, cave peloids (pearls) (Figs. 49D, 50A, C) and calcite rafts (Fig. 50D). While flowstone is the most common type, calcite rafts are hardly recognizable. Although only flowstone and cave pearls could still be treated as *in-situ* precipitate, some calcite rafts and large stalagmites (Fig. 49C) seems to be only slightly dislocated from their original position.

Larger clasts composed of flowstone and stalagmites are more abundant in the lower part of the breccia profile (Fig. 49C). The latter are represented as macroscopic, up to approximately $1m^3$ large breccia clasts and as sub-millimetric to centimetric disintegrated calcite particles (Figs. 49B, 50D) in the breccia matrix and sandstone intercalations.

The outer edge of speleothems which is in contact with breccia matrix or sandstone intercalation frequently shows highly jagged surface with crystalline particles dispersed in the nearby sediment. At such contacts laminas may alternates with irregular patches of neomorphic calcite spar (Fig. 50B). It is possible that small calcareous crystals which often occur in the breccia matrix and sandstone intercalations mainly derived from disintegrated calcite rafts (Fig. 50D).

It is interesting that cave pearls or terrestrial pisolits that occur as clasts in matrix of clast- to matrix-supported coarse stone/coble breccia in the middle part of the breccia profile (Figs. 44B –

section 2, 45B) beside bedrock particle as a nuclei containing also *Microcodium* rosettes and ferruginous/bauxitic grain (Fig. 50A).

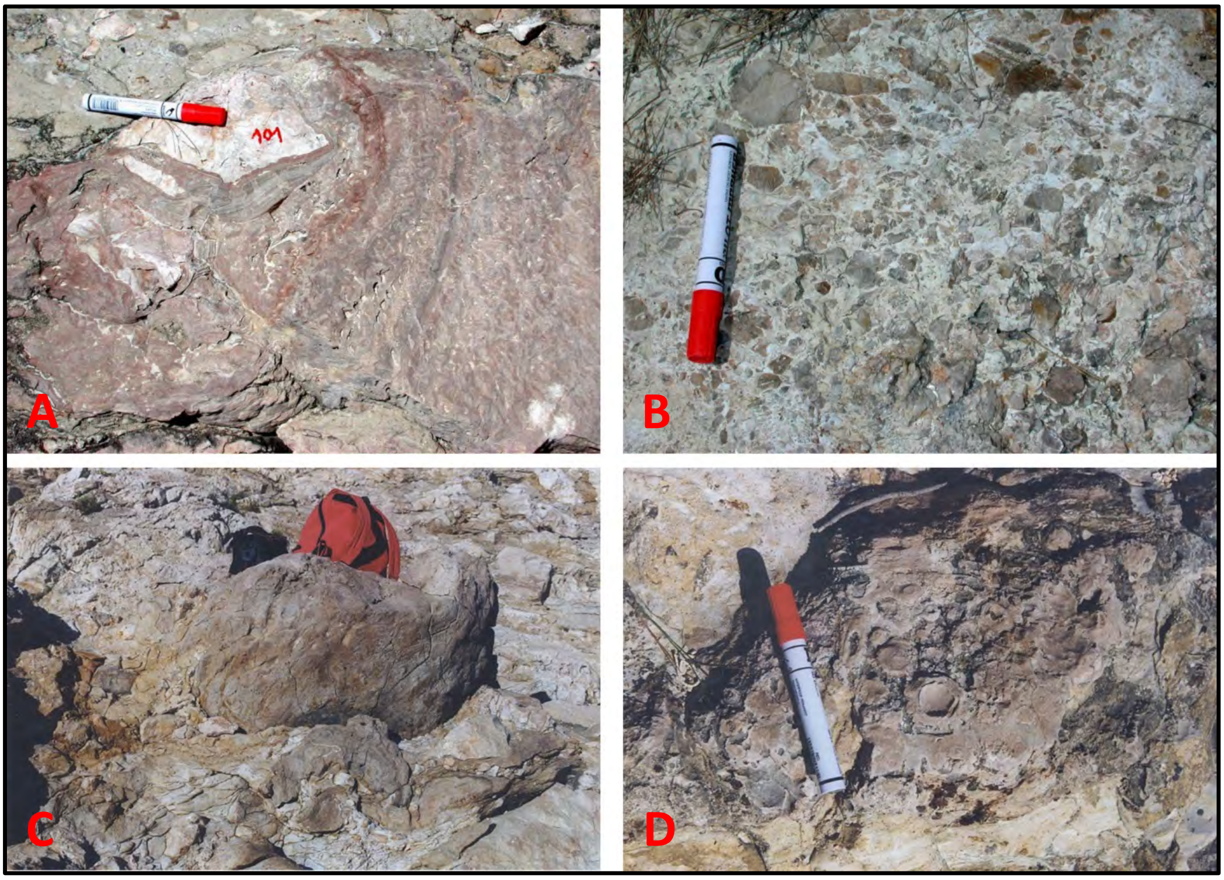


Figure 49: Speleothem types of Ubac paleokarstic site 1: A) Eroded reddish crenulated flowstone deposit on breccia clasts. B) Calcite grains of disintegrated flowstone immersed in clayey/bauxitic(?) matrix (subcutaneous zone of paleokarst). C) Big stalagmite as framework-supported breccia clast. D) Eroded cave pisolites or pearls.

Speleothems are one of the most diagnostic cave indicators in paleokarst profiles. Flowstone, stalagmites and stalactites require subaerial conditions and vadose zone for their precipitation, while calcite rafts and cave pearls are deposits of cave pools.

Alternations of sparitic and micritic laminas (Fig. 50 B, C) probably display periodic environmental changes, introduced to the cave via percolating waters. In addition, microorganisms may have play important role in the formation of micrite layers in stalactites and cave pearls (Jones, 1994). Brown colors of speleothems usually result from humic acids derived from overlying soils, while white coloured speleothems contain fulvic acid with very little humic acid or it display originally aragonitic speleothems which do not take up humic substances (Hill & Forti, 1997). Because higher temperatures and more intense biological activities resulting more complete breakdown of plant material (Hill & Forti, 1997) different stained laminas could reflect seasonality or climatic changes over longer periods.

It is important to note, that speleothems were deposited before significant sediment deposition. Only thin plates of reddish brown flowstone associated with small cave pearls and rafts were occasionally deposited during major clastic depositional events. Disintegration of crystalline speleothems, parts (crystals) of which were later redeposited in calcareous bauxitic sediment are probably due to weathering processes in soil or sediment.

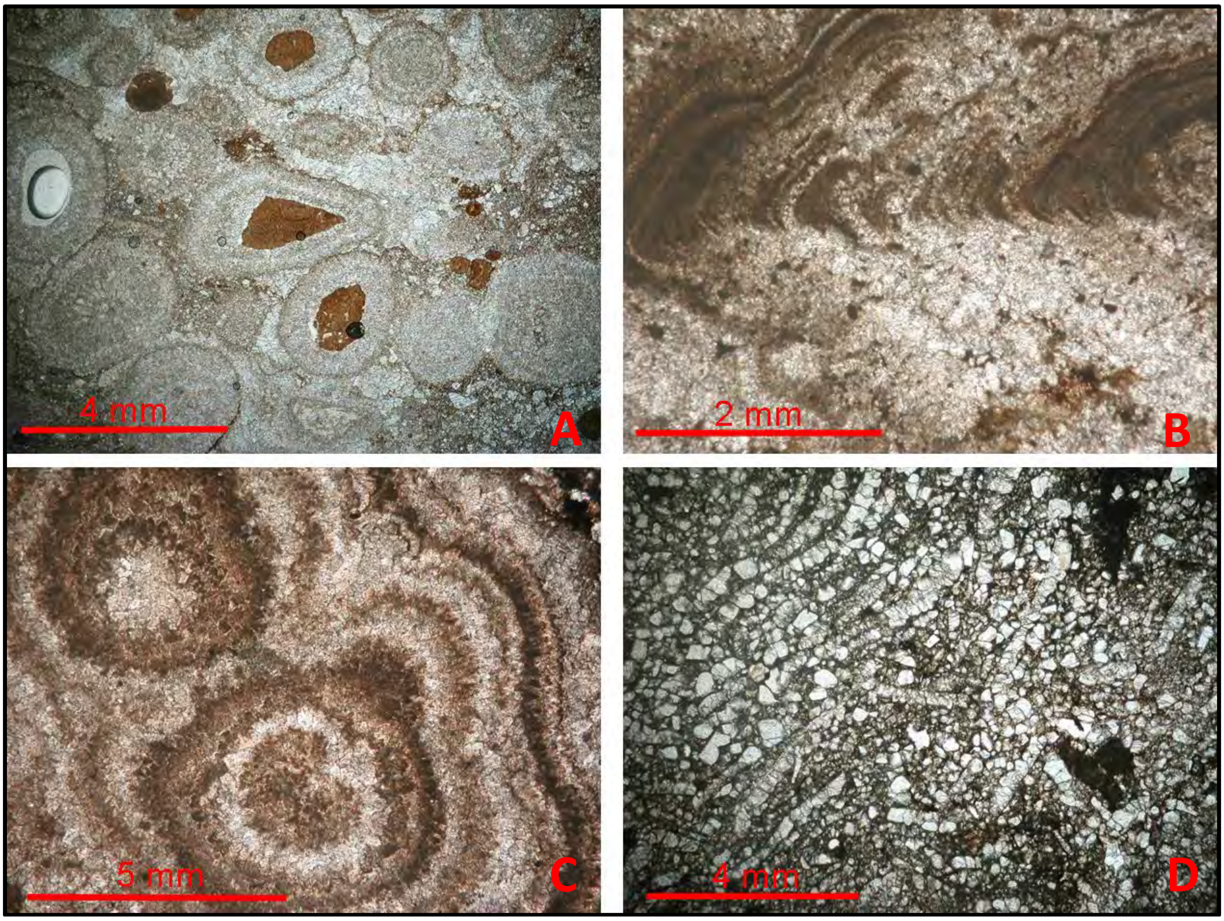


Figure 50: Photomicrographs of speleothems: A) cave pearls or terrestrial pisolits forming a grain in matrix of clast- to matrix-supported coarse stone/coble breccia. Note brown clayey or bauxitic particles and *Microcodium* rosete as pisolit's nucleus. B) Highly weathered and re-crystalized crenulated flowstone. C) Amalgamated cave pearls. D) Partly disintegrated calcite rafts.

Origin of breccia

Numerous petrographic characteristics reveal that breccia body emplaced between stratified shallow marine carbonate successions is at least indirectly a product of karst related processes. Although clastic cave sediments normally comprise a variety of genetically diverse terrestrial sediments (Ružičkova *et al.*, 2001) some diagnostic criteria for deposition in cave environment should be recognized. Chaotic framework-supported breccia in the lower part of the profile was deposited after major speleothem precipitation. Wide size-range of predominantly angular clasts derived from immediately adjacent host rock strata and speleothems as well as infiltrating character of vertically alternating matrix suggest collapse as a possible mechanism for breccia framework deposition. Calcareous/bauxitic sandstone intercalations in breccia deposit (Fig. 46), deformed layers of the sandstone below the breccia clasts and in-situ flowstone deposits in the sandstone portion indicate that framework-supported breccia was not formed by a single collapse but rather through multiple events, interrupted by periods of quiescence when sandy and silty sediment and flowstone were deposited.

In the Middle and Upper more uniform part the breccia body (Figs. 44 B – sections 2 and 3, 45B, C) showing gradually more and more features diagnostic for pedogenic origin and modification. There we may observe even alternating generations of dissolution, deposition and cement precipitation (Fig. 47). Relatively well rounded clasts of clast- to matrix-supported coarse stone/coble breccia in the middle part of breccia profile (Figs. 44 B – sections 2, 45B) indicating subcoutaneous dissolution common process in many recent karst related breccias. We suggest that this section of the breccia body representing a cave entrance facies. Clasts here mainly derive from gradually more and more attenuated cave ceiling which eventually disintegrate. Where widened joints of the cave ceiling and cave passages below were mainly filled then cave ceiling gradually transform into clast- to matrix supported breccia with subcutaneously rounded clasts and mainly soil derived matrix. This type of breccia may also be partly resedimented by slope transporting processes, i.e. creeping. The uppermost part of the breccia body was continuously being subjected to pedogenic modifications till the inundation during the transgression.

Although not exclusive karstic, bauxites that occur in otherwise continuous carbonate succession, indicate periods of subaerial exposure under a humid tropical or sub-tropical climate.

Diagenesis of the bedrock (Fig. 51)

The wall-rock of the breccia bodies reveals complex diagenetic history, involving micritisation, neomorphism, leaching, dissolution and cementation as well as pyrite and gypsum precipitation. Diagenetic features have been observed on macroscopic and microscopic scale. Among the former, reddish-stained, up to a metre thick horizons, parallel to stratification are visible in the field bellow the described cavernous porosity denoted by the breccia deposit (Fig. 51A). Diagenetic history of reddened horizons partly differs from those of the unstained parts and plays an important role in the interpretation of the diagenetic environments involved in the initial phases of the cave development. The best pronounced reddened horizon is the highest one which occurs just below the main breccia body. There, also discrete channels decametric in scale are filled completely with exclusively calcareous micritic, silty and sandy material (white or reddish stained).

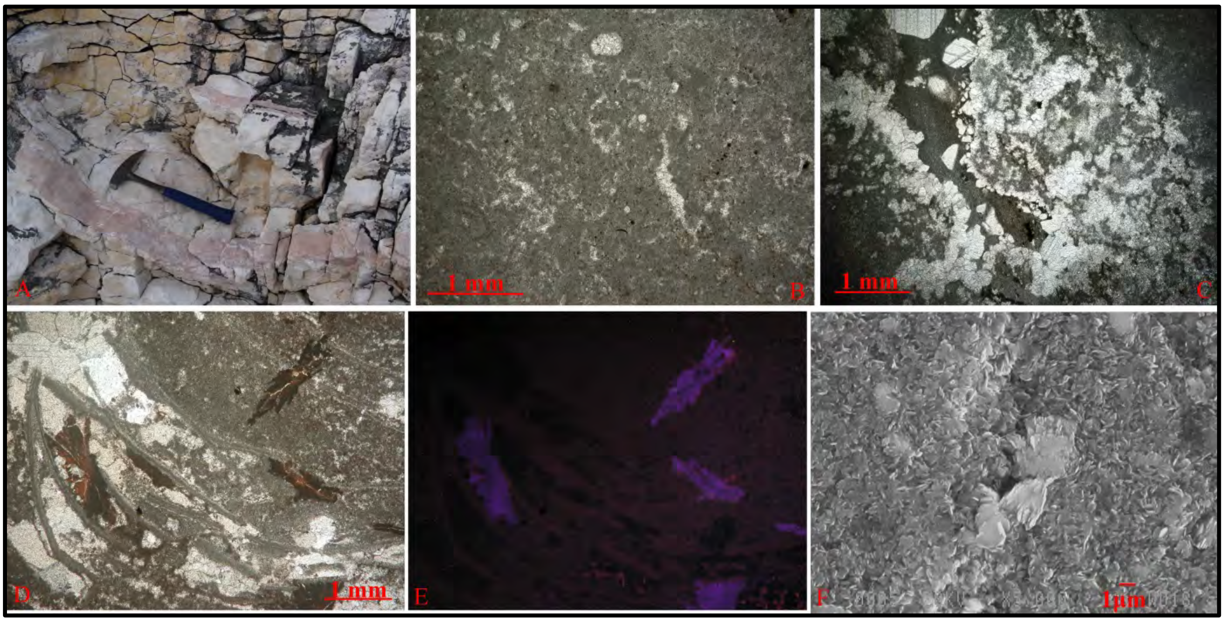


Figure 51: Diagenesis of the host rock. A) Some of the most pronounced features of otherwise more or less intact host rock limestone are reddish stained zones and horizons that occur few to few tens of metres below the paleokarst surface. B) Biopeloidal W/P with clotted micrite and dispersed oxidised pyrite (reddish-stained horizont). C) Dissolution void surrounded by "pseudo" alveolar septal texture mostly formed by selective neomorphism of the void walls. Clear isometric calcite crystals suggesting precipitation in meteoric diagenetic environment. Cavity is filled with vadose(?) micrite/silt. D, E) Brown rosette-like features represents kaolinite (violet under CL) pseudomorphs after gypsum (reddish-stained horizon). Note partly broken tabulae of the interior of rudist shell. F) Micron-size plates of kaolinite fill the rosette-like features of the figures D and E.

The paragenetic sequences can be divided into two stages: shallow marine synsedimentary and near-surface early diagenetic stage. Each stage includes a few diagenetic phases and events.

In addition to bioerosion of the fossil, mainly rudist skeletons, synsedimentary alternation of sediment particles on the sea-bottom includes micritization of skeletal grains and cementation of intrafossil porosity with neomorphosed originally fibrous marine cement. Both phases predate the collapse of rudist tabulae and infiltration of the internal sediment into the intra-skeletal pores (Fig. 51D).

Non-marine paragenetic sequences are strongly dependant on position of bedrock relative to subaerially exposed paleosurface and on diagenetic capacity of the original sediment (availability of mineralogical unstable skeletons, primary and secondary porosity etc.).

The inner marine carbonate succession which was relatively weakly altered during marine diagenetic stage was profoundly affected by the meteoric early diagenetic processes: neomorphism, leaching, dissolution and cementation. Locally, in the upper part of the profile immediately below the paleokarstic surface, evidences of pedogenic modifications and calcrete formation occur.

In the reddish stained horizons the most distinctive diagenetic alternations are related to staining and associate dissolution, neomorphic alternation, gypsum precipitation and calcite cementation. The reddish staining derives from oxidised pyrite and occupies almost exclusively clotted micrite (neomorphised?) that form disseminated mottles (Fig 51B). Less pronounced greenish grey and brownish mottles may be observed in the "unstained" bedrock limestone. They correspond to the parts where finely disseminated pyrite occurs in the micritic limestone. The greenish grey colours correspond to relatively unaltered pyrite, while brownish one to pyrite, which has undergone some alternations through oxidation.

Secondary microscopic (less than 0.5 mm in diameter) not fabric selective dissolution cavites, including vugs and channels, are usually highly irregular in shape with somehow blurred boundaries towards the matrix (Fig. 51C). Locally, cylindrical fenestrae comprise microfabric typical of calcified root mats: micro-laminar micrite, alveolar-septal structure, calcified outer margin of a rootlet or root hair and calcified root cortex. Both, dissolution cavities and fenestrae related to root activity later become occluded by clear non-luminescent equant sparry calcite.

Replacive white (brown or transparent yellowish under microscope) kaolinite rosettes, deep blue under CL, are associated exclusively with intra-fossil reddish stained clotted micrite and cavities (Fig. 51 D–F). Their occurrence in the cavities is rather problematic, because it is difficult to define whether were precipitated as cement or represent a replacement of original micrite. In any case they predate calcite cement precipitation. The shape of the crystals suggests that they probably represent pseudomorphs after gypsum crystals.

In the upper part of the profile (cave ceiling) secondary micro- and macroscopic porosity includes non-fabric selective vugs and dissolution-enlarged fissures, which exhibit diverse shapes and wall morphology. Vugs are usually highly irregular in shape and consist of isolated "chambers" connected with thinly dissolution-modified fissures or channels. Described and some associated microfabrics (i.e. lacy fabrics and alveolar septal textucture) are typical of calcified root mat respectively its origin may derives from microbial processes being operative in the rhizosphere.

Larger cavities (more than 1cm in diameter) may show more complex sedimentary history, including participation of sparry calcite rim, up to 1cm wide, followed by product of alternating dissolution-deposition-erosion processes. In the field these cavities appears as up to ten centimetres width, dissolution enlarged fractures and channels extends up to few metres below the paleokarst surface (see figures of the field trip stop 2b).

Immediately below the paleokarst surface, pedogenically induced accumulations of calcium carbonate and modifications of bedrock deposits have been identified in the bedrock and in the breccia.

Several macroscopic features and microfabrics diagnostic or characteristic for pedogenic calcretes has been identified: rhizoliths, coated grains, blackened pebbles and locally, laminar calcretes. In addition, detrital grains and terrestrial gastropods may represent a significant part of calcretes.

Calcrete microfabrics include “*Microcodium*”, alveolar septal texture, peloids, tubules and less common distorted needle fibre calcite. Porosity is usually occluded by sparry calcite and microspar.

Although we will not discuss a meaning of diagenesis for the course of karstification here, we want to stress out one interesting and commonly observed phenomena related to this unconformity also elsewhere, namely the reddish stained horizons, not directly attached to the paleokarstic surface. Namely, some cavities, gypsum crystals and reddish stained mottles could be the result of or enhanced by reduction/oxidation reactions in mixing zone waters. Bacterial enhanced reduction of aqueous sulphate in the presence of Fe oxides promotes Fe sulphide precipitation which in turn promotes less carbonate-mineral dissolution and more carbonate-mineral precipitation (Stoessell, 1992). These processes may correspond to precipitation of pyrite, recently presents in “unstained bedrock” and possible prolonged neomorphism. Subsequent back-oxidation of aqueous sulphide by mixing with oxygenated waters or by oxidation of waters as they move through fractures opening to the atmosphere could produce sulphuric acid and Fe oxides from solid sulphides (Stoessell, 1992). These processes lead to lowering of the pH and consecutive carbonate-mineral dissolution and to reddish staining of the bedrock by Fe-oxides. Important evidence for carbonate-mineral dissolution by sulphuric acid is presence of gypsum minerals which were precipitated from Ca-sulphate enriched water after the limestone was attacked by sulphuric acid. Later probably in the vadose zone gypsum was dissolved and empty moulds were filled with kaolinite transported in colloidal solution.

Paleokarst model (from prekarst to cessation)

Caves without roof of eugenetic karsts offer unique opportunity to study relative sea-level changes immediately before, during and immediately after certain carbonate platform was subaerially exposed.

In young carbonate successions of the isolated carbonate platforms without non-carbonate basement or hinterland most extensive cave development is related to fresh-water lenses siting on denser marine water below subaerialy exposed parts of the platform (Mylroie & Carew, 1995). The most pronounced dissolution is located to mixing-zone between freshwater lens and vadose zone or marine phreatic zone and especially where these two locations meet, on the flanks of the islands (Mylroie & Carew, 1995).

When particular area at Koromačno site was subaerially exposed for the first time due to a forebulge uplift (see chapter “Stratigraphy and evolution of the forebulge related paleokarst - introduction to the excursions a and c”), platform areas closest to the hinterland were already exposed and maybe even inudated by the sea again. At Koromačno newly established fresh-water lens caused lithification of the bedrock of further cave. Subsequently, an uplifting and concomitant denudation and secondary porosity development lead to attenuation and shift of the lens evidenced by meteoric and subsequent mixing zone diagenesis. Later the wider area at Koromačno became a site of pronounced dissolution and cave development in a mixing-zone, most probably close to the former coast-line during relative stillstand.

Evolution of paleokarstic cave and related palokrastic surface (Fig. 52):

1) In the subsurface, during the initial uplift of diagenetically immature carbonate sediments/rocks above the sea level, relatively homogenous and extended freshwater lens was formed. In the meteoric phreatic zone more or less uniform neomorphic alternations were taking place. Depending on local conditions and climate on the land surface and in the vadose zone simultaneously heterogenous dissolution and precipitation occurred.
2) Continuous hydrologic and diagenetic alternations related to the freshwater lens caused decrease in porosity and subsequent increase in permeability in more or less hardened and stabilised carbonate rock. Thus, more effective mixing of waters with different physical-chemical characteristics increases the dissolution, especially in the outflows of the freshwater lens, where flank margin or similar caves were formed. Autigenic meteoric water from more or less hardened surface became focused to point recharges greatly influenced by roots of higher plants what together with soil CO_2 enhanced dissolution in the vadose zone.

3) Relative fall of sea-level placed phreatic caves in epiphreatic and vadose zone where they were partly or completely filled by speleothems and detritic sediments. Continuous denudation of paleokarstic surface enhanced connection between paleokarstic surface and phreatic caves what increased the infilling of the caves with soil derived material like clays, bauxite and carbonate soil products (e.g. *Microcodium*, terrestrial oncoides…). Some cavities deeper below the surface remained free of surface derived material.
4) In the subsurface different diagenetic environments alternated through time due to oscillations in underground water table and freshwater lens and because of thinning of the cave roof. Subsequently the cave roof disintegrated what gave rise to intensive infilling of remaining cavities and alternation of cave deposits by surface processes. On the land surface bauxite deposits were accumulated, which were periodically resedimented in more or less desintegrated vadose and phreatic cavities.
5) Before the transgression some unroofed caves formed closed depresions and elongated dolines. In these depressions some deposits were resedimented by surface processes like creeping, sliding etc.
6) During the initial transgression over undulated even highly irregular karstic surface underground water table rose and inundated karstic depressions of different extent - a "blue-hole phase" of the transgression occurred. Lowermost carbonate sequences exhibit characteristics of marginal marine and palustrine lithofacies with frequent pedogenic alternations. Due to continuous subsidence of the area, gradually more open marine conditions prevailed with ongoing deposition of foraminiferal limestones.

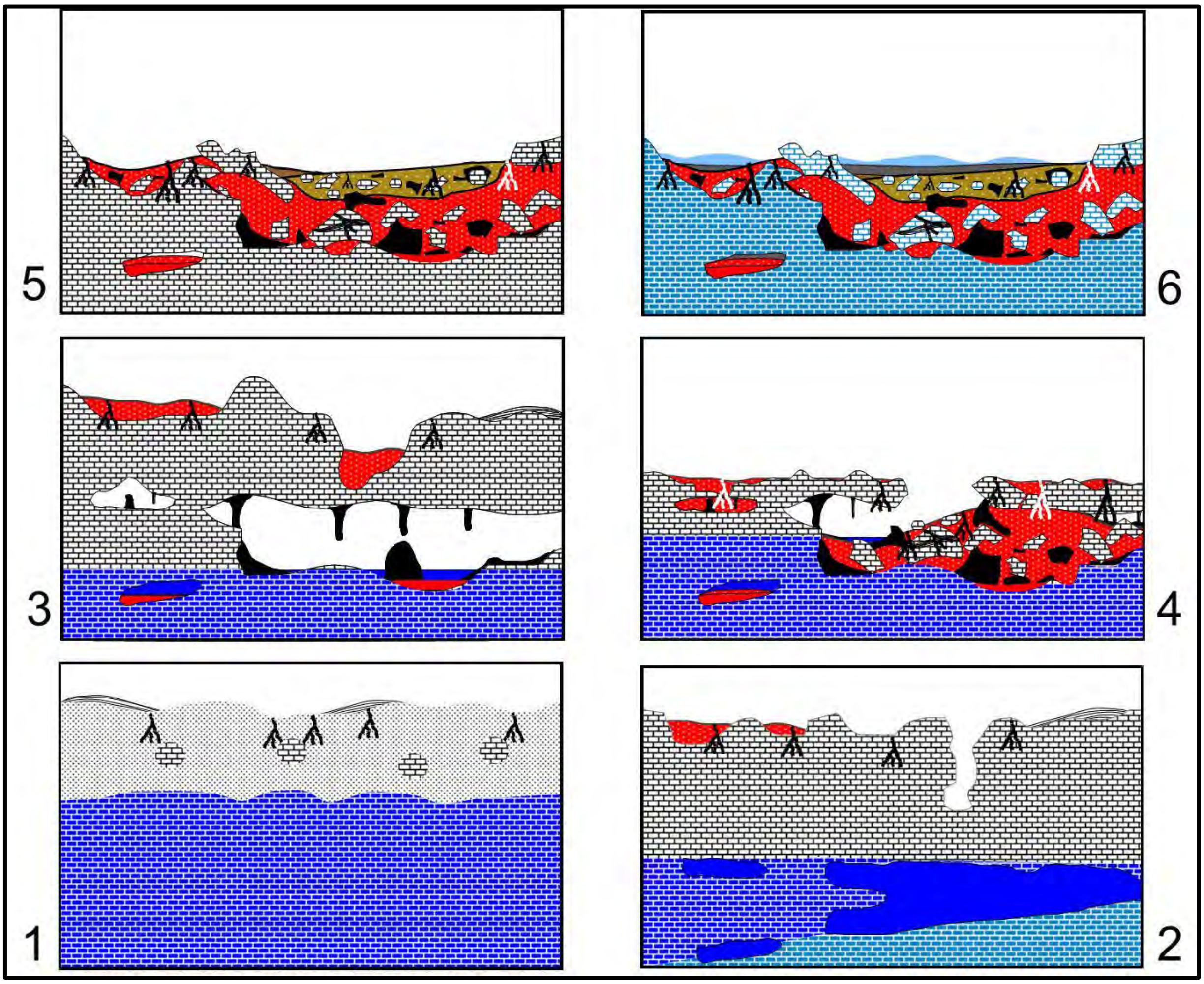


Figure 52: Development phases of the paleokarst surface in the area where the ceiling of halocline paleokarst caves was denuded (unroofed caves); the development phases are explained in text above.

BIG PHREATIC PALEOKARSTIC CAVE OF UBAC PENINSULA AND OTHER SURFACE AND SUBSURFACE PALEOKARSTIC PHENOMENA ADJACENT TO THE CAVE (No. 2B)
(Preliminary notes of reconnaissance survey)
Bojan Otoničar & Adrijan Košir

A remnants of a big more than 1 km long and up to a few metres originally high filled paleokarstic cave (Figs. 53A, 54) parallel to a related paleokarstic surface up to a few metres above the cave (Fig. 53B) could be followed along eastern coast of the Ubac peninsula. There, a variety of speleogenic features could be observed, like cave-wall morphology (Fig. 54), speleothems and other cave deposits (Figs. 53, 54, 55) as well as paleokarstic surface related phenomena and deposits (Figs. 53B, 56). The cave's ceiling is locally still preserved (Fig. 54A) while in other places is disintegrated in *in-situ* or *near-situ* breccia (Figs. 53A, 56B). In places karst profile doesn't include obvious cave related phenomena at all (Fig. 53B). Deposits related to paleokarstic surface comprise two basic types, bauxite (Fig. 56E) and calcrete (Fig. 56F). Deeper below the paleokarstic surface voids of centimetre-scale are filled by reddish stained calcareous silt and freatic cements (marine or/and mixing meteoric/marine or even meteoric) (Fig 57A).

In depressions, the paleokarstic relief is covered by limestone deposited most probably in fresh or brackish water marshes, lakes or even ponds (a "blue hole" phase of transgression). There also coal was deposited (Fig. 57B). Later, palustrine (and occasionally lacustrine) environments with increasing marine influence prevailed.

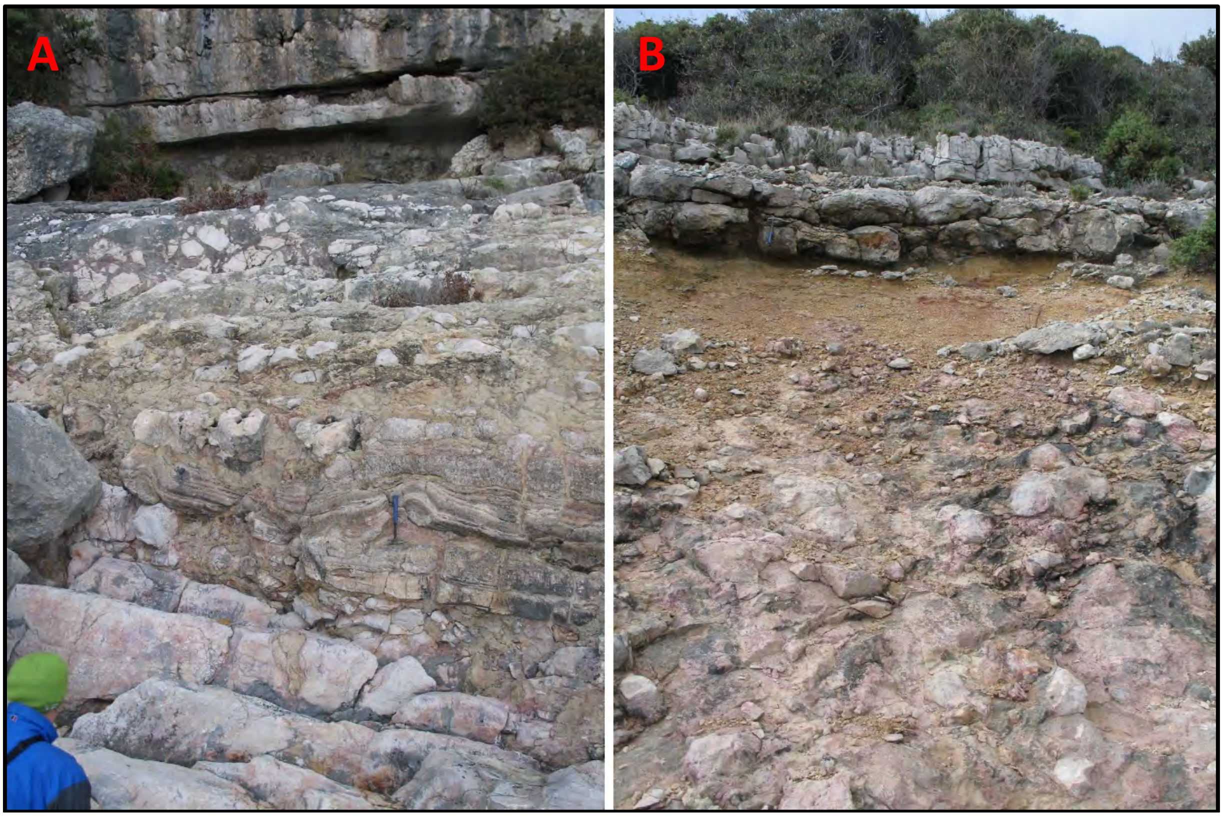


Figure 53: Two different types of paleokrastic profiles (Ubac peninsula; stop 2b) A) Partly disintegrated cave and its ceiling. Cave is represented by thick flowstone deposit while ceiling by coarse-grained clast- to matrix-supported breccia. Note vadose dissolution channels filled with calcareous and clayey material penetrating through whole cave filling profile down to underlying host-rock. Coarse-grained breccia matrix is already a part of Liburnian Formation ("a blue hole phase of transgression"). Thick bedded beds in the upper part of the picture belong to Liburnian Formation. B) Bauxite pit overlain by bedded dark-grey limestone of the Liburnian Formation. Note intensively reddish-stained Upper Cretaceous limestone below the bauxite deposit.

Figure 54: A) Completely filled paleokarstic cave with preserved ceiling. Note alternation of miciritic to silty calcareous sediment and flowstone. B) Lower part of the filled cave from picture A. Note an erosion surfaces, and extensional collapses of fine-grained and laminated cave sediment. Secondary voids are filled by calcite spar. C) Multiple generations of deposition, erosion, dissolution, and flowstone/cement precipitation (lower part of the cave filling deposits in picture A).

Figure 55: Different types of flowstone from the big paleokarstic cave of Ubac peninsula. A) Cave pearls; B) Eroded stalagmites. Note still opened central channel. C) A pile of cemented and somehow thickened calcite rafts or pool shields; D) Accumulation of radial calcite crystals (most probably subaqueous) over vadose stalactites. E) Huge accumulation of flowstone. Note cuted stalagmite-shaped flowstone in the centre of the picture.

Figure 56: Paleokarst surface related features. A) Calcareous material fills dissolutionally widened joints and bedding plane partings up to a few metres deep below the paleokarstic surface (epikarst). B) In-situ disintegrated cave ceiling or chaotic matrix- to clast-supported breccia (see Fig. 53A). Sub-rounded stones and blocks of Upper Cretaceous limestone embedded in locally reddish stained dark-grey freshwater (brackish?) limestone of the Liburnian Formation (a "blue hole" phase of transgression). C) Subcutaneous root related paleokarst. Re-opened paleoroot-casts after soft "bauxitic" material has been washed-out. D) Subcutaneous paleokarst. Note rounded karren exposed after soft "bauxitic or clayey" material was partly washed away. E) Autochthonous or parautochthonous bauxite: bauxite pisolites are emplaced in pelitomorphic bauxite matrix. F) Calcareous soil – calcrete containing locally resedimented calcite pisolites and calcere intraclasts emplaced in sandy calcareous matrix. Calcrete fill dissolutionally widend joint in the upper part of vadose zone (epikarst).

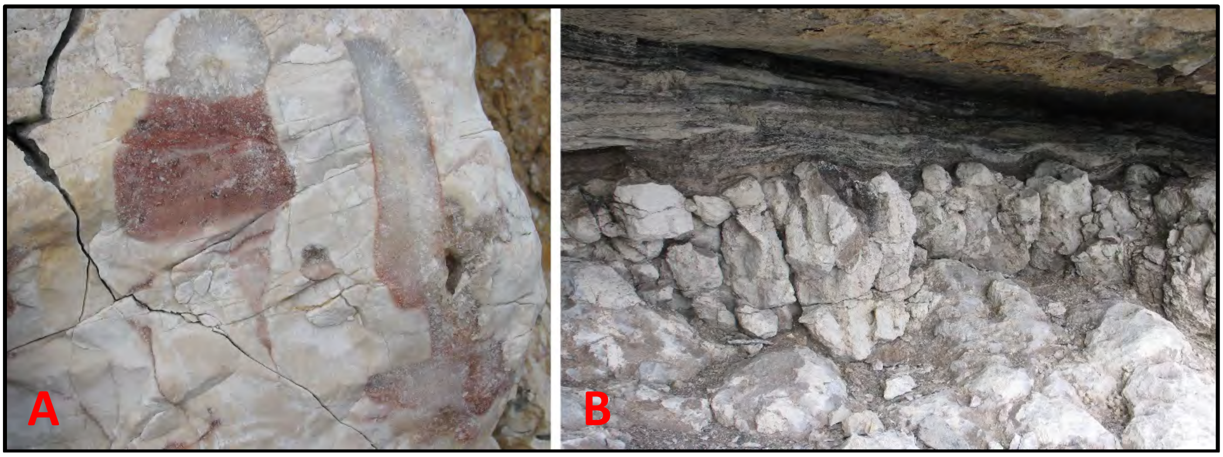


Figure 57: A) Voids in the lower part of the paleokarstic profile or one of the first generation of dissolutional voids of discussed paleokarst period containing geopetally deposited reddish micrite with sparse coarser-grained calcite crystals and centripetally precipitated coconut-meat calcite spar. B) Palustrine Kozina Beds (close to Paleocene/Eocene boundary) of the Lower part of the Liburnian Formation deposited immediately over the paleokarstic surface. Note highly undulating surface on dark-grey limestone covered by marshy marls with coal seams. Undulation is probably due to root related bioturbation into marshy protosoil (?).

Whole-day excursion **(D):**

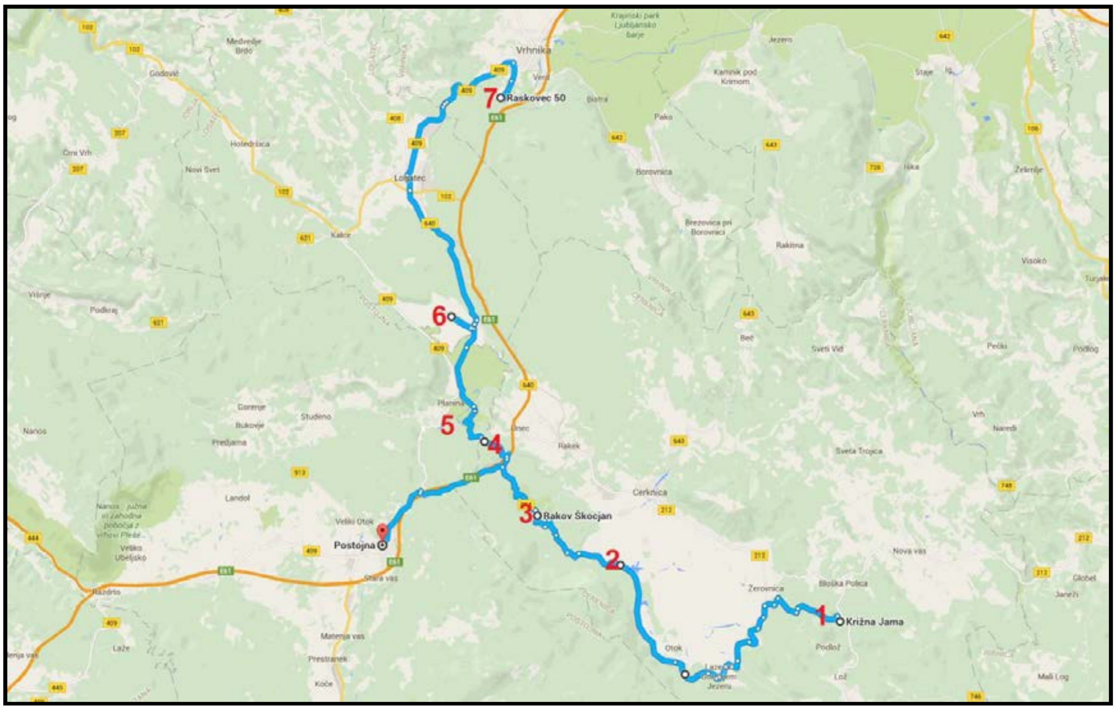
LJUBLJANICA KARSTIC RIVER BASIN

Friday, 17.6.2016, 8.30–18.00

Matej Blatnik, Franci Gabrovšek, Mitja Prelovšek

Stops:

1 – Križna jama (hydrologic and speleogenetic characteristics of the cave);
2 – Cerknica polje (sinkholes, ponors, flooding regime…);
3 – Rakov Škocjan karst valley with natural bridges;
4 – Planinsko polje (discussion on Postojna–Planina cave system, morphology and hydrology of Planinsko polje);
5 – Springs of Ljubljanica river and collapse dolines at Vrhnika.



LJUBLJANICA RIVER SYSTEM

Estimated size of the Ljubljanica drainage basin is 1779 km^2, of which about 1100 km^2 are composed of karstic rocks. The location of the water divide is approximate, but bifurcations have been proved at several boundaries by water tracing. According to studies during the complex water tracing experiments of the nineteen-seventies, the catchment area of the Vrhnika springs, where the main river definitively leaves karst terrain, covers 1108.78 km^2. The mean discharge is 38.6 m^3 sec^{-1}, with a specific run-off of 34.8 l sec^{-1} km^{-2}. Average mean denudation rate is 65 m^3 km^{-2} a^{-1} (Mihevc, 2010).

The karstic rocks are generally micritic, locally oolitic limestones and dominantly late-diagenetic dolomites, mostly of Mesozoic age. 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 basin belongs to the Adriatic sub-plate. The area is composed of several napes that were over thrust during the peak of Alpine orogeny in Oligocene, in a NE to SW direction. Later change of the plate movement direction brought about the formation of the Idria (dextral strike-slip) Fault, which runs through the area in a NW-SE direction.

The highest parts of the basin are high karst plateaus Hrušica, Javorniki, Snežnik and Račna gora. Surface rivers with different names appear only on poljes: Trbuhovica, Obrh, Stržen, Rak, Pivka, Unica and finally after the springs at Vrhnika the name Ljubljanica. Several sinking rivers that drain dolomite or flysch areas also contribute to the system: These are Nanoščica, Cerkniščica, Logaščica, Hotenjka and Rovtarica and many smaller.

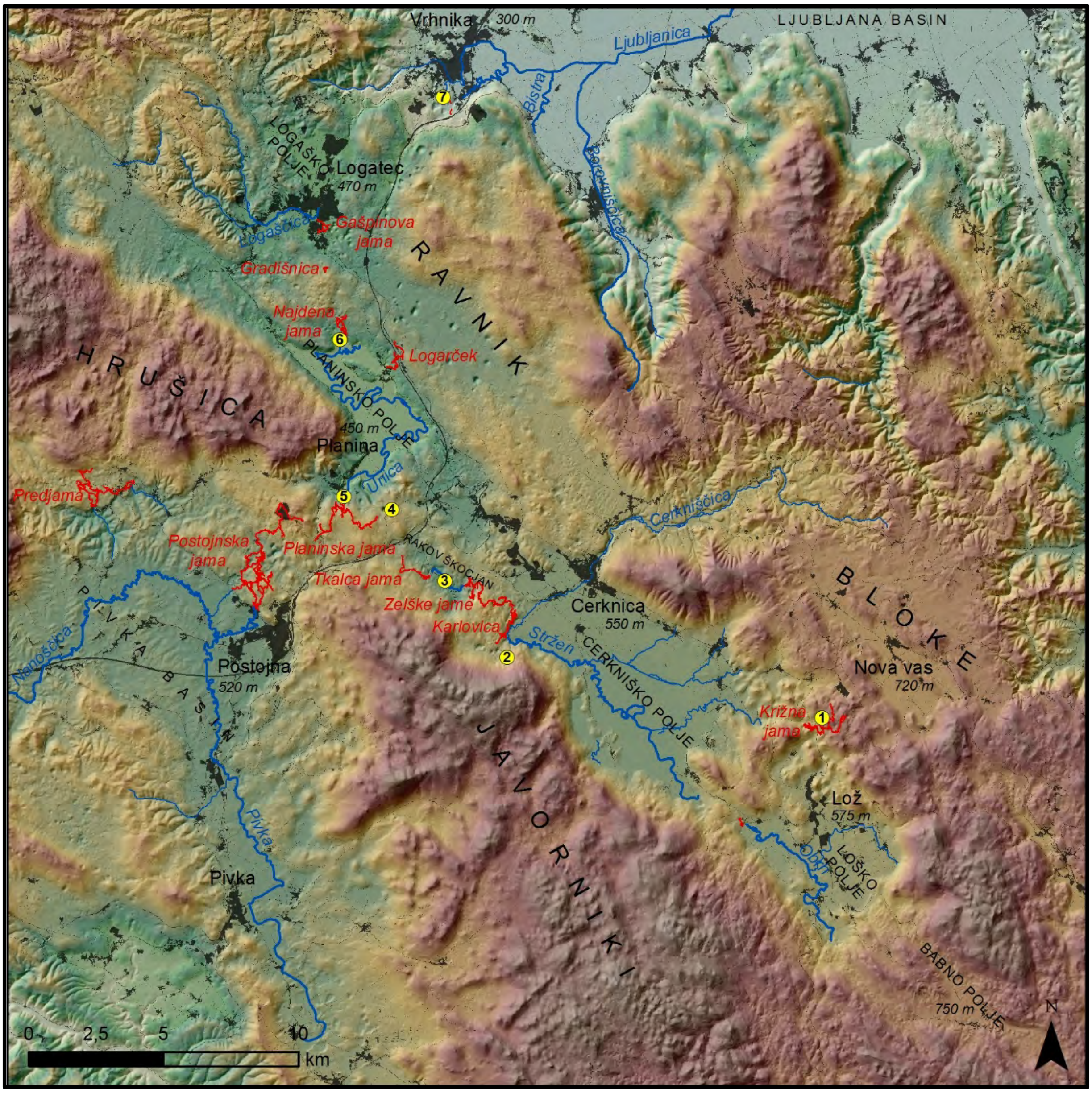


Figure 58: Central part of the Ljubljanica basin with high karst plateaus, lower surfaces with karst poljes and surface rivers. Passages of larger caves are marked with red lines. Main field trips stops are marked with yellow dots: 1 Križna jama, 2 Cerkniško polje, 3 Rakov Škocjan, 4 Unška koliševka, 5 Planinska jama, 6 Planinsko polje, 7 Collapse dolines near Vrhnika and springs of Ljubljanica river.

The highest lying is the karst polje near Prezid (770 m), followed by Babno polje (750 m), Loško polje (575 m), Cerkniško polje (550 m), Rakov Škocjan and Unško polje (520 m), Planinsko polje (450 m), Logaško polje (470 m) and finally by Ljubljansko barje where the Ljubljanica springs are at 300 m. The system discharges through several large springs and many small springs aligned along the edge of the Barje, part of Ljubljana tectonic basin, which is connected with gradual tectonic subsidence of the area. Mean annual discharge of the Ljubljanica at springs is 38.6 m^3 (Mihevc, 2010).

There are 1540 caves, accessible fragments of underground drainage system known in the catchments area of the Ljubljanica. The average length of the cave is 48 m and the depth 18 m. However, the largest caves are the ponor or spring caves; in them we can follow the about 80 km epiphreatic channels.

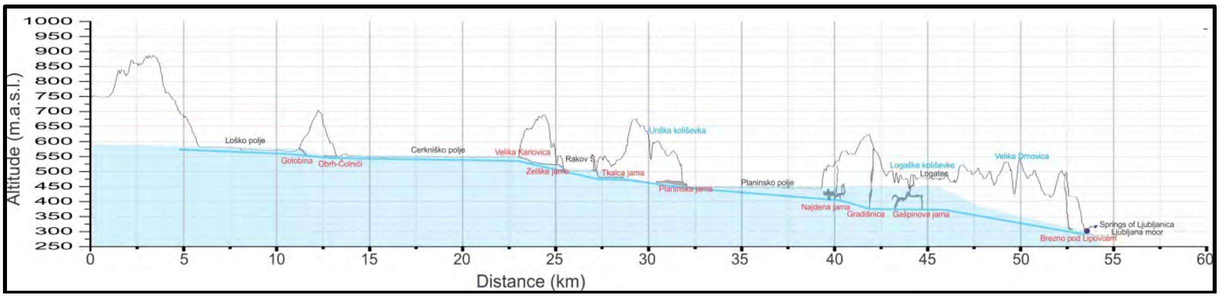


Figure 59: Longitudinal cross section of Ljubljanica karst river basin (Gabrovšek, 2016). It follows a broken line, initially along SE-NW trend of the Idrija fault and from Planinsko polje toward springs at Vrhnika along the N trend. The red text denotes major Caves red, the cyan large collapse dolines.

KRIŽNA JAMA (No. 1)

Križna jama is located between Cerkniško polje (550 m), Loško polje (575 m) and Bloke plateau (720 m). Cave attracts attention especially due to high biodiversity (45 defined troglobionts – 4th place in the world), more than 2,000 excavated bones of cave bear (*Ursus spelaeus*) and stream that pours over more than 40 underground lakes. The latter as well as regionally-outstanding size of passages makes it attractive for tourism receiving about 5,000 visitors per year. Scientific research started with paleontological excavations in the late 19th century. Between World Wars, passages upstream of 1st lake were intensively researched and mapped along a length of 5 km and after 2nd World War extended to present-day length of 8,273 m. In 1960-ies as well as in 2007, tracing tests were performed to get an impression about catchment area toward Bloke plateau and downstream connection with springs located at the SE edge of Cerkniško polje. Research on cave sediments (origin of allochtonous sediments, U/Th and palaeomagnetic dating) was conducted in 1970-ies, 1990-ies and after 2003. Processes of calcite precipitation along underground stream, formation of lakes behind rimstone dams and damage on them due to touristic use were intensively studied after 2004. Downstream continuation of stream passage, known as Križna jama 2 (1,415 m), was discovered in 1991 and later strictly closed due to high sensitivity. Sump between two caves was recently dived to -124 m.

Cave is formed in Lower-Middle Jurassic limestones interlaced by layers and lenses of dolomite that are more abundant in Križna jama 2. Upper reaches of Križna jama are already formed in Lower Jurassic dolomite resulting in narrower passages, many breakdown chambers and final unpassable breakdowns. The sediment that seems to be one of the oldest was dated to <0.78 Ma probably not indicating relevant passage formation strongly influenced by allogenic sediments from Bloke plateau. Typical discharge of underground stream amounts 0.2 $m^3 s^{-1}$ with oscillation between few $l s^{-1}$ and several $m^3 s^{-1}$. Yearly stable water temperature (8.0±0.5°C), relatively low Ca/Mg ratio (<2.5), high water hardness (4.1-5.5 mmol $(Ca^{2+}+Mg^{2+}) l^{-1}$) and calcite oversaturation as a result of intensive CO_2 outgassing in cave indicate prevail of autogenically recharged water genetically related to flow through dolomite and dolomitized limestone aquifer. Present-day speleogenetic processes are strongly controlled by cave ventilation; intensive oversaturation of water (SI_{Cal}>0.5) leading to calcite precipitation (rate up to 0.1 $mm a^{-1}$) is related to only few days of intensive winter ventilation ($T_{out(daily max)}$<0°C) that reduces pCO_2 along +8 km of passages to almost outside concentration (400 ppm). Present-day dissolution is the strongest during summer months but still stays well below 1 $\mu m a^{-1}$. During middle discharge, only 1.3 % of water originates from sinking stream on Bloke plateau. Discharge of +2 $m^3 s^{-1}$ is usually accompanied by intensive overflow of water from Bloke plateau flooding the cave up to 7 m at the 1st lake. This indicates Križna jama to be probably above general regional water level during low and middle water levels.

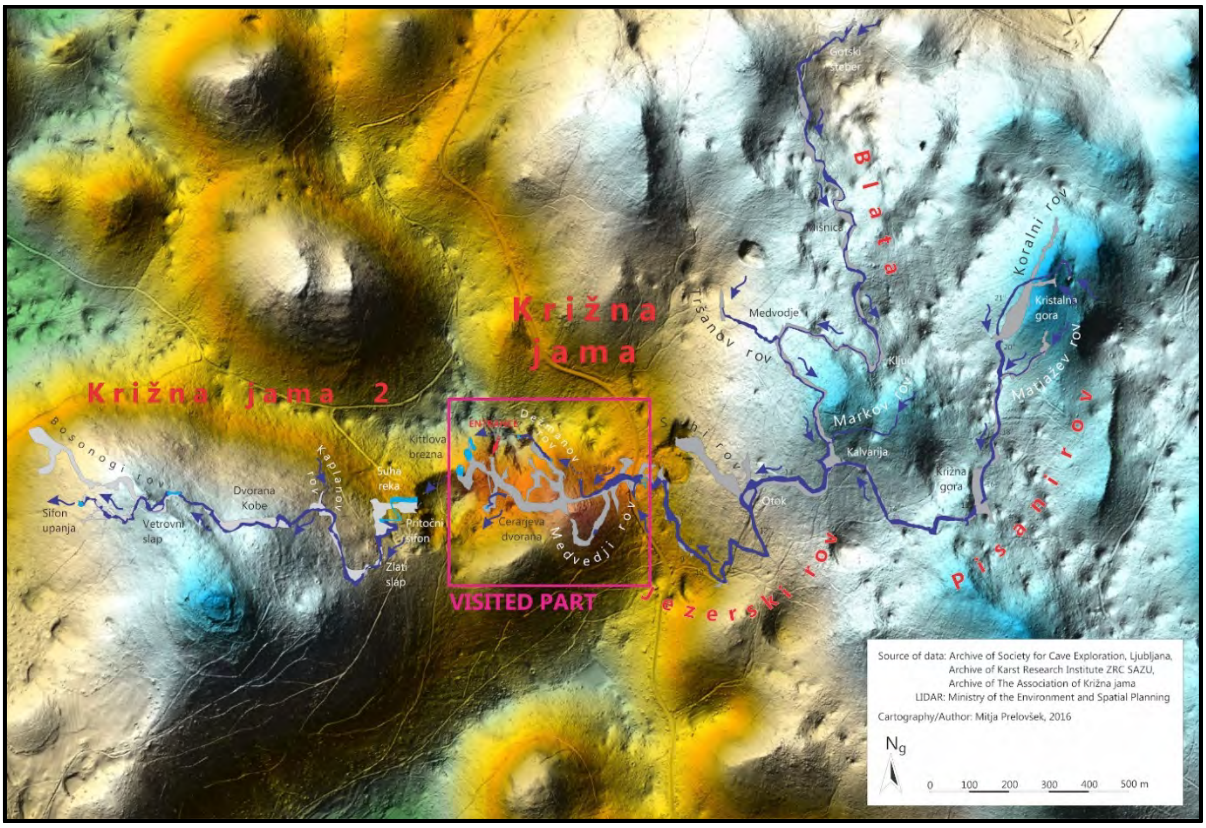


Figure 60: Plan of Križna jama (Prelovšek, 2016).

THE POLJES OF NOTRANJSKA REGION

Idrija fault is a major regional fault system oriented along the so-called Dinaric (SE-NW) direction. Along the fault zone some of the NW most Dinaric poljes have formed. Poljes are large flat-bottomed karst depressions with hydrological regime mainly characterized by regular floodings. Poljes are often the only areas on karst with surface waters. The formation of poljes is preconditioned by tectonics in this case the structures within Idrija strike slip fault (e.g. pull-apart zones); however the forming mechanism is the corrosional planation at the groundwater level.

CERKNIŠKO POLJE (No. 2)

Cerkniško polje is the largest karst polje in Slovenia. Due to its regular flooding it is often called Cerkniško jezero (Lake of Cerknica). 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 polihistor Valvasor, who published his famous study on Cerkniško jezero in 1689 (Mihevc, 2010).
The main part of the polje is underlained by the Upper Triassic dolomite which builds dominates in N, E and SE border. Areas on the W and NW are mainly underlain by the Cretaceous limestone.

The main inflows to the Polje are on E, S and partly on W sides. The only allogenic recharge is Cerkniščica which drains dolomitic area on the SE. The important karst springs on the E side are Žerovniščica, Šteberščica and Stržen. The springs on the SW side (e.g. Suhadolca, Vranja jama) present important recharge during floods. Polje is populated with several estavelas, which act as springs or as ponors, depending on the water (Mihevc, 2010).

Besides estavelas, several ponor areas in the inner part of the polje drain some amount of water directly to the springs of Ljubljanica. However, the main ponors are aligned along the W side of Polje, with Velika and Mala Karlovica as the most prominent. Both caves extend form over 8.5 km between Cerkniško polje and Rakov Škocjan. Only a small unexplored segment (probably obstructed in the collapse zones) missing to connect Velika Karlovica with Zelške jame extending from Rakov Škocjan.

Recent study has shown that during low-mean hydrological situation important part of the water from Mala Karlovica ponors flows to the Kotliči springs positioned in the middle of the Rakov škocjan and a smaller part to the Zelške jame, which would be a logical direction.

Passages of Karlovica caves are generally low and filled by alluvia. Thickness of alluvia in Jamski zaliv, before the caves entrances, is about 8–15 m.

During the last centuries several plans have been made to change the hydrologic behavior of the polje, but none was realized. In 1960-ies a plan for permanent ponding of Cerkniško jezero was already in action; in the years 1968 and 1969 entrances to the caves Velika and Mala Karlovica were closed by concrete walls and 30 m long tunnel was made to connect Karlovica with the surface, but small effect of retention in dry period and dryer years were assessed (Mihevc, 2010).

Flattened bottom of Cerkniško polje is regularly flooded for several months in autumn winter and spring time. Lower waters are sinking mostly in marginal swallow holes and in numerous ground swallow holes and estavellas, which are disposed in central polje's bottom.

RAKOV ŠKOCJAN (No. 3)

Rakov Škocjan is a karst depression about 1.5 km long and 200 m wide. It is situated between Planinsko and Cerkniško polje under the N side of Javorniki Mountain at an elevation about 500 m. Through the depression the permanent river Rak is flowing. The Rak springs from Zelške jame cave, bringing water from Cerkniško polje. Zelške jame are about 5 km long; the end of the cave is in large collapse doline Velika Šujca, where from the other side the Karlovica cave system ends. The entrance part of the Zelške jame is a fragmented system of channels and collapse dolines. The most prominent feature there is Mali naravni most (Small Natural Bridge), where a narrow arch, a cave ceiling remnant, divides two collapse dolines. Downstream, the valley widens and several springs along the SW side of the valley form perennial or intermittent tributaries of the Rak River. The valley narrows at the Veliki naravni most (Big Natural Bridge), a remnant of a cave passage. The height of the cave passage under the bridge is between 9.5 and 17 m, its width is between 15 and 23 m and the length is 56 m. The rocky arch is composed of thick-bedded and anticline-folded Lower Cretaceous limestone (Mihevc, 2010).

The channel opens into a 150 m long canyon that ends in the entrance to Tkalca jama, almost 3 km long cave, which drains water towards Planinska jama. The connections of the Rak with water from Cerkniško polje and with the Unica springs at Planinsko polje were proved by water tracing and by diving. Entrance to Tkalca jama lies at 496 m, while the highest floods 2014 reached to 515 m. The water at the cave entrance was thus 19 m deep at its deepest.

Before the 1st World War Rakov Škocjan was owned by the Windischgrätz family and was closed as their private park; between 1st and 2nd World War, the Italians also closed the area for the public. From 1949 Rakov Škocjan has been a Landscape Park (Mihevc, 2010).

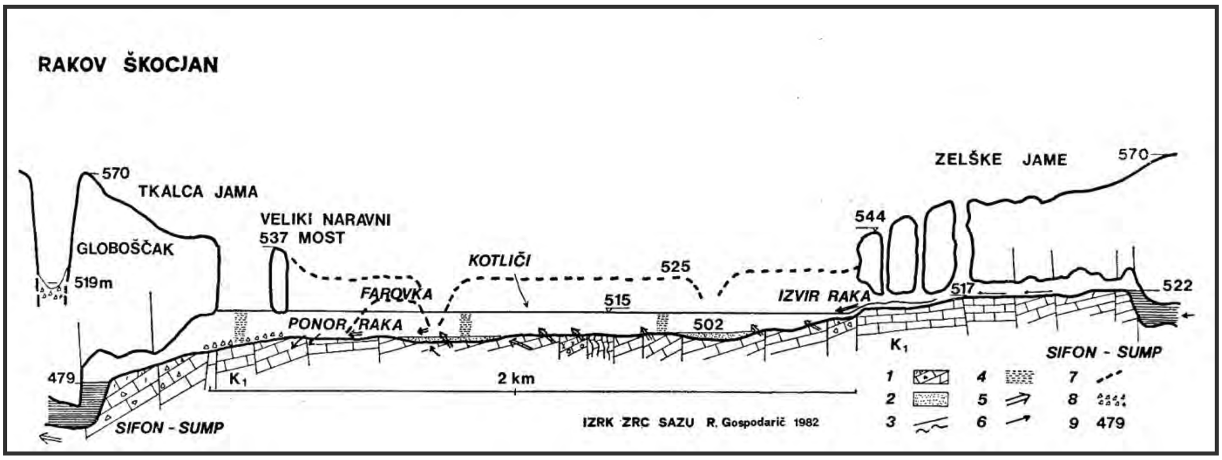


Figure 61: Cross-section along Rakov Škocjan karst depression between spring at Zelške jame and sink in Tkalca jama. Legend: 1 – rocky bottom, 2 – alluvia, 3- fault zone, 4 – flood in 1982, 5 – karst spring, 6 – water flow directions, 7 – terraces, 8 – boulder rocks, 9 – altitude (Gospodarič *et al.*, 1983).

UNŠKA KOLIŠEVKA (No. 4)

Collapse dolines are large closed depressions formed by subsidence and/or partial collapses of cave ceilings. Large collapse dolines form in the crushed/fractured zones above the main groundwater flow, where dissolutional yield is high due to high (rock surface)/(water volume) ratio. Unška koliševka is a fine example of such a doline: it is 100 m deep and up to 150 m wide, with vertical walls, subsiding bottom and vegetation inversion. Between the two wars the area was part of an Italian defence line. Several km of underground tunnels were built in the area of doline, with about 1.5 km still possible to see. Its total volume as calculated from the lidar data is 1.5 x 10^6 m^3.

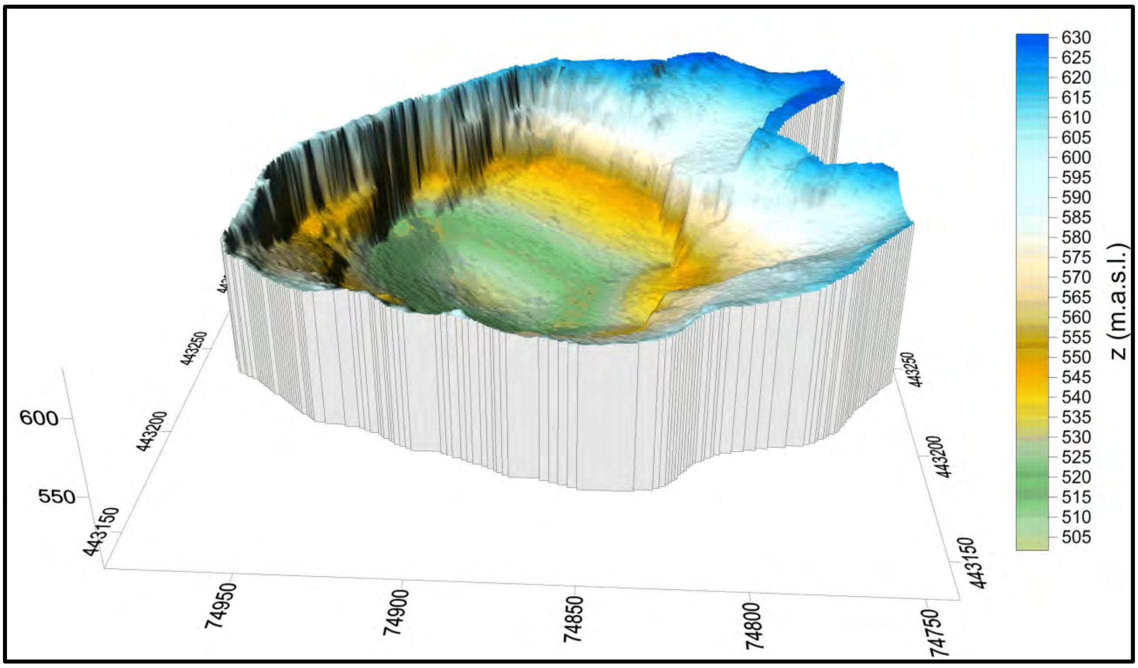


Figure 62: Unška koliševka.

PLANINSKA JAMA (No. 5)

Planinska jama is situated on the southern rim of Planinsko polje, with its entrance at the end of a large pocket valley. It is about 6.6 km long and mostly composed of large (average cross-section > 100 m^2) active river passages. Within the cave we can see a confluence of two regional streams, Pivka river from Postojnska jama and Rak river from Rakov Škocjan. The cave ends with sumps at inflow of both tributaries. Both sumps have been dived, but no connection to the upstream systems has been yet made. The recent exploration of Pivka channel, however give reasonable hopes that such connection will be made in the near future.

The cave discharges the main spring of the Unica river, which flows through the polje. The inner parts of the cave are at a slightly higher elevation than the entrance. A planed surface with many dolines occurs 50 m above the cave.

The cave entrance is situated in the Upper Cretaceous limestones and dolomites. The entrance part and Rakov rokav (Rak branch) are developed in Lower Cretaceous bedded limestones, limestones with chert and limestone breccia (Gospodarič & Habič, 1976). Pivški rokav (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. Bedding dips north-eastwards at 20° in the Rudolfov rov.

PLANINSKO POLJE (No. 6)

Planinsko polje is the most NW of all active Dinaric Poljes. Its wider surrounding is built of Jurassic and Cretaceous limestone and Upper Triassic dolomite, dolomite also underlays large part of the polje's bottom.

It is an overflow type of polje, where tectonically crushed and less permeable dolomite barrier along the Idrija fault zone, forces the karst waters from the higher areas side to surface at the set of springs on the southern side, the largest being Planinska jama and Malni springs. Set of smaller (some intermittent) springs are also aligned along W and NW side. The springs contribute to Unica river, which meanders across the polje and first partially sinks at the set of ponors aligned along the eastern side polje. These ponors take about 20 $m^3\ s^{-1}$. The rest of the water continues towards ponors at the N rim of polje. The total ponor capacity of polje is estimated around 60 $m^3\ s^{-1}$ (Šušteršič, 2002). Unica has mean annual discharge 24 $m^3\ s^{-1}$ (min. 0.3 $m^3\ s^{-1}$, max. >100 $m^3\ s^{-1}$) (Frantar & Ulaga, 2015).

Planinsko polje can be flooded several times in a year, typically in autumn-spring period, when polje can stay flooded for more than two months. In February 2014, the floods reached altitude 453.2 m when 72 million cube meters of water was stored in the polje (ARSO, 2014). To prevent flooding of Planinsko polje, different activities were undertaken in in the beginning of 20th century. To increase the capacity, different constructions were made to prevent plugging of ponors by flotsam.

The area around Planinsko polje is known as one of the cradles of caving in Slovenia. There are numerous cave entrances to active and fossil caves. Few caves are longer than 5 km.

Figure 63: Flooded Planinsko polje on February 2016 (Blatnik, 2016).

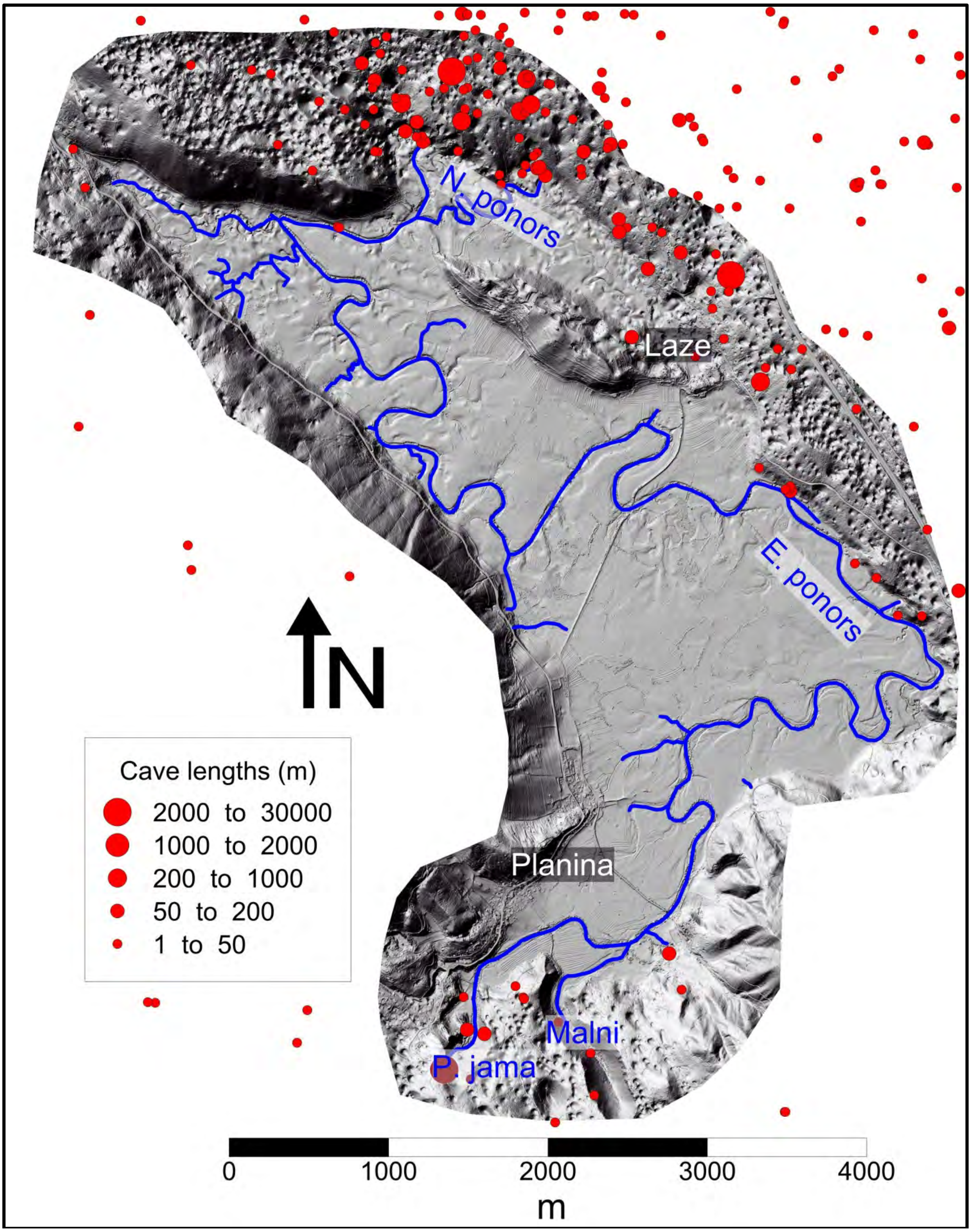


Figure 64: Shaded relief of Planinsko polje with main springs, ponors and flow of Unica river.

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. Data loggers are installed in 7 caves (Logarček, Vetrovna jama, Najdena jama, Gradišnica, Gašpinova jama, Lipovec, Veliko brezno v Grudnovi dolini) and two ponors on the rim of Planinsko polje (Ribce, Putickove štirne). Fig. 65 shows presents the recorder dynamics of underground water in year 2015.

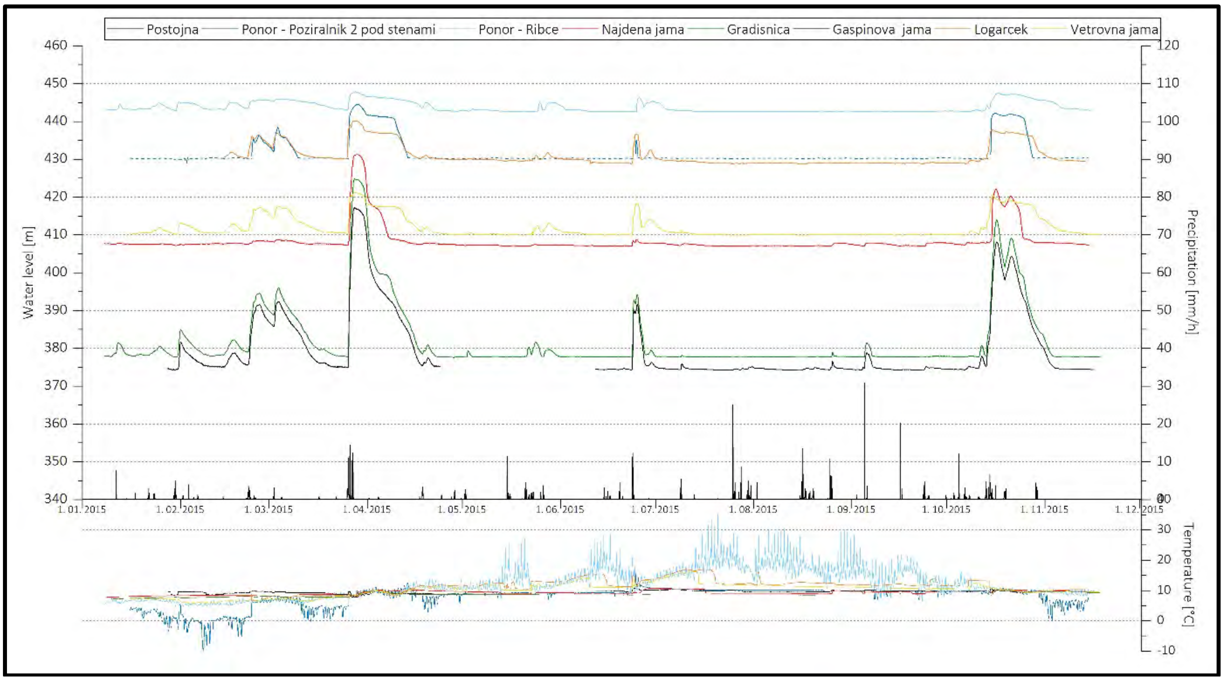


Figure 65: Water level in selected caves between Planinsko polje and Ljubljanica springs in 2015.

COLLAPSE DOLINES BETWEEN LOGATEC AND VRHNIKA AND IN THE VICINITY OF LJUBLJANICA SPRINGS

Between Logatec and Vrhnika several large collapse dolines formed along the main drainage pathways of underground Ljubljanica river. Table 1 lists the bottom elevations, and dimensions of the largest. Estimated volume of the biggest of them (Velika Drnovica) is around 1.6 mio m^3.

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

Tab. 1: Collapse dolines formed along the main pathways of Ljubljanica river (Stepišnik, 2006).

Seven collapse dolines are located in immediate vicinity of main Ljubljanica spring (Table 2). The bottoms are relatively levelled and covered with over 30 m thick loamy sediment. The elevation of bottoms of all these dolines are within 10 meters. Recent floods are observed in Grogarjev dol (Stepišnik, 2006). Estimated volume of Paukarjev dol is around 1 mio m^3.

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

Tab. 2: Collapse dolines located in the vicinity of main Ljubljanica spring (Stepišnik, 2006).

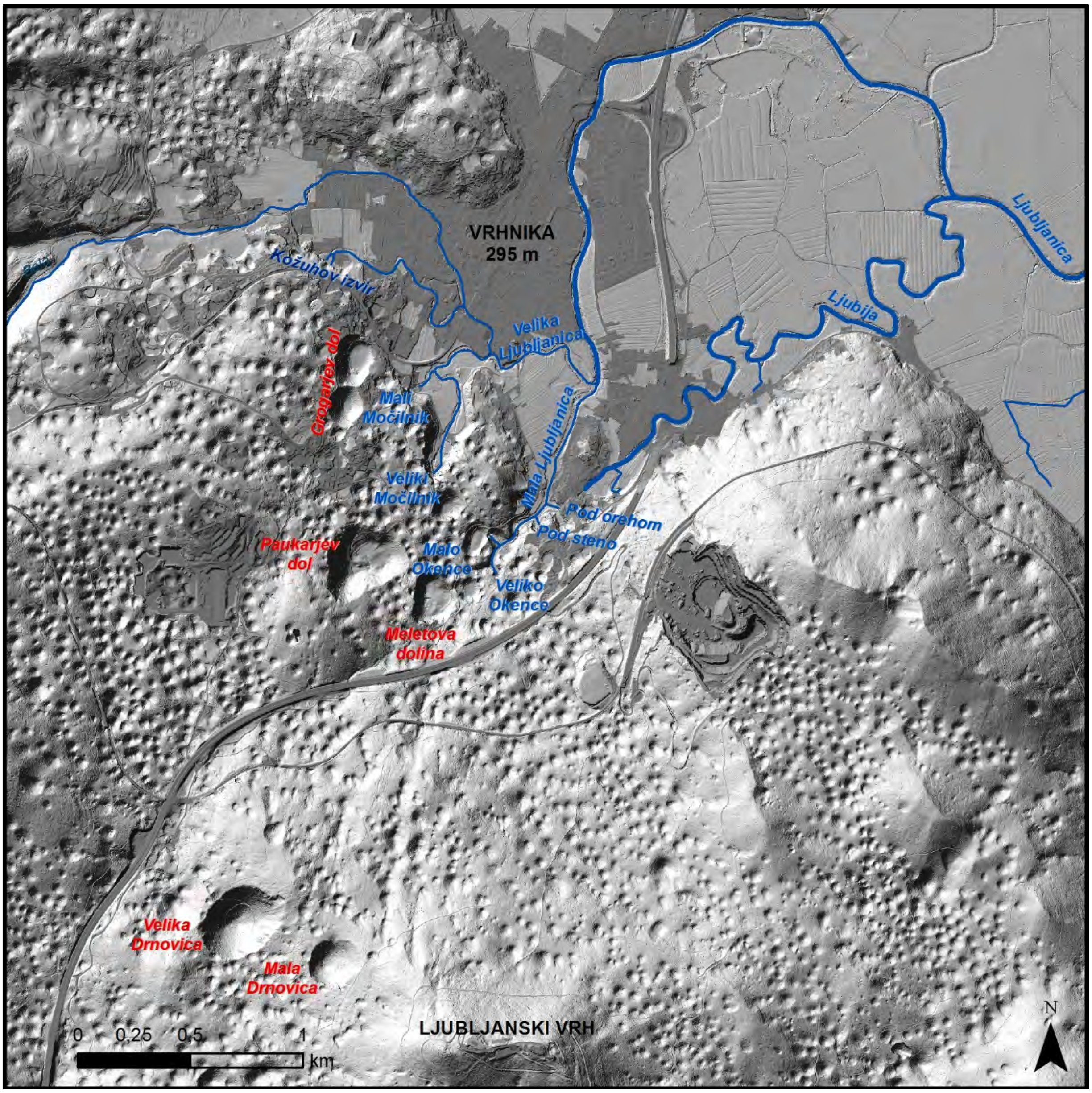


Figure 66: Location of collapse dolines and Ljubljanica springs near Vrhnika.

SPRINGS OF LJUBLJANICA

All the water in Ljubljanica catchment area emerge in many springs located near Vrhnika, on the rim of Ljubljana basin. The most important springs are Mali Močilnik (mean discharge 1.5 $m^3 s^{-1}$), Veliki Močilnik (5.7 $m^3 s^{-1}$), Malo Okence (2.2 $m^3 s^{-1}$), Veliko Okence (2.0 $m^3 s^{-1}$), Pod skalo (8.8 $m^3 s^{-1}$), Pod orehom (1.7 $m^3 s^{-1}$) and Maroltov izvir (0.5 $m^3 s^{-1}$). First two springs feed Mala Ljubljanica Stream and the rest five springs feed Velika Ljubljanica Stream. Mean annual discharge of the Ljubljanica springs is 38,6 m^3. 2 km E are located Bistra springs, which join to Ljubljanica after 3 km of flow. Bistra Stream is fed by three principal springs: Grajski izvir (3.0 $m^3 s^{-1}$), Zupanov izvir (3.0 $m^3 s^{-1}$) and Galetov izvir (mean discharge 2.6 $m^3 s^{-1}$) (Gospodarič & Habič, 1976).

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