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Introduction to the
Dinaric Karst

Andrej Mihevc, Mitja Prelovšek, Nadja Zupan Hajna (Eds.)
INTRODUCTION TO THE DINARIC KARST

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Published by / Izdal in založil: Inštitut za raziskovanje krasa ZRC SAZU, Postojna / Karst Research Institute at ZRC SAZU, Postojna
Represented by / Zanj: Tadej Slabe

Printed by / Tisk: Collegium Graphicum d.o.o., Ljubljana
Printrun / Naklada: 300 copies / izvodov

Postojna, junij 2010

The publication was published within the Karst Underground Protection project which is inancially supported by the Slovenia-Croatia Operational Programme 2007-2013.

Knjiga je bila izdana v okviru projekta Karst Undergorund Protection inanciranega iz Operativnega programa IPA Slovenija-Hrvaška 2007-2013.

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

911:551.44

INTRODUCTION to the Dinaric Karst / edited by Andrej Mihevc, Mitja Prelovšek, Nadja Zupan Hajna ; [photos authors of chapters ; cartography Mitja Prelovšek]. - Postojna : Inštitut za raziskovanje krasa ZRC SAZU = Karst Research Institute at ZRC SAZU, 2010

ISBN 978-961-254-198-9

1. Mihevc, Andrej, 1952-

251366400

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Dinaric Karst

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Contents

Geographical Position and General Overview

Andrej Mihevc, Mitja Prelovšek

The Dinaric karst is the major morphological type of landscape of the Dinarsko gorovje (Dinaric mountains), extending over approximately 60,000 km^2 and forming the largest continuous karst landscape in Europe.

The Dinarsko gorovje are positioned between the Panonian Basin in the northeast and the Adriatic Sea in the southwest, covering an area over 650 km in length and over 150 km wide (Fig. 1). In the north, they border the Alps along the rivers Soča, Idrijca and Dolenjsko podolje (Dolenjska lowland). The inner side of the mountains is delimited by the river Sava valley. The eastern border of the mountains is in the Kolubara and Morava river basins, the edge of the Kosovo basin and the Prokletije mountains. The transition to the Alps in the northwest and the Albanian mountains toward the southeast is not very distinctive.

The Dinarsko gorovje are separated into different natural belts. All have a common direction (northwest-southeast; the Dinaric direction), which is the direction of most of the relief features. The main geomorphologic differences of the mountains are defined by differences in lithology. Inland non-carbonate rocks on which fluvial relief has developed prevail. The main parts of the mountains, central

Fig. 1: Delimitation of the Dinaric karst toward northeast after Roglić (1965) and after Gams (1974).

and outer belts, are formed mostly of Mesozoic and Tertiary rocks, mostly limestone and dolomite. Here the highest relief is found and karst landscapes prevail. Closer to the coast, relief is generally lower; there are also several narrow belts of Eocene flysch between the limestones. They are expressed as belts of lower relief and have important control over the underground discharge of the main karst belt.

The highest elevations occur in the central belt of the Dinarsko gorovje. Here displaced separated units of higher relief occur, including karst plateaus like Snežnik (1,796 m), Risnjak (1,528 m), Velika and Mala Kapela, Plješivica (1,657 m), Velebit (1,758 m), Dinara (1,913 m), Vitorog (1,907 m), Vran, Čvrsnica (2,228 m), Prenj (2,155 m), Bjelašnica (2,067 m), Jahorina, Lelija, Maglič, Durmitor (2,522 m), Tara, Njegoš (1,721 m), Orjen (1,895 m), and Lovčen (1,749 m). These high plateaus, which are all elongated in the Dinaric direction, are separated by lower plateaus and levelled surfaces on limestone or deep trough valleys flowing from non-carbonate rocks.

During the cold stages of Pleistocene the snow line in the Dinaric Mountains was at about 1,100 m, so glaciation affected the higher parts. Glaciation partially blocked or interrupted karst drainage and slightly modified the karst features. Mostly glaciers developed on plateaus in rugged karst terrain full of closed depressions. Glaciated karst plateaus were smoothed slightly and small moraines were developed. In most cases, glaciers ended in closed depressions with karst outflows.

Characteristic forms associated with the karst mountains are large levelled surfaces, plateaus and intramontane depressions in which karst poljes have developed. There are no fluvial rivers valleys; only in some places are some dry valleys preserved. Smaller relief features are uvalas, dolines, dry valleys, collapsed dolines, and caves. Because of the pure limestone that prevails, only thin non-continuous soil cover developed on the karst. Even though in most of the area there is enough precipitation, the thin soils and karst cannot keep it on the surface, so in general aridity is the problem, especially on the southern side of the mountains closer to Mediterranean Sea.

On both edges, where non-karstic rocks are in contact with the main karst belt, insulated karst areas are developed. There are also areas of karst in dolomite, forming fluviokarst. There are areas of contact karst with sinks and ponors. On the edges of the karst, there are also large springs.

The Dinaric karst is very rich with cave fauna, with many endemic species of animals. The reasons for this are a long, uninterrupted evolution and the age of the karst. Some of the animals, like *Proteus anguinus* (Fig. 3) and *Marifugia cavatica* can be found on all extreme sides of the Dinaric karst, proving similar and simultaneous evolution of the whole Dinaric karst.

Modest natural resources are the reason for the low human population. Traditionally this was the area of pasture, transhumance, and later, forestry. The natural vegetation in the area was forest. Wood was used for firewood, charcoal, for shipbuilding and for construction. In the lower areas, along the coast and on the Kras, the forests completely disappeared (Fig. 2). Inland, because of a more humid climate and different land use, the forests remained.

There are two reasons for the reforestation of the area: numerous protective regulations and reforestation attempts. More important is the change in the economy in the past century. There is no longer such enormous pressure on the land.

Fig. 2: Coastal part of Dinaric karst experienced severe deforestation which started already in the Neolithoc period (photo: A. Mihevc).

Fig. 3: Mountainous Dinaric karst - Popovo polje in Herzegovina (photo: M. Mihevc).

Short History of Research

Andrej Kranjc

Dinaric karst is the landscape where the sciences of karstology and speleology took their origin and started to develop thus contributing several karstological terms to international karst terminology. In the antiquity already some of karst phenomena were mentioned from the Dinaric karst, but here are considered published sources mostly from the 16th century on, when the modern karst research started. In those times Dinaric karst belonged to different states. Adequate sources were used and and it was a difficult task yet not completely achieved but it presents a relatively new approach. For the older period some Venetian and Turkish works are included. Emphasized are Austrian and Austro-Hungarian researchers working in Bosnia and Herzegovina as well as Serbian researchers. The contribution which can be no more than an unpretentious overview mentions early philosopher N. Gučetić discussing karst phenomena, and travellers through the Balkans like B. Hacquet, B. Kuripečič, E. Čelebija, and A. Fortis, and also well-known geomorphologists and speleologists A. Penck, E.-A. Martel, J. Cvijić, A. Melik, and J. Roglić.

Pre-scientific phase

Karst phenomena or better phenomena which we are called nowadays as karst ones are relatively often mentioned by ancient Greek and Roman authors. The groundwater and its connection with the sea are noted by Homer, Thales of Millet, Anaxagoras, Plato, Aristotle, Lucretius, and Seneca. Among these descriptions there are also some from Dinaric karst. Pseudo-Skylax's Periplous (The Circumnavigation of the Inhabited World) of 4th century BC mentions the springs of Timavo (Herak & Stringfield 1974) which were later studied by Poseidonios of Apameia (135 – 50 BC). In connection with them he mentions also »the chasm« - Škocjanske jame (Škocjan caves; Kranjc 1998). In Virgil's Aeneida the Timavo springs are called the Mother of the sea and Strabo's Geography names Lugeon Lacus. Curiously all these phenomena are from the north-western part of the Dinaric karst. Taking into the consideration that this is the most distant related to Greece, I would say that we do not know the appropriate references.

From the Middle Ages it is not known much more. Tabula Peutingeriana showing the springs of the Timavus is in fact a Roman map. Karst phenomena are mentioned in the documents from different reasons but without a notion of karst yet. In 888 the king Beranger donated the church in the cave Sv. Ivan v Čele – San Giovanni d'Antro located in the last parts of the karst above the plain of Friuli, the Croatian word for the cave Pechice, Pechie or Pechine ossia Grotta, that is *pećina*, figures on the map of the domain of a monastery on the Ugljan Island in the year 1096 and 1166 respectively as shown in many contributions of late M. Malez (1984). Well known is Byzantine's Emperor Constantine Porphyrogennetos description of his empire *De Administrando Imperio* (948 – 952) where many karst sites are mentioned like the rivers Pliva and Buna (one of the biggest karst springs), poljes of Imotski and Krbava, and the place Vrulja (Bury 1920). The study of this work from the karstological point of view is still waiting to be done.

It can be said that during the 16th century the interest for the karst, future karstology started. In 1531 a lawyer from Ljubljana, Benedikt Kuripečič (Kuripešič) (born 1490) published a diary of his voyage through the Balkans as the interpreter to the Turkish sultan Suleiman to Constantinople (Curipeschitz 1531). From the point of view of karst he mentions just some karst spring (Kranjc 2008). Equally unimportant is Leonberger's long poem about the Lake of Cerknica. According to the description (oral or written) of S. Herberstein, Vienna's diplomat by the origin from Vipava, G. Wernher (1551) published a description of this lake (in fact seasonally flooded polje), including the map (Simoniti 2010). On the other side of Dinaric karst a philosopher from Dubrovnik, Nikola Gučetić (Gozze 1584) published a discussion of the wind in the Cave of Vjetrenica (Wind Cave) and of the speleothems from the cave Šipun. The reputation of the Cerkniško jezero (Cerknica lake) grew which can be well seen from the contemporaneous maps of Lazius, Ortelius or Mercator for example: the lake is drawn much bigger than it deserves according to the scale of the map.

Evliya Çelebi (Evlija Efendi), his full name was Evlijā ibn Derviš Mehmed Zillī, travelled the whole of his life (1611 – 1682), a lot through Balkans too. In his diaries, discovered little more than 100 years ago, are described karst landscapes, water phenomena, caves (mostly in connection with fighting guerrilla). Curiously he knows a sort of corrosion: to make the road through limestone terrain large enough to pass the canons, soldiers had to pour the acid on the limestone (Kranjc 2008)! This is also a time when one of the leading scientists

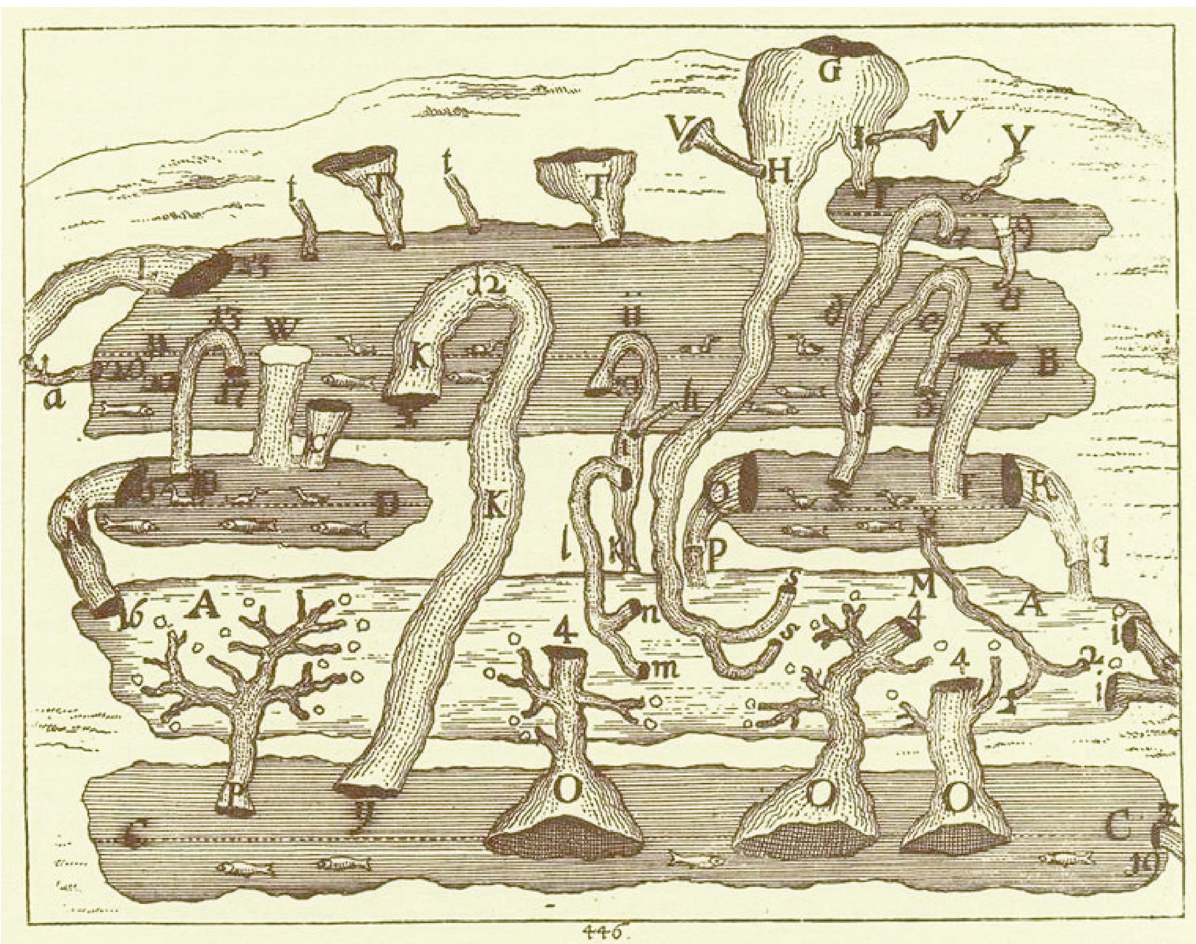


Fig. 4: Valvasor's hydraulic model of Cerkniško jezero (Cerknica lake).

of his time, a Jesuit Athanasius Kircher (1678), has published his monumental work Mundus Subterraneus (1665 the first edition). The big karst springs are explained by enormous underground reservoirs *hydrophillatia* and as the proof of his theory the Cerkniško jezero is used (Fig. 4). Ten years later Valvasor (1689) travelled many times to Cerknica, to explore it by himself (neither Wernher nor Kircher ever visited it). He did not agree with Kircher and made his own explanation which earned him the London's Royal Society membership.

The fame of the Dinaric karst phenomena, from Carniola specially, is in great deal due to Valvasor's descriptions; he was not interested in the Cerkniško polje (Cerknica polje) only, but in other karst phenomena also: sinking rivers, karst springs and caves especially. In 1748 the emperor Franz I. Stephan sent the director of his Cabinet of rarities J. A. Nagel (1748) to Carniola to found out what are these unusual phenomena, and to bring some samples for his collection. After returning Nagel wrote a detailed report; the most important is his explanation of the periodicity of Cerkniško jezero and the observation of the age of speleothems. F. Steinberg (1758) published the whole book on the Cerkniško jezero and T. Gruber (1781) was the first who published (probably the ideas of his brother Gabriel) the accurate explanation of the lake. He even advised a sort of meteorological stations to be able to calculate the quantities of in- and output of the water.

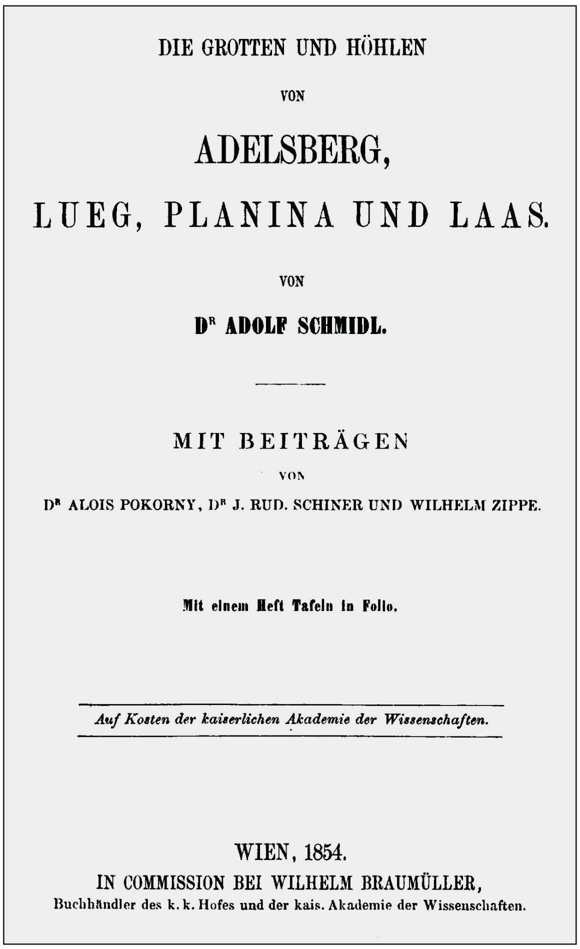
For the coastal part of Dinaric karst the description and exploration even of karst phenomena by the Abbot Alberto Fortis published in 1774 is especially important due to the political situation on the Balkans. He was accompanied by foreign scholars and even by an English bishop so his book was well known. Commentaries were published about the book (Lovrich 1776) but without discussing his views of karst phenomena. Just to mention that Fortis supports the collapse theory of foibas (shafts) formation. In the same time another scholar travelled through Dinaric karst too, B. Hacquet (1778). He was a doctor of medicine but by his own opinion he was a chemist. Some of his ideas about geological development, about rocks and the solution of limestone (corrosion) were too early and although they were published and despite his relations with learned societies and scholars all round the Europe his ideas were not recognised. Maybe he is the first to largely use the expression Dinaric Alps. In 1785 he has published "The physical-political travel from Dinaric through Julian, Carnian, Rhätian and Noric Alps", including the panoramic view from the river Zrmanja to the mountain Dinara (Hacquet 1785).

The first phase of karst geomorphology research

During the 19th century the boom of geological research touched the Dinaric karst too. Vienna was very important scientific centre and Dinaric karst, well developed and large karst region in its vicinity, became the source of main ideas on karst. In 1830 already F. Hohenwart writes in the preface of a guide book to Postojnska jama (Postojna cave) that the karst is not on the plateau of Karst only, but stretches from the Friuli plain to the Greek Island of Cephalonia.

In 1848 A. v. Morlot published the map and the text about the geology of Istria including discussion of morphological features, especially dolines. The basic work on speleology of the Carniolian part of Dinaric karst was achieved by A. Schmidl (1854) exploration in the middle of the 19th century (Fig. 5), helped by Vienna's Academy and the Southern Railway Company (the railroad Vienna – Trieste was opened in 1857). Western scholars, it is true that few, were interested in the Turkish part of the Balkans, like A. Boué (1840) who published "La Turquie d'Europe; observations sur la géographie, la géologie, l'histoire naturelle". Later he was interested in karst (Karst und Trichterplastik from 1861) and in Bosnia specially. There were some serious published reports whose titles imply narrow application but in fact they include numerous data and general observations on karst, as are Beyer et al. (1874) and Wessely (1876).

Following the occupation of Bosnia and Herzegovina (1878) a new and complex approach to karst problems coincided with the beginning of the geological survey. Leading Vienna's geologists of the time, E. Mojsisovics, E. Tietze and E. Bittner (1880) gave a scientific explanation of the karst features genesis, but the discussion between the supporters of collapse and of solution theories continued. Leading Vienna's geomorphologist, A. Penck was the most prominent protagonist of the new discipline, karstology. He suggested to his student J. Cvijić for his doctor thesis to study karst. He got main ideas of karst on the plateau of Karst (Kras) and in 1893 he published *Das Karstphänomen* (Fig. 6), a turning-point and at the same times the beginning of the intensive study of karst morphology, including the use of the term karstification. In 1899 W.M. Davies joined Penck and his students at the field trip to Bosnia and Herzegovina. The previous fluvial erosion and the cyclic evolution (dolina – uvala – polje) were introduced into the theory of karst.



DIE GROTTEN UND HÖHLEN

VON

ADELSBERG,

LUEG, PLANINA UND LAAS.

VON

DR ADOLF SCHMIDL.

MIT BEITRÄGEN

VON

DR ALOIS POKORNY, DR J. RUD. SCHINER UND WILHELM ZIPPE.

Mit einem Heft Tafeln in Folio.

Auf Kosten der kaiserlichen Akademie der Wissenschaften.

WIEN, 1854.

IN COMMISSION BEI WILHELM BRAUMÜLLER,

Buchhändler des k. k. Hofes und der kais. Akademie der Wissenschaften.

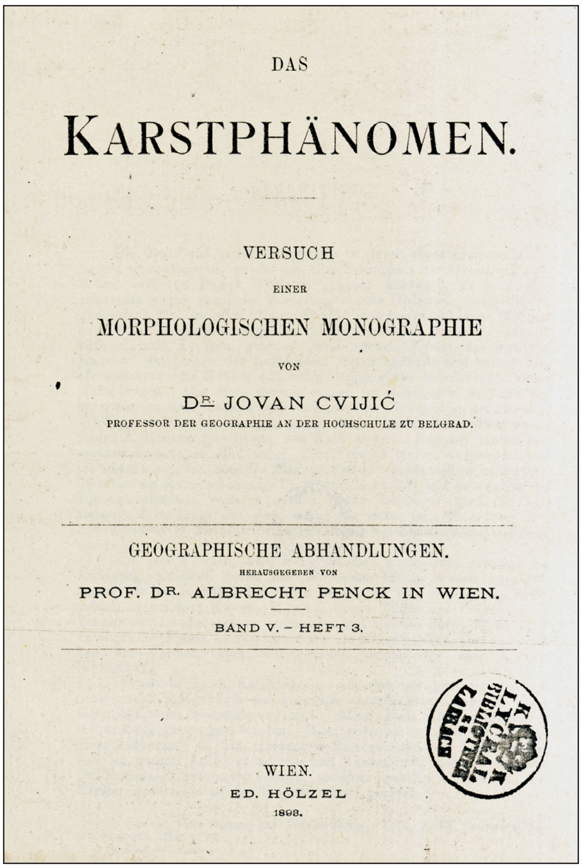
Fig. 5: In 1854, A. Schmidl published the basic work on speleology for the area of Carniola, Slovenia.

In 1903, A. Grund, also the disciple of Penck, has published a basic work on karst hydrography which is a new milestone also in karst morphology, introducing a concept of karst groundwater concordant with the cyclic theory too and supported by Penck himself. Speleologists, Knebel and Martel especially, and some geologists (Katzer) and geographers (Kraus 1894) opposed strongly to Grund's karst groundwater. 1910 Grund has published the work of the relief of the Dinarsko gorovje (Dinaric mountains) based on his observations in Bosnia and Herzegovina, where his views on the evolution of poljes and karst plains are explained. Hungarian geologist H. Terzaghi in 1913 introduced a theory of marginal or border corrosion to explain limestone plains and flat polje surfaces. Two decades passed before it was recognized and later further developed by the most prominent Croatian geomorphologist J. Roglić (1952). During the 1st World War when he was teaching at Sorbonne Cvijić has prepared a synthesis of his views about the evolution of karst relief and has published it in 1918 (Cvijić 1918). He accepts karst groundwater and distinguishes three hydrographical zones: permanent inundation, periodical inundation, and a dry zone. He renames Grund's "Halbkarst" (half-karst) into "merokarst" and introduces fully developed "holokarst".

The defeat of Austro-Hungarian Monarchy resulted in almost complete lethargy in the Viennese centre of karst research. After the 1st World War the investigations of karst relief stagnated, followers of the respected masters were few and did not produce worthwhile contributions. The first phase was rich in general ideas and poor in real analyses (Roglić 1974).

The second phase of karst research

The previous research, including Penck-Grund concept did not resolve the problem of the water circulation through fractures, fissures, and joints and its relation to the evolution of karst relief. This was explained by Vienna's geomorphology group member O. Lehman (1932). According to nearly forgotten Terzaghi's marginal corrosion Kayser (1934) explains the plains at the border of Skadar Lake (Montenegro). Roglić (1938) describes and explains accordingly to the theory of a border corrosion such terraces of the Dinaric poljes. The new concept was largely adopted by the authors of different general or specialised works related


DAS

KARSTPHÄNOMEN.

VERSUCH

EINER

MORPHOLOGISCHEN MONOGRAPHIE

VON

DR. JOVAN CVIJIĆ

PROFESSOR DER GEOGRAPHIE AN DER HOCHSCHULE ZU BELGRAD.

GEOGRAPHISCHE ABHANDLUNGEN.

HERAUSGEGEBEN VON

PROF. DR. ALBRECHT PENCK IN WIEN.

BAND V. – HEFT 3.

WIEN.

ED. HÖLZEL

1893.

Fig. 6: The book Das Karstphänomen of Jovan Cvijić was a pioneering monograph and marked the beginning of modern karst studies (Shaw 1992).

to Dinaric karst. The example is the work of A. Melik, Slovenia and Sima M. Milojević, Serbia.

Conclusion

The second phase was tragically interrupted by the 2nd World War. Soon after the war investigations of karst morphology were revived and increased in volume as well as in intensity in an essentially different way than those in the past. In the post-war period there are global scientific contacts and exchanges. The different countries are easily accessible. Observations and data are multiplying, concepts are modified and combined, sophisticated methods, based on computer and digital technologies are widely used. With more exact observations and data, the corresponding conclusions have been improved. In the area of Dinaric karst specially, important practical work in the prospection and exploitation of ore deposits has been carried out, as well as the construction of accumulation basins, hydroelectric power plants, tunnels, railways, and motorways. Scientific concepts have necessarily become adapted to new ideas and facts. So the Dinaric karst has given a lot of data and other material to study, there were a great number of authors and even much greater number of professional and amateur works, there are new centres working on Dinaric karst, there are specialised journals, meetings from the World congresses to local symposia. But the same can be said for the karst all over the world. New theories and concepts are elaborated on the knowledge of other karsts, not the Dinaric one. So this contribution ends somewhere with the 2nd World War. On one hand it would require too much work and time to analyse in detail the imposing investigations of the Dinaric karst in the last 60 years, and on the other hand, regarding the investigations of the karst worldwide it would be too difficult to find out the role, the importance and the influence of the Dinaric karst studies upon the general karstology.

Geology

Nadja Zupan Hajna

The Dinaric karst is geographically and geologically part of the Dinarsko gorovje (Dinaric mountains; Dinarides) and includes all of the External Dinarides and some parts of the Internal Dinarides (Fig. 7).

According to some authors (for instance, Schmid et al. 2004), from a tectonics perspective the Dinarides (Dinaric Alps) include the Southern Limestone Alps, External and Internal Dinarides. Other researchers (for instance: Placer 1999, 2008; Tari 2002; Kastelic et al. 2008) take the view that only the External and Internal Dinarides are included.

The geological evolution of the Dinarides is closely associated with the history of the Tethys Ocean, which closed during the Mesozoic and Cenozoic as a result of the convergence of the Africa and Eurasian Plates. Intermediate microplates played an important role in ocean shortening. The present geological structures resulted from post-collision processes in the Alpine orogenic system, which started before about 35 Ma (Vrabec & Fodor 2006).

The Dinaric karst denotes an area within the Dinaric Mountain System, confined mostly to the External Dinarides, which consists predominantly of Triassic, Jurassic and Cretaceous limestones and dolomites; see the Geological map (Fig. 8). Geological data (i.e.,Vlahović et al. 2002) indicate that the External Dinarides were formed by the destruction of a single, (yet, in morphological terms, highly variable) shallow water carbonate platform. The platform was very dynamic in some periods because of its paleogeographic position during the Mesozoic, especially during the Late Creta-

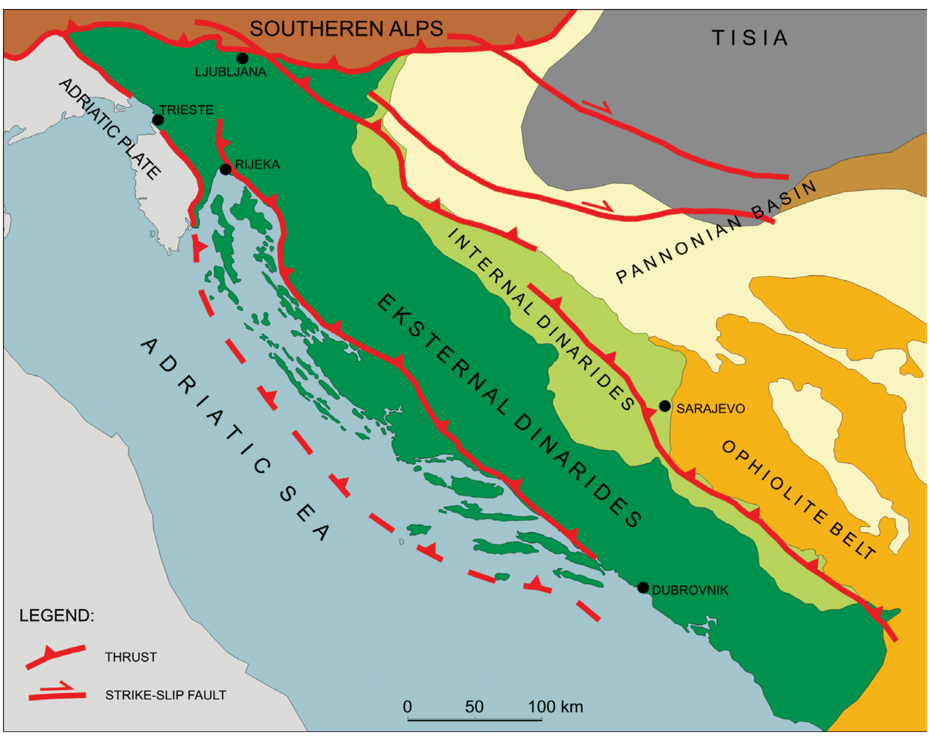


Fig. 7: Simplified tectonic map of Dinaric Mountains (after Schmid et al. 2004; Šumanovac et al. 2009).

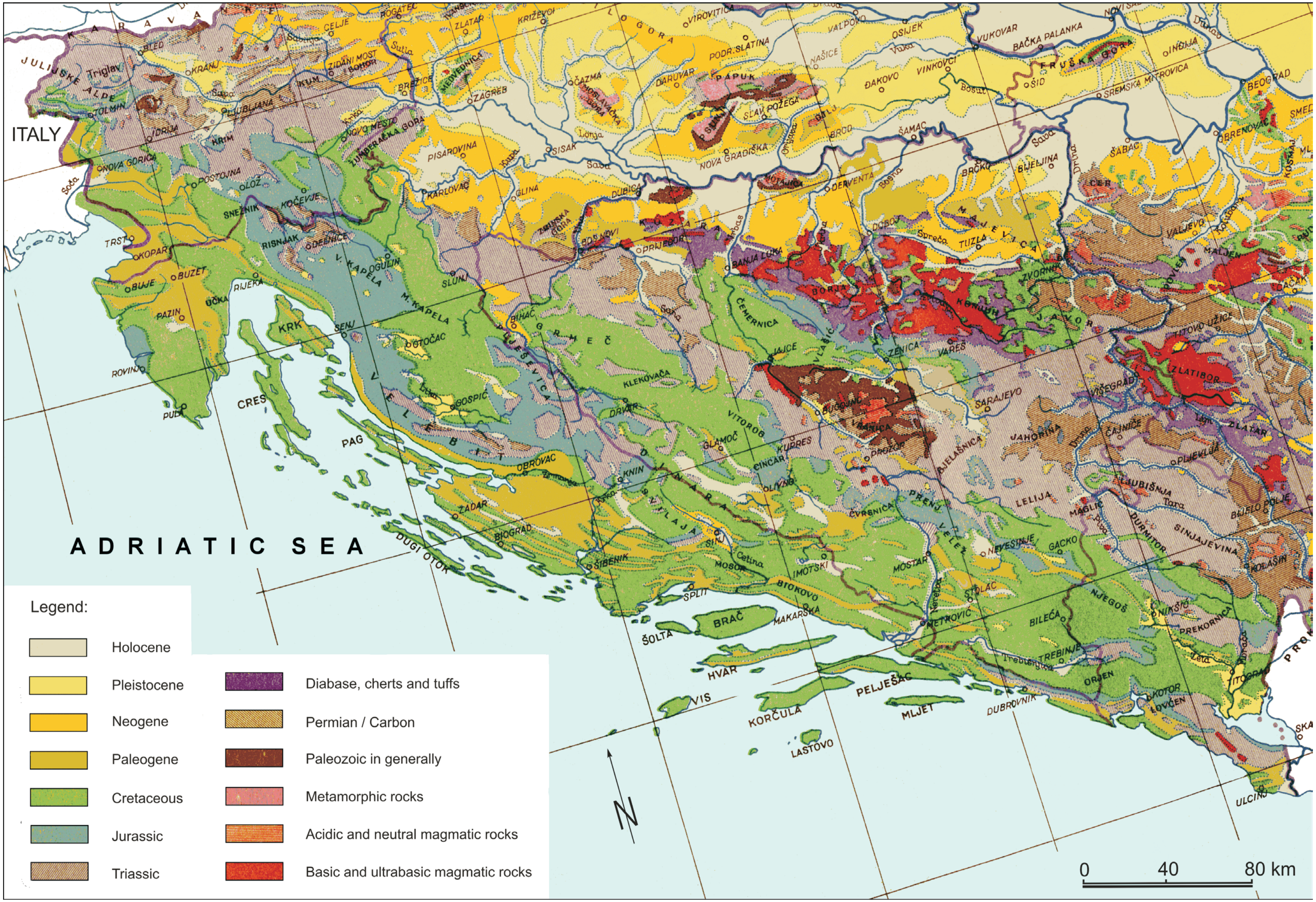


Fig. 8: Geological map of Dinaric karst; modified after Atlas svijeta, 1974).

ceous. The final disintegration of the platform area culminated in the formation of flysch trough(s) in the late Cretaceous and Paleogene and the subsequent uplift of the Dinarides. There is confusion among the scientific literature due to the different names used for this same shallow water carbonate platform. Probably the best, although not the ideal, name is the most frequently used one: the Adriatic Carbonate Platform (Vlahović et al. 2002). Its duration is estimated to be from the Late Lias (Fig. 9) to the Late Cretaceous, representing the most important part of a thick carbonate succession in the Dinaric karst (ranging from Carboniferous to Eocene).

Fig. 9: Liassic limestone with lithiotides; Rujno above Paklenica canyon (photo: N. Zupan Hajna).

Differing opinions about the geologic evolution of this system in the northeastern Adriatic region reflect its complexity (Korbar 2009). After Korbar (2009), the External Dinarides are a fold-and-thrust belt, part of the Alpine orogenic system, characterized by generally southwest-verging structures, and can be considered as the detached, backthrust and highly deformed upper crust of the Adria during subduction to the northeast. This belt, along with the related part of the Adriatic foreland, is geographically situated within the Dinaric karst region.

The main tectonostratigraphic units of the Dinarides (Tari 2002; Fig. 10) are related to: a) Early and Middle Triassic rifting; b) Late Jurassic to present day compression.

Early and Middle Triassic rifting was marked by strong magmatism and horst and graben-related deposition overlying the Variscian basement. Along the "eastern" Apulian margin toward the Sava-Vardar, ocean rifting was followed by subduction-generated extension from the Early Triassic until the Late Jurassic. Subduction-related attenuation of continental crust along the eastern margin of Apulia caused the formation of a back-arc basin in the oceanic crust. The remnants of these active continental margin lithologies are found within the Eastern thrust belt as the ophiolite melange of the Central Dinarides Ophiolite Belt.

Late Jurassic-to-present day compression generated:

- the Eastern thrust belt, foredeep and foreland: the Dinaridic carbonate platform toward the west presented the foreland of the generally west directed thrusting. During the Early Cretaceous, compressional stresses began to be transmitted westward through the Dinarides, causing the migration of the foredeep basin and regional uplift of the Eastern thrust belt.
- the Northern Dinarides accretionary wedge: subduction of the oceanic plate along the northern margin of the Dinarides resulted in the accumulation of this accretionary wedge from the Maastrichtian to the Eocene.
- the Western thrust belt, foredeep and foreland: from the end of the Cretaceous until the early Eocene the entire carbonate platform was uplifted. During the Eocene, the Dinaridic carbonate platform was finally buried under the flysch deposits in the broad foredeep basin of the Western thrust belt.
- the Eastern Adria imbricated structures: at the beginning of the Oligo-

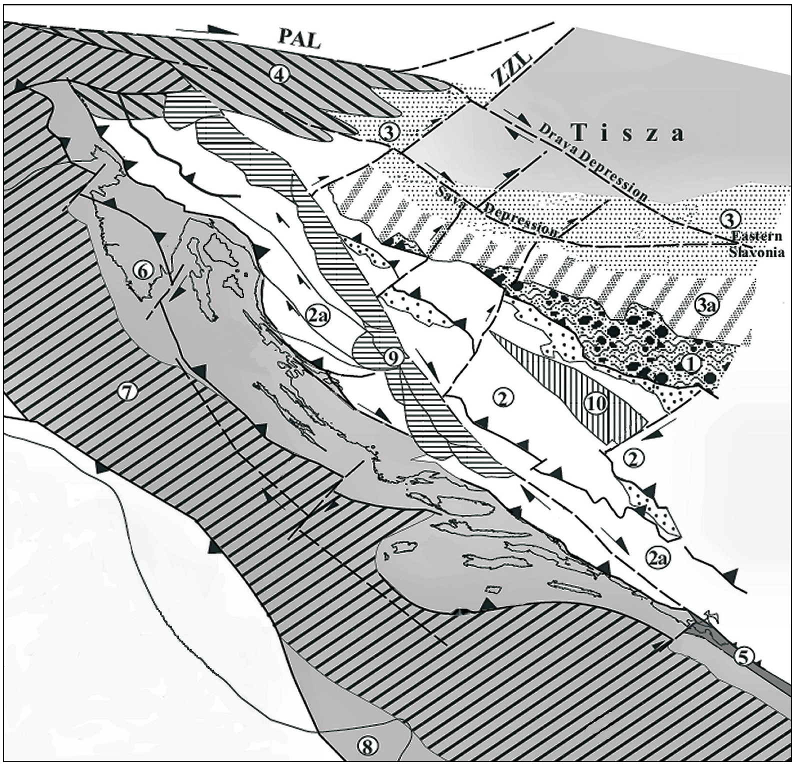


Fig. 10: The main tectonostratigraphic units of the Dinarides and Adria; after Tari (2002).

Legend:

1. *Eastern thrust belt;*
2. *Dinaridic carbonate platform, foreland of the Eastern thrust belt;*

2a. *Frontal thrust of the Western thrust belt;*

3. *Maastrichtian-Paleogene accretionary wedge;*

3a. *Maastrichtian- Paleogene retroarc area, North-Bosnian flysch;*

4. *Slovenian Basin;*
5. *Budva-Cukali Basin;*
6. *Gently tectonised Adriatic carbonate platform;*
7. *Adriatic Basin;*
8. *Gargano-Sazani-Paxos carbonate platform;*
9. *Miocene wrenching;*
10. *Miocene tectonic inversion.*

cene, collision and progressive underthrusting of the Adria below the Dinarides created the imbricate structures of Adria provenience in front of the Western thrust belt. The structural style of the Dinaridic thrust belt is a result of the polyphase tectonic compression and the competence of the sedimentary units involved. The competent carbonate rocks are the strongest influencing factor on the structural style of the thrust belt. The compression started with ramping along the deep decollement from the root zone with a southwestern tectonic transport. In this way, by progressive overstepping of the thrust faults, various structural forms were created along the eastern and western thrust belt - fault bend folds, tear fault-related folds and folded thrust structures reworked by footwall deformations.

- Wrenching and tectonic inversion: the northeast-southwest striking system of the dextral strike slip faults during Oligocene - Miocene was followed by northwest-southeast striking and wrenching in the early and middle Miocene, affecting the South Pannonian Basin, the Western thrust belt and the Adriatic foreland. This activity is reflected in the large flower structures of the Dinaridic thrust belt.

The main structures of the Dinaric karst have a strike trend in a northwest - southeast direction (in the so-called "Dinaric" direction). This structural pre-disposition is visually reflected in the directional trend of high plateaus and karst poljes from south Slovenia to Montenegro.

Mountains above 1,100 m a.s.l. in the Dinaric karst were glaciated during the Pleistocene. Valley glaciers reshaped the original fluvial valleys into typical U-shaped valleys and deposited vast amounts of sediments. There are a number of characteristic glacial features such as hanging valleys, remains of moraines, fluvioglacial sediments, eratic blocks and

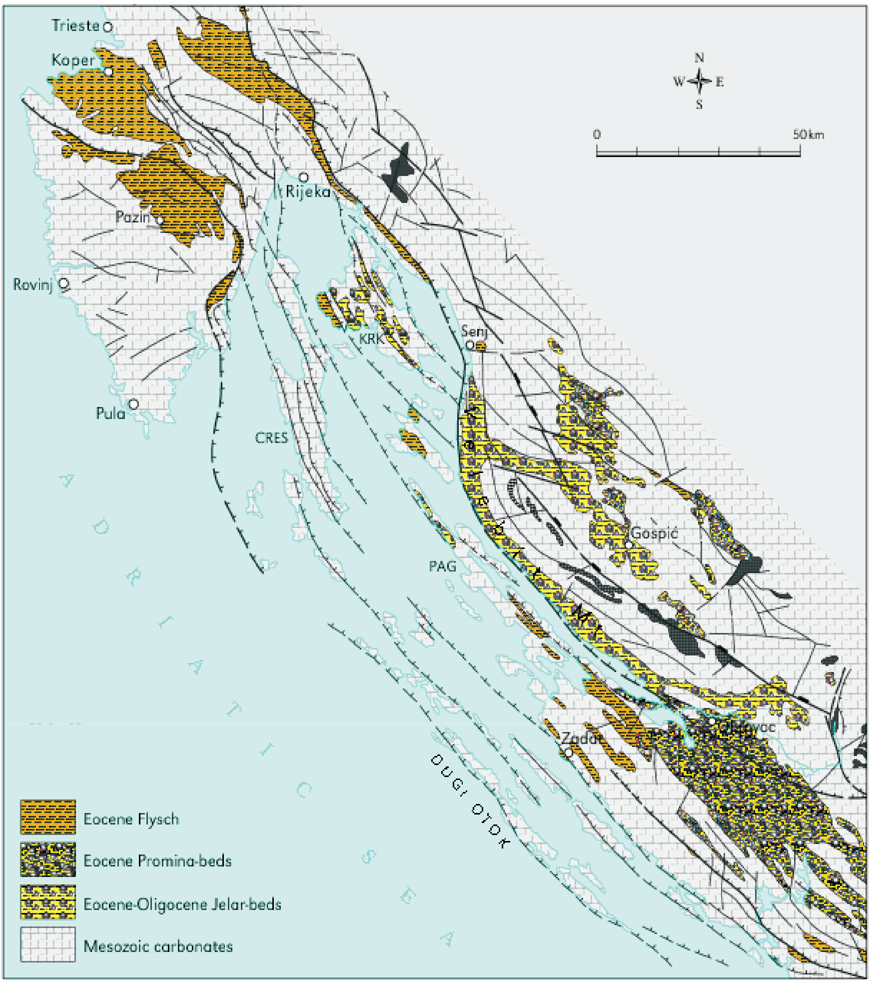


Fig. 11: Locations of Jelar Breccia and Promina beds; from Perica & Marjanac (2009; after Olunić et al. 1972; cartography: Iztok Sajko).

striated cobbles and boulders. The remains of Pleistocene glaciations are visible from Snežnik Mountain in Slovenia, Risnjak and Velebit mountains in Croatia to Orjen, Lovčen and Durmitor mountains in Montenegro.

Along Dinaric karst, karst features are favored specially in massive and thick bedded Cretaceous limestones (with rudist shells) and in two characteristic lithological units (Fig. 11) which host an exceptional abundance of well developed karst features. These two are the Promina Beds, Eocene-Oligocene in age, and the Jelar Breccia, of unknown age - Oligocene or younger (McCann 2008).

The Tertiary Jelar Breccia covers large areas along the northeastern Adriatic coast on the southwest rim of Velebit Mountain (western Croatia). The largest outcrop is >100 km long, 2–10 km wide, and thicker than 500 m in places. The Jelar Breccia was poorly studied because of its very complex composition, unclear structural position and intense younger tectonic deformation (Vlahović et al. 2007). It is usually considered a result of the disintegration of frontal parts of the major thrusts. The Jelar Breccia is a massive, thick-bedded carbonate rock, comprised predominantly of angular, poorly sorted debris (Fig. 12). The breccia has a carbonate matrix, which is gray- to reddish in color. The lithostratigraphic composition of the debris is varied (Bahun 1974). Clasts of Cretaceous limestones and dolomites are the most common, with lesser amounts of Triassic carbonates and Paleogene limestones. The debris grain sizes are highly variable, with clasts in ranging in size from a few mm up to several meters.

Due to its specific mechanical and petrographic properties, the Jelar Breccia is characterized by an abundance of such solutional karst features as karren (Perica & Marjanac 2009), dolines, conical hills and caves. In the Jelar Breccia along the south- and southwest parts of Velebit, ridges of conical hills (named "Kuk" in the local language) are numerous. Between these hills, big and deep karst depressions are developed. Well known examples

Fig. 12: The Jelar Breccia is a massive, thick-bedded carbonate rock, comprised predominantly of angular, poorly sorted debris; North Velebit (photo: N. Zupan Hajna).

include Hajdučki and Rožanski kukovi near Zavižan (Northern Velebit National Park); Dabarski kukovi next to Baške Oštarije; Bojinac (Fig. 13) above Paklenica Canyon (National Park Paklenica) and Tulove grede on the south edge of the Velebit.

The deepest explored caves in Croatia are developed in Jelar Breccia (Garašič 2005), and are found north of Velebit. These caves are Lukina jama-Trojama (-1,392 m), Slovačka jama (-1,320 m), Velebita cave system (-1,026 m) with a 513 m underground vertical shaft and Meduza (-679 m) (these data are from Lacković et al. (1999) and the web pages of the Croatian Speleological Federation (http://www.speleo.hr/deepest.htm); Fig. 30 on page 41). Several significant caves were also discovered in the Jelar Breccia of Crnopac area (South Velebit). Their main morphological characteristic is a network of multiphase cave passages, some of them with very large cross-sectional dimensions (Bajo et al. 2009). The most important caves of Crnopac massif are Munižaba (5,993 m long, -437 m) and Kita Gaćešina (10,603 m long, -456 m).

The Promina Beds (Promina Formation) consist of two different lithological parts (McCann 2008). The lower part is characterized by an alternation of marls, sandstones, conglomerates, limestones and cherts. The upper parts are alluvial sediments – conglomerates with marly beds with coal and plant remains. Promina beds are Eocene-Oligocene in age (Babić & Zupanič 2007). The Promina Beds can be seen on Promina Mountain, at Kistanjski ravnik and Ravni Kotari (the area between Velebit, Novigradsko more (Novigrad Sea) and the River Krka).

Fig. 13: Karst in Jelar Breccia; Bojinac at South Velebit. In the distance is Adriatic Sea and levelled surface around Novigradsko more (Novigrad Sea; photo: N. Zupan Hajna).

Climate

Mitja Prelovšek

The Dinaric karst is situated between 42° and 46° N at the northeastern edge of the Mediterranean Sea. From a climatic point of view, this geographic position falls within a temperate climatic zone where mid-latitude westerly winds (westerlies) prevail throughout the year. Nevertheless, the declination of the Earth and its movement around the Sun shifts the position of temperate belt 23° northward during summer and southward again during winter. This means that these latitudes can be under a strong subtropical zone influence during the summer months and under the influence of polar fronts during winter since the polar front can move southward of Greece (Kocsis 2007). Westerlies can therefore be very dry during several summer months but also very wet during winter.

Besides the global atmospheric circulation system, the climate of the Dinaric karst is strongly influenced by the Dinarsko gorovje (Dinaric Mountains), which form an orographic barrier that affects precipitation patterns (Fig. 16) and hinders winter intrusions of cold polar air flowing from continental regions in the east toward Adriatic coast. Westerlies usually blow from the Atlantic Ocean over the warm Mediterranean Sea. If the pressure is low over the Mediterranean Sea, air masses become enriched with humidity. When they hit the Dinarsko gorovje, the result is a high amount of precipitation on the west-facing side (Crkvice, Orjen-5,317 mm/a-the highest amount in Europe; Rodić 1987) and a much smaller amount of precipitation on the east-facing side. Lower amounts of precipitation are also characteristic for low-lying areas along the Adriatic coast and low islands (e.g., Pula-713 mm/a, Vis-676 mm/a; Rodič 1987). In summer, high pressure over the Mediterranean Sea hinders uplifting and condensation of the air masses over the sea, while over the continent precipitation is possible due to strong convection. In winter, the Dinarsko gorovje prevent intrusions of cool air masses that develop over continental Eastern Europe. Nevertheless, if the pressure difference between marine and continental air masses is too high, pockets of cold air spill over the orographic barrier, causing strong katabatic winds called "the Bora", which can exceed even 200 km/h. The main ridge of the Dinarsko gorovje, which ranges in altitude from 612 m to more than 2,500 m, also causes a strong vertical decline of temperature. Average annual temperatures decrease with height over quite short horizontal distances (80 km) from 15.3 °C (Podgorica; Kovacs & Dobos 2007) to about 2°C (Durmitor). Even steeper spatial temperature changes are characteristic for mountain Velebit. At such high altitudes, snow is present for up to half a year.

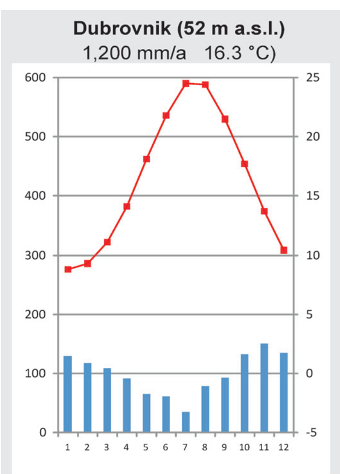
The Adriatic Sea has a strong moderating influence especially on temperatures along the coast and islands. Along the coast, at the southwestern boundary of the Dinaric karst, winter temperatures are much higher in comparison with places on the northeastern edge of the Dinaric karst. Along the coast, temperatures below zero are rare even during winter but very common on the continental edge of the Dinaric karst at only slightly higher altitudes (~170 m a.s.l.). Consequently, snow at the coast is very rare, but not impossible (when it does occur, it is always related to the intrusion of cold continental air from the northeast). In summer, daily temperatures along the coast are usually lower than in the continental part of the Dinaric karst due to the maritime influence of the Adriatic Sea. In some cases, the influence of the Adriatic Sea can extend even further toward the Dinarsko gorovje through wide valleys of rivers such as the Krka, Bojana, Morača, Zeta and the downstream part of the Neretva.

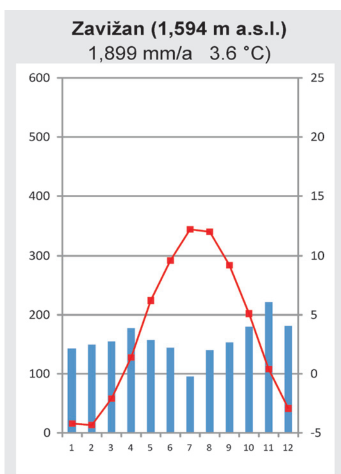
On the continental side of the Dinarsko gorovje, the absence of the maritime influence results in more extreme diurnal and seasonal temperature variations. Snow can persist on the ground for more than one month on average during the winter, and up to several months at higher altitudes. Another difference in comparison with Mediterranean part of Dinaric karst is higher amount of summer precipitation, which is a result of higher daily summer temperatures and more intensive convection during the day. Nevertheless, the influence of the Mediterranean Sea can be still observed in relatively high autumn-winter amount of precipitation, which is not characteristic for the pure continental climate (where peak precipitation occurs in the summer months).

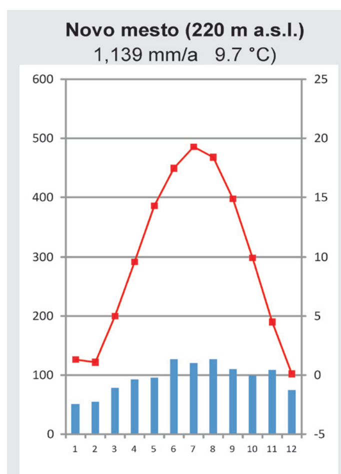
While global factors define the framework for general climate conditions, the highest influence on the Dinaric karst climate is the Dinarsko gorovje, which act as an orographic barrier. While latitudinal dependence (in NW-SE direction) is of minor importance, the greatest differences in climate can be observed across a southwest-northeast transect, along which three different distinct climates with gradual transitions can be identified:

- Mediterranean and Transitional Mediterranean climates
- Mountainous climate
- Transitional Continental climate.

The Mediterranean and Transitional Mediterranean climates extend along the Adriatic coast. The extent of these climates into the mountainous massif depends on topographic relief, ranging from 2 km below coastal mountains up to 120 km along the river Neretva (Rodić 1987). These climates are characterized by mild wet winters and hot dry summers. The average January temperature of the Mediterranean climate (southern Dinaric karst, e.g. Dubrovnik) is higher than 5 °C while that of the Transitional Mediterranean climate (northern Dinaric karst) is only slightly above 0 °C. Average July temperatures can be up to 26 °C and they decrease toward the Dinarsko gorovje and toward Adriatic Sea (since the sea is some degrees cooler during summer). Precipitation is highest in the early winter months (December/January; for Transitional Mediterranean climate in November), with lesser amounts in April/May, while the lowest amounts of precipitation occur during the summer. Amounts of precipitation vary from 600 to 1,500 mm/a (the island of Palagruža receives as little as







311 mm/a; Zaninović 2008) and increase from the low islands and coast toward sea-side part of Dinarsko gorovje. Moving from the soutwest to the northwest, the characteristics of the typical Mediterranean climate decreases.

Mountainous climate extends over the majority of the Dinarsko gorovje. Changes from the Mediterranean and Transitional Mediterranean climates are caused by higher elevations and increased distances from Adriatic coast. The average amount of precipitation can exceed 3,000 mm/a at the karst plateaus Trnovski gozd, Snežnik, Gorski Kotar, Velebit and the wider area of Orjen. Areas near the Adriatic coast have the lowest amounts of precipitation in summer months, while mountainous areas on the northeast side of Dinarsko gorovje receive the lowest amounts of precipitation during winter months. At Zavižan meteorological station (Velebit, 1,594 m a.s.l.), the average annual temperature can be as low as 3.5 °C, with 1,899 mm/a of rain which on average results in almost 6 months of snow-covered ground (Fig. 14) and up to 320 cm of snow (Zaninović 2008). Even more severe conditions can occur at some karst depressions at even lower elevations.

The Transitional Continental climate is similar to the Continental climate but it is moderated somewhat by its relatively close proximity to the Adriatic coast. It is characterized by higher annual temperature ranges (even more than 20 °C between January and July), lower mean annual temperatures (up to 11 °C at karst leveled surface between rivers Kupa/Kolpa and Una; Zaninović 2008), with an average January temperature close or below 0 °C. The Transitional Continental climate has lower July temperatures due to night cooling in comparison with the Mediterranean climate but higher maximum daily summer temperatures and lower amounts of annual

Fig. 14: Several meters high snow cover can be seen at Dinarsko gorovje even in the beginning of summer (exemple from Durmitor, Montenegro; 11th June 2006; photo: M. Prelovšek).

Fig. 15: Temperature and vegetational inversion in the Smrekova draga closed depression (Trnovski gozd, Slovenia; photo: A. Mihevc).

precipitation. The lowest amount of precipitation typically occurs in the winter months. Precipitation amounts peak in the autumn months (only close to Panonian basin, e.g. in Novo mesto, in the summer months) and is above 800 mm/a, which differ slightly for the Transitional Continental climate in comparison with the Continental climate. Amounts of precipitation decrease toward the northeast as distance from the orographic barrier (Dinarsko gorovje) increases.

Although these three climates can be easily observed, less obvious microlocal changes of climate can be important in several cases, especially in karst areas where the strongest influence comes from topography. As a rule, the interiors of karst depressions are colder than the higher ground surrounding them. This is especially true for karst poljes, where absolute minimum temperatures can be as low as -34.5 °C (Babno polje at Notranjsko podolje (Notranjska lowland) at 756 m a.s.l.) and -41.8 °C (Veliko polje below mountain Bjelašnica (Rodič 1987) due to temperature inversions. Besides lower absolute minimum temperatures, greater numbers of cold days, and greater amounts of snow cover, fog and frost are also characteristic for enclosed karst depressions (Fig. 15).

Fig. 16: Spatial distribution of precipitation (modified after Pojatina 1987, Senegačnik 1994, Pinna, 1989), watershed between Adriatic and Black Sea and major karst springs (after Nicod 2003; Burić 2010).

Hydrology

Mitja Prelovšek

The present day hydrological characteristics of the Dinaric karst are the result of its complex geologic structures and a long and intensive geomorphic evolution. In addition to its varied geology and geomorphology, the hydrology of the Dinaric karst is one of its most distinctive and recognizable elements. The Dinaric karst is an area where hydro-geomorphic phenomena were studied for the first time in the world in details and where some hydrogeological ideas were born. It is a place of rivers that sink and reappear several times, a place of abundant ponors and springs connected by hydrologically active caves, a place where the typically impressive features of contact karst occur, and a place where the complex hydrological systems between poljes were modified and used for production of hydroelectricity after the 2nd World War.

The Dinaric karst is a region that extends over Dinarsko gorovje (the Dinaric mountains) and comprises both permeable (karstic) and non-permeable rocks. Due to this mixed geology, two major types of drainage have developed: non-karstic surface drainage and the prevailing subsurface drainage typically associated with karst. Even pure and fractured limestone can support superficial flow if regional factors (e.g., hydrological barriers, hydraulic gradients that are too low) do not favor underground flow (i.e., as occurs at karst poljes). Nevertheless, fully developed underground drainage is characteristic for areas with very pure limestones (those with less than 1 % of impurities are abundant in Dinaric karst), with springs at relatively low elevation and without important fault zones. At such places, subvertical drainage which turns subhorizontal at water level and drains toward springs nearby. Very good examples of such drainage are at the mountains Velebit, Biokovo and also at some lowland plateaus (e.g. plateau Kras).

Fig. 17: Glavaš is over 115 m deep spring of river Cetina (photo: A. Mihevc).

Aside from superficial drainage on impervious rocks (such as Eocene flysch, Lower Mesozoic and Upper Paleozoic rocks), very extensive areas of the Inner Dinarides exhibit the fluviokarstic type of drainage. This type of drainage is especially characteristic for dolomite that is not able to transfer all the water underground due to rapid superficial weathering, too high fractionation or too slow solubility. In such cases, a portion of water flows on the surface, especially during heavy rain or intensive melting of snow in springtime, but the rest can flow underground toward springs at the sides of deep valleys. Fluviokarstic drainage is impressively developed in the southeastern part of the Dinaric karst where dolomites are widely exposed. Here, the rivers Tara and Piva have formed canyons exceeding 1,000 m in depth.

At the interfaces between permeable and impermeable rocks, impressive contact karst developed where the superficial rivers encounter permeable karstic rocks. At these geological contacts, superficial streams strongly influence the characteristics of underground hydrology, especially with respect to point recharge, flow regime and high sediment load. During their long history of sinking, these rivers and streams have formed big, and still hydrologically active, underground passages, as well as blind valleys and collapse dolines. One of the best examples of such a sinking river is the Reka, which sinks into Škocjanske jame (Škocjan Caves). Concentration of water is also characteristic for some sinks at the downstream ends of karst poljes, where long epiphreatic cave systems have been developed (i.e. Postojnska jama, Vjetrenica).

Based on described lithological factors, major geomorphic features and hydrological characteristics, the Dinaric karst is usually hydrologically divided into three spatial regions (Gams 1974; Herak et al. 1969; Šarin 1984): low coastal and insular Adriatic karst, continental mountainous karst and low northeastern and high southeastern inland karst. All of these hydrogeological regions are parallel to Adriatic Sea.

Fig. 18: Travertine dams are building for impresive waterfalls along Croatian Krka river (photo: A. Mihevc).

Low coastal and insular Adriatic karst, formed mainly in Cretaceous-Tertiary rocks, is characteristic for nearly all of the islands along the Croatian coast, the northeastern coastal part of Italy (northwest of Trieste/Trst), the coastal area of Croatia, Bosnia and Herzegovina and Montenegro. In Slovenia, the coastal area is formed in Eocene flysch rocks and is therefore non-karstic. The main characteristic of the low coastal and insular Adriatic karst is the contact of fresh water with seawater.

Fig. 19: Canyon of river Cetina with mountain Mosor in the background (photo: A. Mihevc).

Seawater usually underlies fresh water on the islands, resulting in lenses of fresh water below surface. The interface between fresh and salt water along the Adriatic coast is more complex due to different patterns of inflow of fresh water (superficial or underwater), different discharge and different geometry of conduits. On the western peninsula Istra (Istria), below the mountains Učka, Velebit, Biokovo, in Stonski zaljev (Ston Bay) and in the bay of Boka-Kotorska, examples of submarine springs, also called "vruljas", are numerous and efficacious. In some cases water is mixed (i.e., brackish), which presents a problem for water supply, especially in summer when discharges are the lowest. A lot of coastal springs are located above sea level and discharge fresh water – the biggest ones are Timavo/Timava (Q_{min}= 9 m^3/s, Q_{avg}= 30.2 m^3/s, Q_{max}= 138 m^3/s; Ford & Williams 2007 after Smart & Worthington 2000) and Ombla spring, near Dubrovnik, with a natural average discharge of 33.8 m^3/s (after 1965, the average discharge was reduced to 29.6 m^3/s due to the construction of a hydroelectric plant in the hinterland; Milanović 2006). Parsts of the hinterland along coast rise steeply to Učka, Velebit, Biokovo and Orjen, but in many cases shallow karst is developed in areas with little topographic relief (e.g., Istra, Sjevernodalmatinska zaravan (North Dalmatian plain), Ravni kotari). A similar situation occurs on the continental leveled surface between rivers Kupa/Kolpa and Una. Homogeneity of such karst is often interrupted with belts of Eocene flysch rocks trending in a northwest-southeasterly direction, which often divert the general southwesterly flow of streams parallel to the Dinaric direction (NW-SE) and stimulate superficial drainage, while on the karst rocks canyons are developed. The canyons along the rivers Krka, Zrmanja and Cetina (Fig. 19) are up to 180 m deep and were even deeper during Ice ages, when the sea level was lower and travertine dams (Fig. 18) were probably absent. Downstream parts of the canyons are submerged due to the tufa dams and the rise in sea level at the beginning of Holocene. In Istria, the canyons of the rivers Mirna and Raša are shallower but also partly submerged at the downstream ends.

Fig. 20: Spring of river Buna (photo: M. Prelovšek).

The most characteristic hydro-geomorphic phenomena of the continental mountainous karst are high plateaus and karst poljes. The main ridge of continental mountainous karst lies above 612 m a.s.l. The width continental mountainous karst ranges between 30 to 110 km (Šarin 1984). The transition from the southwestern coastal Adriatic karst can be double this width in places. In some parts of Adriatic coast, Dinarsko gorovje rise from the coast very steeply without leveled transition (Učka, Velebit, Biokovo, Orjen, Lovčen). In such areas, water is drained vertically through vadose zones up to 1,350 m deep and often discharges in vruljas along the Adriatic coast. Behind Istra and Sjevernodalmatinska zaravan, the rise is more gradual. In eastern Herzegovina, the rise in elevation goes through several karst overflow poljes, where the lowest are in southwest and the highest in northeast. Water appears and disappears here several times, from the highest Gatačko polje and Nevesinjsko polje (Nevesinje polje)) through Cerničko (Cernica polje), Fatničko (Fatnica polje), Dabarsko (Dabar polje), Ljubijsko (Ljubinje polje) and Ljubomirsko polje (Ljubomir polje) to Popovo polje and finally to the spring Ombla at Adriatic coast and springs along the river Neretva (Milanović 2006). Besides Ljubljanica springs (Q_{min}= 4.3 m^3/s, Q_{avg}= 39 m^3/s, Q_{max}= 132 m^3/s; Gospodarič & Habič 1976), the most efficacious springs in Dinaric karst are located in this area (Fig. 16 on page 24: Buna spring (Q_{min}= 3.0 m^3/s, Q_{avg}= 23.7 m^3/s, Q_{max}= 123 m^3/s; Fig. 20), Bunica spring (Q_{min}= 0.7 m^3/s, Q_{avg}= 20.3 m^3/s, Q_{max}= 207 m^3/s) and Trebišnjica spring (Q_{min}= 2 m^3/s, Q_{avg}= 80 m^3/s, Q_{max}> 800 m^3/s; Milanović 2006; Ford & Williams 2007 after Milanović 2000). Similar topography and hydrological systems have developed in west Bosnia and Herzegovina. Underground water flow between karst poljes can be directed either perpendicular to the main ridge of Dinarsko gorovje (this means also perpendicular to the smaller ridges and karst poljes –e.g., western and eastern Herzegovina, the higher part of Slovene Dolenjska) or parallel to it (part of Ljubljanica basin, NE of Velebit). Some tectonic windows of older (Paleozoic) impervious, or less permeable, rocks enhance superficial runoff that drains into ponors (e.g., NE of Velebit, central Bosnia), but in very rare cases rivers can flow across Dinarsko gorovje (Neretva, Kupa/Kolpa, Morača). The continental mountainous Dinaric karst was for many hydrological phenomena (polje flooding, complex underground water flow between poljes, big ponors, springs and estavellas, hydro technical works) the first area to be studied or extensively used. In recent years, big karst springs are recognized also due to their surprisingly deep sumps (Fig. 17 on page 25) of Una (-205 m), Divje jezero (-160 m), Sinac (-155 m), Kupa/Kolpa (-154 m; Knab, 2008). Nowadays, at least 14 sumps are deeper than -100 m. An even more exceptional case is Crveno jezero (Red lake; Fig. 21) with depth -281 m (Knab 2008) and without clear genesis.

The low northeastern and high southeastern inland karst lies northeast of continental mountainous karst. The northeastern part is characterized by low elevation hills and plains, where both surface and subsurface drainage occur. A great portion of the relief is occupied by a karst-leveled surface (e.g., Bela Krajina, the leveled surface between the rivers Kupa/Kolpa and Una), in which canyons are deepened (Slovene Krka, Kupa/Kolpa, Dobra, Mrežnica, Una). The elevation of the rivers is similar and the elevation of subsurface water between them is slightly higher; this prevents from underground circulation between rivers. Regarding these characteristics, the low northeastern inland karst is similar to Sjevernodalmatinska zaravan and Ravni kotari along the Adriatic coast. In the northeastern direction, the elevation of inland karst decreases until it sinks beneath young sediments of the Panonian basin. Toward the southeast, the southeastern inland karst becomes more and more hilly and karst valleys become deeper due to a higher portion of Triassic dolomite and higher elevation. Rivers (e.g., the Tara and Pliva) flow in canyons over 1,000 m deep between dissected karst plateaus with combined surface and underground drainage flow. Big karst springs are absent, but several of them can initiate larger rivers (e.g., the Neretva, Vrbas, Miljacka, Željeznica, Usora; Papeš & Srdić 1969).

Fig. 21: Crveno jezero (Red lake; photo: A. Mihevc).

Geomorphology

Andrej Mihevc

In folk language, “karst” meant “barren stony land.” This term often occurred in local toponyms and could denote an entire landscape. Today, the word “karst” means a landscape with specific relief, water, and underground features that formed in long geological periods on water-soluble rock, mostly limestone and dolomite (Gams 1973; Kranjc 1998).

Relief on impermeable non-karst rock is primarily sculpted by water that runs on the surface in river networks. Rivers sculpt fluvial valleys that dissect the surface into valleys, slopes, and ridges. The valleys are deepened by the mechanical erosion of rivers, which is greater where the inclination is steeper and there is more water. The slopes above valleys are shaped by sheet erosion or denudation. As a rule, closed depressions do not form in this relief, but if they do, they are immediately filled by water or sediment.

On karst, however, relief is formed by water that chemically dissolves the limestone and carries the solution away. Gravel therefore does not form on the surface and very little insoluble debris remains on the limestone. Gravel and insoluble debris could fill nascent depressions in the relief, cover the bedrock, and be the basis for the formation of soil. Since this is not the case, the karst surface is rocky and hollowed.

Pure water can dissolve only a little limestone or its main component, the mineral calcite. Solubility increases when CO_2 from the air or soil is dissolved in the water resulting in weak carbonic acid. Dissolving or corrosion is further accelerated by acids produced by plants or the decomposition of organic matter in the soil.

The dissolution of karst rock is strongest on the surface or a few meters below the surface, but water remains aggressive for a long time and can form caves underground. Sheet erosion and the lowering of the surface results in karst denudation. Various methods have determined that denudation has amounted to between twenty and fifty meters in a million years in Slovenia’s karst regions (Gams 1974). This also means that surface denudation has already reached individual caves and removed their ceilings to create roofless caves (Mihevc 2007)

Rivers flow onto karst areas and form underground streams. Because they carry large amounts of water and sediment from impermeable neighbouring areas, they are capable of dissolving a considerable amount of limestone, but their effect is limited only to the vicinity of the watercourse (Gams 1962; Mihevc 2001).

Karst rock features

Some dolomites and most of the limestone are mechanically very resistant types of rock, but they are all subjected to dissolution. Precipitations start to dissolve them as soon as they get into contact with the karst rocks. Intensity of the corrosion depends on properties of the rock, aggressively of the water and the way in which water flows on the surface of the rock. Small corrosion features that form on the rock make its surface uneven and rough or form different shapes.

Karen is common term used for dissolution features on exposed soluble rock surfaces. (Gines 2009). Two basic processes control their formation, the dissolution by thin water films flowing down inclined surfaces and the dissolution kinetics of the CO_2-containing rainwater (Dreybrodt & Kaufmann 2007). Some of these features and widely spread so they got special names.

According to Ford and Williams (2007) the main groups are circular plane forms like micropits, pits, pans, heelprints. Linear forms that are fracture-controlled are microfisures, splitkarren and grikes. Linear forms that are hydrodynamically controlled are microrills, solution chanels or rillenkarren, solution runnels, decantation runnels and flutings.

Polygenetic formsare mixtures of solution channels or assamblages of karren: karenfeld, limestone pavement (clints and grikes), stepped pavements, pinnacle karst, corridor karst, costal karren.

Common features on the bare horizontal rock surfaces exposed to rain are solution pans. This is circular or irregular depression in the surface of the rock with flat bottom and often undercut edges. They are from few cm to 1 m large. Corrosion in them is encouraged by biologic processes like decay of organic matter where organic acids form. Water from them evaporates; crystals of calcite are blown by wind or washed out by rain. Shepards often used for watering the animals (Perica 2009).

Characteristic form of corrosion is rillenkarren. They are formed by channelled flow of the rain water on steep slopes on the tops of limestone blocks. They are few cm wide and deep, semi-circulars in cross section and have sharp edges of crests between them. On the lower side they often transform into plat, non dissected surface.

Down the slope of the exposed rock larger channels, runnels form. They are few tens of centimeters wide and can be several meters

Fig. 22: Kamenitza on Velebit mountain (photo: N. Zupan Hajna).

long. They are smoother especially if they were formed below the soil.

Corrosion dissects karst rocks into clints by creating grikes along joints or bedding planes. The size of clints depends on the thickness of the limestone layers. Clints are larger on limestone with thicker layers and less joints.

Corrosion sculptures the surface of the rock also under cover o soil. Soil or even moss that grows on limestone blocks is soaked with water and this water slowly and more evenly corrodes the rock. Surfaces of such rocks are smoother and more rounded and there is no forms indicating the vertical flow of water. Where soils were eroded the sculpture of the rock shows the height to where soil was covering the clints.

Small corrosion forms on the rock depend on the properties of the rock but also on the climatic conditions. In the lower positions especially in Mediterranean climate with dry summers sharper forms like rillenkarren and kamenitzas are frequent. In higher karst areas, where is more precipitations, long lasting snow cover and higher air humidity, rocks are more rounded. Mosses which grow on rocks in forests also make smooth rounded surface of the rock.

Leveled Corrosion Plains

Leveled surfaces are one of the very distinct relief features of the Dinaric karst. They can be found at different elevations. They are common in all the karst regions on the inner side of the Dinarsko gorovje (Dinaric mountains), and especially on the seaward side. They are absent only in the central highest part of the karst (Roglič 1957).

These corrosion plains have been produced over a long period of denudation by corrosion planation in the level of the karst water. Later uplift connected with regional tectonics caused entrenchment of major allogenic through-rivers. Canyons were formed and the

Fig. 23: Kras plateau - view toward south (photo: A. Mihevc).

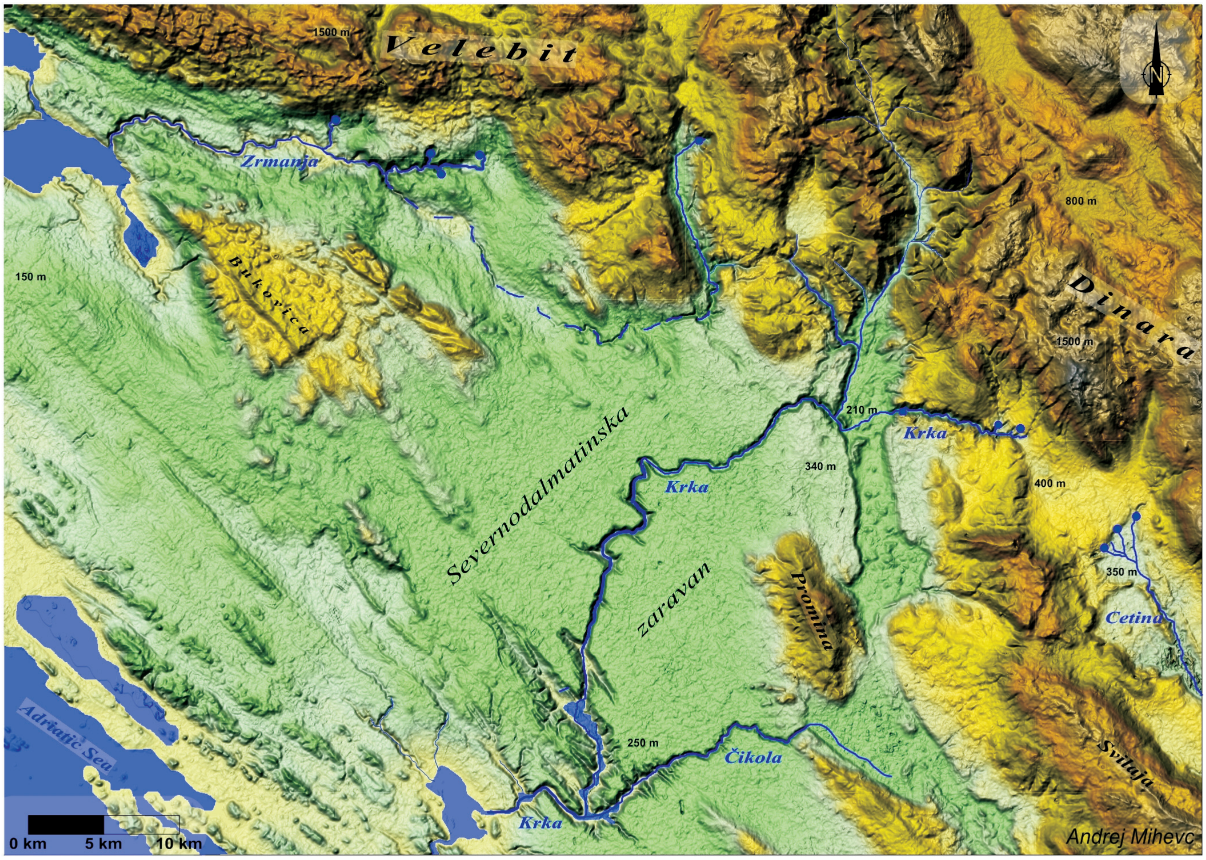


Fig. 24: Sjevernodalmatinska zaravan (North Dalmatian plan) with canyons of Krka, Cetinja and Čikola (DEM source: ASTER GDEM 1"; figure made by: A. Mihevc).

water table dropped beneath the level of the uplifted corrosion plain. Percolating rainwater could escape vertically and form solution dolines.

An example of such an uplifted and slightly tilted leveled surface is Kras, a plateau on the NW part of the Dinaric karst (Fig. 23). Before uplift there were two rivers crossing its surface. Two dry valleys remain there. Only later did dolines and collapse dolines dissect the surface.

Elongated remnants of former leveled corrosion plains developed in higher relief are named "podolje" or "ravnik" (Gams 1973). They are smaller features, a couple of kilometers wide and several tens of kilometers in length. In some of them, deeper poljes like Planinsko polje and Fatničko Polje have developed.

Larger leveled surfaces are often called "zaravan". A leveled surface forms the main part of Istria. It is slightly tilted and dissected by large dry valleys, some canyons and numerous dolines. The largest is 40-km long Severnodalmatinska zaravan between Velebit and Dinara mountains and the sea (Fig. 24). On this surface, the 150-m deep canyons of the Zrmanja, Krka and Čikola rivers are entrenched. Large leveled surfaces are also cut by the Neretva and Cetina rivers. In the high leveled surface at Durmitor Mountain, the River Tara cut a 1,000-m deep canyon.

On the inner side, toward the Panonian Basin, Kordunska zaravan is developed around Kolpa, Una and Sana rivers (Roglič, 1952). It is large - approximately 100 km long and up to 30 km wide. This leveled surface is cut by the canyons of several rivers in which travertine is now depositing. Best known are the travertines at Plitvička Jezera, in the Korana River, which form numerous lakes behind travertine dams.

In some cases rivers could not follow the uplift, so canyons became dry and are preserved in such surfaces. The largest dry valleys of the Dinaric karst is the 20-km long and 300-m deep dry Čepovanska dolina, cut into Trnovski gozd plateau. A dry valley in Istria is 40 km long and 150 m deep. The dry valley of Bregava is 10 km long and up to 700 m deep. The dry valley Zavala, a former outlet of Popovo polje, is 10 km long and 500 m deep.

Closed depressions

The water that shapes the karst comes mainly from precipitation. Water dissolves the rock and carries it through the underground in solution. Dissolution occurs on the surface on bare rock or under the layer of soil and sediment. This direct corrosion sculpts tiny rock relief forms.

Precipitation is dispersed evenly on the surface and percolates into the karst via fissures in the limestone widened by corrosion. The varying solubility of the rock and other factors foster the formation of an irregular and rough surface dotted with depressions of all sizes. Depression features can form and preserve their shape because the water percolates into the ground carrying the dissolved rock with it or because there is no surface drainage and insoluble debris is not transported across the surface to fill them.

Closed depressions are a characteristic feature of the Dinaric karst. In some places they occur only as topologically lowered surface, while elsewhere depressions with distinct shapes form. The most numerous are corro-

Fig. 25: Digital elevation model (DEM) and spatial distribution of Dinaric karst poljes (DEM source: ASTER GDEM 1", poljes after Gams, 1974).

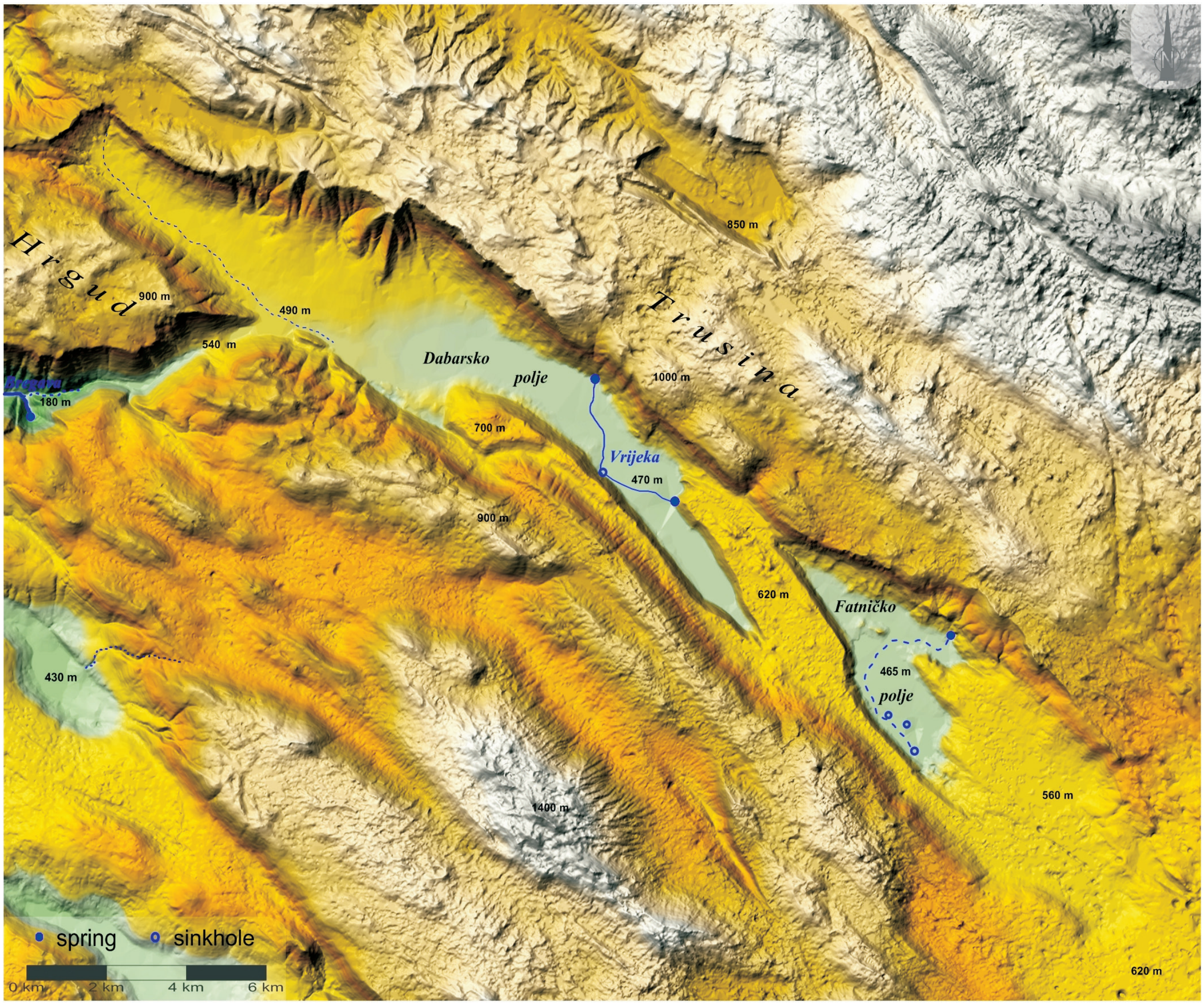


Fig. 26: Fatničko polje (Fatnica polje) in the eastern Herzegovina (DEM source: ASTER GDEM 1"; figure made by: A. Mihevc).

sion dolines that form due to locally stronger corrosion. Suffusion dolines form primarily at the edges of karst poljes due to the washing of sediments. Some dolines are collapse dolines. Larger features of the Dinaric karst include uvalas and karst poljes.

Poljes

Karst poljes are the largest flat-floored enclosed depressions in karst (Fig. 26). They differ from other closed depressions in size and their large flat bottoms which formed as baselevel corrosion plains. Typical forms have a sinking river, steep slopes and a sharp transition between the polje floors and slopes. The bottom of the polje may be covered by sediments. There are about 130 poljes in the Dinaric karst (Gams 1978); about 44 of them are recognized as outstanding (Fig. 25).

Gams (1978) defined some criteria that must be met for a depression to be classified as a polje. These include a flat floor in the rock or in unconsolidated sediments such as alluvium, a closed basin with steeply rising marginal slope on at least one side, and karstic drainage.

Three basic types of poljes have been defined: border poljes, structural poljes and baselevel poljes (Ford & Williams 2007).

Border poljes develop where water table fluctuations in karst control allogenic fluvial activity at the surface, so lateral planation dominates valley incision.

Structural poljes are dominated by bedrock geological controls. This type of poljes prevails on the Dinaric karst. They are connected with graben or overthrust structures, or as inliers of less karstified rocks like dolomite, marl or even flysch.

Baselevel poljes occur where dissolution has lowered the karst surface to the regional epiphreatic zone. Typically these poljes develop in lower parts of the karst, but they also occur in higher parts of the Dinaric mountains where impermeable formations may act as hydrological barriers.

Dinaric poljes are polygenetic features. They are generally elongated along the strike of the Dinarsko gorovje (i.e. in a northwest—southeast direction). Poljes are developed at all elevations, between 1,200 and 20 m above sea level. A complex suite of processes governs their genesis. They develop along regional faults, graben structures and overthrust. The highest is Trebistovo polje, (1,278 m a.s.l.) and the lowest are Bokanjačko polje and Vrgoračko jezero (Vrgorac lake; only 20–25 m a.s.l.).

The largest poljes are Liško polje (460 km^2) and Livanjsko Polje (65 km long and 6 km, 402 km^2), but the majority of poljes are smaller, covering only few 10 km^2.

In natural conditions floods are normal phenomena for many poljes. In some poljes like Cerkniško polje and Buško blato they lasted about half a year. The flooding of 60 km long Popovo polje under natural conditions reached a height of 40 m in the lowest section of the polje, and the average yearly flood duration was 253 days.

Poljes are very important for human settlement. In them the best, and often only, arable land in the Dinaric karst is available. There is always some water available and floods are regular and limited to lower parts of poljes, so all of the largest settlements are located there.

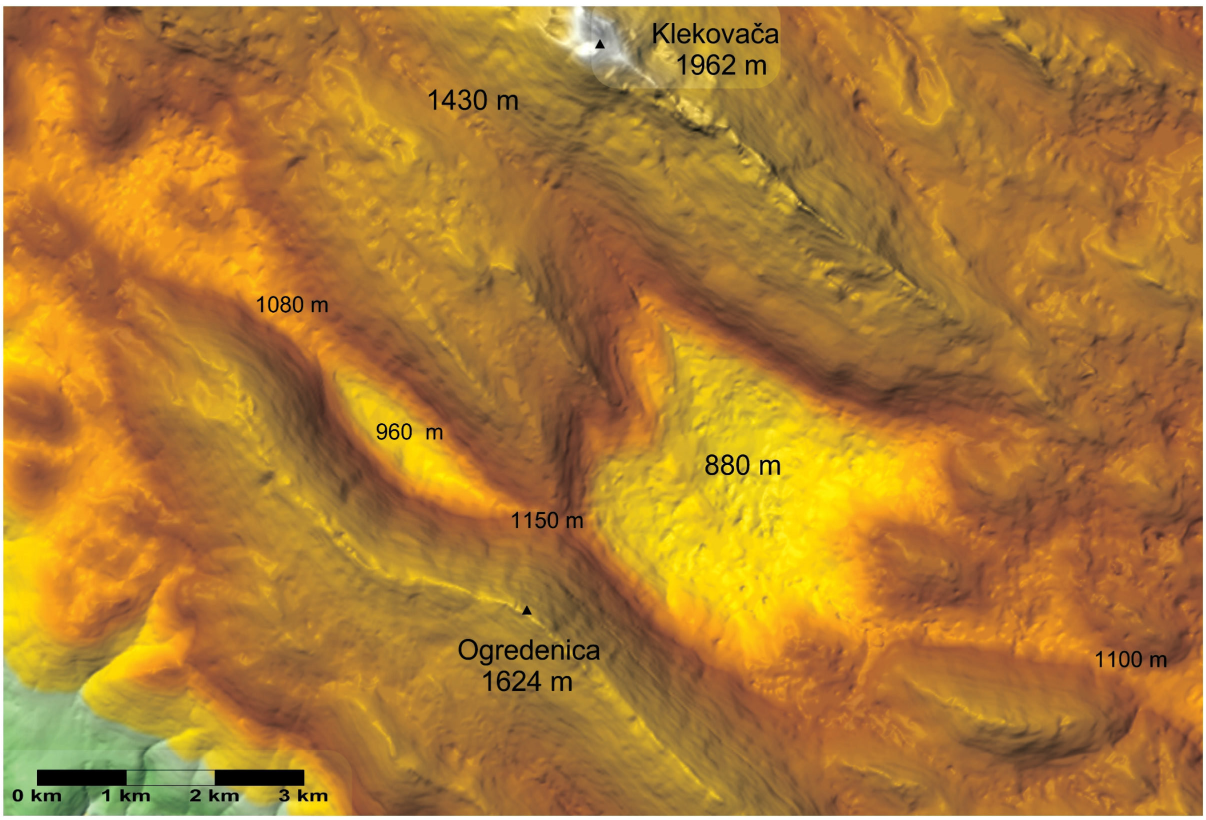


Fig. 27: Klekovača and Materniča uvala are two large closed depressions northern of Livanjsko polje in Bosnia. Note that the bottom of large uvala is dotted with dolines (DEM source: ASTER GDEM 1", figure made by: A. Mihevc).

Uvalas

Uvalas are large, km-scale closed karst depressions of elongated or irregular plan form. Their bottoms are undulating or pitted with dolines, seldom flattened by colluvial sediments. Uvalas are always situated above the karst water table. They are polygenetic features and are strongly guided by geological structure and tectonics (Čalić 2009). The word "uvala" is common toponym in the Dinaric karst, always denoting a large depression. In folk language it has a morphological meaning only.

The term was introduced into literature by Jovan Cvijić (1893) for dolines with huge diameters, but unfortunately with an erroneous explanation of their genesis – that the uvalas are transitional evolutional elements between dolines and poljes, formed by the coalescence of several dolines which have enlarged and merged towards each other (Cvijić 1901, 1960). Because of this erroneous explanation, the term "uvala" is mostly abandoned in professional literature outside the Dinaric karst.

There is considerable variety among the dimensions, and also the shapes, of the uvalas, but there are also some common general characteristics (Čalić 2009). In most cases the uvalas are developed along tectonically broken zones of regional extension. Their perimeters are of irregular shape, the plan dimensions vary from approximately 1 km up to several kilometers along the longer axis, while the depths below the highest closed contours are at least 40-50 m, and sometimes exceed 200 m. Uvalas are not present on karst leveled surfaces, but only in areas with more or less dissected relief, so the bottoms are always above the karst water table.

Uvalas have internal karstic drainage; occurrences of small seasonal surface flows are an exception. Sediments in the bottoms are scarce; their origin is from denudation from the slopes. Infill is not threatening to fill up a depression. The inclinations of the slopes are generally smaller than those of dolines. Uvalas are formed because of differences in solubility of the karstified rock, structural elements and recent tectonics. Formation of such topologically closed areas within larger karst areas needs only sufficient time and favorable climatic conditions.

Uvalas can be found in all of the Dinaric karst except in low positions and on leveled surfaces. In many uvalas, because of some colluvium, small settlements developed. Some uvalas were affected by glaciation; in some, glacial tongues ended and fluvioglacial till was deposited. In them, the lowest temperatures in the area were observed because of temperature inversions.

Dolines

Dolines are the most frequent karst depressions. They are centric and mostly round relief forms. Dolines commonly have circular to sub circular plan geometry, and a bowl- or funnel-shaped concave profile. Their depths range from a few decameters to a few hundred meters, and their inner slopes vary from sub horizontal to nearly vertical. Dolines up to ten meters deep and 100 meters wide dominate.

Their genetic definition is difficult because although they formed in very diverse conditions, all the processes led to the same funnel or bowl shape. Morphologically, the same or similar dolines can therefore have different origins. In order to understand how dolines and other, closed karst depressions develop, it is necessary to examine their morphology and size, their relationships with the topographic and geomorphologic settings, their structures, their hydrological behaviour and related solution processes, examples of evolution, and peculiar morphologies that occur under specific environmental conditions (Sauro 2005).

Corrosion dolines occurred where vertical percolation into the karst was possible and dissolution of rock was stronger than in the surrounding area. The round shape with one lowest point indicates a spatially limited and active process of rock mass removal. In most cases, the soil plays a major role due to the

Fig. 28: Typical dolines of Dinaric karst, Smoljana near Bosanski Petrovac (photo: A. Mihevc).

production of biological CO_2 that locally amplifies the corrosion of the limestone. Dolines are found everywhere in Dinaric karst, but most are located on karst plains where, if small their number can exceed one hundred per square kilometer. The number of dolines is much smaller on slopes and there are none at all on steep slopes. Larger dolines are found on higher karst plateaus, some of them up to a hundred meters wide (Gams 2000; Faivre 2002).

Dolines are a very important relief form of the Dinaric karst. Because soil is only found at their bottoms, they are used for fields or gardens. In the past, rocks were carefully removed from the slopes and the bottoms were levelled. Some of the rocks were buried under the soil at the bottom while the rest of were used to build dry stone walls (Gams 1991, Mihevc 2005).

The bottoms of dolines were often used as water reservoirs. Soil was removed from selected dolines and cattle were driven across the clay to compact it and make the bottoms impermeable enough to hold water well into a dry summer.

More than any other karst form, dolines reflect man's changed relationship to the environment, as the fact that villagers have transformed numerous cow ponds and dolines into dump sites demonstrates.

A special type of doline is formed by the washing, subsiding, and settling of sediments on karst. In the past they formed only where layers of sediment piled up, for example, on karst poljes, but in current conditions the sediment is washed as particles into the karst underground.

Collapse dolines

In the Dinaric karst, collapse dolines are quite common relief features. The term "collapse doline" presumes the formation of a doline by collapse into a karst cave situated beneath. Expert literature understands collapse dolines as dolines with exceptional dimensions and steep or vertical walls (Gams 2004). Smaller collapse forms are frequently left aside because of lack of signs of collapse processes. In practice, it is often difficult to distinguish a real collapse doline from other types of depression. It is even more difficult to do so in the case of the older features, which have been modified by corrosion and other surface processes, and where the primary origin is no longer clear (Šušteršič 1974; Stepišnik 2006).

The cave roof collapse is a slow process that proceeds by the breaking of the walls and ceiling until equilibrium is established on the slopes of the doline. The volume of the newly formed feature (i.e., the collapse doline) should be smaller, since the collapsed rock occupies a larger volume than the solid rock.

With respect to genesis and dimensions, there are two distinctive types of collapse dolines on the Dinaric karst. One of these types is dolines formed by the collapse of relict caves, usually when denudation thins the ceiling above the underground chamber. As most of the known cave chambers within the area have dimensions of up to some 10,000 m^3, we should expect the dimensions of collapses to be smaller than that. These collapse dolines differ from other dolines because they have vertical walls or slopes'.

The second type of dolines of collapse origin is often several hundreds of m in diameter, with steep or vertical walls and volumes of to several million m^3. The formation of large chambers by collapsing, and of collapse dolines, is a result of a combination of several factors and not just simple collapse because of rock failure in the cave ceiling (Habič 1982). It cannot be treated as the decay of caves, but as a distinct speleologenetic and geomorphic process (Mihevc 2009). Their immense dimensions are mainly the result of the removal of

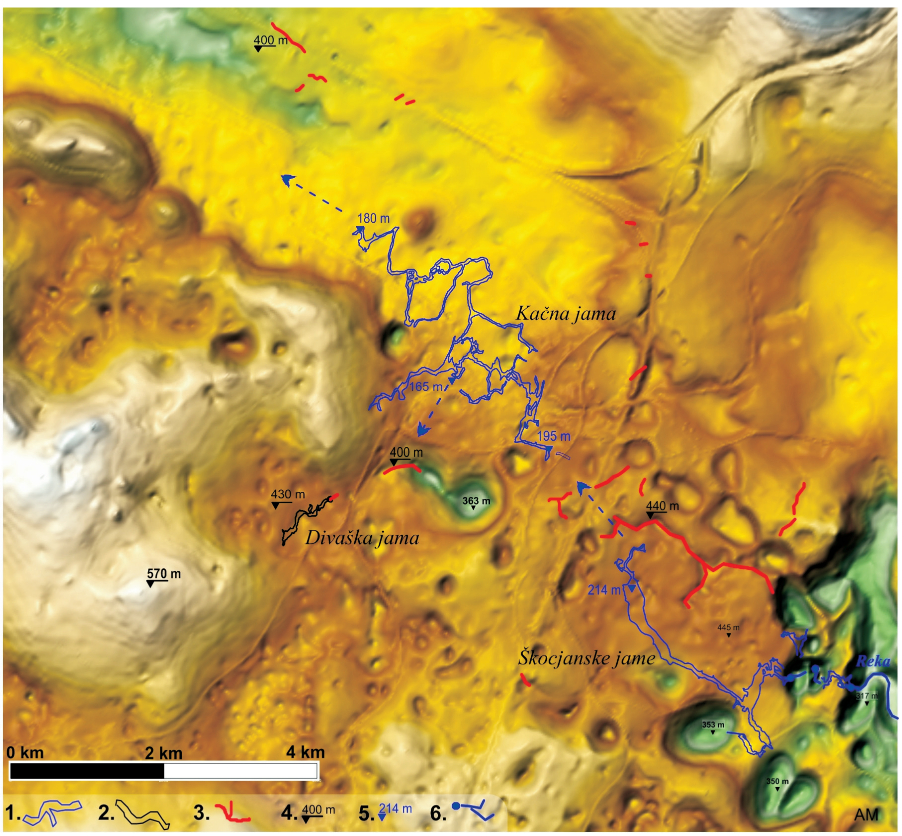


Fig. 29: Divača karst is the best Dinaric example of the interrelation between contact karst features - ponor caves, collapse dolines and unroofed caves (DEM source: ASTER GDEM 1"; figure made by: A. Mihevc).

Legend:

1. *hydrologicaly active caves;*
2. *dry caves;*
3. *unroofed caves;*
4. *terrain elevation;*
5. *water level;*
6. *surface water flow.*

the disintegrated collapsed rock at depth by solution of the underground flow. Therefore, the volumes of these collapse dolines are much larger than the volumes of the pre-existing cavities.

Usually these dolines are connected with main underground watercourses, and are more abundant in levelled surfaces near sinks or springs of the rivers. In Slovenia, there is a concentration of dolines on the Kras plateau above the underground course of the Reka river. More than 16 large dolines are situated here. The largest has a volume of 9 m^3 (Mihevc 2001). There are numerous dolines in the Ljubljanica river basin above cave Postojnska jama, between Cerkniško and Planinsko poljes. On the edge of Imotsko polje, there are several large collapse dolines. One of them is Crveno jezero, which is the deepest collapse doline of the Dinaric karst. Its maximum depth is 528 m, and it is filled with water 287 m deep. Recent diving explorations have found large openings in the submerged walls of the doline and cave entrances at its floor (Garašić 2000).

There are groups of large colapse dolines around Liško polje, Lušci polje, above springs of Pliva, springs of Zeta, between Duvanjsko polje and Buško bato, and on Nevesinjsko polje. Many others scattered on the karst surfaces.

Karst on dolomite

Dolomite is a type of rock that dissolves and is karstified similarly as limestone. Dolomites are rarely pure; they are formed of different mixture of mineral dolomite and calcium carbonate. There are important differences between karst landscape on dolomite and those on limestone. Jurassic or cretaceous dolomites are resistant, but they disintegrate on the surface into fine sand. Triassic dolomites which prevail are less resistant against frost shattering and they easily disintegrate into gravel and sand. This is sometimes so intensive, that whole surface is covered with dolomite gravel. Precipitations infiltrates trough this material into the undamaged and karstified dolomite.

The sediment on the surface and the smaller permeability of the dolomite can slow down the infiltration, therefore after rains waters often flow across the surface. Because of limited permeability a mixture of fluvial and karst features can develop on dolomite. This type of karst was named fluviokarst (Gams 2004). On the dolomites there are less caves, they are usually shorter and smaller.

Characteristic features of dolomite areas are dells, dolines and large surfaces with underground drainage but no distinct karst or fluvial relief features. Where rock is more resistant to weathering tors develop. In steeper relief or in high mountains fluvial features like gullies and erosion valleys divided with ridges and develop. On smaller slopes most common feature is dells and on smaller even doline (Komac 2004).

Dell is a shallow valley with steep slopes and lesser gradient of the bottom. There are no traces of erosion and the bottoms and slopes are covered with soil. Sometimes they open out on a plain on lover end; sometimes they end blindly in a doline.

Typical for the dolomite areas is soft landscape with no rocks exposed. In past these areas were used for agriculture, pastures, meadows and even field are located on dolomite. Also they are favourable for settlements. They are widely used in quarries for sand for building and road constructing.

Dolomites are more common on inner side of Dinaric karst. There are large areas of dolomite karst or fluviokarst in eastern side of Dinaric karst in Slovenia, around Plitvička jezera and Lika in Croatia, around Una river, upper valley of Neretva river in Bosnia and north of Orjen in Montenegro.

Contact karst

One of the possible classifications of the karst is by the dominant morphological process. Karst formed by the influence surface river flow could be designated by the term of contact karst. The term grows familiar in Slovenia and Croatia where the karst contacts non carbonate rocks and specific relief forms and phenomena developed (Roglič 1957, Gams 1973). The term is reasonable, because such karst essentially differs from the karst which surface and underground was formed by precipitation water only. In the international karstological literature these forms and phenomena are usually named as karst influenced by allogenic inputs (Ford &Williams 2007).

Contact karst develops where water flows from fluvial relief onto karst. The distribution of contact karst is preconditioned to spatial distribution of karstic and non-karstic rock or less karstified rocks like some dolomites. Because here is more water available dissolution of limestone is faster than on other karst surface where only precipitations shape the relief. Surface waters also transport and deposit sediments before they sink into sinks or ponors and caves (Gams 1962). That is because the underground channels are shaped by low or average water and can not transfer the high waters, which causes short but regular flooding and precipitation of sediments in front of ponors. Corrosion is faster also because of the sediments are accelerating the corrosion beneath them because of organic CO_2 produced in sediment or soil. The results of these are often widened bottoms of blind valleys before sinks.

Contact karst features are limited only to the area influenced by sinking rivers. They are mostly depressions, most common are blind valleys. These are valleys, which from non karst fluvial valley protrude some distance to karst and end above the sinks. His relief has some characteristics of fluvial relief, but the features are karstic. The sinking into the karst is controlled by the gradient and the morphology in the whole karst area between sink and a spring. If this is changing due to tectonic movements, evolution of the caves also the contact karst forms change. So we have often a set of evolutionary stages in the contact zone, reflecting the changes trough whole evolution of karst (Mihevc 2007).

We must differentiate between sinking rivers on poljes and allogenic sinking rivers. Difference is that the flooding in contact karst is because of surface inflow, while in the karst poljes because of oscillation or rise of the level of karst water.

Areas of contact karst with developed relief of blind valleys and similar border depressions in Dinaric karst are in the inner side of the mountains where older noncarbonate rocks and Triassic dolomite are in contact with limestone. On the Mediterranean side of the karst main supply for allogenic sinking rivers are Eocene flysch rocks. Best examples are blind valleys in Matarsko podolje (Mihevc 1993) and blind valleys in Istra peninsula.

Largest sinking rivers are Reka with mean discharge 8 m^3/s (max over 200 m^3/s) that sinks on the edge of Kras in Škocjanske jame caves (Fig. 29). Large sinking rivers of contact karst are also Pivka river (4 m^3/s), Pazinska reka in Istra sinking in Foiba cave, Dobra which sinks near Ogulin. Large sinking river is Zalomska reka that sinks in Biogradski ponor on Nevesinjsko polje with capacity over 110 m^3/s.

Caves

Caves are one ob the most remarkable karst features. We can find them from the highest karst mountain to the lowest parts along the sea, and some of them are submerged below the recent sea level. Caves are active or relict parts of the karst drainage system. Most accessible or known caves however are just small fractions of old relict cave systems. Active caves are often flooded or obstructed with sediments. The cave distribution, morphology and sediments give us information about evolution of the whole karst.

On the high karst mountains vertical shafts and deep caves without horizontal passages prevail. They were formed by vertical percolation of precipitations. The deepest caves are on Northern Velebit, where three caves are deeper than 1,000 m (Fig. 30). The deepest Lukina jama 1,355 m ends only 83 m above the sea level which is only 10 km away (Bakšič 2000).

Horizontal caves are common on the levelled surfaces and lower karst plateaus. They are formed by more horizontal flow of water towards the springs. The longest like Postojnska jama (20.5 km), Đulin ponor - Medvedica (16,396 m), and many others were formed by sinking rivers. These caves have also large passages. One profile in Škocjanske jame the passage is in general 20 m wide and about 80 m high. The sinking rivers like Reka in Škocjanske jame can take more than 270 m³ at flood. Biogradski ponori of river Zalomska rijeka discharge is 110 m³ (Milanović 2000).

In Slovenia only on 7,000 km^2 10,000 caves is known, but that number shows only actual knowledge. These caves together are longer than 700 km.

Caves are important archaeological historical religious and cultural sites. They are important scientific localities and also great subject to be explored or visit by cavers.

Today Postojnska jama, Škocjanske jame, Cerovačke pečine, Vjetrenica, and many smaller caves are managed. They are important tourist attraction and are visited by nearly one million visitors per a year.

The age of the Dinaric karst

The age of the karst can be defined as the time when the karst rocks were uplifted out of the sea. For the most of central part of Dinaric karst this occurred after the Eocene, because there is no evidence of younger marine sediments, on the inner part however marine sedimentation lasted till Neogene. As soon as the carbonate rocks were exposed, we can expect that the karst start to form, but there are no remnants of karst features from that time. Denudation has already destroyed them.

The other view on the age of karst is to define the age of karst features that are present on the surface and underground. We know the conditions in which features form. If these conditions changed in past, features may still be unchanged or only slightly changed by general karst denudation. Such features are levelled now dissected surfaces high above the ground

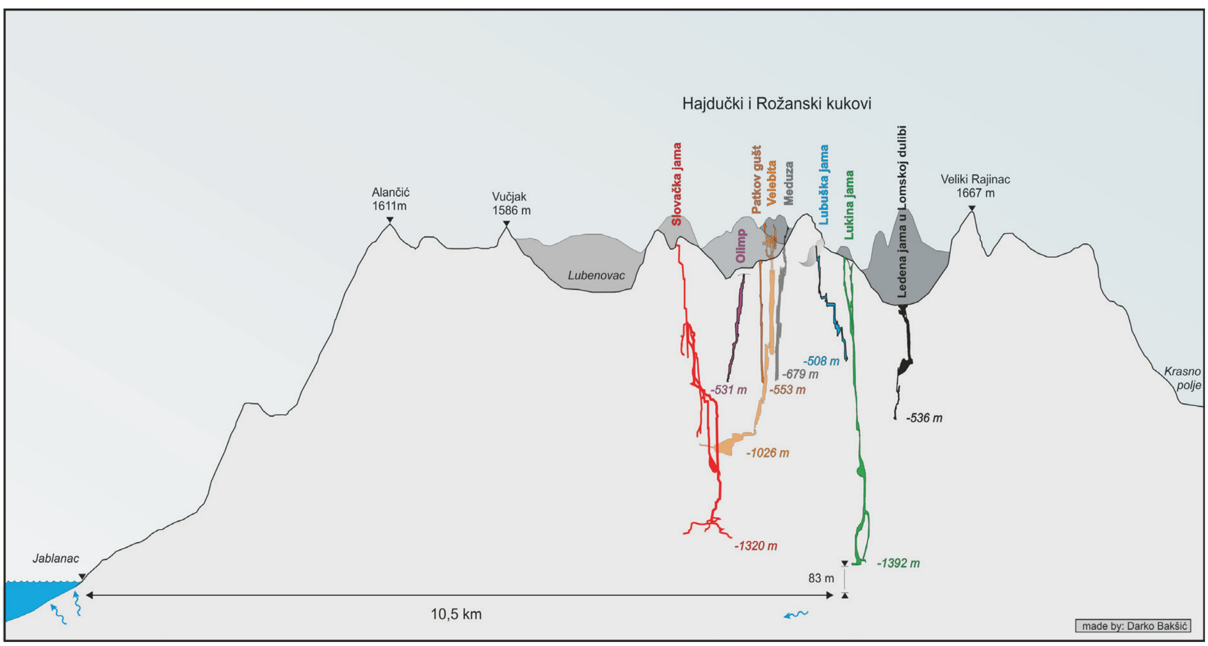


Fig. 30: Cross-section through Velebit mountain with outstanding caves (published with permision of the author-D. Bakšić).

Fig. 31: The oldest caves are found on the surface where they are incorporated into the karst surface. Example of unroofed cave by Povir at Kras plateu, Slovenia (photo: J. Hajna).

water level, dry and blind valleys and caves that are now exposed to the surface due to karst denudation. This tells us about the genesis of the landscape trough different phases but not the age of a karst features itself.

Measurements show, that denudation is lowering surface of karst with rate between 30-50 m/Ma (Gams 1963; Gabrovšek 2009). If we consider, that the then we understand that most of the surface karst features can not be older than maybe 3-6 Ma. The oldest elements in karst are probably the caves that formed deep below the surface and are now exposed as unroofed caves (Mihevc 1996, 1998, 2001; Fig. 31).

Real datation of karst is possible only from the sediments that were deposited in karst features, caves or karst depressions. Different methods are used and they can date only the time of the sedimentation.

Datation of flowstone using different U/Th methods we can date only about 500,000 years old sediments, that is the limit of the method. Paleomagnetic analyses can give us paleomagnetic record in sediments, but method is relative, so the data has to be calibrated by some other method, like palaeontology (Zupan et. al. 2008). This method is basing on comparison of animals remains that preserve in caves.

The oldest cave profiles are in Račiška pečina, where with combination of paleomagnetic method and palaeontology method a sedimentary profile was dated to 3.2 Ma. In unroofed cave cut in Črnotiče quarry sediments with same methods were about 4 Ma old. They were covering remains of cave animal *Marifugia cavatica*, which was living in that at the time water cave. This is also the oldest known remnant of the cave animal and with it we can also reconstruct the paleoenvironment of that time (Mihevc 2001).

Land Use

Nadja Zupan Hajna, Andrej Mihevc, Mitja Prelovšek

The lack of soil cover on the stones and the disappearance of water under the surface are the main characteristics of the Dinaric karst. In the past, when most of the people made a living from farming, these characteristics were the main limiting factors for populating and developing settlements in the area. Many studies (Gams 1974, 1991, 2003; Gams et al. 1993; Gams & Gabrovec 1999) show that the management phases have been in relation with the historical conditions and changes.

The largest problem was the soil. The inhabitants cleaned the surface of the stones and piled them into walls and heaps which also protected the arable land against strong bora wind. In this way, they created thin patches of soil that were connected and thus made some farming possible. Thicker layers of soil emerged at the bottom of dolines (Fig. 32, Fig. 34). Small fields were created there, where the drought was not so devastating. Other more stony surfaces of the plateau were used for pastures, which replaced the natural forests.

To illustrate the amount of the work involved, and also man's impact, three villages were studied by Mihevc (2005). Village Divača has 7.9 km^2 of land in its cadastral unit. The karst surface was cleaned of rock that was piled to dry walls. There are 69.5 km of dry walls, which gives 11.3 km, or 2,825 m^3, of stones removed from one square kilometer. In this way they gained 99 hectares of field sur-

Fig. 32: Thicker soil in dolines was often used for fields and later replaced by grassland. Example from Lovčen, mountainous part of Dinaric karst (photo: A. Mihevc).

Fig. 33: Island Kornat. Especially along the Adriatic coast, deforestation led to bare rocky country (photo: A. Mihevc).

faces. Out of that, 24.6 ha are fields in the bottoms of 261 dolines. The rest of the surfaces were used as pastures.

At Račice village, 11.9 km² of the land is mostly covered by forest. There are 1,395 dolines. While cleaning the land, the stones were piled into 23.2 km of dry walls. The volume of the removed stones is about 5,815 m³, or 488 m³ per km². On some Adriatic islands, quantity of removed stones is similar; at Krk island, more than 1,000 kg of stones were removed from one m² of the surface (Gams 1987). During long history of cleaning the land, width and length of walls increased together with fragmentation, while the area of arable land decreased.

Volčji Grad village is in the central part of the Kras plateau. It has 4.8 km² of land. Cleaning started in Bronze Age and by this means they gained 38.6 ha of fields. All of the dolines were cultivated too, and there are 20 ha of cultivated land in the 162 dolines.

Even with such long and intensive land use, there was no more than about 10 cm of soil erosion on the slopes of dolines.

One of the main parts of the Dinaric karst - the Kras, the islands and low plateaus of the Dalmatian coast - present the types of land use typical of Mediterranean countries. These land use activities produce changes in the surface (Nicod 2003) like stone clearing, the building of dry walls and hill slope terraces and management in the dolines, uvalas and poljes.

From historical data, it is known (Kranjc 2008) that a great part of the Dinaric karst was deforested and that the landscape transformed into a bare rocky country, a real stone desert. Human deforestation began during the Neolithic period (6,500-6,000 BC). There were several reasons for deforestation, mostly requirements of new land for pasture and timber use.

The Dinaric karst became more and more barren and a great part of it became synonym for 'bare limestone desert' – the karst (Fig. 33). Reforestation is mentioned earlier in some of the areas, but successful reforestation did not begin until the 1850s. Subsequently, large parts of the Dinaric karst were artificially reforested, and eventually the process continued by itself as the trees propagated naturally. However, instead of 'natural' forest with an optimal tree association, monoculture forests, dominated mainly by black pine, have resulted (Gams & Gabrovec 1999). Nowadays, the great part of arable land between dry walls is no longer cultivated due to fragmentation and social changes (depopulation and deagrarization); box-like countryside slowly vanishes in dense bushes and degraded forests. Nowadays dense natural forests, extensive forest plantations, dry karst shrublands and also completely barren karst areas can all be found on the Dinaric karst (Kranjc 2008). Inland, because of a more humid climate and different land use, the forests remained.

Fig. 34: Dry wals and small field above uvala Kruščica on the southern side of Orjen (photo: A. Mihevc).

Fig. 35: Water reservoir built in the bottom of small doline in Boljuni, near Stolac in Herzegovina. This water was used for animals only (photo: A. Mihevc).

The other problem of karst is water, especially along Adriatic coast where the highest lack of water occurs during summer. This is a result of low amount or precipitation and high evapotranspiration. For the water supply, some aqueducts were made in antiquity (Bonacci 1987). More common are wells, which were often built in closed depresions (Fig. 35).

Fig. 36: During Austro-Hungarian Empire and Yugoslavia kingdom surface streams were regulated, ponors were widened and screens were installed in front of them to hold back deposits, all in order to shorten the flood time in karst poljes. Example from Šica ponor at Radensko polje (Račna polje; Slovenia; photo: M. Prelovšek).

A greater impact was made by the irrigation of some poljes to avoid long lasting floods. They enlarged ponors on poljes and even dug some tunnels for the floodwaters. None the less, enlargement of ponors successfully reduced the length of floods only at places, where a restristions were close to the ponors. At places with regional rise of water level, enlargement of ponors brought only minor success.

However, the main impact on the karst was made by the use of waters in power stations. Especially high mountainous karst has been very interesting from the hydroenergetics aspect due to a high amount of precipitation, high runoff coefficient (about 0.7), high relief amplitude and relief suitability. Especially during the 1950s and 1960s, big hydroenergetic projects were initiated on Dinaric karst poljes in Croatia, Bosnia and Herzegovina. Large works were done in the Trebišnjica river karst by flooding part of the karst (Fig. 37 and 38), by diverting water to other catchment areas (Fig. 39) and stopping regular flooding of the Popovo polje (Milanovič 2006). Important hydroenergetic objects were placed also in Cetina, Lika-Gacka and Zeta river basins. In the present day situation, hydroelectric power plants in the Dinaric karst have a total install power of over 2,727 MW. Nevertheless, the level of environmental concern about some areas (e.g., Planinsko polje, Cerkniško polje, Pivka basin, Reka valley, and the Kupa/Kolpa River) was so high that these areas remain hydroenergetically untouched.

Fig. 37: Hutovo accumulation lake at the downstream end of Popovo polje (on the right), Herzegovina (photo: M. Prelovšek).

Fig. 38: Grančarevo dam in the upper part of Trebišnjica valley. Behind the dam, Bileća lake with starage capacity of 1,28 billion m^3 (Milanović 2004) was formed and flooded spring of Trebišnjica (photo: A. Mihevc).

Fig. 39: Canalized Trebišnica river on Popovo polje. On the right bank, remnants of one of the 43 flour mills (Lučić 2007) that were built along Trebišnica river are located (photo: A. Mihevc).

Case Studies from the Dinaric Karst of Slovenia

Andrej Mihevc, Nadja Zupan Hajna, Mitja Prelovšek

The Dinaric karst (Dinarski kras) is the major karst area of Slovenia. In past centuries, the Dinarski kras of Slovenia represented one of the world's prime sites of early scientific exploration of karst phenomena (Kranjc 1997; Shaw 1992) due to the large number of outstanding karst features such as caves, large sinking rivers and flooded poljes. Speleology, karst hydrology and biospeleology were born here. The most prominent phenomena are situated in the north-western part on the plateau named Kras. In Slovene language, kras means a rocky, barren surface. The name is often used as toponym (Kranjc 1994, 1997). Kras plateau became a textbook example for this kind of landscape because of the extraordinary karst phenomena, and explorations done in the 19th Century. The name Kras in the German form of the word (der Karst) became an international scientific term. The area where these early explorations took place is called the Classical Karst (term introduced by Radinja 1966, also 1972 as Matični Kras; which should not be confused with the misinterpretation by Šušteršič 2000).

The dominant relief features are rather extensive levelled surfaces at different elevations, large closed depressions (e.g., poljes), and conical hills. Fluviokarst features like dells are common on dolomites. Karst rivers appear only in the bottoms of poljes, where they result from a high level of karst water. Allogenic rivers flowing from non-carbonate regions either sink at the karst boundary, forming blind valleys, or cross the karst through deep karst valleys and canyons. There are numerous extensive and complicated cave systems formed by sinking rivers and connected with the surface also by numerous vadose shafts. The surface karst morphology is typified by the abundance of karren, dolines of various diameters and depths, sometimes extensive collapse dolines, cave entrances, unroofed caves, etc.

For the Dinaric karst of Slovenia, two types of relief are characteristic: High Dinaric karst (high karst plateaus: Javorniki, Hrušica, Nanos, Trnovski gozd, Banjščice and Snežnik) and Low Dinaric karst (karst in the lower parts: Notranjsko podolje, Pivka basin, Kras). There are presented limestones and dolomites of Permian, Triassic, Jurassic, Cretaceous and Paleogene, cut by faults in the dominant Dinaric direction (i.e., NW-SE). The most dominant karst forms in the area are dolines, collapse dolines, karst poljes and high plateaus (Mihevc 1997). The main factor in relief development has been the dissolution process; others (fluvial erosion, slope processes, etc.) have a subordinate role. Along Idrija Fault the main karst poljes in Slovenia are developed: Loško polje (Lož polje), Cerkniško polje (Cerknica polje), Planinsko polje (Planina polje). There are many caves developed, among which is the outstanding Postojna caves system with about 20 km of known passages.

Kras

The Kras is a distinct plateau, especially when viewed from the seaward side. The Kras trends NW–SE between Trieste Bay, the northernmost part of the Adriatic Sea, Vipava valley in north-east, and the Friuli–Venezia Giulia lowlands and river Soča in northwest (Fig. 40). The 45°45´´N and 14°00´´E lines of latitude and longitude cross the Kras near Divača village. There are steep limestone slopes a few hundred meters high rising directly from the sea or from the neighbouring lowlands to the northwest. Higher relief on flysch in the east separates the Kras from the Pivka region. In the southeast, the border of Kras is again well defined by contact with the non-carbonate flysch of the Brkini hills and the valley of the Reka river. Toward the south, the transition to karst ridges and Matarsko podolje karst plateau is less obvious. The climate is sub-Mediterranean with warm dry summers. Cold winters, with most of the precipitation, show the strong influence of the continent.

The Kras belongs to the Adriatic–Dinaric Carbonate Platform of the External Dinarides, composed of shallow marine fossil-bearing Cretaceous and Palaeogene carbonates. Eocene flysch rocks encircle the carbonate plateau. Kras and Matarsko podolje tectonically belong to Komen thrust sheet (Placer 1999), which is thrust over Eocene flysch and Palaeocene/Eocene limestone of the Podgorski kras, a part of Kras imbricated structure (before known as Čičarija imbricated structure; Placer 2007). The whole structure is sub-thrust by the Istria unit.

The main part of the plateau is essentially levelled, inclined slightly towards the northwest, with numerous dolines, caves and other karst features. There is a belt of slightly higher relief in the central part of the plateau, formed by conical hills-like Grmada (324 m a.s.l.), Volnik (545 m a.s.l.) and Stari tabor (603 m a.s.l.), and dissected by large depressions. The higher relief divides the Kras into two separated levelled surfaces. The southern one is named Nabrežinsko podolje. In the northwestern part, the plateau descends to below 50 m a.s.l. on the edge of the Friuli Plain; on its south-eastern edge altitudes are about 500 m a.s.l There are about 300 m of accessible vadose zone with caves formed at all altitudes from the surface to the sea level and below it. No superficial streams occur on the Kras surface because all rainwater immediately infiltrates to carbonate rocks. There are two dry valleys crossing the plateau and some NW–SE-trending belts of lower relief which were believed to represent primary river valleys also because they contain remnants of fluvial sediments dated to a pre-karstification phase (Melik 1955; Radinja 1985).

Geomorphologic and speleogenetic studies and especially new interpretations of fluvial sediments from the Kras surface as the fluvial fill of now unroofed caves have enabled a new explanation of the evolution of the Kras (Mihevc 1996, 1998, 1999a-c, 2001b, 2007; Zupan Hajna et al. 2008a).

Nabrežinski kras

Nabrežinski kras (Nabrežina Karst) is the north-western part of the Kras around the village of Nabrežina (Aurisina in Italian). It is only about 150–180 m a.s.l. There are several old collapse dolines on the surface, more than 300 m wide and to 50 m deep. Smaller solution dolines are less abundant, most of the surface having plain or slightly undulating relief. Toward the north-east, the surface of the Nabrežinski kras gradually transforms into the slopes of the Volnik (545 m a.s.l.) hills and Grmada (324 m a.s.l.). An abrupt change of the surface occurs in the south-west, where the surface drops from about 160 m a.s.l. to the sea level on the distance of 300 m only. There are numerous caves, some of them are over 100 m deep, but they do not reach the underground karst water level or the main flow of the underground Reka river that appears in springs at sea level only about 7 km to the north-west.

Divaški kras

Divaški kras (Divača Karst) is the karst surface above Škocjanske jame; it is sometimes called also the Škocjanski kras. The Divaški kras is situated in the south-eastern edge of the Kras between ponors of the river Reka and Divača village. It is composed chiefly of Cretaceous and Palaeogene limestones. The surface is levelled at altitudes between 420 and 450 m a.s.l., inclined slightly north-westwards and dissected by karst denudation. There are outstanding karst features covering an area of 32 km^2, including ponors of the Reka river and two smaller streams, 15 large collapse dolines, 64 caves, among them Škocjanske jame, Kačna jama, Divaška jama and Trhlovca, plus hundreds of dolines. The Reka river sinks in Škocjanske jame and flows into Kačna jama. Explored passages of Divaška jama and Trhlovca are situated some 200 m above the underground water course and contain a lot of fluvial sediments. A number of fossil caves completely filled with sediments were uncovered during the highway construction in the area. A comparison of the proportion of area of smooth relief and the area covered with dolines and collapse dolines shows that levelling is a dominant geomorphologic process

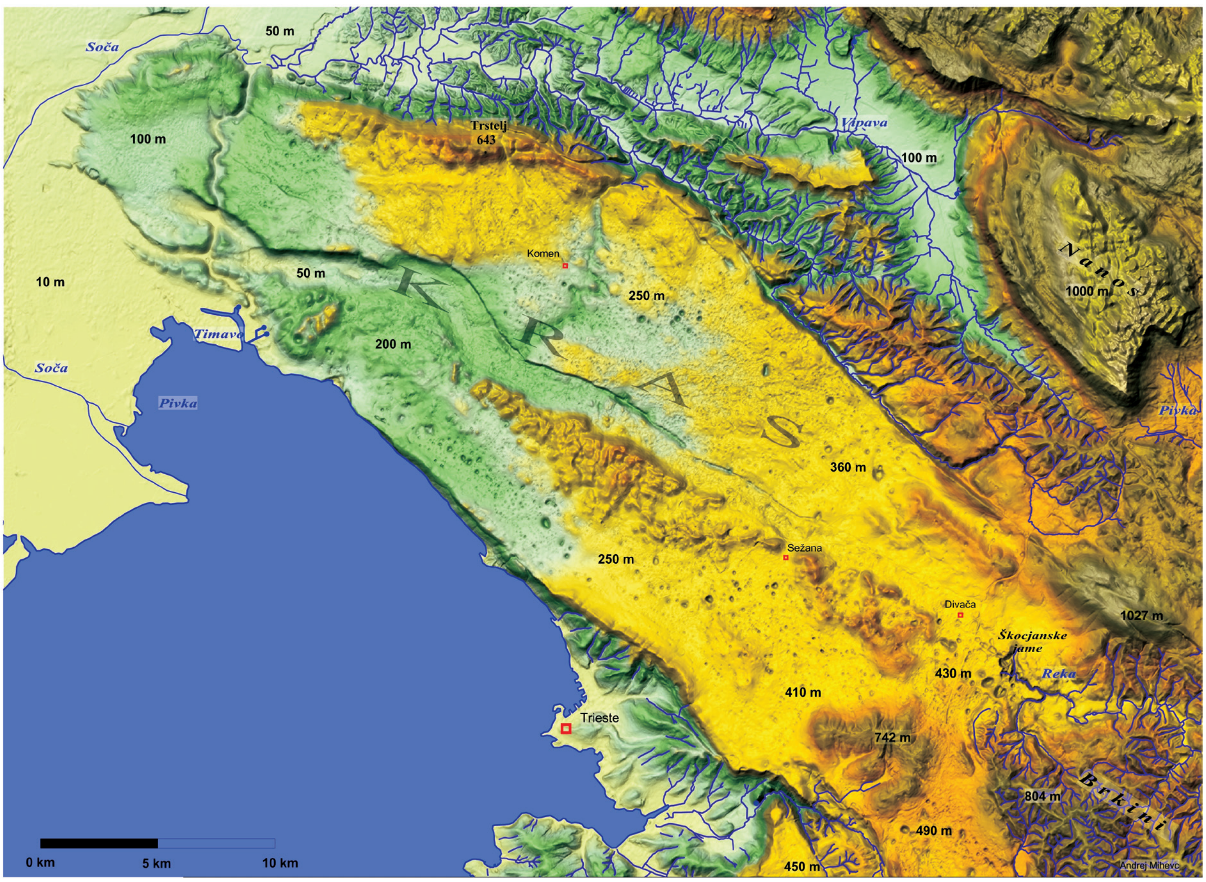


Fig. 40: Digital elevation model of Kras plateau (DEM source: DMV 12.5 m, Geodetska uprava Republike Slovenije; figure made by: A. Mihevc).

in this part of the Kras (Mihevc 2001). The proportional area of dolines is low, despite the great vertical gradient in karst. In comparison with doline surfaces, the speleological elements (collapse dolines, unroofed caves and cave entrances) are an important part of the relief. Even more important is the proportion of speleological elements in karstic relief if we compare volumes of ordinary dolines and collapse dolines. Even though the areas of the dolines are only twice those of collapse dolines, the volumes of collapse dolines are five times larger than those of collapse dolines.

Ljubljanica River System

The karst area along underground Ljubljanica river is important from a historical point of view because karst hydrology studies begun here in the 16th century and numerous karst features were first described here and are the reference features for the similar features elsewhere. Important features of the Ljubljanica karst are: poljes (Cerkniško polje, Planinsko polje); high karst plateaus (Hrušica plateau), dolines, collapse dolines, cave systems (Postojnska jama – Planinska jama cave system, Križna jama, Rakov Škocjan) and karst hydrology (sinking rivers, ponors, springs, floods; Fig. 41).

Ljubljanica River collects the water from southwest part of the Dinaric karst in Slovenia and belongs as right Sava affluent to Danube part of Black Sea water basin. The real watershed is placed somewhere in the underground, and the waters from karst plateau are flowing to all sides. The Ljubljanica water basin is about 1,100-1,200 km^2. The mean annual precipitation in the basin is 1,300-3,000 mm, during 100 to 150 rainy days. The one-day maximal amount to 100 mm, in extreme cases even 300 mm.

Most of the river basin is formed on Mesozoic rocks, mostly limestone. On these rocks the precipitation infiltrates directly into the karst and there are no surface rivers. Triassic dolomite is important, allowing some surface flow, forming bottoms of some karst poljes or forming hydrologic barriers.

The highest parts of the basin are high karst plateaus Hrušica, Javorniki and Snežnik and Racna gora. On the poljes among them, surface rivers appear only, but they have different names: Trbuhovica, Obrh, Stržen, Rak, Pivka, Unica and finally after the springs at Vrhnika the name Ljubljanica. The highest lying is the karst polje near Prezid (770 m), followed by Babno polje (750 m), Loško polje (580 m), Cerkniško polje (550 m), Rakov Škocjan and Unško polje (520 m), Planinsko polje (450m), Logaško polje (470 m) and finally Ljubljansko Barje (300 m), where the Ljubljanica springs are at 300 m a.s.l. There are several large springs are dispersed along the edge of the Ljubljana Moor, which is connected with the gradual tectonic subsidence of the area. Mean annual discharge of the Ljubljanica River at the springs is 38.6 m^3.

There are about 1,540 caves, accessible fragments of underground drainage system known in the catchment area of the Ljubljanica. Almost fifty kilometres of cave passages are known to exist along significant underground watercourses. 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 71 km of passages of the main rivers, tributaries of Ljubljanica. Larger caves found in this area include the Karlovice, Zelške jame, Tkalca jama, and Planina caves. In Planina Cave these waters are joined by the Pivka River from Postojna Cave. From the Planinsko polje, the underground Ljubljanica River flows through Logarček, the Najdena jama cave, and the Vetrovna jama cave. These caves provide a habitat for the *Proteus anguinus* salamander (the "human fish") and other subterranean water animals.

Logaško polje (Logatec polje)

The Logaško polje developed on the contact of dolomite and limestone between 470-480 m a.s.l. A number of small streams flow onto in it, the largest being the Logaščica, which collects run-off from an area of 19 km^2. The mean flow is 0.3 m^3/s. Short lasting floods occur at the swallow-holes Jačka on the Logaško polje when the flow exceeds 30 m^3/s.

The bottom of the polje is covered by a thin sediment cover of sinking streams that flow from Triassic dolomites and marls and Palaeozoic rocks. Sediments deposited on levelled surface reveal the catchment area of the depositing streams. At the present the washing of sediments into the ponors is main process from which subsidence connected with piping of sediments appears, and there is also some erosion of the river banks.

Planinsko polje (Planina polje)

Planina polje is an overflow polje, of rectangular shape, 6 km long, 2 km wide, with two narrow pocket valleys on SW part, 50 m deep, with a 16 km^2 flat surface at height of 450 m. Its wider surrounding area is built by Upper Triassic dolomite, Jurassic and Cretaceous limestone. The development of the closed karst depression is result of accelerated corrosion, controlled by geological structures.

It presents the most important water confluence in the river basin of Ljubljanica. A tectonically crushed and almost impermeable

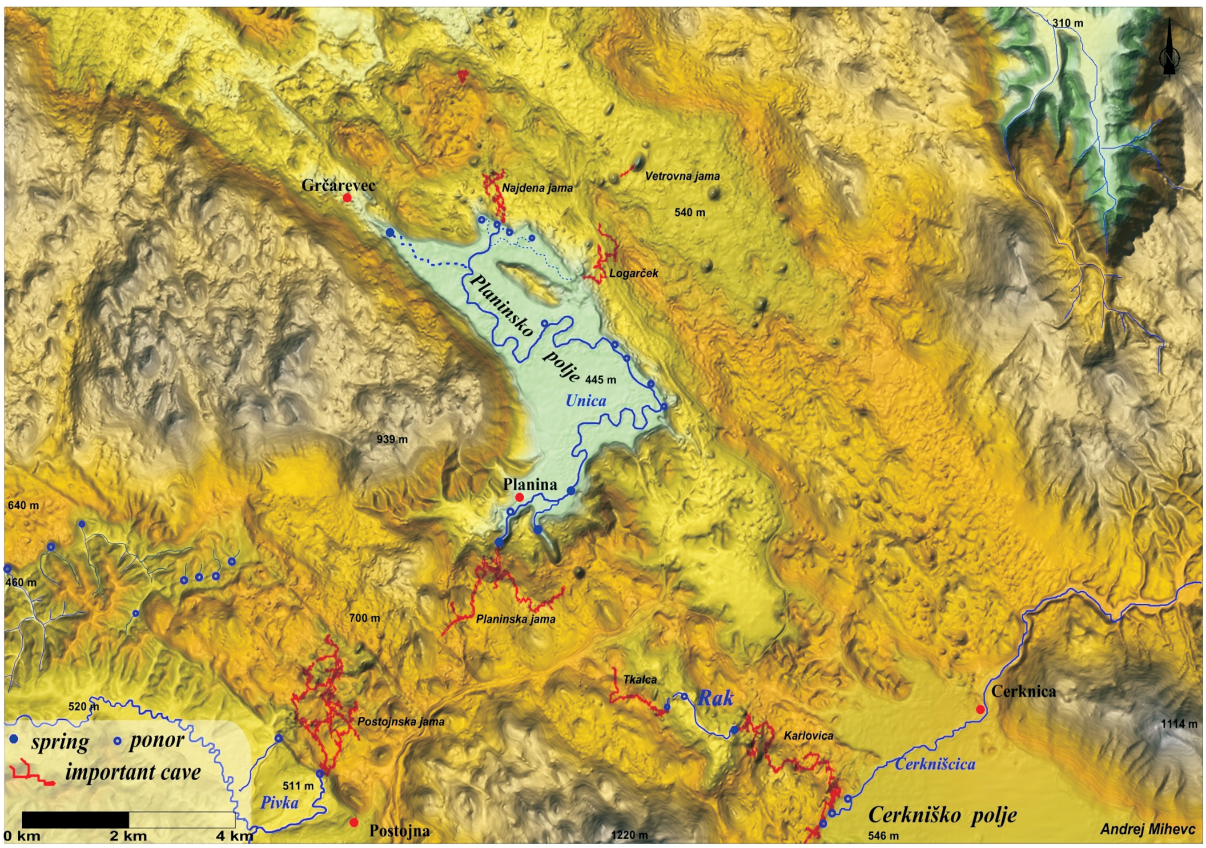


Fig. 41: Digital elevation model of Planinsko polje (Planina polje) with the most important springs, ponors and cave passages (DEM source: DMV 12.5 m, Geodetska uprava Republike Slovenije; figure made by: A. Mihevc).

dolomite barrier along the Idrija wrench fault zone, which crosses the polje, forces the karst waters to overflow from higher karstified limestone background to the surface, and after crossing Planinsko polje toward the northeast they can sink into the underground again. The principal Unica springs, with mean annual discharge 24 m^3/s (min. 0.3 m^3/s, max. 100 m^3/s), are situated in the southern polje's part in Cretaceous limestone, where the confluence of waters from Cerknica, Javorniki Mt. and Pivka is located. Main spring is 6,656 m long cave Planinska jama.

The principal Unica swallow-holes are disposed at the northern edge, where mostly medium and high waters are sinking. At low waters the whole Unica is disappearing in swallow-holes at eastern polje's border. Up to 160 m long ponor caves are known, but there are several horizontal caves in vicinity of the polje, where water oscillations can be observed. Larger caves behind the ponors are over 5,110 m long Najdena jama cave and Logarček.

Rakov Škocjan

Rakov Škocjan is a karst depression about 1,5 km long and 200 m wide. It is situated below the N side of Javorniki Mountain at elevation about 500 m between Planinsko and Cerkniško polje. Through the depression flows the permanent river Rak. 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 huge collapse doline Velika Šujca, where from the other side the Karlovica cave system ends. In Karlovica system is the main outflow from Cerkniško polje. Numerous collapse dolines are situated around the entrance of Zelške jame. In one of them the small natural bridge is present. Downstream, the valley widens and several springs bring additional water to the Rak River. The valley narrows at the Great Natural Bridge and afterwards the Rak sinks into Tkalca jama cave, from where the water flows towards the cave Planinska jama at Planinsko polje. The connections of the Rak with water from Cerkniško polje and with the Unica springs at Planinsko polje were proved by water tracing. From 1949 Rakov Škocjan has been a Landscape Park.

Cerkniško polje (Cerknica polje)

Cerkniško polje (Cerknica polje; Fig. 42) is the biggest karst polje in Slovenia. Often it is called just Cerkniško jezero (Lake of Cerknica), because of its regular floods, or intermittent lake. The intermittent lake covers 26 km^2 when is full; it is 10.5 km long and almost 5 km wide. Its hydrological properties caused that already in the beginning of New Age scholars from all round Europe were attracted to it. The lake becomes still more known through the Valvasor's description in 1689. Bottom of Cerkniško polje covers 38 km^2 in elevation of about 550 m. Inflows are on E, S, and partly on W polje's side. The largest tributary to polje is Cerkniščica, drained about 45 km^2 large mostly dolomite catchment area. The important karst springs are Žerovnica, Šteberščica and Stržen. Stržen flows on the W side of polje towards the ponors in the middle of the polje, from where water flows directly to Ljubljanica springs, and towards NW side of polje, from where the water flows to Rakov Škocjan. From the foot of Javorniki mountain to the contact with dolomite in the polje bottom are 12 ponor caves. They are connected to Karlovica cave system, to which also the highest waters from polje flows. The system there is more the 7 km of passages. Passages are generally low, because they are filled by alluvia. Thickness of alluvia in Jamski zaliv, before the caves entrances, is about 8 –15 m.

Cerkniško polje is a karst polje developed in the important regional fault zone – Idrija fault. Idrija fault has the "Dinaric" direction (NW-SE); in the same fault zone are developed: Planinsko polje, Loško polje and Babno polje. Bottom of polje is formed on Upper Triasic dolomite, which is presented also on the N, E and SE side

Fig. 42: Cerkniško polje with meandering river Stržen and ponoring places Rešeto and Vodonos (photo: A. Mihevc).

of the polje; there are some Jurassic dolomites in the area. On W and NW the Cretaceous limestone are presented.

During the last centuries, a lot of plans for the hydro melioration of polje have been made, but not any of them were realized. In 1965 it was proposed to make Cerknica polje a permanent lake; 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 less moistened years were assessed.

The flattened bottom of Cerkniško polje is regularly flooded for several months in autumn winter and springtime; at floods it alters to spacious karst lake. 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. Principal ponor caves and swallow holes are disposed at the polje's northwest border.

Outflow from the polje was not oriented to one channel, rather to a mesh of channels, which about 200 m from the edge of polje combine into a couple of larger galleries. They are generally low, because the bottom is filled with alluvia. Alluvium at altitude of 550 m is distinctive in all ponor caves; its thickness is possibly the same as a thickness of alluvia in Jamski zaliv.

Karst of Dolenjska and Kolpa

The karst of Dolenjska (Lower Carniola) occupies an area between the Ljubljansko barje (Ljubljana moor), the eastern edge of the Bloška planota (Bloke plateau), the river Kupa/Kolpa, the mountains Gorjanci, the settlement Krško and the southern of the Dolenjsko podolje (Dolenjska lowland). It is also described as the covered lowland karst of Dolenjska (Gams, 1974; Kranjc, 1990), and occupies the northeastern part of the Dinaric karst region.

Tectonically the area corresponds to the eastern part of the Hrušica thrust sheet, which is the part of the northeastern External Dinarides (Placer, 1999). The rocks are Triassic dolomites, Jurassic carbonates (dolomites and limestones) and Cretaceous shallow marine carbonates (mainly limestones) overlain by Pliocene-Quaternary deposits and soils up to a few meters thick in places (Pleničar et al., 1977). Dolomites are widespread especially along the northern, northwestern and eastern edges of Dolenjska.

The highest part of the karst of Dolenjska (up to 1,289 m a.s.l.) is located in the west and is similar to the karst of Notranjska (i.e., high karst plateaus, uvalas and karst poljes). Toward the east, the elevation generally decreases to the flood plain of the river Krka and the levelled surface of Bela Krajina (both at ~170 m a.s.l.). Bela Krajina is the northern part of the plateau between rivers Kupa/Kolpa and Una separated by the canyon of the river Kolpa. Between the Krka flood plain and Bela Krajina are the mountains Gorjanci (1,178 m a.s.l.). While the western part of Dolenjska shows features and hydrogeological conditions characteristic of deep karst, the eastern part is more fluviokarstic due to low spatial differences in elevation and, in some areas, dolomites. Water is close to the surface, and the surface is covered with a thick layer of red karst soil due to the low elevation and consequently low erosion. The red soils above dolomites are thicker and more cohesive than those above limestones (Gams & Vrišer 1998). Wide linear and conical depressions and rounded hills predominate in the relief although some karst poljes are also developed in this area (e.g. Radensko polje, Globodol). The biggest morphological feature is the Dolenjsko podolje – a 48 km-long valley-like feature running in a northwest-southeast-

Fig. 43: Middle course of the river Kupa/Kolpa where it crosses levelled surface along Rajhenav tectonic block. Due to subsidence of this block, canyon bottom is relatively wide (photo: M. Prelovšek).

erly direction between Ljubljansko barje and the Krka flood plain near Novo mesto. Below the thick soil cover, subcutaneous stone teeth up to 8 m high are developed (Knez & Slabe 2006).

The central surface stream of Dolenjska is the river Krka, which cuts a shallow canyon into the karst surface. It is situated in the central part of the Dolenjska karst and therefore attracts underground waters from the major part of Dolenjska karst. Its catchment area (2,250 km^2) is 19 % larger than that of the river basin of Ljubljanica (1,884 km^2) but due to a lower amount of precipitation it has a practically identical average annual discharge (54 m^3/s; data from http://www.arso.gov.si/vode). The river Krka is characterized by travertine dams, which are the result of the higher hardness of the water in comparison with the karst of Notranjska (Gams 2003). Due to a higher amount of precipitation and a larger drainage basin that covers southern Dolenjska karst and extends also to Croatia, the river Kolpa has higher discharge (Q_{avg} = 72 m^3/s). The deep sump (more than -154 m) of the river Kolpa in Croatia (Knab 2008) is situated only 23 km from the Adriatic coast (Fig. 16 on page 24), but it belongs to the catchment of the Black Sea. Its upper watercourse is cut between high plateaus and high leveled surfaces, while the downstream flow is situated in a canyon (up to 40 m deep; Fig. 43) cut into the leveled surface between rivers Kupa/Kolpa and Una. A very small, but hydrologically very interesting, stream is the river Temenica (Q_{avg} = 4.3 m^3/s), which emerges as springs at the northern edge of the Dinaric karst near Trebnje and flows southeast toward the river Krka. Along its 42 km-long superficial streams, two separate underground courses of the river Temenica are located, with a combined length of more than 3.5 km.

Contact Karst of Matarsko podolje

The Matarsko podolje (Fig. 44) is 20 km long and 2 - 5 km wide levelled karst surface south of Brkini hills. The surface probably developed as a base-levelled plain; later it was dissected by the dolines. It gently rises from about 490 m on NW to 650 m on the SE side. The lowered surface continues towards southeast but from the highest point near the blind valley Račiška dana blind valley it lowers on the distance of 2 km for 200 m towards southeast to surface of Brgudsko podolje. This bend is most likely result of neotectonic shifting.

Along the contact series of 17 brooks sinks in the karst edge of Matarsko podolje. The allogenic discharge into the karst is responsible for the creation of several large blind valleys and caves and lot of allogenic sediments deposited on the surface and underground (Mihevc 1993, 1994). Most of the brooks developed blind valleys bottom widened by corrosion bottom. The bottoms of these valleys are situated between 490 to 510 m. As the valleys are incised in the border of the karst, uplifted towards SE, the blind valleys lying more to the south are deeper. The first, Brezovica blind valley is cut for 50 m only while the deepest is the last Račiška and Brdanska blind valleys. They are deepened into border limestone for 250 m and its bottom lies 120 m below the surface of the Matarsko podolje.

More than hundred vadose caves are known in the karst plain. Great oscillation of karst ground water was observed. Water tracing showed that the sinking streams flow to three groups of springs: (1) submarine springs along the coast in the Kvarner Bay on the

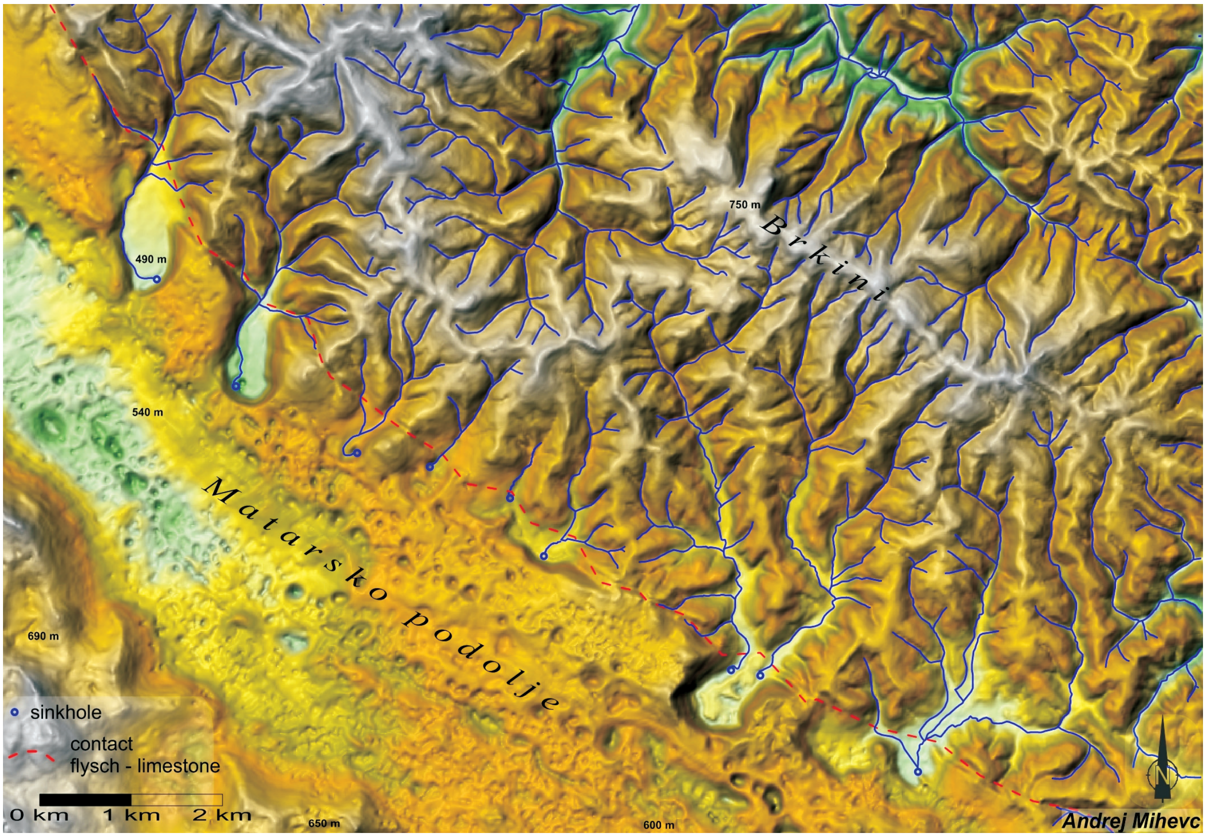


Fig. 44: Blind valleys of Matarsko podolje (DEM source: DMV 12.5 m, Geodetska uprava Republike Slovenije; figure made by: A. Mihevc).

south, (2) springs in Istria on the south-west, and (3) the Rižana springs at 70 m a.s.l. on the west (Krivic et al. 1987).

The contact karst of Matarsko podolje at the foot of Brkini hills was explained within the frame of cyclic and later climatic geomorphologic theory. The period of fluvial relief development should be followed by the karstification when the impermeable cover was removed. At the karstification beginning the superficial streams shortened and the last remains of this pre-karstic phase should be the blind valleys (Melik 1955). Various forms of the blind valleys were later contributed to the climatic changes (Gams 1962). Now we understand the contact karst features as a type of interaction of two systems of drainage, fluvial and karstic and that has also geomorphic expression. Allogenic sediments are very important for the formation.

The surface of the Matarsko podolje probably developed as a base-levelled plain; later it was dissected by the dolines and blind valleys. Stronger tectonic uplift in the southeast part upraised the lowered surface, and due to stronger uplift incomparable deep blind valleys developed there (Mihevc 1993). The deepening and the contemporaneous widening of the valleys followed the lowering of the karst water to the altitudes about 500 m. Because the bottoms of the blind valleys practically remain on the same altitude were probably controlled by the piezometric level. The blind valleys started to cut into the corrosion plain with small transverse and longitudinal gradient as in the contrary case the fluvial valleys should develop in them. They should be preserved on karst as dry valleys. Bad permeability or low gradient of the karst caused the deposition of the sediments on the edge of the karst in front of ponors and the deposits affected the planation and corrosion of the bottom of the blind valleys. The sedimentation was especially intensive in the cold periods of the Quaternary and these deposits are preserved on the bottom of most of the blind valleys. Due to lack of sediments the sequence of the events could not be temporally defined.

In actual conditions the karst water table stays deep under the altitude of the blind valley bottoms. The bottoms of the blind valleys are out of reach of the floods of the sinking streams in front of ponors and the gradient in the karst is so big that the old deposits from the surface are washed off into the karst by the suffosion processes.

Fossil blind valleys developed in upper southeast part of the lowered surface only and according to altitude, preservation of sediments or size they are no more comparable among themselves. The characteristic of this contact where are the most of the fossil blind valleys on higher position in comparison to impermeable flysch where the water basins of sinking streams developed and sink in the blind valleys.

Caves in blind valleys have been often refilled with allogenic sediments, originating from the impermeable surroundings. On the sediments of last infill stalagmites are growing, and some of them have been dated.

Caves

In 2010, almost ten thousand caves were registered in the Cadastre of Caves maintained by the Scientific Research Center of the Slovenian Academy of Sciences and Arts and the Speleological Association of Slovenia. The longest cave system in the Dinaric karst is Postojnska jama system with 20.570 km, followed by Jama pod predjamskim gradom with 13,092 km, and Kačna jama with 13,250 km. Slovenia's oldest tourist cave is Vilenica, where the first tourist visit was recorded in the early 17th century (Gams 2003). The best known and most visited cave in Slovenia is Postojnska jama, where tourism flourished after the discovery of the interior parts of the cave in 1818. The Škocjanske jame system with its underground canyon is also very attractive and popular with tourists; since 1986, the Škocjanske jame have been on the UNESCO List of World Natural Heritage Sites (Kranjc 1997). Their geomorphological, geological, hydrological, zoological, and botanical features make these caves a very important part of Slovenia's natural heritage (Institute of the Republic of Slovenia for Nature Conservation 2000).

Water arrives on the karst as precipitation or in rivers from the non-karst surroundings. Due to gravity, the water seeps through fissures, widening them in the process and forming vertical shafts. It trickles downward until it reaches the level of the karst water table. The karst aquifer inclines toward springs. The water flows along the lowest cave passages that in some places are completely filled with water and run as much as a hundred meters or more below the top of the water table. In these passages the water can even flow upwards. The cross sections of these caves are often round or oval. One example is the cave Gabranca near Neverke where low water periods allow a 214-meter descent into the cave, but heavy rains cause the water to erupt from the cave and from the spring of the Sušica river with a discharge of several cubic meters per second. Vertical shafts formed by rainwater are usually fissures widened by corrosion and are normally several dozen meters deep. Shafts that can reach great depths in steps often occur on high plateaus. A typical example is the 218 m deep Strmadna shaft on the Nanos plateau.

High karst water tables that remained stable over a long period enabled the formation of large horizontal caves. This is how large ponors and spring caves such as the Postojnska jama and Planinska jama and the caves in Rakov Škocjan park formed in the karst river basin of the Ljubljanica river and caves such as the Škocjanske jame and Kačna jama along the underground flow of the Reka river.

The greater part of Dinaric karst territory in Slovenia is drained by the Reka river in the Kras region and by the Ljubljanica river in the Notranjska region. These rivers formed large cave systems that are partly accessible. The Reka sinks into the Škocjanske jame and can be followed as far as the siphon. After a short break, we can follow its course again in the cave Kačna jama, then in the Jama v Kanjeducah, and finally in Jama v Stršinkini dolini. Altogether almost twenty kilometres of cave passages are accessible along the underground course of the Reka river.

Due to denudation, cave passages get ever closer to the surface. Finally they are left without ceilings and roofless caves become part of the morphology of the karst surface. As the surface continues lowering, the remains of cave passages and sediments disappear completely.

The evolution of the caves in Slovenia (from the start up to their total destruction by denudation) 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 the Oligocene to early Miocene. The interpretation of palaeomagnetic data (Zupan Hajna et al. 2008a), with some support from palaeontological finds, indicates that karst developed in pulses tightly linked with tectonic evolution and changes of the geodynamic regime. Individual pulses were not sharply limited, however, and therefore cannot be tied to precisely defined karst phases. Moreover, the complicated geological structure and tectonic/geomorphic evolution makes the picture less clear due to the differing tectonic evolution of individual morpho-structural units, which often have also quite different histories of evolution of the relief and karst.

Postojnska jama

Postojnska jama is developed in Postojnski kras where the surface is at 600 to 650 m a.s.l. The evolution of the Pivka basin (Eocene flysch rocks) is defined by the altitudes of the ponors of Pivka River that drain into this cave. The gentle fluvial surface of the basin itself stands out in sharp contrast to the karst lands above the cave and to other higher karst plateaus, where there are no traces of fluvial valleys or other elements of the early fluvial relief today. These surfaces are dissected with numerous dolines. Sixteen large collapse dolines developed above some parts of Postojnska jama, blocking certain passages. The thickness of bedrock overburden above the cave is 60 to 120 m.

The cave was formed by the Pivka river. Its modern ponor is at 511 m a.s.l. and the terminal sump in Pivka jama is at 477 m a.s.l. There are still more than 2,200 m of unexplored galleries before the river re-appears in Planinska jama at 460 m a.s.l.

The historical entrance at 529 m a.s.l. is located above the modern ponor. Other entrances and parts of the system, i.e. Otoška jama, Magdalena jama, Črna jama and Pivka jama, are scattered on the surface above the cave. All these caves are interconnected and form a cave system 20.5 km in length, the longest in Slovenia.

The entrance to Postojnska jama is situated near the contact between the Eocene flysch and the Upper Cretaceous limestones (Buser et al. 1967). The entire cave system is developed in an 800 m thick sequence of the

Upper Cenomanian and Turonian to Senonian limestones. The cave passages are formed in the Postojna anticline, which is oriented NW–SE (Gospodarič 1976), most of channels being in its steeper south-western flank. The cave system is in the tectonic block confined by two distinctive dextral strike-slip fault zones in the Dinaric trend, the Idrija and Predjama faults (Buser et al. 1967; Placer 1996). Habič (1982) explained different features, such as collapses and sumps in the cave, as the results of neo-tectonic movements. A geological survey of the cave passages was made by Gospodarič (1964, 1976) and Šebela (1994, 1998a, b) added structural mapping in detail. The cave and the Pivka underground river have a general N–S trend.

The known passages were formed at two main levels. The upper level is between 529 m a.s.l., at the main entrance to the cave and 520 m a.s.l. in the Črna jama. This level is composed of large passages, generally up to 10 m high and wide. Their profiles are more rounded and show also traces of paragenesis (levelled ceilings, side notches on the walls and scallops on the walls and ceiling). There are also remnants of cave fills indicating repeated fillings of the cave and successive erosion of the sediments. Speleothems were deposited in different phases above clastic sediments. The natural floor of the cave was modified for the construction of a railway during opening for tourists.

The second level is about 18 m below the upper one, where the modern underground Pivka river flows from its entrance. The river bed has a low gradient and, except for some collapses and sumps, there are no natural barriers. It leaves the system through a terminal sump. The active river passages are mostly

Fig. 45: Postojnska jama - the longest and the most touristic cave of Dinaric karst (photo: N. Zupan Hajna).

smaller than the higher ones. The river bed is composed mostly of gravels derived from the Eocene flysch. The mean annual discharge of the river is 5.2 m^3/s. The water level can rise 10 m during floods.

Cave fill was originally expected not to be older than Middle Quaternary (i.e. about 0.4 Ma). Pleistocene large mammal fauna such as hippopotamus, cave lion and cave bear, were found here (Rakovec 1954) as well as Paleolithic stone tools from the last glacial (Brodar 1969). Later numerical dating (Th/U and ESR) indicated ages older than 0.53 ka. New palaeomagnetic data from selected sedimentary profiles within the cave system detected normal polarization in prevalent amount of study profiles. Reverse polarized magnetozones, interpreted mostly as short-lived excursions of magnetic field, were detected only in places. Therefore we (Zupan Hajna et al. 2008a, b) interpreted most of studied sediments as younger than 0.78 Ma, belonging to different depositional phases within the Brunhes chron. Palaeomagnetic properties on two profiles in the caves intersected by artificial tunnel between Postojnska jama and Črna jama with reverse polarized magnetozones, and sediments in Zguba jama, can indicate age deeply below 0.78 Ma.

The cave system shows long evolution governed by the function of the Planinsko polje in the relation to the evolution of resurgence area in Ljubljana Moor farther on the east. The general stabilization of the hydrological system with low hydraulic head led to evolution of caves in epiphreatic and paragenetic conditions for a long time-span. Individual cave segments or passages were fully filled and exhumed several times during the cave evolution. The alternation of depositional and erosion phases may be connected with changing conditions within the cave system, functions of the resurgence area, collapses, climatic changes, tectonic movements and the intrinsic mechanisms of the contact karst.

Škocjanske jame

Škocjanske jame are 5.8 km long cave. The Reka River enters the cave at an altitude of 317 m; in the Martelova dvorana room, it is 214 m above sea level (i.e. 103 m lower). The Reka can also sink before it enters the cave. Floods usually reach up to 30 m, higher floods are common too, and the largest known flood in the 19th century raised the water table level for 132 m. Caves are developed in a contact area of Cretaceous thick-bedded rudistic limestone and Palaeocene thin-bedded dark limestone.

The cave is composed of phreatic tunnels, and gravitational or paragenetic reshaped galleries. The proto-channels developed in phreatic conditions along tectonised bedding-planes. The water flow demanded a high degree of phreatic rising and falling between individual bedding-planes which, in the area of the chambers Svetinova dvorana and Müllerjeva dvorana, is approximately 175 m. Large quantities of water could flow through all these tunnels, but meanwhile, rubble was transported through water table caves above them. Such a cave is the unroofed cave in Lipove doline at an altitude of around 450 m.

A long period followed when the piezometric water table was 340-300 m above sea level and the gradient was in a southwest direction. In it Reka formed new or adopted old passages by paragenesis and bypassing. These large galleries were Mahorčičeva and Mariničeva jama, Tominčeva jama, Schmidlova dvorana in Tiha jama. The largest chambers are Martelova dvorana, with a volume of 2,100,000 m^3, and Šumeča jama (870,000 m^3). Some of big chambers collapsed forming the big collapse dolines like Velika and Mala dolina.

In the further development of Škocjanske jame, potent entrenchment prevailed. Cutting occurred in inner parts of the cave, in Hankejev channel for about 80 m, much less, about 10 m, in the eastern, entrance part of the cave.

The first paths in the cave area were made in 1823, but the construction of paths for exploration and for the visitors started in 1884. Cave exploration and construction of the pathways were done by cavers of DÖAV from Trieste. The most important explorer was Anton Hanke. In 1891 they reached the final sump in the cave.

Because of their extraordinary significance for the world's natural heritage, in 1986 the Škocjanske jame were included in UNESCO's World Heritage List. The Republic of Slovenia pledged to ensure the protection of the Škocjanske jame area and therefore adopted the Škocjanske jame Regional Park Act. The Škocjan Caves were entered also on the Ramsar List of Wetlands of International Importance in 1999. Together with the underground Reka River, they represent one of the longest karst underground wetlands in Europe.

Križna jama

Križna jama is large river cave 8,273 m long. It is situated in the area between Loško, Bloško and Cerkniško poljes. The relief above the cave is characterized by conical hills and closed depressions, dolines, uvalas and small, polje-like levelled surfaces. The entrance of the cave is located in an elongated karst depression to the east of Križna gora (856 m a.s.l.).

The cave is developed in the light grey micritic Liass/Dogger limestones, with lenses of dolomite (Gospodarič 1974; Buser, Grad & Pleničar 1967). The cave was formed in rather stable conditions between the Cerkniško and Loško polje, as indicated by the mostly epiphreatic conditions of passage evolution. A small river with autogenic catchment area flows in the cave and continues through at least 124 m deep terminal sump towards the west into the cave, Križna jama II, and to springs at Cerkniško polje. The active water passages are located at about 610 m a.s.l. The older passages are slightly higher, between 620 and 640 m a.s.l. Remains of fluvial sediments are preserved throughout the entire cave, indicating that it was filled by more sediments in the past (Gospodarič 1974). The remains of Ursus spelaeus in clay inter-beds among flowstone sheets are important in the Medvedji rov. They were studied by Hochstetter (1881), Rabeder & Withalm (2001), Pohar et al. (2002) and the others. The most detailed study of fluvial sediments was done by Gospodarič (1974), who concluded that the cave was much more filled by sediment in the past and less open than it is at the present time.

Unroofed Caves and Surface Denudation

On several places on Kras allogenic sediments, quartz sands and pebbles can be found on the surface. Their appearance was explained as remains fluvial deposits of surface rivers. These sediments were the basis for the presumption of pre-karstification period and several karst forms were described as remains from that period (Radinja 1969; Melik 1962). New interpretation of these localities together with geomorphologic and sedimentary studies reveal (Mihevc 1996; Mihevc & Zupan Hajna 1996; Mihevc 2001) that these are the cave sediments exposed to the surface because the denudation removed the rock above the caves.

The appearance of old unroofed caves and their fills resulted from denudation, erosion and chemical dissolution of limestone above the cavities. Fills exposed on the present surface include speleothems and cave fluvial deposits. The ancient directions of flow, different catchment areas of sinking rivers and different organisation of the ancient underground drainage were reconstructed from several unroofed caves opened during highway construction in the Divaški kras (Mihevc 1996; Mihevc & Zupan Hajna 1996). The thickness of rock overburden removed above cavities was established to have been 50–100 m. The age of cave fills was calculated from denudation rates and the expected thickness of missing overburden to 0.7–5 Ma (Mihevc 1996, 2001). This large time range resulted from the expected minimum (20 m/Ma) and maximum denudation rates (50 m/Ma) calculated or measured in the area (Gams 1962; Cucchi et al. 1994). Unroofed caves were also described by Šebela & Mihevc (1995), Šebela (1995, 1999), Mihevc, Slabe & Šebela (1998), Šušteršič (1998), Knez & Slabe (1999a, b).

The study (Zupan Hajna et al. 2008a) of cave deposits in unroofed caves of the Kras provided entirely new insights into the age of cave and karst sediments and introduced new ideas concerning the development of karst. Geomorphic comparative method used for dating of processes and landforms showed that many accessible caves in the Kras are of Pliocene age at least or even older (Mihevc 1996, 2000, 2001).

The shape of unroofed caves depends on (1) the morphology of the present surface; (2) size, type and original arrangement of caves, and (3) the cave fill. Unroofed caves are usually altered by surface processes. They represent an important element of the epikarst zone. On the surface, they are expressed as narrow and often meandering shallow trenches, shallow oblong depressions, doline-like forms in rows and collapsed dolines. Mihevc (1999a) offered models of their origin and their relation to the presently accessible caves.

Lipove doline

Unroofed caves are an important part of the surface morphology of Divaški kras where 2,900 m of the unroofed caves were mapped (Mihevc 2001). In such features, flowstone, allochtonous sediments and morphology are testifying their cave origin. The proportion of denuded caves is small in area (only approximately 0.16 % of the total area). The largest such denuded or unroofed cave of the Divaški kras is located on the surface northeast of Škocjanske jame, named after great number of dolines Lipove doline. The mapping of the surface showed a 1800-m long series of dolines and elongated dolina-like depressions 450 m above sea level and interconnected without higher thresholds. The bottoms of the dolines are 5 m to 10 m below the level of the rest of the surface; the depressions are 20 m to 30 m wide. Chert pebbles, yellowish red sandy loam and massive flowstone were found at the bottom of the dolines. The denuded cave passage forks in a number of places. In the western part of this roofless cave, in one of the Lipove dolines, quartz sand was exploited, during which a large amount of flowstone and a large stalagmite were exposed. The stalagmite and the sediments were first described by Pleničar (1954), who interpreted the cave as small cave with a collapsed roof located near the surface. The unroofed cave in Lipove doline is similar to Škocjanske jame in its dimensions, as the width of the tunnel was in some places likely to be more than 20 m. Anticipation from the massive stalagmite, the ceiling of the cave was at least 10 m thick and at least 500 m above sea level during the time when flowstone was deposited.

The unroofed cave Ulica and Ulica pečina cave

The unroofed cave Ulica and Ulica pečina cave (Fig. 46) are situated in the southeast part of the Matarsko podolje (SW Slovenia), near the Croatian border. They are presumably remains of the same cave system as Račiška pečina (Mihevc 2004). The passages of Račiška pečina are in elevation between 598-589 m. The 1,200 m distant Ulica pečina cave has its paragenetic ceiling in elevation 585-589 m, while sediments at the bottom of the passage are between 585-562 m. In similar height, 580-585 m, is also the floor of the unroofed cave Ulica.

Ulica pečina is 125 m long, 10-15 m wide cave with two entrances. Cave is developed in Lower Cretaceous thick-bedded limestone. The cave represents relict of old cave system, which was opened by denudation to the recent surface. The bottom of the cave is composed of clastic sediments, clays, rocks and gravel. There is evidence of fast sliding of sediment into the lowest part of the passage as a result of periglacial processes in the cave. The thickness of roof above the cave is about 10 m.

On the south side, the cave opens on the slope of the hill, while on the north side cave was continues in unroofed cave Ulica. The unroofed cave Ulica is a 250-m long series of elongated depressions. The unroofed cave is about 10 m deep and 20-30 m wide. The walls of the unroofed cave are mostly steep, the floor of it are composed of sediments, on one spot with massive flowstone. Continuation of the unroofed cave is not clear, possibly is towards norhwest, where are some large boulders, the remnants of collapsed cave ceiling.

Even if the caves are not of the same system, they were most likely developed at the same time, and were probably connected with the sinking rivers from the flysch. Dating of Račiška pečina sediments shows their ages up to 3.4 Ma. After the presumed lowering of the surface with denudation rate of about 50 m/Ma with this age there was about 100 m of the rock above the caves removed since de deposition of the dated sediments.

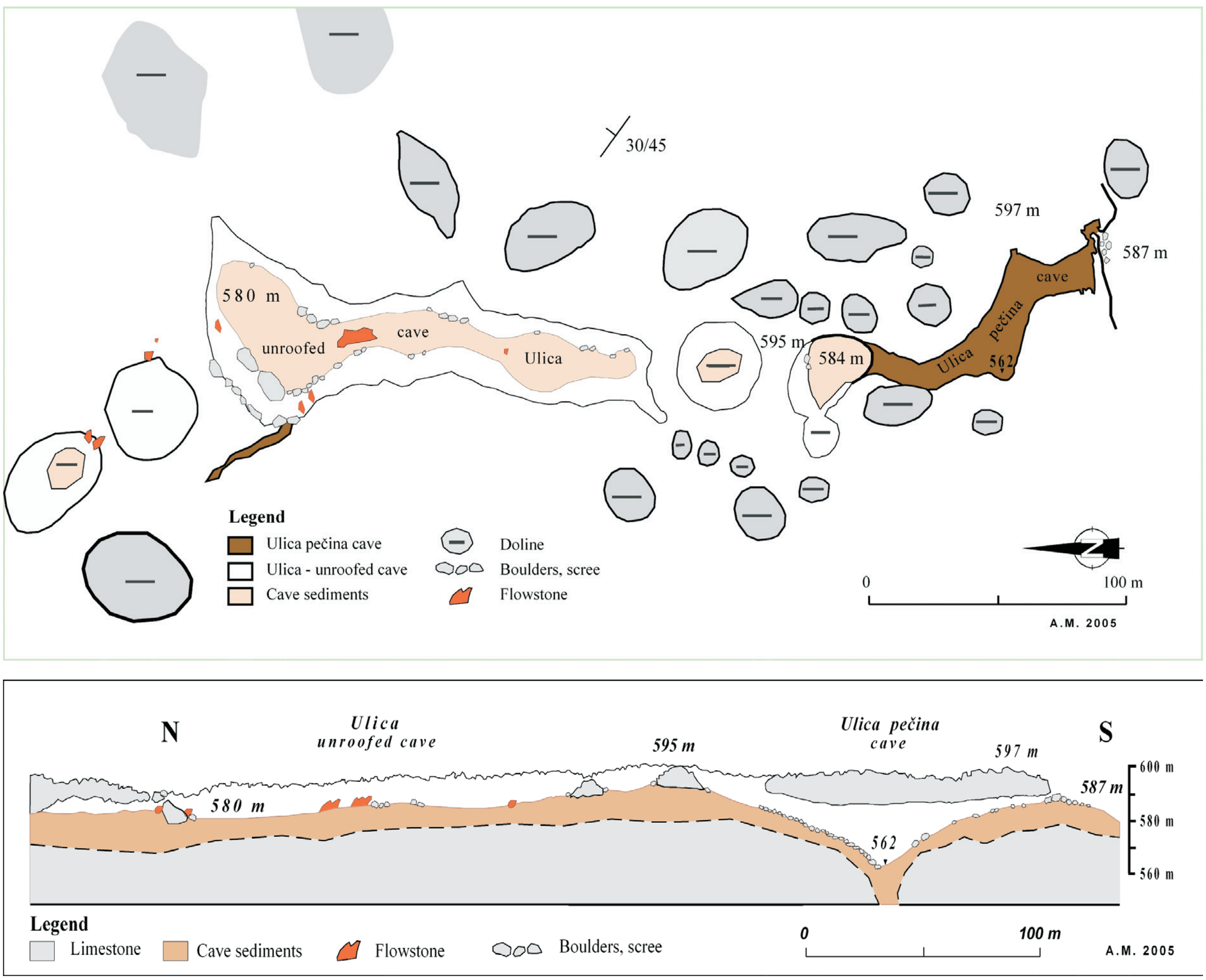


Fig. 46: Plan and cross-section of cave Ulica pečina and unfoofed cave (figure made by: A. Mihevc).

Use of Karst and its Protection

The Nature Conservation Act in Slovenia provided a basis for the overall conservation of biodiversity and protection of valuable natural features (included karst surface and underground) as part of Slovenia's natural heritage. Nature conservation legislation and the Cave Conservation Act (from 2000) regulate the protection and conservation of caves. This Act governs the protection and use of underground caves, protection arrangements, protective measures and other rules of conduct, including the restoration of polluted or damaged caves.

The conservation of caves is often difficult to implement because important segments of life on karst take place above them. Because large caves along underground rivers are important economically as tourist caves, as a source of water supplies, and for science, it is necessary to protect them or exploit them without devaluating them in the process. Unnecessary activities that often take place above the caves could easily be avoided through more reasonable planning. For instance the entire Kačna jama cave lies below the town of Divača. While it is impossible to move settlements, the sewage treatment plant and its discharge could easily be installed farther away from the cave. It is also not necessary to build an industrial zone directly above the cave passage that connects the Kačna jama cave and Škocjan Caves, a world-class phenomenon. The industrial zone could be built one kilometer further north and not threaten the underground world. This is not just about the conservation of the two caves but about the tourist exploitation of the caves as well; the situation will be much worse if the surface above the caves is built up. Along the underground Reka River is another problem with the Sežana sewage treatment plant in Kanjeduce, which is located above the underground passages of the cave and its discharges are far from achieving the required standards. The entrances to Postojna Cave, Planina Cave, and the caves in Rakov Škocjan Park face similar problems. Thoughtless encroachments are destroying important assets and society will benefit from them much less in the future.

There is a problem with tourist visits to caves. For example two hundred years of tourism have left a number of negative traces in Postojna Cave. Some have damaged the natural condition of the cave, while others threaten the tourist exploitation of the cave and have reduced the value of the cave. While these changes are negative, they could be minimized if we are aware of them. Stalactites have been removed, the floor of the cave has been changed excessively, and large amounts of dust have accumulated in the entrance parts of the cave. Other activities in the vicinity of the cave may present an even greater threat to the cave than tourist exploitation: the poor condition of the sinking Pivka River due to the inefficient treatment plant, the construction of industrial buildings in the immediate vicinity, for example, on the site of former military barracks near Veliki Otok, abandoned military facilities above the cave, and a car dump site beside the old road toward Planina. Such activities should be moved farther from the cave since they present a serious threat and are certainly not examples of good practice.

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