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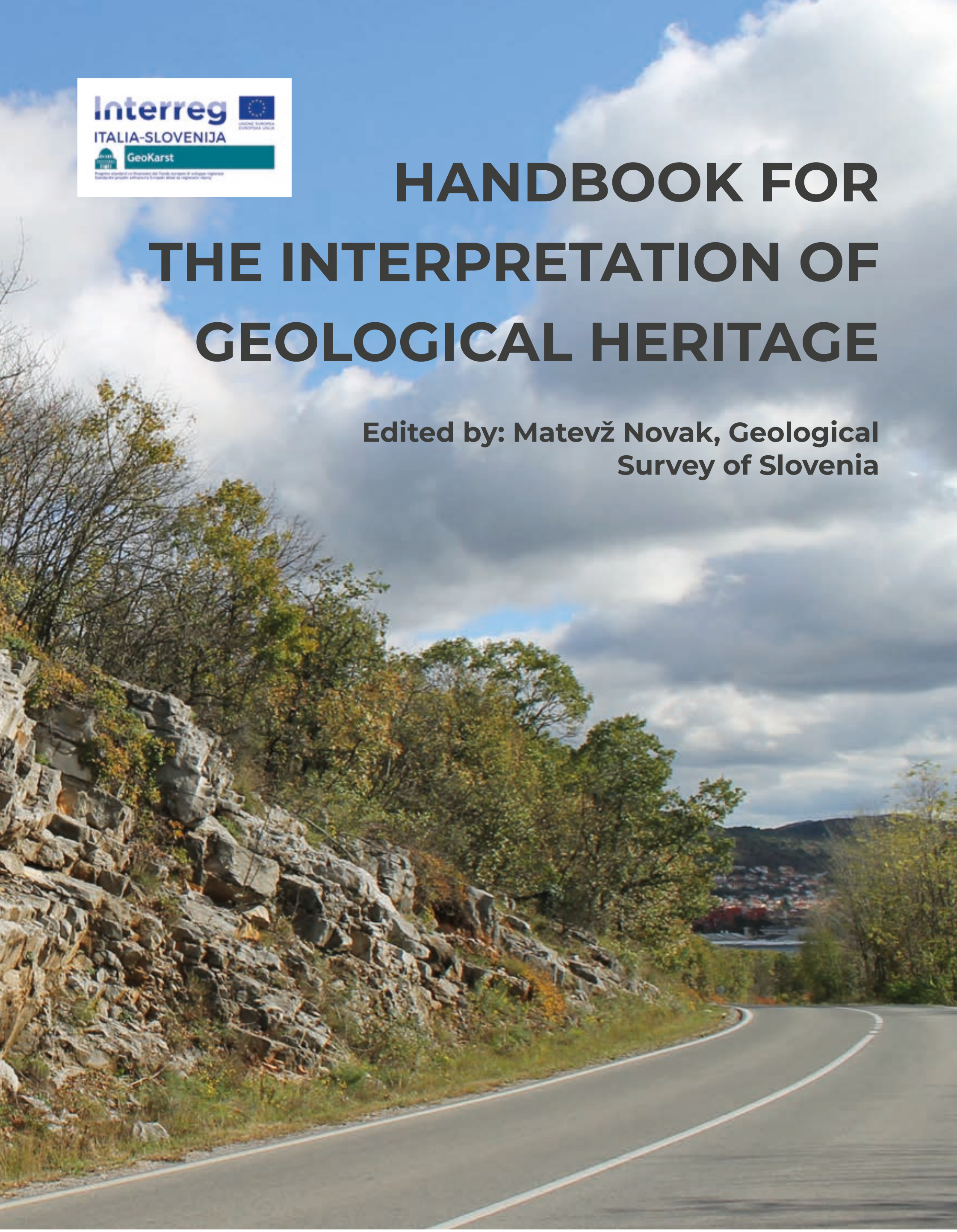
ITALIA-SLOVENIJA
GeoKarst



HANDBOOK FOR THE INTERPRETATION OF GEOLOGICAL HERITAGE

Edited by: Matevž Novak, Geological Survey of Slovenia

KRAS CARSO GEOPARK

GeoZS
Geološki zavod Slovenije

Authors
Matevž Novak and Bogdan Jurkovšek[1]
Geological Survey of Slovenia

Coordinator
Matjaž Harmel, director of ZaVita d.o.o.

Graphics and digital layout
Matevž Novak, Petra Gostinčar (Geological Survey of Slovenia), Anna Tamiazzo, Lorenzo Oretti (eco&eco Economia ed Ecologia srl)

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Translation
Matevž Novak (GeoZS), Lorenzo Oretti (eco&eco Economia ed Ecologia srl), Department of Mathematics and Geosciences - University of Trieste

English proof-reading
Paul Tout

Cover photo by: Bogdan Jurkovšek

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To users of the handbook

The handbook is intended for all those who are faced with the difficult task of presenting geology to lay visitors of the Classical Karst. It is primarily intended for tourist guides, curators of museum collections and teachers in schools in the geopark area, but it can also be useful for managers of tourist attractions and quarries, as well as for any local who lives near one of the geological attractions of the Karst.

In order to be able to present the challenging geological material even without in-depth knowledge of geology, we tried to write the contents in this manual in a short and user-friendly way. This is so that one can use it as a sample to present the key and most interesting information about geology on a few hours guided tour of the geopark. For this reason, the content of the manual is limited to the presentation of geology and data closely related to it. All other content, such as geomorphology (karst forms), hydrology, archeology, and history, as well as the explanation of the concept of geoparks, are richly described in other publications about the Karst, unlike the geological content.

Some explanations of key concepts and interesting facts related to the geology of the Karst are added in the boxes. To obtain basic geological knowledge and a more comprehensive explanation of the content, we recommend using the additional resources listed at the end of the manual.

1. THE RELATIONSHIP BETWEEN THE KARST AND GEOLOGY

(an exemplar of introductory address to visitors)

The Classical Karst owes its identity to the mostly white to pale grey rock called limestone that represents its backbone. That limestone was formed in ancient seas over a period of nearly 100 million years. Since calcium carbonate that makes up limestone in the form of the minerals calcite and aragonite is soluble in fresh water, when these rocks are exposed above sea level, this water acts as a fine chisel to carve the limestone into characteristic features. The variety and beauty of these features are so remarkably well represented in the Classical Karst area that they are referred to as karstic and the geomorphological phenomenon itself took the name "karst" from this area.

Although limestones across the Karst Plateau may appear almost uniform to the inattentive visitor, an observant eye can notice differences in the thickness of the layers, colour variations and peculiar fossils. Each layer of these rocks represents one page of a thick book of the long geological history of the Karst. The inner structure of rock, minerals and fossils are the letters of this geological chronicle. They provide fascinating information about the depth, temperature, and salinity of the ancient seas in which these limestones formed. They convey fascinating information of what environment and life in the geological past looked like and how they changed over time.

2. GEOLOGICAL HISTORY OF THE GEOPARK

The episodes of the chronicle of the Classical Karst are set a long time before the history of humankind, in the geological periods of Cretaceous and Paleogene, during the Mesozoic and the Cenozoic eras. In the rocks of the Karst a timespan of almost 100 million years from the beginning of the Cretaceous, about 140 million years ago (mya), to the middle of Eocene about 45 mya is recorded (Figure 1).

2.1 The world at the time of the formation of the Karst rocks

In explaining that the limestones of the Karst were formed in the sea, many visitors imagine this very statically, i.e., that the area of the Karst, just as it is today, was once submerged by the sea. They should be reminded that the Earth's surface changes very slowly, but constantly, throughout geological history, and that the area where the rocks of today's Karst were formed was far from similar to today's.

In the Cretaceous, not only the environment in which the rocks building the Karst Plateau were formed, but the entire world, looked a lot different from that we know today. Only at the beginning of the Late Cretaceous, did the Southern Atlantic Ocean open up between Africa and South America, and India finally separated from Africa and started on its journey that would eventually bring it into collision with Asia. North America was still attached to Europe, and Australia to Antarctica. Towards the end of the Cretaceous, the previously large, dismembered land masses of the old Gondwana supercontinent moved towards Eurasia, causing the formation of a large Alpine-Himalayan mountain belt (Figure 2).

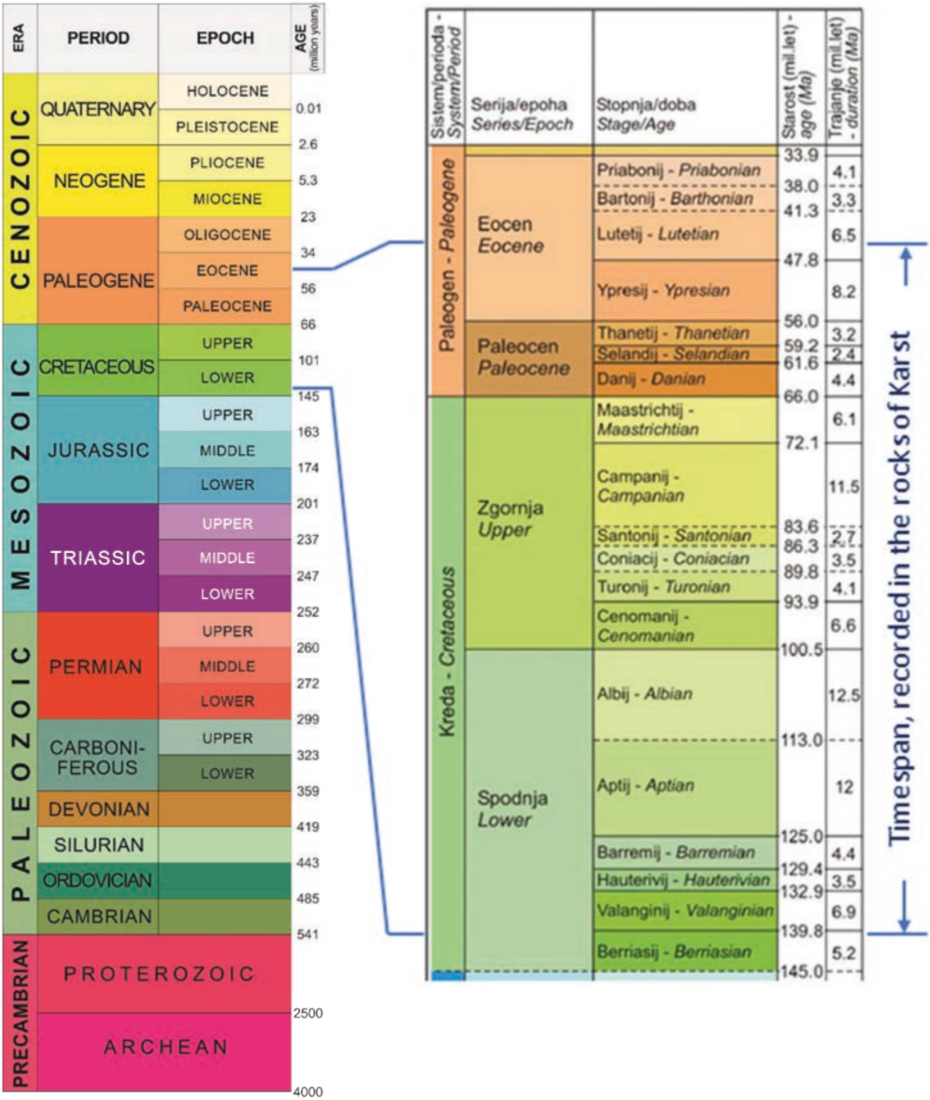
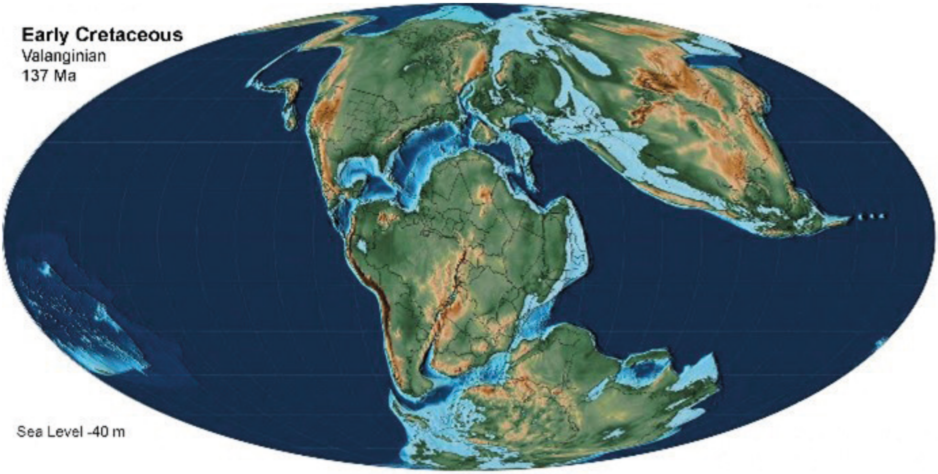
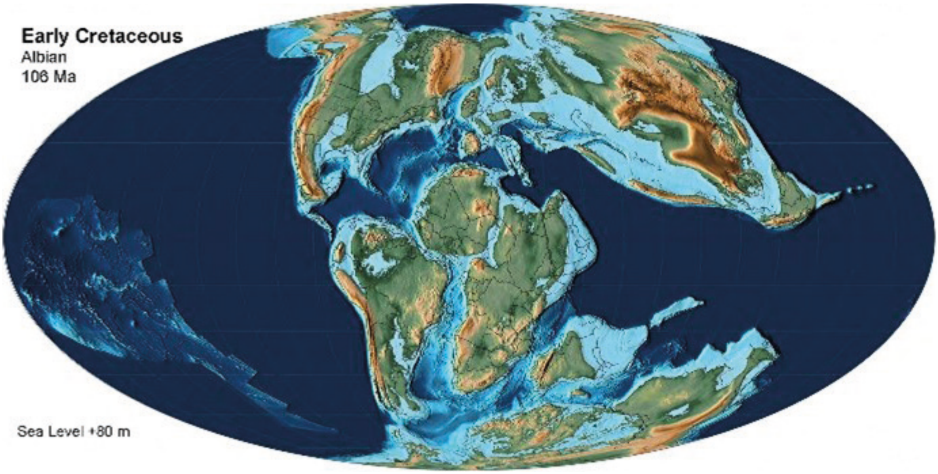
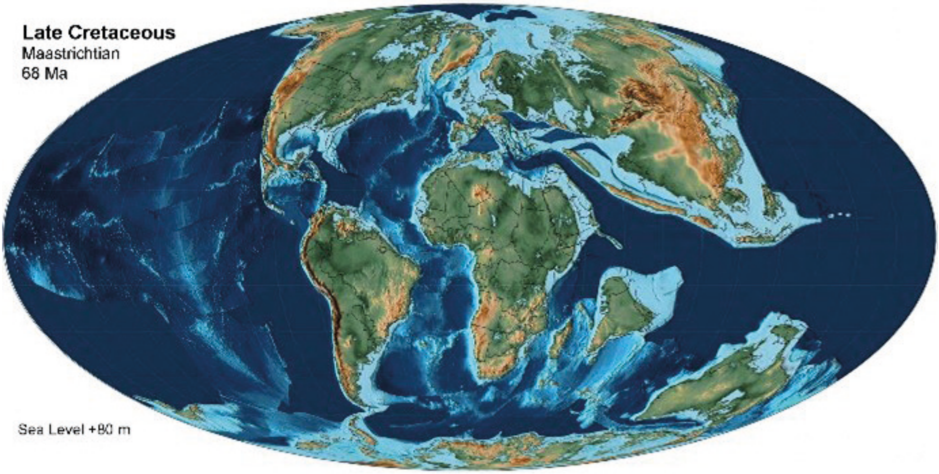


Figure 1: A timespan of geological history, which is recorded in the rocks of Karst (Adapted from Jurkovšek et al., 2013 and Rman & Novak, 2016)


Early Cretaceous
Valanginian
137 Ma
Sea Level -40 m


Early Cretaceous
Albian
106 Ma
Sea Level +80 m



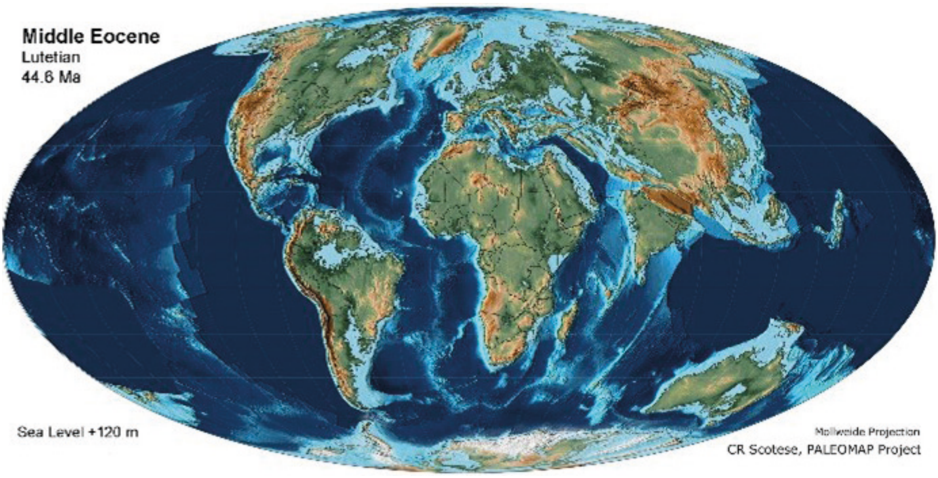


Figure 2: The changing world from Early Cretaceous to Middle Eocene, in times of formation of rocks that build the geopark (after: Scotese, 2014; PALEOMAP Project)

INTERESTING FACT

Global warming. How warm is Earth's climate today?

Today we hear a lot of discussion about climate change, the greenhouse effect, sea level rise, CO_2 emissions and the potential effects of these phenomena on humankind, on society and on the Earth's ecosystems. In this perspective, the story told by the rocks of the Classical Karst is particularly interesting.

Ask visitors what they think: are we living today in a very cold period, a very warm period, or somewhere in between, depending on conditions in geological history. In our experience, under the influence of the aforementioned discussion, most visitors answer that we live in a very warm climate.

The truth is quite the opposite. In all of geological history, there have only been a few very short periods as cold as now, and the rest of the time it was warmer (Figure 3).

The Late Cretaceous epoch was indeed one of the warmest times in Earth's history. Back then, the mean annual temperature in the northern hemisphere during summer months was above 20°C (according to some models even 27°C), more than 5°C higher than the average of the last 30 years (which is just below 15°C), the CO_2 content in the atmosphere was 3-6 times higher. With such high temperatures, no polar ice-caps existed and sea level was much higher than today. By the end of Cretaceous, the temperature had fallen to about 16.2°C, and to 13.9°C by the middle Eocene. The temperature variations were paralleled by strong oscillations in sea level that rose by more than 120 m and dropped by more than 40 m with respect to its present-day level. The conditions described resembled the worst-case scenarios that could occur by the end of this century, according to projections by the Intergovernmental Panel on Climate Change (IPCC, 2018).

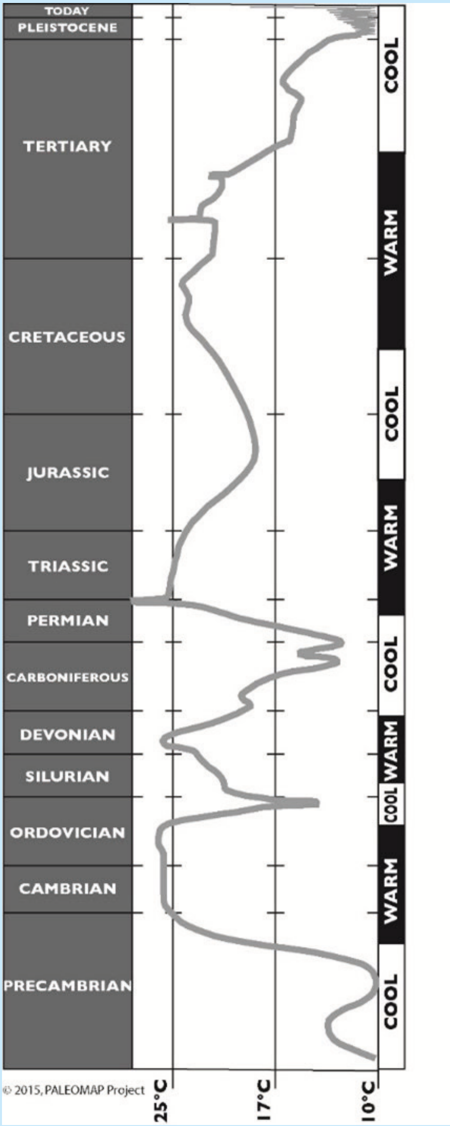


Figure 3: During the last 2 billion years the Earth's climate has alternated between a frigid "Ice House", like today's world, and a steaming "Hot House", like the world of the dinosaurs. This chart shows how global climate has changed through time (Scotese, 2015; PALEOMAP Project; http://www.scotese .com/climate.htm)

2.2 The environment in which the Karst rocks were formed

The Classical Karst area is made up of sedimentary rocks of the former **Adriatic-Dinaric Carbonate Platform**. This shallow-sea area in the Tethys Ocean, on which carbonate sediment was deposited, was formed on the so-called **Adria Microplate** (Figure 4). The small Adriatic tectonic plate was initially part of the African Plate, but in the Mesozoic, it separated from it and traveled northward in front of it. During the Cretaceous, the Adria Microplate was located approximately 2,000 km to the south, within a (sub)tropical climate belt. At these latitudes, conditions were ideal for the formation of limestone.

Figure 4: Paleogeography of Europe in the Late Cretaceous (75 million years ago). The Adriatic-Dinaric Carbonate Platform developed on the Adria Microplate (after: Scotese, 2014)

EXPLANATION

What is a carbonate platform?

A carbonate platform develops when the accumulation of limestone in the sea is such that a relief is built up on the seafloor. The uppermost portion of this so-called build-up is often close to sea level and flat (and therefore termed a "platform") so that an area with relatively shallow waters exists, similar to a lagoon. At the outer edges of a platform, slopes of variable steepness link its top to the surrounding deeper ocean floor in a manner that resembles the aprons of debris at the base of a mountain. In some cases, these platforms can be very large. Modern examples include, for instance, the Bahamas in the Gulf of Mexico (Figure 5) or the Great Barrier Reef in Australia.

Figure 5: Satellite image of the Bahamas, with shallow sea (light blue) on a carbonate platform and surrounding deep ocean (dark blue) (NASA's Earth Observatory, 2009)

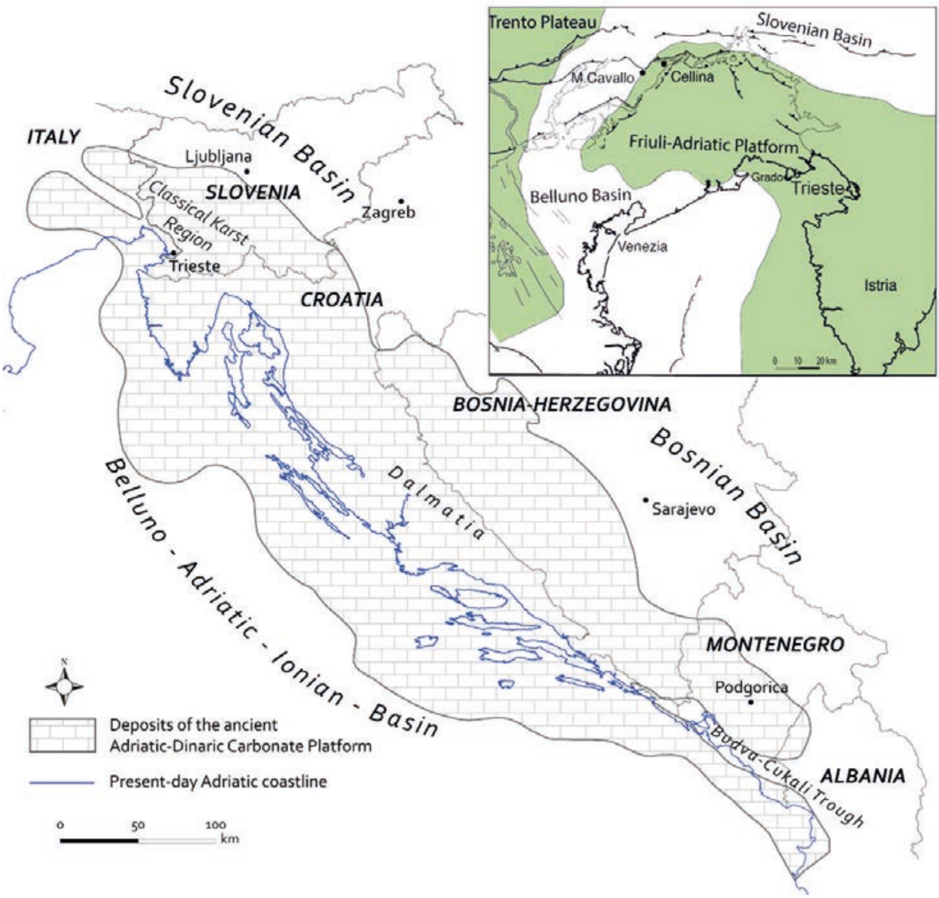


Figure 6: Present-day geographic map overlain by one showing the extent of the Adriatic-Dinaric Carbonate Platform rocks (modified from Dragičević & Velić, 2002) and a detail of the northern part with the Friuli-Adriatic Platform (modified from: Consorti et al., 2021)

The Adriatic-Dinaric Carbonate Platform was indeed large, as evidenced by its rocks outcropping from northeastern Italy, along the entire length of the Dinarides, as far down as Montenegro (Figure 6).

The thick carbonate rock succession of the Classical Karst region was formed in the inner part of the Adriatic-Dinaric Carbonate Platform, an area that resembled the lagoon of the Bahamas today. The Italian portion of this area is also called the Friuli Platform and corresponds to the northwestern limb of the Adriatic-Dinaric Carbonate Platform that, during the Cretaceous, was surrounded by a deep sea (Figure 6). The environment that characterized the platform did not change much for several millions years during the Cretaceous. A more pronounced differentiation started in the younger part of the Late Cretaceous when the platform started becoming involved in the tectonic movements connected to the Alpine orogenesis. In the early Eocene, the collision between the Adria Microplate and the Eurasian Plate brought about the rise of the Alpine chain and the platform's foundering in the oceans. This event is testified to by the sandstones of the flysch that derive from the erosion of uplifting mountains, and which were deposited when the area where the platform once stood was occupied by a deep sea at the beginning of the Cenozoic period (66 mya).

3. CHARACTERISTIC FOSSILS OF THE GEOPARK

In this chapter, only those groups of fossils that are very common in the Karst and those that are interesting on a global scale are described. Other fossils are listed in descriptions of geological units.

3.1 Clams (bivalves)

Rudist clams or rudists are a peculiar group of bivalve mollusks of very unusual shapes. They first appeared at the end of the Jurassic, but flourished in the Late Cretaceous and, together with many other plants and animals, became extinct at the end of the Cretaceous period.

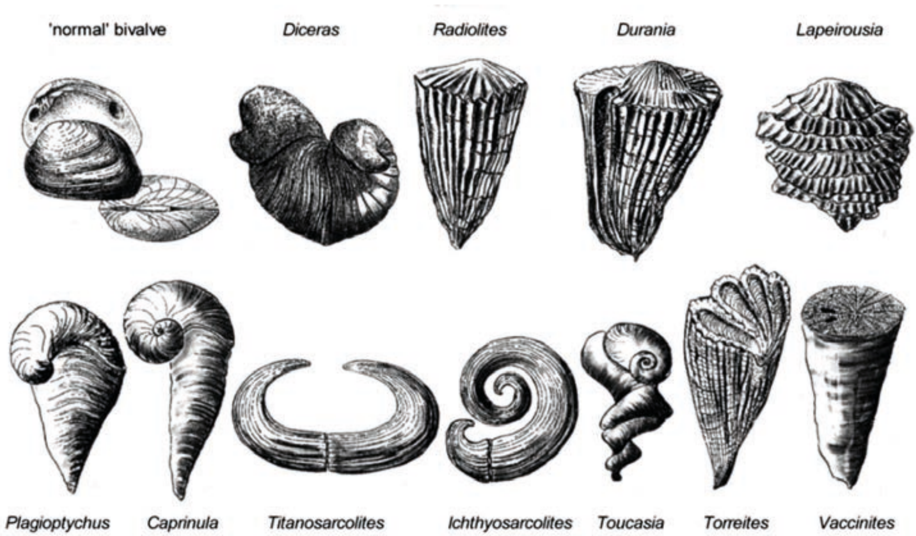
During the Late Cretaceous period rudist clams, perfectly adapted to living attached to a variety of substrates, evolved into an amazing number of species with different shapes (Figure 7), which help geologists to determine the relative age of the rocks in question. Most typical ones resemble a cow horn. The two valves are completely different with the big conical valve usually the one sitting on the seafloor, and the small cap-shaped upper valve serving as the cover. Rudists ranged in size from just a few centimetres to over a metre. During the Late Cretaceous rudists thrived in the shallow waters of tropical seas and formed extensive rudist thickets and reefs. Their shells represent an important constituent part of the Cretaceous carbonate rocks and are one of the geological signatures of the Classical Karst. In some instances, they grew in such high numbers that rocks appear nearly entirely made up of their shells (Figure 9).

Chondrodont clams are another extinct group of bivalves common in Upper Cretaceous limestones. These oyster-like clams also lived only during the Cretaceous period. They lived partially buried in the soft seafloor, similar to pen shells today (Figure 10). They can reach a size of 50 cm. The most characteristic species among them is *Chondrodonta joannae*, which looks like an elongated or fan-shaped leaf with wavy longitudinal ribs (Figure 11). In the stone, the cross-sections are visible as serrated lines of varying thickness (Figure 12).

When describing fossils, you can point out to visitors the geological analogy to the saying used by historians that the past is the key to understanding the present. In geology, the reverse is also true, i.e. that **the present is the key to understan-**

Figure 8: A typical shape of rudist shell (from: Carnets de nature. Fossiles d'Europe, Editions Milan, 1999)

Figure 7: Different shapes of rudist shells (after: Schumann & Steuber, 1997)



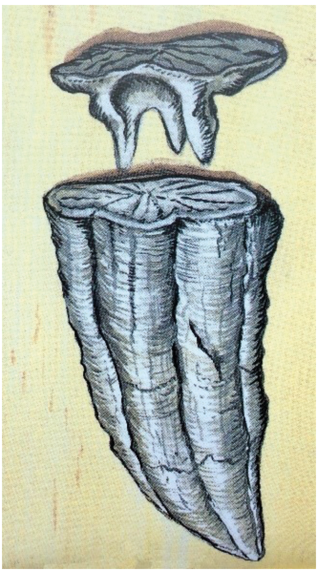


Figure 9: Polished slab of Lipica Limestone displaying a cross-section of rudist cluster (Photo: Bogdan Jurkovšek)

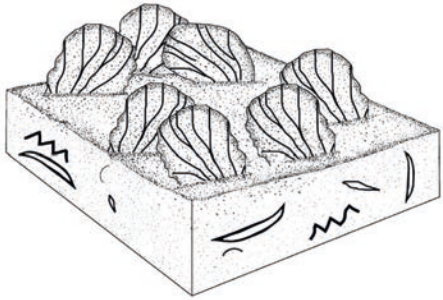
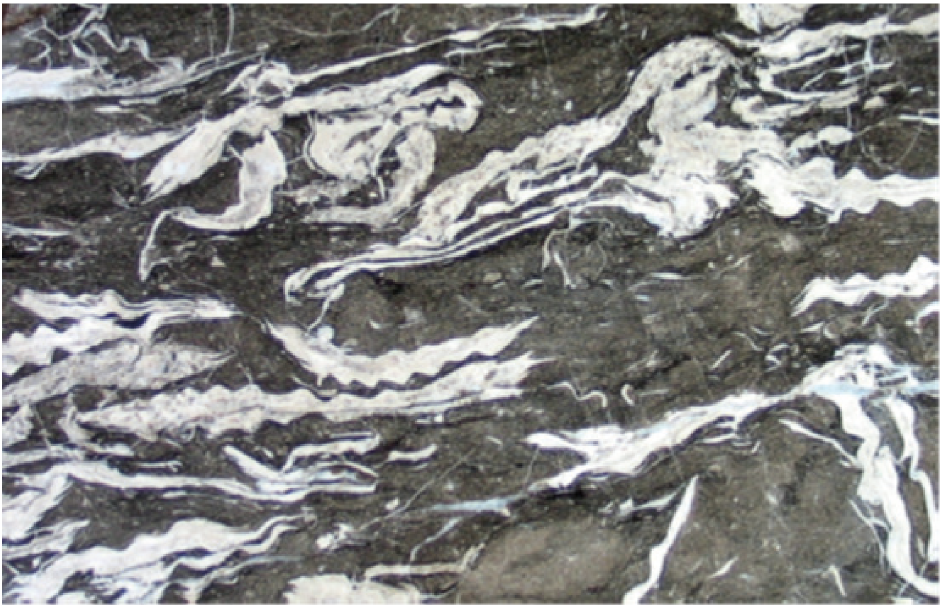


Figure 11: Upper Cretaceous limestone with chondrodont shell fossil from near of Coljava (Photo: Bogdan Jurkovšek)

Figure 10: Reconstruction of chondrodont clams on the seabed and their characteristic cross-sections (after: Ayoub-Hannaa & Fürsich, 2011)

Figure 12: Cross-sections of chondrodont shells in the dolomite from north of Sežana (Photo: Bogdan Jurkovšek)



ding the past. *And why? We wrote at the beginning that the Earth is a living planet where everything is continuously changing. However, something is constant, namely the physical and chemical laws. Since life forms depend on physico-chemical conditions, this means that related organisms in the geological past most likely lived in the same environments as today. Since snails and oysters live in shallow marine environments today, their occurrence in Cretaceous limestone strata indicates that they originated in the same environment.*

3.2 Foraminifera

Foraminifera are single-celled organisms with differently shaped shells (or tests). Most are microscopic and some live as plankton in the water column, others are larger and live as benthos on the sea floor.

Figure 13: Longitudinal and transverse section of a nummulitid tests (after: Zittel, 1876 and del Ramo, 2015)

Large benthic foraminifera – a group of large seafloor-dwelling foraminifera with calcite tests. Karst limestones contain many different species of large foraminifera.

Nummulitids are an extinct group of large foraminifera that lived on the seafloor during the Paleocene and Eocene. They had flat or lenticular, spirally coiled limestone tests, divided into small chambers. They were one of the largest single-celled organisms on Earth, a sort of single-celled dinosaurs. They can be larger than 3 cm and resemble ancient coins and therefore were given the name of Nummulitids (from the Latin word *nummus* meaning the coin). In limestone, their longitudinal surfaces look like bright buttons, and their cross-sections look like thin, elongated scales (Figure 13). We also often find individual specimens, naturally leached from the weathered surface of the limestone (Figure 14).

Alveolinids had a peculiar structure characterized by the presence of numerous cavities that, when observed

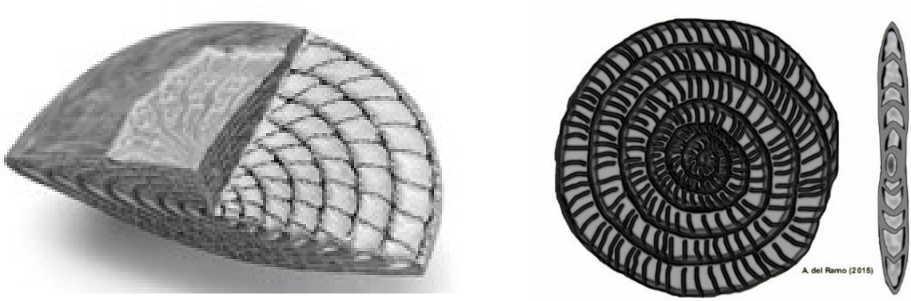


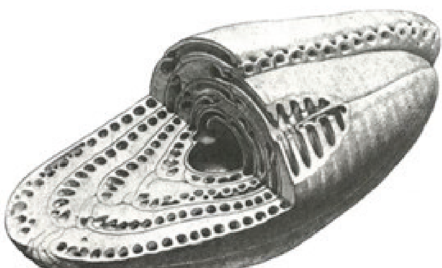
Figure 14: Nummulitids, resembling coins, naturally isolated from weathered rock (Photo: Matevž Novak)

with a hand-lens, look like small circular holes (Figures 15 and 16). The name derives from the Latin word *alveolus*, meaning a small cavity or hole. They often occur together with nummulitids, from which they are distinguished by the white colour of their porcelaneous test and the more convex, lenticular shape, some are almost spherical.

3.3 Vertebrates

Fish, crabs, turtles, crocodiles, dinosaurs – Under special conditions, otherwise rarely fossilized terrestrial vertebrates or those with more fragile skeletons have been preserved in rocks formed during sedimentation in quiet, low-oxygen environments. In the Fisherman's Village (Villaggio del Pescatore), in addition to the remains of crocodiles, crabs, bony fish and pterosaurs, two dinosaur skeletons have been found, which are among the most complete and best preserved in the world. However, in the black, platy limestones in the Komen and Tomaj area, so many exceptionally well-preserved fish fossils were found that the strata there were called fish shales. Besides the fish, a turtle skeleton was also found there.

Figure 15: Longitudinal and transverse section of a alveolinid test (after: Checchia-Rispoli, 1905)



3

Figure 16: Alveolinid foraminifer, as seen through the microscope (Photo: Matevž Novak)

CAUTION!

The Nature Conservation Act provides general protection for all fossils, minerals and their deposits, so that they are not damaged or destroyed. Stricter protection is provided for protected localities, natural values and for exceptional or rare types of minerals and fossils, such as fossil vertebrates in the Karst.

And the request for guides.

In our experience, formal protection through regulations and prohibitions tends to be ineffective if people do not know why it is necessary. The most effective way to prevent or at least limit fossil and mineral collecting is to educate people about their great value. Therefore, explain to visitors that fossils, like minerals and rocks, are important witnesses of the Earth's past. Their knowledge enables understanding of geological processes and insights into the secrets of the origin and development of life on Earth. Their removal or damage is roughly comparable to the deletion of letters and words in a single copy of a very old historical book. Everything we know today about the origin and evolution of life on our planet is based on fossil remains.

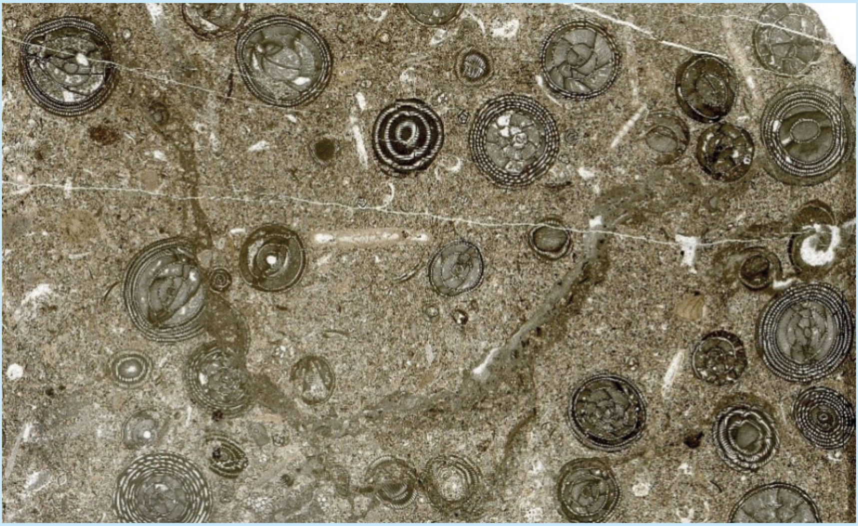
INTERESTING FACT

The microscopic world of Karst stone

A whole new world of astonishingly beautiful microfossils opens up to us when we observe the thinned-to-transparency tiles of karst limestone samples through the microscope.
Microfossils are the remains of various groups of organisms, usually smaller than 0.5 millimetres. Since definitions of the upper limit of size vary, it is best to say that microfossils are all those fossils that we need to look at under the microscope to see how they are built and to determine to which species they belong.
Some rare representatives of groups of very small fossil organisms, otherwise classified as microfossils, significantly exceeded the size of their relatives, reaching sizes of several millimetres or even centimetres. Such "microfossils", such as large benthic foraminifera, can be seen in stone with the naked eye. A hand magnifier with 5 or 10 times magnification or even a magnifying glass is very useful to observe them.

Microfossils are the most important group of fossils for the study of Earth history. Their advantages are that they often occur in large numbers, that they are found in almost all sediments and sedimentary rocks, that they are very diverse forms that have changed rapidly in evolution, and that many of them were planktonic during at least one period of development and are therefore widely distributed. For this reason, they are of great importance in determining relative ages, correlating sedimentary and rock sequences, reconstructing paleoenvironments, studying paleoclimate and plate tectonics, the petroleum industry, searching for and locating deposits of mineral resources, etc. The most useful microorganisms include the foraminifera, radiolarians, diatoms, cyanobacteria, spicules (needles) of sponges, bryozoans, ostracods, parts of vertebrates (conodonts, teeth, bones, fish scales), red and green algae, and plant spores and pollen. Below are some photos of characteristic microfossils in polished plates of rock samples from the Karst under the microscope (Figures 17–20).

Figure 17: Large benthic foraminifera (alveolinids and nummulitids) from Dutovlje (Photo: Matevž Novak)



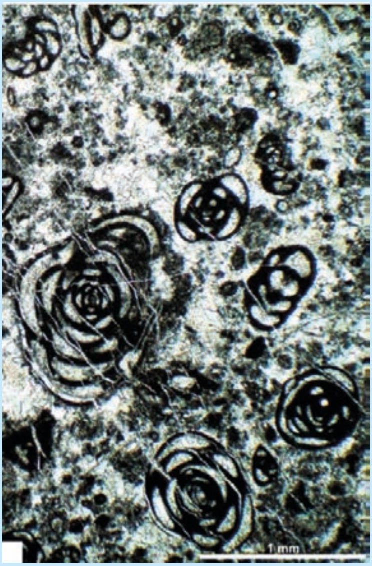
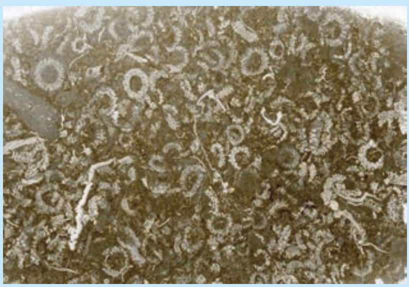


Figure 18: Small miliolid foraminifera from Kreplje (Photo: Bogdan Jurkovšek)

Figure 19: Green algae of genus Clypeina from Rakitovec (Photo: Matevž Novak)



4. THE ROCKS AND GEOLOGICAL UNITS OF THE GEOPARK

As a result of the long-lasting stability of the sedimentary environment, a thick pile of carbonate sediments deposited right across the Adriatic-Dinaric Carbonate Platform. From them, an almost 1,500 metres thick succession of carbonate sedimentary rocks formed, which make up the territory of Classical Karst.

The succession of rocks of the Classical Karst has been subdivided into several geological units. In this handbook, a simplified scheme was adopted in which the rocks of the Classical Karst are subdivided into five most distinctive units. The following descriptions they are presented in stratigraphic order, that is, from oldest to youngest. Their spatial distribution is shown in the geological map (Figure 46).

4.1 Lower to Upper Cretaceous limestones, dolomites and breccia

These are the oldest carbonate rocks of the Karst deposited between approximately 140 and 90 million years ago (mya), mainly in a calm, shallow lagoon environment. Most of these rocks are limestone, although dolomite also occur. Whereas limestone is mainly composed of the mineral calcite, dolomite is a rock that is made in great part of the mineral dolomite, closely related to calcite (both are carbonate minerals) but has a slightly different chemical composition and different structure. Therefore, dolomite rock is less soluble in water than limestone. Dark grey dolomite often occurs in the oldest rock unit of Karst.

In times when sea level dropped, large portions of the Adriatic-Dinaric Platform became emergent, exposing the limestone to dissolution with the formation of karst features in all ways similar to those that are formed today. Phenomena indicating ancient karstic weathering in the geological past, such as karst cavities filled with sediments and flowstones, are called **paleokarst**. A particularly prolonged episode occurred about 110 mya and is thought to represent a worldwide lowering of sea level (called “eustatic sea level fall” by geologists). In Karst, it is evidenced by a **layer of breccia**, a coarse-grained clastic sedimentary rock consisting of angular clasts or fragments into which older rocks have been broken by weathering and erosion. This breccia, that outcrops in a narrow band stretching across the Classical Karst, probably formed because the rocks of the platform, once exposed, were fragmented and eroded into cavities produced by the ongoing karstic dissolution (Figure 21).

After this time of emersion, the sea rose again, and this brought with it the re-establishment of marine conditions. Limestones formed in this period contain numerous fossils such as foraminifera and green algae. Rudist shells can also be found, sometimes concentrated in levels that deposited during storms, but are not as abundant.

4.2 Upper Cretaceous rudist limestones with fossiliferous platy limestone layers

Most of the Upper Cretaceous sequence of Karst consists of pale grey to white limestone, usually occurring in beds several decimetres thick, or the beds are not pronounced at all. One of the most striking features of this rock is the presence of rudist shells, which can be more or less numerous, preserved whole or broken into pieces of various sizes (Figure 22).

Figure 21: Breccia testifying to the important emersion episodes that the carbonate platform underwent (in Brestoviški dol) (Photo: Bogdan Jurkovšek)

EXPLANATION

What are sediments and what are sedimentary rocks?

Sedimentary rocks are formed by the solidification of **sediment** which is formed by accumulated sedimentary grains. Such accumulations occur when wind, water, or gravity can no longer move the grains. This is usually at the foot of glaciers, in river valleys, lakes, deserts, and especially in seas and oceans.

Immediately after deposition, the sediment (e.g., carbonate mud) is still soft and unbound, then it compacts in the compaction process and adheres to hard rock with a binder (usually calcite cement). This process is called **diagenesis**. It refers to all changes that take place in the sediment from its deposition to solidification (lithification) into **sedimentary rock**, as well as all subsequent changes in the already solid rock due to changes in temperature and/or pressure.

Sedimentary grains form in two ways. The first way is through weathering and erosion of older rocks. Rocks composed of such grains (or clasts) are called **clastic sedimentary rocks**. Another way sedimentary grains are formed is by precipitation directly from an aqueous solution. Such rocks are called **chemical sedimentary rocks**. Most grains are actually the skeletons of various organisms (e.g., mussel shells), which is why such rocks are called **biochemical sedimentary rocks**. Mineralized skeletons consist almost entirely of calcium carbonate (the mineral calcite or aragonite). When such a sediment lithifies, it forms a rock called limestone.

INTERESTING FACT

Sea level oscillations

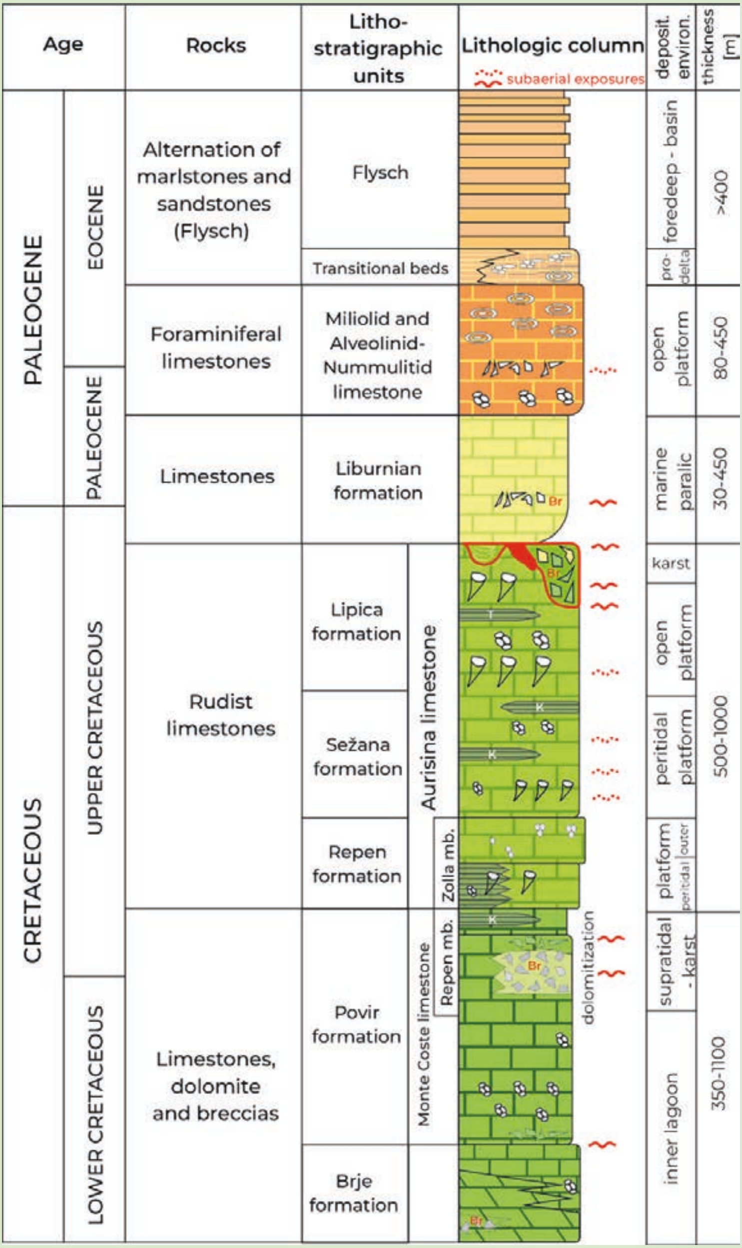
The shallow marine environment in which Karst rocks formed did not change dramatically during the Cretaceous. However, due to the shallow water depth, at least some parts of the platform were easily exposed when the sea level dropped. Geologists also refer to such periods when the seafloor became a dry land emersions. It is important here to keep in mind that sea level can change on different time scales and for a range of reasons. We all know about tides, sea level oscillations that occur every day and are caused by the gravitational attraction of the Moon. But there are also phenomena that can cause these variations globally over longer periods of time. For instance, these include the formation or the melting of ice sheets at the poles, or vertical movements, up or down, of the Earth's crust, such as those that cause the growth of a mountain chain. Carbonate platforms are particularly prone to be exposed or flooded because most of their surface sits at depths so shallow that even a modest oscillation of the sea level can cause the emersion or the submersion of vast areas.

EXPLANATION

Geological or lithostratigraphic column

Geological units that group together rocks that are genetically related, i.e., rocks that formed under similar conditions, are called formations by geologists - sometimes further subdivided into smaller parts called members. One way to represent such units in a given area is the **geological or lithostratigraphic column** (Figure 20). In a lithostratigraphic column (the word lithostratigraphy comes from the Greek words *lithos*, meaning rock, and *strata*, meaning layers), the formations are depicted from oldest at the bottom to youngest at the top, as they formed in geological history. This representation of the geological units of the Karst highlights the main phases of the evolution of the environment in this area in a period of over nearly 100 million years. For some of these units, Slovenian and Italian geologists use different names and some parts of the succession are also subdivided differently.

Figure 20: Geological column depicting geological units building the geopark, a more detailed subdivision into lithostratigraphic units (formations), and sedimentary environments (Br – breccia, K – Komen limestone, T – Tomaj limestone) (after: Jurkovšek et al., 2016 and Consorti et al., 2021)


Age
Rocks
Litho-stratigraphic units
Lithologic column
subaerial exposures
deposit. environ.
thickness [m]
PALEOGENE
CRETACEOUS
EOCENE
PALEOCENE
UPPER CRETACEOUS
LOWER CRETACEOUS
Alternation of marlstones and sandstones (Flysch)
Foraminiferal limestones
Limestones
Rudist limestones
Limestones, dolomite and breccias
Flysch
Transitional beds
Miliolid and Alveolinid-Nummulitid limestone
Liburnian formation
Lipica formation
Sežana formation
Repen formation
Povir formation
Brje formation
Aurisina limestone
Zolla mb.
Repen mb.
Monte Coste limestone
dolomitization
Br
K
foredeep - basin
pro-delta
open platform
marine paralic
karst
open platform
peritidal platform
platform
peritidal
outer
supratidal - karst
inner lagoon
>400
80-450
30-450
500-1000
350-1100

Abundant accumulations of chondrodont shells can be also found near Sežana and at the Monrupino sanctuary in the limestone of this unit.

Extensive deposits of rudist limestone in the Classical Karst area are found, for instance, near Lipica, Kazlje, Vrhovlje, Povir, Gorjansko, Aurisina and Borgo Grotta Gigante. Due to its structure and homogeneous texture, the limestone belonging to this unit represents the most commercially valuable rock found in the Classical Karst Region. It is extracted in many quarries as a valuable architectural stone. The *Cava Romana* Quarry at Aurisina/Nabrežina in Italy dates back to the 1st century B.C.E. The largest quarry of Lipica limestone (which belongs to the same unit as Aurisina Limestone in Italy) today is Lipica in Slovenia, where large blocks of massive rudist limestone are extracted (Figure 23; see also chapter Quarries and types of Karst natural stone). In addition to the Lipica Limestone, the Repen, Kopriva and Granitello limestones are also valuable.

Figure 22: Rudist limestone in the road-cut at Divača (Photo: Bogdan Jurkovšek)

Figure 23: Slabs of Lipica Limestone with a cross-section of a rudist cluster in the pavement of the Reception Center of the Škocjan Caves Park (Photo: Matevž Novak)

The peculiarity of this geological unit is the occurrence of some of the most interesting and fossil-rich rocks of the geopark, **platy and laminated limestones**. Dark grey to black, thin-bedded, laminated limestones contain layers or lenses of dark grey to black chert and can have a strong bituminous odor when broken (Figures 24 and 25). This is because they contain high concentration of organic matter, the conservation of which was favoured in the poorly oxygenated waters. This latter feature also allows for quick fossilization and enables excellent preservation of even the finest structures of organisms. Such limestones occur as thicker, individual packages within various thick-bedded light-coloured shallow-water limestones which belong to the different Upper Cretaceous formations between 95 and 80 million years old.

One of the platy limestones, named the **Komen Limestone** after the village of Komen (known also as "Komen shale" - and even "Fish shale" in the older literature by a famous Croatian paleontologist Dragutin Gorjanović-Kramberger in 1895) contains the remains of fishes, various reptiles, and plants in an exceptional state of preservation (Figure 26).

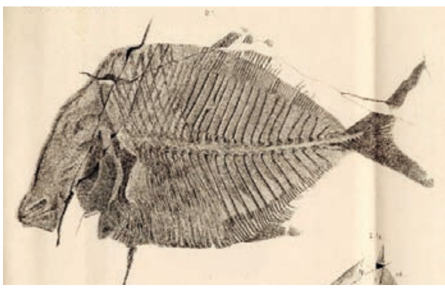
Another, slightly younger platy and laminated limestone with thin lenses or layers of chert is the **Tomaj Limestone**. It frequently contains numerous and well-preserved fossil fish (Figure 27), turtles, ammonites (cephalopods, extinct relatives of squids with coiled calcareous shells, which were the rulers of the seas in the Mesozoic era), planktonic crinoids, and other inhabitants of the open sea. The presence of fossil plants with dominant conifers (Figure 28) indicates the close proximity of land to the south of the lagoon (Figure 29). One of the most important fossil localities in Karst is the abandoned Tomaj Limestone quarry of Kazlje (see Chapter 10).

Komen and Tomaj limestones are mostly found in the central and northern areas of the Classical Karst (Fi-

Figure 24: Platy and laminated Komen Limestone on Mrtvaški hrib along the Komen–Škrbina road (Photo: Matevž Novak)

Figure 25: Characteristically laminated Komen Limestone with a layer of black chert on Mrtvaški hrib along the Komen–Škrbina road (Photo: Matevž Novak)

Figure 26: Fish fossil from the Komen platy limestone at Komen (Photo: Bogdan Jurkovšek) and the drawing of the holotype (the first described specimen) of a fossil fish Coelodus vetteri from the monograph on fossil fish by Gorjanović-Kramberger, published in 1895.



gure 30). They are undoubtedly one of the oldest building materials in Karst region. Even in the late 19^{th} and early 20^{th} centuries, local people collected slabs of these rocks for paving and roofing.

Figure 28: Plant fossil of a conifer, found in Tomaj Limestone at Kazlje (Photo: Bogdan Jurkovšek)

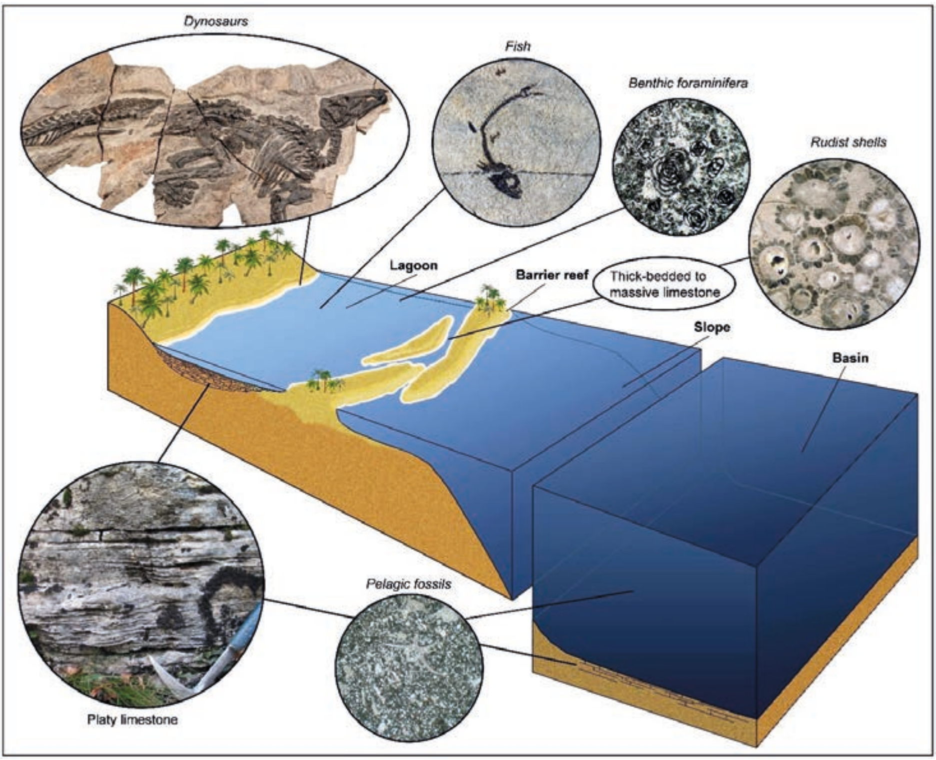
Figure 27: Two sides of a fish fossil found on the split slabs of the Tomaj Limestone at Križ (Photo: Bogdan Jurkovšek)

INTERESTING FACT

Terra rossa

When dark platy limestones with chert are exposed to atmospheric agents, a thick layer of reddish-brown soil called *terra rossa* can form. The characteristic red colour of this soil is due to iron oxides, mostly found in the form of grains of a mineral called hematite. Vines thrive very well in such soil.

Figure 29: Depositional environments of platy, thick-bedded and massive (non-bedded) limestones within a shallow-water carbonate platform, platform margin (barrier reef), and adjacent deep marine basin (Model after: Vlatko Brčić; Photo: Bogdan Jurkovšek and Marino Ierman, Museo Civico di Storia Naturale di Trieste. The image of the dinosaur is used with permission of the ABAP FVG - MiC Superintendence and further reproduction for profit is prohibited.)

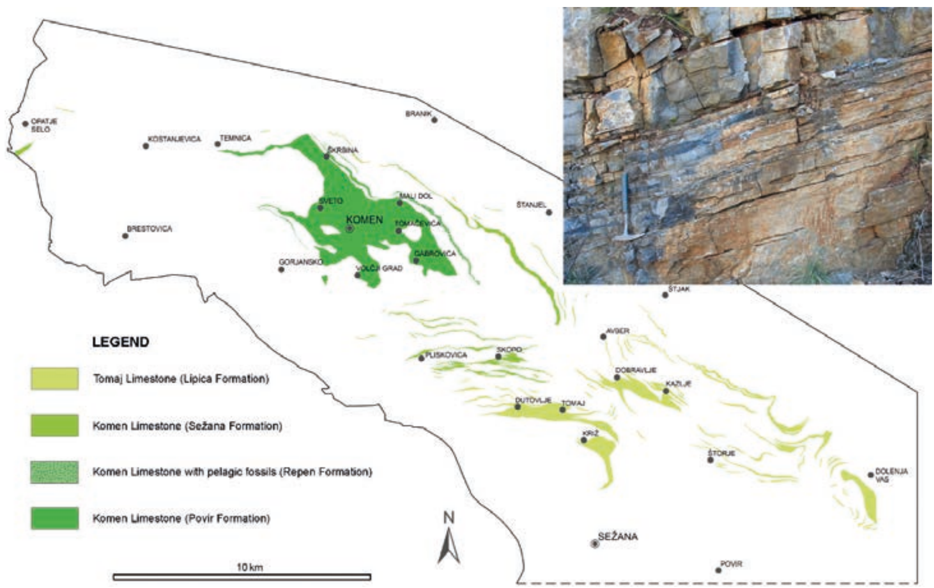


INTERESTING FACT

Why are most limestones in Karst light coloured, but some are dark grey or even black?

During the Cretaceous, due to the warm climate and high sea level, large parts of the continents that are now land were covered by extensive shallow, epicontinental seas (seas on continents). This allowed marine life to flourish. In shallow, well-aerated water, thick layers of light-coloured limestone are formed. However, the Earth's poles were ice-free at that time, water circulation was slower, and oxygen concentrations were lower. In the more sheltered and slightly deeper areas of the lagoon on the Adriatic-Dinaric Carbonate Platform, this led from time to time to the accumulation of black, organic-rich sediments on the seabed. Very thinly layered black limestones were formed from these sediments.

Figure 30: Upper Cretaceous platy limestones of different age in the Karst area (modified from: Jurkovšek et al., 2013). Top right: Laminated Komen limestone with chert lenses at Škrbina (Photo: Bogdan Jurkovšek)



4.3 Upper Cretaceous-Paleocene limestones; an account to major changes at the Cretaceous/Paleogene boundary

Major environmental changes took place at the end of Cretaceous. As a result of the collision between the Adria Microplate and the Eurasian Plate, the land began to rise, which ultimately led to the formation of the Alps. As a consequence of this uplift, the environment on the Adriatic-Dinaric Carbonate Platform became characterized by shallower waters that could now become less saline because of the input of meteoric freshwater. This environmental change was reflected in the rocks and in their fossil content. Grey to dark grey bedded limestone with interlayers of brownish to black marly limestone predominates. Fossils are very diverse and feature animal and plant fossils indicative of environments that could be terrestrial or aquatic with brackish or saline water.

In the sea, rudist clams and foraminifera dominated (the most common is the large *Rhapydionina liburnica*), on land plant remains (conifers, characean algae), thin-shelled mussels and snails (Figure 31).

Figure 31: Dark Upper Cretaceous limestone of the Liburnian Formation west of Rodik with a snail of the genus Stomatopsis (Photo: Bogdan Jurkovšek)

Some parts of the Adriatic-Dinaric Carbonate Platform surfaced again from the sea and were subjected to intense karstification. Both surface and underground karst phenomena were created (Figure 32). Vegetation was so abundant on the emergent parts of the platform that coal deposits can be found in these rocks at Vremski Britof, Rodik, and in the wider Lipica and Štorje areas. These were mined in the 19th and early 20th century.

The expansion of land areas above sea level permitted the life of both amphibious and larger terrestrial animals. This is evidenced by the discovery of fossil remains of crocodiles, and the bones and teeth of herbivorous dinosaurs belonging to several families (Hadrosauridae, Iguanodontidae, and Dromeosauridae). The most exquisitely preserved fossils have been found in the dark, finely laminated limestones from this period and exposed near Villaggio del

Figure 32: Paleokarstic surface denoted by small scale depression in a motorway road-cut at Kozina. Note colour contrast between light grey shallow marine limestone and dark grey palustrine limestone (Photo: Bojan Otoničar)

Pescatore near Trst/Trieste (Figure 33). There, two complete skeletons of the hadrosauroid species Tethyshadros *insularis* were found. Besides the hadrosaurs, this limestone also contains the remains of pterosaurs, crocodilians, fish, and other vertebrates (see Chapter 10).

The Slivia-Slivno Quarry abandoned quarry exposes breccia made up of disorganised limestone blocks (Figure 36). This collapse breccia also indicates a longer emersion episode accompanied by the development of an extensive palaeokarst system. The **Slivia Breccia**, also known comercially as “Napoleon Slivia” or “Breccia Carsica Marble”, was widely used as ornamental building stone.

Figure 33: Laminated limestones near Villaggio del Pescatore, in which dinosaur fossils were found (Photo: Sara Biolchi)

Figure 36: Slivia-Slivno old quarry exposing paleokarstic breccia (from: Consorti et al., 2021)

INTERESTING FACT

Were dinosaur fossils also found in the Slovenian part of Karst?

Fossil remains of Upper Cretaceous vertebrates, especially dinosaur teeth and bones, were also found in the limestone breccia in the paleokarstic cavity near Kozina (Figures 34 and 35).

Figure 34: The locality of dinosaur bones in the breccia with limestone clasts of the Liburnia Formation that fills the paleokarstic cavity in limestones of the Lipica Formation in the road-cut at Kozina (after: Košir et al., 1999)

Figure 35: The bones of dinosaurs, crocodilians, and other terrestrial vertebrates in the paleokarstic breccia (left) (Photo Matevž Novak) and the structure of dinosaur bones through the microscope (right) (after: Košir et al., 1999)

INTERESTING FACT

Mass extinction at the boundary between Cretaceous and Paleogene

Within the Upper Cretaceous-Paleocene limestone, a very important moment of geological history is recorded: the Cretaceous-Paleogene boundary (K-Pg boundary), marking one of the most devastating mass-extinctions to have ever occurred on the planet. It coincides with the impact of a large asteroid in the area now occupied by the Yucatan Peninsula in the Gulf of Mexico. The changes that occurred at the K-Pg boundary were so severe that geologists have placed the transition between the Mesozoic and the Cenozoic eras at this point in time.
This event drastically changed life on Earth, wiping out 73% of living species (Figure 37), including dinosaurs, ammonites, rudists, and many other organisms that had thrived on the continents and in the oceans for millions of years. In Karst, the K-Pg boundary has been investigated in a sequence of limestone beds along the road near Dolenja vas.

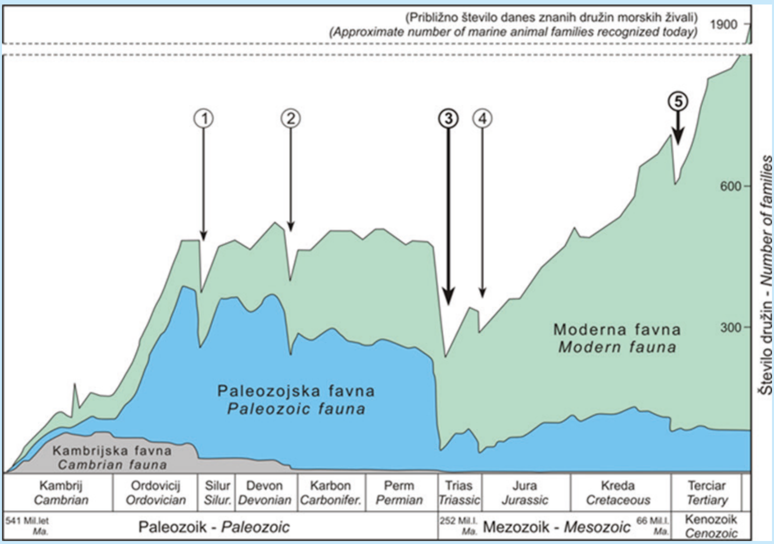


Figure 37: The last of the Big Five mass extinctions in Earth's history occurred at the Cretaceous-Paleogene boundary. (Jurkovšek et al., 2013)

4.4 Paleocene and Eocene foraminiferal limestones

At the end of the Paleocene, the sea level slowly began to rise again and marine conditions predominated once more. A new sequence of light grey to grey, indistinctly bedded to massive limestone records this phase of the history of Karst. In the Paleocene and Eocene rocks many forms of algae and foraminifera are found but are very different from those that can be observed in the Cretaceous rocks. Foraminifera, in particular, saw the appearance of many new species and became progressively larger so that in the youngest parts of these rocks they can be so large as to be seen with the naked eye. Due to the presence of a range of large benthic foraminifera, in some strata these accumulated in large numbers, these limestones are easily identifiable (Figure 38).

The most widespread are layers with alveolinids and nummulitids, which form the **Alveolinid-Nummulitid Limestone** unit.

4.5 Flysch of the middle Eocene deep ocean basin

The youngest of the rocks that characterizes the Classical Karst area

Figure 38: Foraminiferal limestone with nummulitids and alveolinids from west of Kozina (Photo: Matevž Novak)

Figure 39: Alternation of marlstone and sandstone beds composing a flysch sequence south of Gora (Photo: Bogdan Jurkovšek)

are completely different from those of earlier ages. Unlike the limestone that make up most of the Karst Plateau, these rocks are mainly sandstones and more or less clayey rocks (siltstone, claystone and marlstone), alternating within a sequence of thin layers that is well known by the term flysch (Figure 39).

Visitors should be reminded that flysch is not a rock, but a characteristic sequence of alternation of different rocks.

The sediments that make up these rocks derive from the erosion of older rocks and reveal the uplift of the Alps. While the mountains were growing, progressively older rocks were exposed to rain, winds and other atmospheric agents. They were therefore eroded and, through rivers, brought down to the sea. At times such sands and clays, when they were not yet lithified, slid down the continental slopes in the form of submarine landslides into the deep ocean basin. Such landslides generated dense sediment-laden submarine flows called **turbidity currents** by geologists. After having slid into deeper parts of the seas, these currents lose velocity and therefore slowly release their sediment load. The submarine deposits generated by a turbidity current are called turbidites. The flysch is mainly made up of turbidites, organized into thin layers (Figure 40).

Figure 40: Scheme of formation of flysch layers (after: https://parkstrunjan.si/presezniki/klif/)

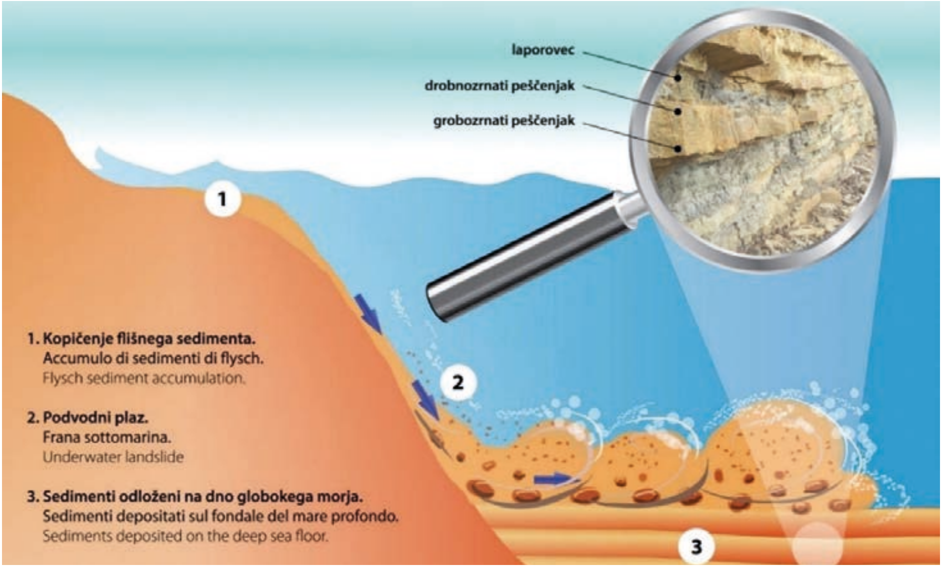


Figure 41: Fossil traces of crawling in the flysch sandstone of Cape Strunjan (Photo: Matevž Novak, Staša Čertalič)

On the surfaces of some layers, traces of crawling and burrowing can be seen, mostly made by unknown animals in the former sandy seabed (Figure 41). Such fossil traces are called **ichnofossils**. Furthermore, these rocks sometimes contain abundant plant fragments, revealing the presence of extensive vegetation cover on the nearby emergent lands.

INTERESTING FACT

On which surface of the layer do the fossil traces occur most often?

Without thinking, everyone would probably assume that fossil traces are found on the upper surfaces of rock layers. But is this really so? No. Traces of crawling are most often preserved in the rock as "imprints" on the lower surface of the layer that covered the trace on the older layer (Figure 42). Therefore, ichnofossils help us to determine the original position of vertical layers.

Figure 42: Several types of fossil traces on the lower surface of the flysch sandstone at Cape Kane near Izola (Photo: Matevž Novak)

5. WHEN AND HOW DID THE TERRITORY OF THE GEOPARK BECOME LAND?

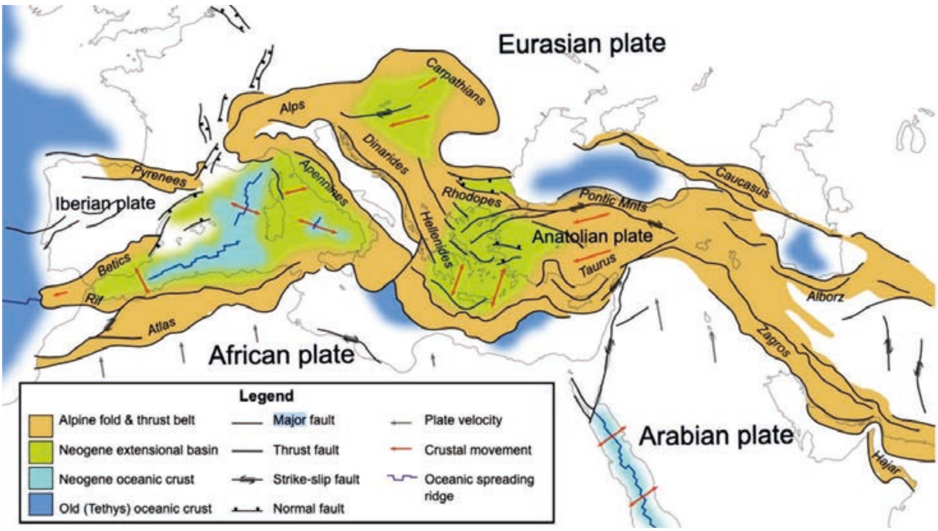
5.1 Tectonic processes that lifted the rocks of the shallow marine platform to become land

The present-day morphology of the Classical Karst area results from a long history of tectonic deformation through several mountain building (orogenic) phases that involved the area over the last 70-80 million years, from the Cretaceous up to now. **Orogeny** is a process by which mountains are formed due to a convergence between two tectonic plates. The two plates, in this case, were the Adria (the northernmost segment of the African late), and the Eurasian plates.

During the **Dinaric orogenic phase**, the Dinaric mountain range was formed, the southern part of the European Alpinids, which begins at the Italian-Slovenian border and ends where Albania ends and Greece begins (Figure 43).

The Classical Karst is located in the northern sector of the Dinarides. As mentioned before, the Dinarides result from the convergence between

Figure 43: Tectonic map of Europe (Source: Wikipedia)



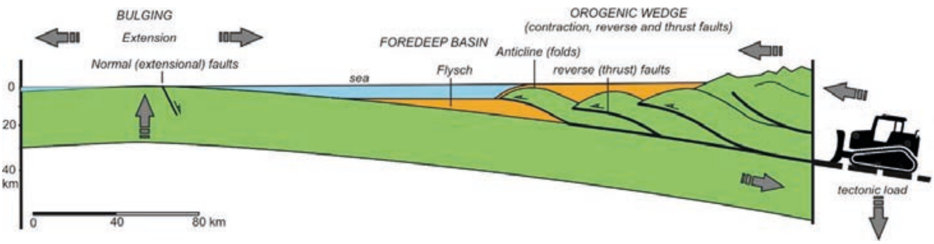


Figure 44: Simplified evolutionary sketch of the Dinaric orogeny (Diagram: Lorenzo Bonini)

two plates, during which the rocks of the oceanic crust of the Adria Plate began to dive (subduct) under the continental crust of the Eurasian Plate. Note that the oceanic crust is denser than that of the continental plates. The process of creating a mountain belt reaches its apex when all the oceanic crust have been subducted and the two equally dense continental crusts collide. The process of gluing together (accretion) of parts of the tectonic plates begins, where one can imagine the upper plate as a bulldozer or snowplow that tears away some portions of the lower plate rock, accumulating them at its leading edge. This “front” is thicker close to the “bulldozer”, that is to say, close to the overriding, or upper plate, and thinner toward the lower plate, forming a sort of wedge. Geologists name the area where the bulldozer works as the “hinterland” with the “foreland” being the sector where the wedge is headed (Figure 44).

Returning to the Classical Karst area, we can imagine that a bulldozer starts to compress, fold and break the rocks from northeast to southwest, creating an advancing wedge with its most external part being the Karst. This natural bulldozer moved above a subducting plate at a rate of a few millimetres per year, but it worked for a million years creating the Dinaric orogenic belt. At the front of the advancing wedge, the lower plate bent due to the bulldozer's weight, creating a basin for sediments that derived from the erosion of this huge wedge to form flysch. This process ended 20 million years ago. Hence, the geological structure of the Karst area is substantially the same today as it was 20 million years ago, depicting a large asymmetric fold, namely an anticline (a fold with a shape of A).

5.2 Today's geological structure of Karst

If we imagine vertically cutting through the Karst, we will observe its internal structure, namely the Karst anticline (Figure 45).

The Karst anticline is asymmetric, meaning that one limb is steeper than the other. The limb dipping toward the southwest is more inclined than the limb dipping toward the northeast. This asymmetry is because the rocks have been pushed from northeast to southwest. To understand this process, one may imagine moving a towel on a table (Figure 46). When the towel is pushed, the folds are asymmetric because the hand is pushing in one direction.

Coming back to the rocks outcropping in the Karst area today, the **geological map** (Figure 47) shows that in the center of the Karst plateau outcrop the older rocks, i.e., the Lower to Upper Cretaceous rudist limestones with fossiliferous platy limestone layers (green areas in Figure 47) and moving towards the edges of the Karst the younger rocks are present (orange areas in Figure 47).

The geological map also shows red lines crossing the area. These red lines are the major faults. In general, **faults** represent discontinuities in the rocks that are formed as a consequence of compressional or extensional tectonic phases during the geological evolution of the area.

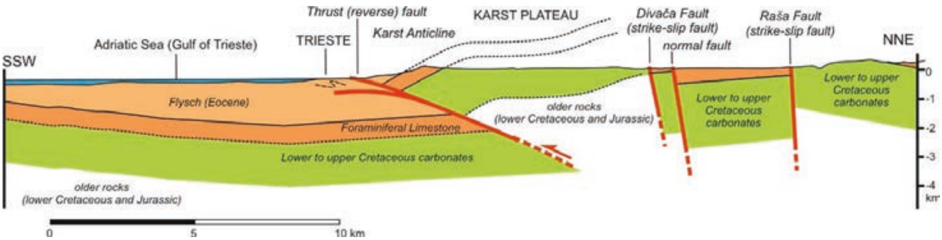


Figure 46: Mechanism showing the generation of a fold deforming a towel

The geological map and the cross-section show a reverse fault in the southwestern area, cutting the topographic surface in Trieste. This reverse fault is also known as a thrust fault, namely, a low-angle reverse fault, formed during the last compressional phase of the Dinaric orogeny, together with the Karst anticline. Both these structures are derived from the contraction of the rocks. Moving northward there are two major faults: the Divača and Raša (Figure 49; see also Chapter 10). These are strike-slip faults generated during a younger phase and are still active today.

Figure 45: Geological cross-section through Karst showing the main tectonic structures (faults and folds) (Diagram: Lorenzo Bonini)

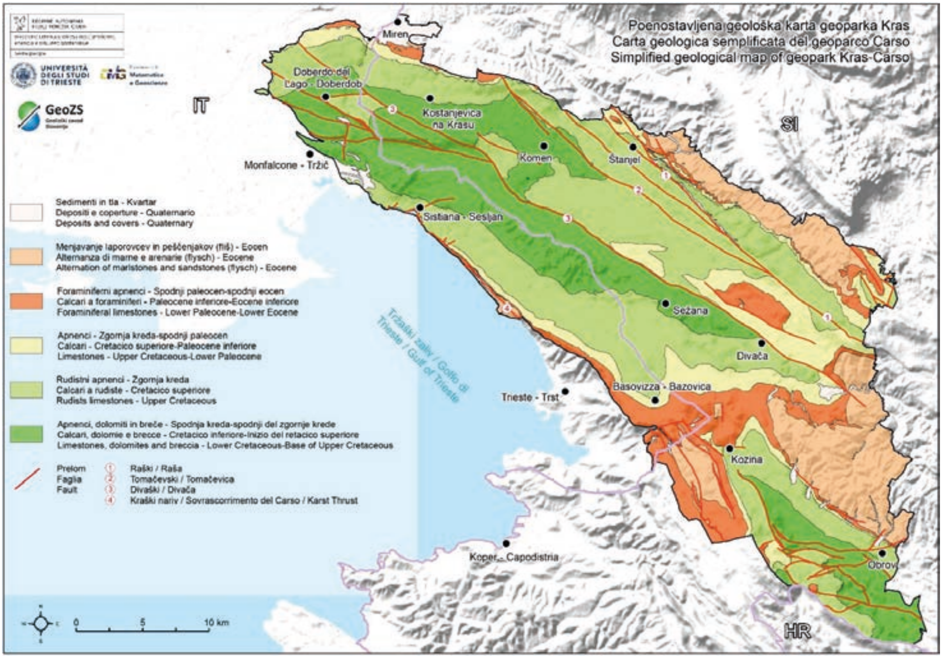


Figure 47: Simplified geological map of the Classical Karst (Data: Geološki Zavod Slovenije (GeoZS), Geological Service, Autonomous Region of Friuli Venezia Giulia (SGEO), Dipartment of Matematics, Informatics and Geosciences – University of Trieste (UNITS))

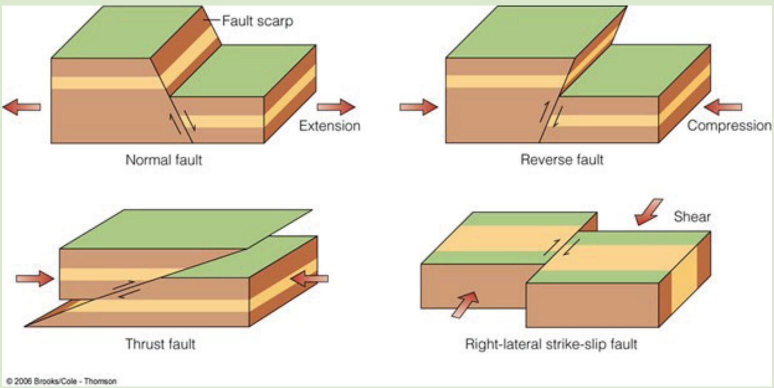
Figure 49: The valley of the Raša river follows the straight Raša Fault (Photo: Matevž Novak)

EXPLANATION

Types of faults

In reverse faults, the upper rock block, above the fault plane, moves up and over the lower block during compression; in normal faults, the block above the fault plain moves downward relative to the lower block during extension; in strike-slip faults, two rock blocks slide side by side during shearing. A thrust fault or thrust is a low-angle reverse fault. In the Classical Karst area, all four types of faults exist (Figure 48).

Figure 48: Types of faults that occur in differently directed stress fields (Brocks/Cole - Thomson, 2006).



6. QUARRIES AND TYPES OF KARST NATURAL STONE

Karst limestones are generally regarded as excellent building and ornamental stones. They have good geomechanical properties and the variety of colours allow for diverse use in architecture. Stone walls, churches, simple or impressive buildings, towers, bridges and paving stones are therefore one of the most recognizable elements of Karst cultural landscape. The compactness, homogeneity and workability allow artists and craftsmen to create simple or magnificent works of art that decorate the houses and squares.

In some areas of the Classical Karst, sedimentary and diagenetic processes have favoured the formation of particularly compact, homogeneous and thick limestone horizons from which large blocks suitable for use as architraves, load-bearing columns, doorposts, window frames, and blocks from which statues, sculptures and urns can be made. This type of limestone is often called ''marble of the Karst''.

Today, several types of limestone are exploited with different commercial names: *Aurisina Chiara, Aurisina Fiorita, Aurisina Granitello, Roman Stone, Fior di Mare, Repen Classico Chiaro, Repen Classico Zolla, Lipica Unito, Lipica Fiorito* and *Kopriva*. Besides the types still in production today, the Komen platy limestone (Figure 50), the colorful Karst breccia, the red or yellow flowstone and the black spotted Gabria were all quarried.

From the material traces and also from the written sources or oral tradition, it is clear that in the 18th and 19th centuries there were more than 400

INTERESTING FACT

Mineralogical and geomechanical properties of Karst limestones

The chemical composition of Karst limestones has a calcium carbonate ($CaCO_3$) content of over 98% and a magnesium carbonate ($MgCO_3$) content of less than 1% with insoluble residues in traces. The volumetric weight range is up to 2.65 kg/dm^3, imbibition coefficient is very low, the values of resistance to compression, flexion, impact and wear are excellent, and the thermal expansion coefficient is insignificant.

EXPLANATION

Is the rock that is quarried in the Lipica Quarry by Marmor (meaning marble) Sežana really marble?

Marble is a massive metamorphic rock formed by the transformation of limestone or dolomite at high temperatures and high pressures in the Earth's crust. But we have written that the Classical Karst is built only of sedimentary rocks. Therefore, the name Marmor Sežana can be misleading, because the Lipica Limestone is a carbonate sedimentary rock. The point is that marble is often a marketing name used by stonemasons for different types of rock. A similar example in Slovenia is Hotavlje Marble, which is also a limestone.

limestone quarries on the Classical Karst. The oldest traces of stone extraction can be found in the Aurisina/Nabrežina basin in the upper part of the walls of the *Cava Romana* (Figures 51 and 52).

Since the earliest settlements, almost the entire population of Karst was involved in some way in the process of stone extraction. The local population specialized in the work in quarries or in stone cutting, organizing themselves into several stonemasonry workshops. Until the beginning of the 20th century, in this area practically every family had at least one member involved in one of the activities and gained modest income from it.

The process of stone extraction has changed over the centuries. In roman times, the work was done both in open pits and underground. Stone blocks were cut by digging grooves with picks and chisels, detaching them with wooden wedges, later with wet or iron wedges, before being beaten or forced with long iron levers. To move the stones, cylindrical rods were used, while to lift them special devices with several pulleys were used. Transfers of stone over a distance saw winches were employed.

Figure 50: Abandoned surface extraction of the Komen platy limestone in Gabrovica, used for roofing and paving (Photo: Bogdan Jurkovšek)

Figure 51: Photograph of Aurisina/ Nabrežina Cava Romana on a period postcard

From the second half of the 19th century, explosives and gunpowder were used. In the early 20th century, drills using compressed air and the helical wire came into use and employed extensively in Karst until the early 1980s. In recent decades, the most modern techniques require the use of a diamond wire or a diamond chain cutting machine.

After the construction of the Southern Railway, the line that connected Vienna with Trieste in 1857, the period of greatest wealth began for the Karst quarries. Aurisina/Nabrežina became the most important processing and distribution centre for stone from the entire area of the Karst and also from the Istrian region. The Aurisina/Nabrežina quarry provided the stone for several famous monu-

Figure 52: The Cava Romana of Aurisina-Nabrežina Quarry: on the left the excavations on the slope, on the right the excavations in the tunnel (no longer active) (Photo: Giancarlo Massari)

INTERESTING FACT

The Mausoleum of Theodoric with the block of Aurisina/Nabrežina stone

Among the blocks quarried in the quarry of Aurisina/Nabrežina, the most famous is the *ingens saxum*, the monolithic roof of the Mausoleum of Theodoric in Ravenna (Figure 53), which since 1996 has been a UNESCO World Heritage Site. It is circular, with a diametre of 10.76 metres and a thickness of 3.09 metres, which means almost 300 tons of rock! It is still a mystery how the block was excavated, how it was transported to Ravenna and how it was placed (around 520 C.E.) on the decagonal - circular structure of the mausoleum at a height of fifteen metres.

Figure 53: Mausoleum of Theodoric in Ravenna with a roof, made of a single block of Aurisina/Nabrežina Limestone (Photo: Franco Cucchi)

ments, including several representative buildings in Trieste (the Greek Orthodox Church, the Stock Market, Miramare Castle), in Vienna (Burgtheater, National Opera, Hofburg and Parliament), the railway station in Milan (1930), Budapest and other European cities, as well as the entrance to the Suez Canal.

Nowadays, in the Slovenian part of Karst only two companies own the concessions for limestone extraction. The first company quarries stone blocks in several locations including Kopriva (*Kopriva Limestone*), Doline (*Repen* and *Kopriva Limestones*) and Lipica (*Lipica unito* and *Lipica fiorito Limestones*). The other small company has a quarry in Debela Griža pri Povirju (*Repen Limestone*) (Figures 54 and 55).

As far as the Italian part of the Karst is concerned, in the Aurisina basin there is a small company and a consortium which includes some concerns that exploit several quarries. The quarried material is purely local: *Aurisina chiara, Roman stone, Aurisina fiorito* and *Aurisina granitello*. In the Zolla and Rupingrande area a third company quarries the Repen classico and Fior di Mare varieties.

A request for guides

Because today, due to environmental issues, people's negative attitude towards quarries is strongly prevalent, it is necessary to explain to visitors that the quarries in Karst were important, and must be preserved, as quarrying is part of the tradition and identity of the area. Nevertheless, it is necessary to take into account the aesthetic and the environmental vulnerability of the area. Abandoned quarries are often an impressive element of the cultural landscape, especially where quarrying and stonemasonry were the main economic activity of an entire area. Quarries are often perceived as "wounds" in the natural environment, but today they offer other possible uses. In all operating quarries and in potentially interesting deposits of dimension and technical stone, quarrying should be possible only if high environmental standards are met. Smaller quarries should be preserved to allow limited extraction of those autochtonous karst stone varieties suitable for restoration of authentic karst architecture.

Figure 55: Most valuable Karst stones are Lipica Fiorito (top left) and Lipica Unito (bottom left) from the Lipica Quarry (which correspond to the Aurisina Fiorita and Aurisina Chiara types from Aurisina/Nabrežina Quarry), then Repen (top right) and Kopriva (bottom right) types of limestone from the Doline Quarry (corresponding to Repen Classico Zolla and Repen Classico Chiaro in Italy and the boutique dark Kazlje Limestone (Photo: Matevž Novak, Bogdan Jurkovšek)

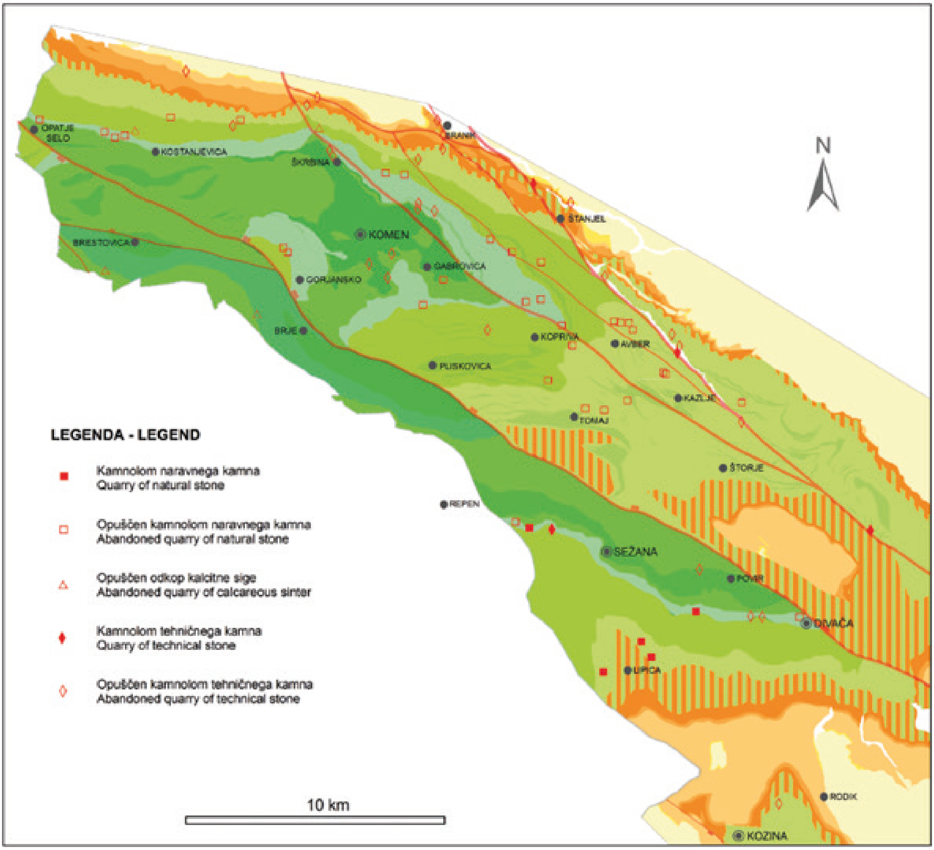
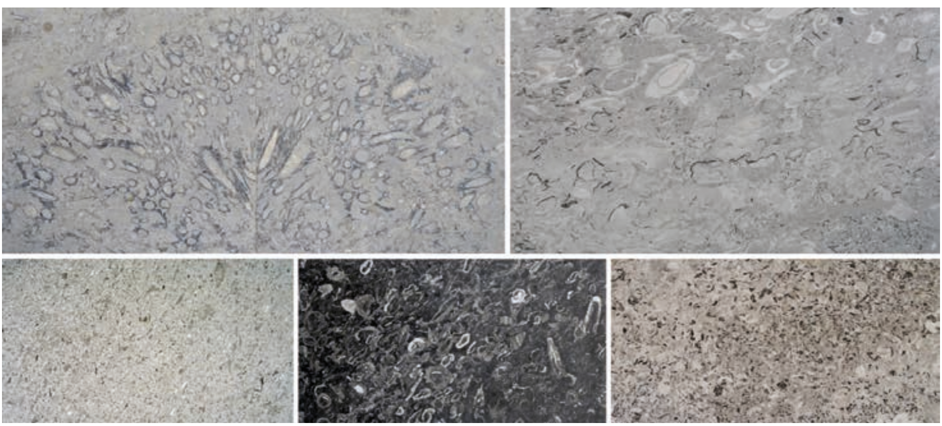


Figura 54: Carta geologica semplificata del Carso con una selezione di cave in funzione e abbandonate (da Jurkovšek et al., 2013)



7. HYDROGEOLOGY OF THE GEOPARK AREA

7.1 The Classical Karst aquifer

In Karst, water only stays on the surface for short periods of time. The extensive network of geological discontinuities (bedding surfaces, fractures, faults, ...), enlarged and expanded by karst phenomena, allows for the easy infiltration and a rapid accumulation of water below the surface, creating one of the most important and productive aquifers of the entire Mediterranean area (an **aquifer** is a body of rock and/or sediment that contains water and releases it in appreciable amounts). The symbol of the Kras aquifer are the Škocjan Caves and Timavo Springs, that, with their average flow rate of 30 m^3/s, represent the most important source in the area of the geopark.

As we have already described in the previous chapters on the Classical Karst there are two different lithologies: carbonate rocks (limestone and, in part, dolomite) and siliciclastic rocks, here represented by flysch (an alternation of marlstone and sandstone in which the silicatic component prevails over the carbonate one). These two lithological units have different hydrogeological properties which influence the recharge and outflow in the aquifer. In fact, the former are extremely karstified and facilitate infiltration and underground flow (high permeability), while the latter are not karstified at all, favouring surface runoff and representing a barrier to underground flow (low permeability).

When observing the Geological Map (Figure 47), note how the flysch is present in an almost continuous fashion, both in the northern and eastern part of Karst, nearly surrounding it. Its presence is a hydrogeological barrier that favours the accumulation of water in the limestone and the groundwater flow towards the north-west, up to the area between Aurisina-Nabrežina and Tržič-Monfalcone where the barrier is lacking and the groundwater can reemerge in numerous springs.

7.2 The Reka/Timavo aquifer system

The Notranjska Reka River, named the Timavo Superiore in Italian, originates on the slopes of Mt. Dletvo on the border between Slovenia and Croatia. It flows for more than 50 km on flysch until it enters onto the limestone about 7 km upstream of the Škocjan Caves. In this part of the river the karst is already developed and the Reka loses part of its water. This phenomenon is particularly evident near Gornje Vreme where during low flow periods all the Reka waters sink and downstream the riverbed is dry.

When the flow rate is higher than about 1 m^3/s the Vreme swallowhole is unable to capture all the water and Reka River continues its flow towards Škocjan Caves. The Reka enters the Škocjan Caves at an altitude of 317 metres above sea level (a.s.l.), crosses some very deep collapse dolines and after having covered about 3.5 kilometres of a gigantic underground gorge it disappears into the siphon of the Dead Lake at 212 metres a.s.l.

Speleologists discovered and explored numerous caves, reaching the Reka/Timavo's underground conduits, among which the most famous include the cave system of Brezno treh generacij (Three Generations Abyss) - Kačna jama (Snake Cave), the Kanjaduce Cave, the Trebiciano-Labodnica Abyss, and the Grotta meravigliosa di Lazzaro Jerko (Wonderful Cave of Lazzaro Jerko).

Along the coastline from Aurisina-Nabrežina to the town of Monfalcone-Tržič, where the limestone/flysch contact is at topographically low altitudes and often below sea level, the presence of numerous springs draining the waters of the Karst aquifer can be observed. The largest springs are located below sea level to the west of the Bay of Sistiana-Sesljan. In the westernmost area, between Doberdò-Doberdob and Monfalcone-Tržič, a complex system of springs, karst lakes, and sinkholes can be observed, giving rise to a unique hydrogeological system and ecosystem.

The Timavo Springs represent the central junction of the hydrogeology of the whole Karst, as they drain most of the waters that feed the aquifer. At this point the waters of the Reka, the waters coming from the Isonzo-Soča and Vipacco-Vipava Rivers, and the waters linked to the precipitations of the whole Karst flow together with different regimes.

8. SUMMARY OF THE MAIN GEOLOGICAL HIGHLIGHTS OF THE GEOPARK KRAS-CARSO

Each geopark demonstrates geological heritage of international significance. It promotes its significant geological processes and features, periods of time, historical themes linked to geology, or outstanding geological beauty.

The main geological highlights of the geopark Kras-Carso are:

- Karst geomorphology, characterized by all kinds of superficial and underground karst phenomena and by a particular hydrogeological network through which the Classical Karst contributed to the emergence and development of karstology, speleology and speleobiology as scientific disciplines in the 19th century. Due to the distinctive relief forms, local terms for karst phenomena, such as "*Karst*" itself, *dolina*, and *polje* have entered the international scientific terminology.

- The geological evolution of the geopark is best reflected in the karst caves formed in the River Reka/Timavo hydrogeological system. The Škocjan Caves, an outstanding karst system with one of the largest known underground canyons in the world, formed here. Textbook examples of sinkholes, natural bridges, gorges, potholes, collapse dolines, abysses, an underground canyon, springs, and passages covered with flowstone deposits lend this small area worldwide significance in the study of karst features and processes. Due to their natural and cultural importance, Škocjan Caves have been on the UNESCO World Heritage List since 1986. Comparable in their outstanding appearance and size is the Grotta Gigante/Briška jama with the largest hall in a touristic cave in the world.

- The sedimentary succession, covering a timespan of nearly 100 million years from the beginning of the Cretaceous period, about 140 million years ago (mya), to the middle of Eocene period about 45 mya. It records the changing geological environments on a shallow-marine carbonate platform, influenced by the climate changes, eustatic sea-level changes, and global and local tectonic movements.

- One of the most complete and best preserved dinosaurs in the world, found at the Villaggio del Pescatore/Ribiško naselje and other exceptionally well-preserved fossil vertebrates are found in the platy limestones in the areas of Komen and Tomaj, along with very rich and diverse fossil inventory of several faunal and floral elements.

- The Cretaceous-Paleogene (Mesozoic-Cenozoic) mass-extinction event, one of the most devastating mass-extinctions that occurred on the planet, is recorded in different profiles in the area.

- The Karst cultural landscape, strongly characterized by its rocky surface and the use of stone as construction material. The art of dry stone walling, knowledge and techniques was listed by Unesco in 2018 as intangible Cultural Heritage of Humanity.

9. VISUAL AID

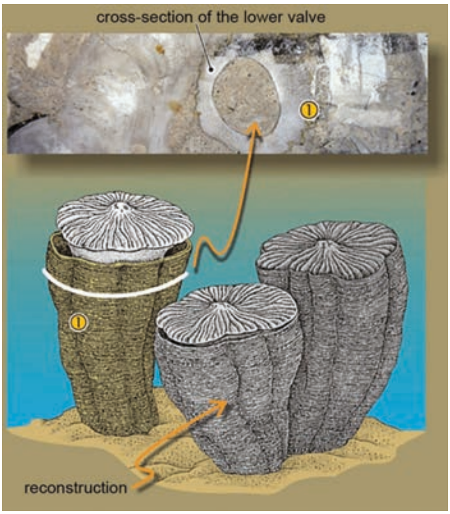
We add a visual aid for guides based on our own experience with the most common questions curious visitors ask on geology tours.

What are rings in a rock?

These are **rudist shells**. Their thick shells are shaped like large letters V or U in longitudinal sections and like rings in transverse sections. Often the outer surface is ornamented with ribs or protrusions that give the cross-sections the shape of stars or flowers. Such cross-sections are among the most recognizable limestone structures in karst and are also found on the beaches along the eastern coast of the Adriatic Sea.

West of Štjak (Photo: Matevž Novak)

On the Adriatic coast in Croatian Istria (Photo: Matevž Novak)



Reconstruction of a rudist shell and its cross-section in stone (after: www.paleo urbana.com)

What are lattice structures in rock?

These are also **sections of rudist shells**. A reticulated arrangement of pores in the shell is characteristic of some groups of rudists.

Along the road Griže–Sela
(Photo: Matevž Novak)

Along the road Griže–Sela
(Photo: Matevž Novak)

What are dark formations in limestone?

These are **cherts**. Chert is a micro- to cryptocrystalline (amorphous) sedimentary rock composed of silicon dioxide (SiO_2), i.e., a type of quartz. It differs from limestone, in which it often occurs in the form of nodules, lenticular bodies, or layers of various thicknesses, in its glassy appearance, fracture with sharp edges, and, of course, hardness. Due to its better resistance to weathering, chert usually stands out from the surface of limestone. Cherts come in different colours: white, grey, black, red, etc. In Karst, grey and black are the most common. Many people know chert by the name of flint, because in prehistoric times it was used by man to make fire and, because of its very sharp edges, for blades and arrowheads.

Veliki dol at Kazlje
(Photo: Bogdan Jurkovšek)

Gabrovica pri Komnu
(Photo: Bogdan Jurkovšek)

What are crystalline formations on the surface of a stone?

These are **calcite crystals**, which are very common in Karst, as well as elsewhere in Slovenia. They fill tectonic veins, karst cavities or caves. Coatings of one or more sheets of such elongated, prismatic crystals or larger formations (speleothems, such as stalactites, cave curtains, etc.) you probably know by the name of **flowstone**. It can form layers several metres thick. The crystals are coloured due to various impurities and their concentration in the supersaturated aqueous solution from which the crystals are precipitated. In Karst, flowstone was even mined for decorative stone in some quarries, for example in Rusa jama near Gorjansko. Beautiful examples of its use are the top slabs of the stone fence of the upper garden of the Bled Castle and the wall cladding of one of the floors of the Parliament building in Ljubljana.

Lipica Quarry (Photo: Matevž Novak)

What are the striated stepped surfaces on some rock faces?

These are **tectonic slickenlines**. White or brownish striped coatings are visible on some rock surfaces. Such mineral coatings, typically step-like, form on fault planes, that is, on surfaces along which displacement of adjacent tectonic blocks occur. Due to the friction between the two blocks, the surfaces are smoothed and often covered with a coating of mineral fibers (usually calcite) that grow during movement. Stepped tectonic slickenlines indicate the relative direction of movement along the fault. A tectonic block sliding on such a surface slid parallel to the fibers down the stairs.

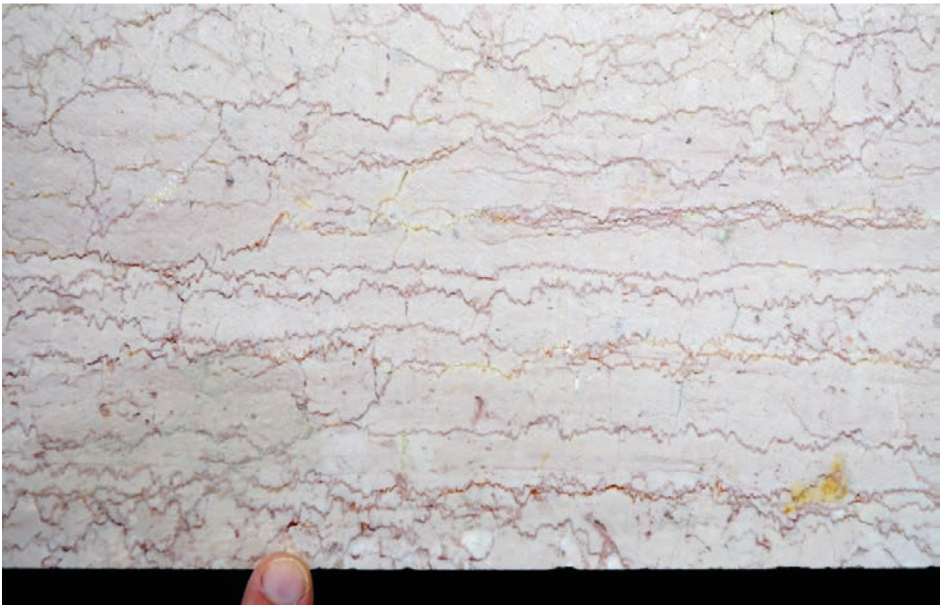
Griža Quarry (Photo: Staša Čertalič)

What are zigzag lines in stone?

The thin serrated surfaces within the rock layers are **stylolite seams**. They occur almost exclusively in homogeneous, very fine-grained rocks. They are formed in already solid rock due to pressure. When younger sediments are deposited on the layer, they compress it by their weight and partly dissolve it. Dissolved calcite crystals are removed from the layer with solutions, and the insoluble residue of harder minerals (e.g. clay minerals, pyrite and various oxides) mixed into the rock in small quantities forms a white or differently colored surface. In cross-section, such a surface looks like a thread. In the case described, where the compressive force acts perpendicular to the layer, stylolite seams form parallel to the layer planes. However, pressure can also be the result of tectonic forces that can compress rock layers in different directions. The seams formed in this way are oriented at different angles to bedding planes.

Along the road Griže–Sela
(Photo: Matevž Novak)

Lipica Quarry
(Photo: Matevž Novak)



10. THE GEOLOGICAL HERITAGE OF THE SLOVENIAN CLASSICAL KARST

The geological heritage is represented by those places having a scientific interest which allows an understanding of the history or evolution of an area. These places, called geosites, are worthy of conservation and protection, and are part of what we call "natural heritage", which is that set of biotic and abiotic aspects distinguishing an area. Seven geosites have been selected from the long lists of geologically and geomorphologically valuable natural features, officially designated a nature conservation status in a register maintained by the Institute of the Republic of Slovenia for Nature Conservation and protected by the Nature Conservation Act. These geosites are thus the icon sites to describe the geodiversity of the Slovenian Classical Karst and its scientific value for the understanding of karst phenomena and the geological processes which created them.

In Chapter 13 there is a map and the list of geosites within the Slovenian Classical Karst.

10.1 The Škocjan Caves and Kačna Cave (geosites 53 and 49)

The geological evolution of the geopark is best reflected in the karst caves formed in the Reka/Timavo hydrogeological system. One of the largest cave spaces has been formed here, not only in Europe but also in the world.
The Škocjan Caves are a 6550 m long and 223 m deep cave system consisting of eleven karst caves, four of which have separate entrances on the surface (Fig. 10.1).

These active and relict or fossil speleological objects are connected to the karst surface through the Mala and Velika Dolina collapse dolines. Most of the caves were formed in the Cretaceous thick-bedded limestone and only a small part in Paleocene bedded limestone. Although Škocjan Caves can be defined as a water cave formed by the sinking Notranjska Reka river, the main cave is generally divided into a water part (Šumeča Jama) and a dry part (Tiha Jama). The river first sinks into the Mariničeva and Mahorčičeva Jama caves, 80 m below Škocjan Village at an altitude of 317 m above sea level. It then flows on the surface in the Mala Dolina, crosses under the natural bridge (Okno) and finally sinks into a major

Fig. 10.1 – The Notranjska Reka river sinks into Škocjan Caves below Škocjan and Matavun Villages. Before disappearing into the underworld for the last time the Reka appears in Mala and Velika Dolina collapse dolines (Photo: Matej Blatnik)

part of the Škocjan Caves below the viewpoint in the 160 m deep Velika Dolina at 269 m above sea level. In the central part of the Škocjan Caves, the Notranjska Reka river flows through several halls, and further into the Hanke Channel, which is the longest single cave channel in the caves, with a length of about one kilometre, a width of 10-15 m, and a height of up to 90 m, the largest underground canyon in Europe (Fig. 10.2).

The Hanke Channel is followed by two large halls, the second of which, the Martel Hall, is the largest known underground hall in Slovenia and second largest in Europe. It is 308 m long, 89 m wide on average, 123 m at its maximum, 106 m high on average and 146 m high at the highest point. At the end of the Martel Hall, in the Martel Lake, the lowest point of the cave is located at 214 m a.s.l. The Martel hall (Fig. 10.3) is followed by a 1.5 m high and 9 m long passage to the Marchesetti Hall. Behind the siphon of the Marchesetti lake, another 680 m of passages have been discovered in the last twenty years.

The Tiha Jama is a dry fossil channel of the Škocjan Caves. Due to difficult access from the direction of the Šumeča Jama, it was discovered relatively late compared to the other passages of the Škocjan Caves. It is 525 metres long and lies between 340 and 350 metres a.s.l.
Some 800 metres of undiscovered passage separate the Škocjan Caves from Kačna Cave, a cave west of Divača, with an entrance at an altitude of 435 metres (Fig. 10.4). It is 280 metres deep and consists of a network of channels about 20.5 km long, located between 154 m and 290 m a.s.l. This currently makes it the third longest cave in Slovenia after the Migovec cave system and the Postojna cave system.

The first explorations of the cave were related to the search for water resources for the supply of Trieste and the search for the underground course of the Reka/Timavo river. The bottom of the entrance shaft was reached in 1891 by A. Hanke with the help of local people.
The entrance to the cave is a large doline, at the bottom of which opens a 186 m deep system of parallel shafts. These all eventually come together and end at the ceiling of the 60-metre-high entrance hall. The river appears at normal water level in a siphon near the Risnik collapse doline at an altitude of about 200 metres a.s.l. and disappears in a drainage siphon at an altitude of 154 metres. During floods, the water level in the cave rises about 126 metres.
All the caves where the Reka/Timavo river watercourse is encountered are extremely important from a scientific point of view, because they allow us to see and study the karst aquifer “"in situ", which is often considered a "black box". In this way, we can directly verify the characteristics of the aquifer itself, which we can normally only determine using data from springs and/or sinkholes and precipitation.

10.2 The Vilenica Cave (geosite 24)

For the study of the geological (tectonic) and geomorphological evolution of the area, the relict or fossil and roofless caves are of particular importance. Between Divača and Sežana there are several rather large relict/fossil caves, which represent the former main drainage paths of the Karst aquifer formed in the flooded, i.e. phreatic, hydrogeological zone. During the later tectonic uplift of the Karst, they “hung” in a vadose hydrological zone and could be defined to some extent as the former, now abandoned underground riverbed of the Reka/Timavo river. A characteristic cave of this type is Vilenica (Fig. 10.5), one of the longest (841 m) and deepest caves in the Classical Karst. It is located in the Sežana Karst and with its current depth of 190 m, or at the cave

Fig. 10.2 – Up to 90 m high Hanke Channel - the largest underground canyon in Europe with the Hanke bridge (Photo: Matej Blatnik)

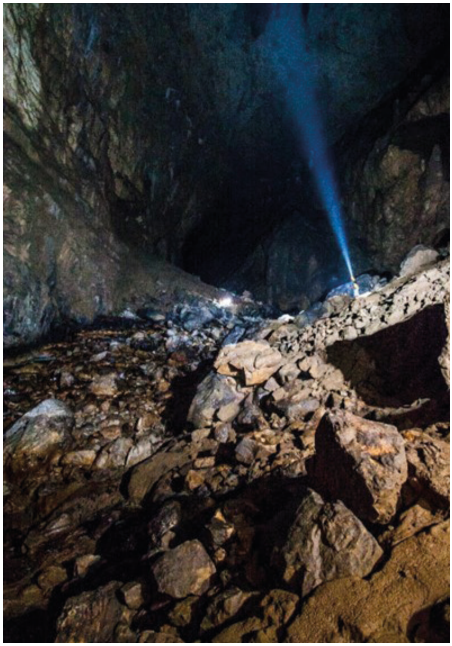


Fig. 10.3 – With a volume of over 2.5 million m³ the Martel hall is the largest known underground hall in Slovenia and second largest in Europe (Photo: Matej Blatnik)

floor at an altitude of 227 m, and its location between Kačna cave and the newly discovered water caves (Jama 1 v Kanjaducah, Brezno v Stršinkni Dolini) it is perhaps still connected with the Reka/Timavo river in its lower part. The cave channels in the part of the cave that is arranged for tourist visits are spacious and decorated with beautiful flowstone.

Vilenica is considered to be the oldest tourist cave in Europe and probably in the world. The data show that the owner of the land began to receive income from entrance fees as early as 1633. Since 1980, literary evenings have been held in the cave, and since 1986, the Vilenica International Literary Festival - a meeting of poets and writers from all over Europe – when also Vilenica Prize is given to a Central European author for outstanding achievements in the field of literature and essay writing.

Fig. 10.4 – The 186 metres deep entrance shaft of the Kačna cave widens into 60-metre-high entrance hall in the lower part (Photo: Matej Blatnik)

10.3 Blind valleys of Matarsko Podolje: Odolina blind valey (geosite 61)

Apart from the unique blind valley of the Notranjska Reka river sinking into the Škocjan Caves, the most characteristic and geologically interesting contact karst features are the blind valleys of Matarsko Podolje on the SE border of the geopark (Fig. 10.6 and Fig. 10.7).

This is a system of 17 parallel surface streams that form a surface drainage system on the siliciclastic flysch of the Brkini hills that sinks near the contact with the carbonate rock under the 20 km long and 2 to 5 km wide levelled karst surface of Matarsko Podolje. Since the valleys are cut into the karst edge due to the uneven uplift of the area, the deeper valleys are on the SE part of Matarsko Podolje. The shallowest blind valley, Brezovica in the NW part of Matarsko Podolje, is cut only 50 m deep, while the deepest Brdanska Dana is cut 250 m deep into the limestone hills and its floor is 120 m below the levelled surface of Matarsko Podolje. At present, the karst water level is deep below the floors of the blind valleys even during floods. The recent gradient in the karst is so high that the old deposits are washed from the surface into the karst by suffosion processes.

Odolina (Fig. 10.8) is a typical blind valley of Matarsko Podolje. Near the transition of the stream into the limestone, the narrow river valley widens and forms a blind valley 1 km long and 300 m wide, cut 60 m into the karst plain at its end. At normal water levels, the stream sinks into the riverbed immediately upon reaching the limestone, while during heavy rains the water sinks into the 117 m deep originally phreatic ponor caves. The bottom of the blind valley is covered with coarse-grained siliciclastic Quaternary sediments derived from flysch. In the ponor cave of the Jezerina blind valley, no significant deposits of clastic sediments have been recorded for the last 12 ka, as flowstone has begun to grow on alluvial sediments. These alluvial sediments are presently cut by river erosion, and alluvial dolines and sinkholes up to 25 m deep have formed on the floor of the Odolina blind valley.

Fig. 10.5 – Vilenica, the oldest show cave of Europe. Tourists have been able to admire its beauties since the 17th century (Photo: Matej Blatnik)

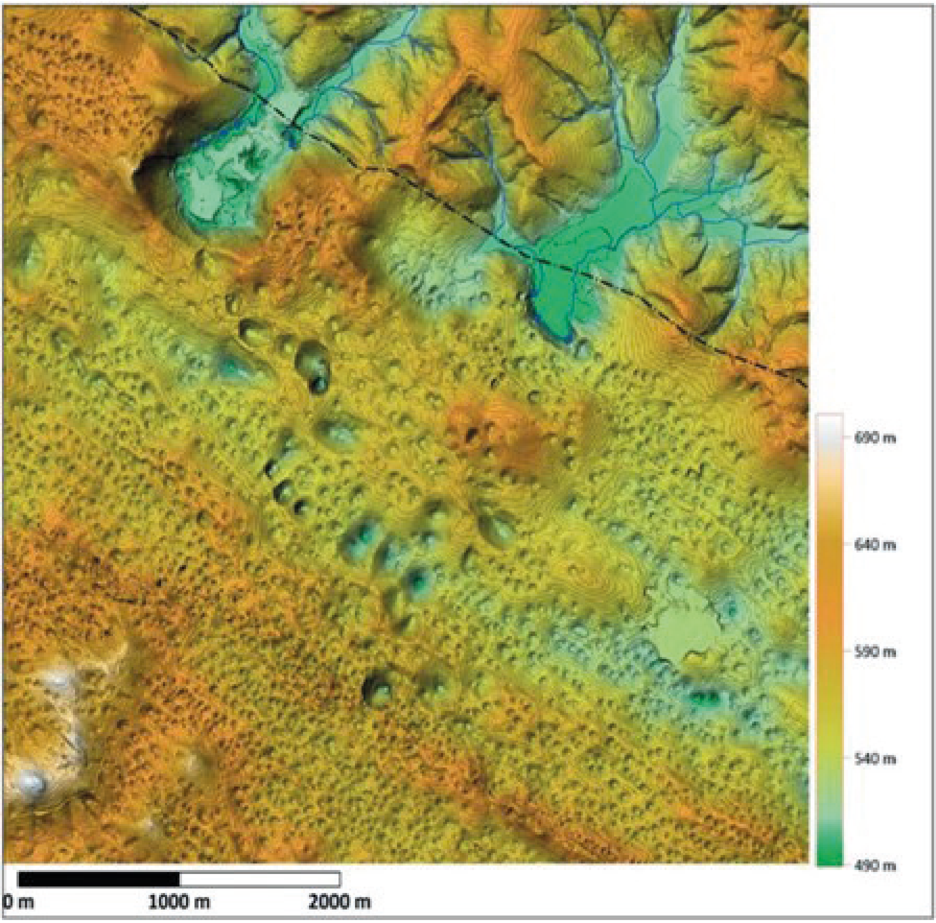


Fig. 10.6 – Contact karst with typical blind valleys. Surface streams flow from the impermeable flysch region of the Brkini hills (NE) and sink into the levelled karstic surface of Matarsko Podolje (archive of IZRK ZRC SAZU)

Fig. 10.7 – The Brezovica blind valley is the most north-western and thus the shallowest blind valley of Matarsko podolje. Left figure: view to the NE towards the Brkini hills with a surface drainage system (Photo: Matej Blatnik); right figure: view to the SW over the karstified Matarsko podolje levelled surface (Photo: Matej Blatnik)

Fig. 10.8 – The bottom of the Odolina blind valley is covered with coarse-grained siliciclastic sediments of Quaternary age, derived from flysch. The stream on the left side sinks as a waterfall into originally phreatic 117 m deep ponor cave at high water flows (Photo: Matej Blatnik)

10.4 Fossiliferous Tomaj Limestone (geosite 34)

The abandoned Kazlje Quarry in the Tomaj Limestone is one of the most important sites for fossil vertebrates, invertebrates and plants from the Late Cretaceous in the northern part of the former Adriatic-Dinaric carbonate platform. The paleontological findings from this site have been published in a number of scientific publications.

The Kazlje Quarry is located in a forested area about 400 m southeast of the centre of the village of Kazlje. Tomaj Limestone is a thin-bedded to platy limestone, once used as roofing and flooring material. It occurs as individual horizons within the thick-bedded Upper Cretaceous rudist limestones and forms vertical walls up to 4 m high in the abandoned quarry. The limestone is dark colored and laminated. In the limestone layers nodules and lenses of chert occur, a hard, dense rock composed of microcrystalline quartz. The presence of pelagic fossils together with terrestrial plant fossils shows a good connection between the open sea and the lagoon where this limestone was formed about 84 million years ago. A large number and variety of well-preserved fossils, including plants, ammonites, fish, turtles, sea urchins, brittle stars, planktonic organisms and even imprints of soft-bodied jellyfish have been found in the Tomaj Limestone in the wider area and described in the scientific literature (Fig. 10.9 and Fig. 10.10).

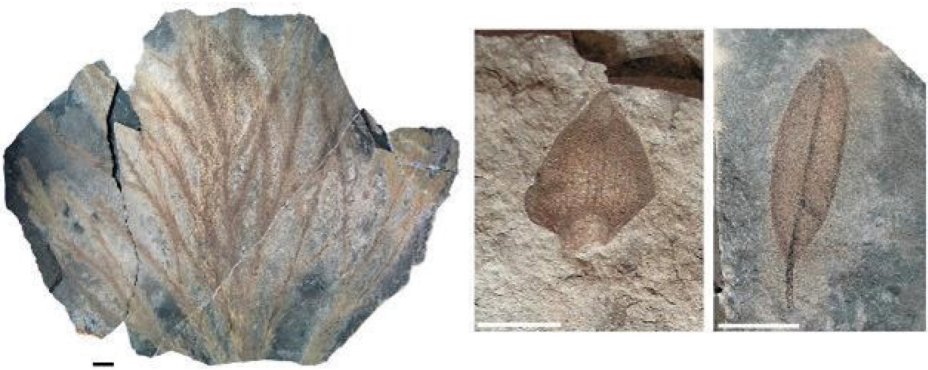


Fig. 10.9 – Plant fossils, found in Tomaj Limestone (from left to right: conifers Brachyphyllum and Araucarites, and Magnoliaphyllum). Scale bar 1 cm (Photo: Bogdan Jurkovšek)

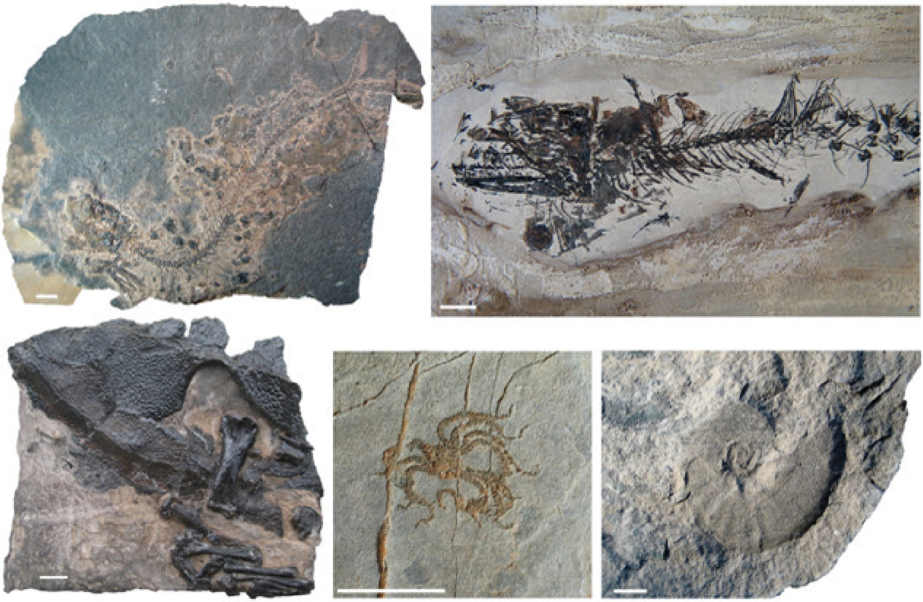


Fig. 10.10 – Animal fossils of Tomaj Limestone (from left to right: fish Chirocentrites and Enchonodus, turtle, ophiuroid brittle star, and ammonite). Scale bar 1 cm (Photo: Bogdan Jurkovšek)

10.5 The Lipica rudist limestone quarry (geosite 45)

The Lipica Limestone, one of the Upper Cretaceous rudist limestone types, contains numerous varieties of limestone that differ both in structure and colour. This limestone represents the most commercially valuable rock in the Classical Karst area (Fig. 10.11). Both the names of the limestone and the natural stone are derived from the village of Lipica.

Rocks of the Lipica Formation were formed about 85 million years ago in the immediate vicinity of thickets of rudist clams that were the inhabitants of the shallow marine carbonate platforms and marginal areas of the Tethys Ocean during the Cretaceous period.

Near the western edge of the quarry, younger and softer Upper Cretaceous-Lower Paleocene limestone beds overlay the Lipica Limestone. As a result, the terrain towards Lipica is less karstified and coal layers are frequently found between the limestone beds. Coal was mined in the 19th and early 20th century in this area.

Fig. 10.11 – The Lipica 1 Quarry lies northeast of the well-known Lipica Stud Farm. In this quarry, large blocks of massive Cretaceous limestone are exploited. The quarry is situated in the most economically promising part of the Lipica Limestone in the north wing of the Lipica syncline, a large bowl-shaped fold with an axis slightly plunging towards the southeast (Photo: Matevž Novak)

Fig. 10.12 – Today, two types of limestone are obtained in the Lipica 1 Quarry. The first is a light olive-grey, homogeneous, fine- or coarse-grained uniform ('unito') type with fossils or fossil fragments of only a few millimetres big (left). The other type is composed of a more fine-grained groundmass that contains mainly rudist shells and other fossil remains of different size. Due to their flower-like cross-sections this limestone is named the Lipica rosy ('fiorito') type (right). Besides rudists, both types of limestone often contain foraminifera, sponges and skeletal parts of other inhabitants of the warm, well-ventilated shallow marine environment of the former Adriatic-Dinaric carbonate platform (Photo and drawing: Bogdan Jurkovšek)

10.6 The Raša Fault zone (geosite 38)

Several long, regional faults run through the Outer Dinarides in southwestern Slovenia in a NW-SE direction, which were formed in past geological periods. One of them is the Raša Fault (Fig. 10.13), named after the Raša river on the edge of the Classical Karst plateau. The Raša Fault runs almost in a straight line from the edge of the Southern Alps near Gemona to Ilirska Bistrica and further to the southeast, probably across the Velebit. It is one of the faults along which the North Adriatic Block is laterally displaced and thrust under the Southern Alps. Based on the location of the seismic foci, it is assumed that the Raša Fault is seismically active today southeast of Vremščica, while seismic activity along this fault in the Classical Karst and Friuli area is less reliable.

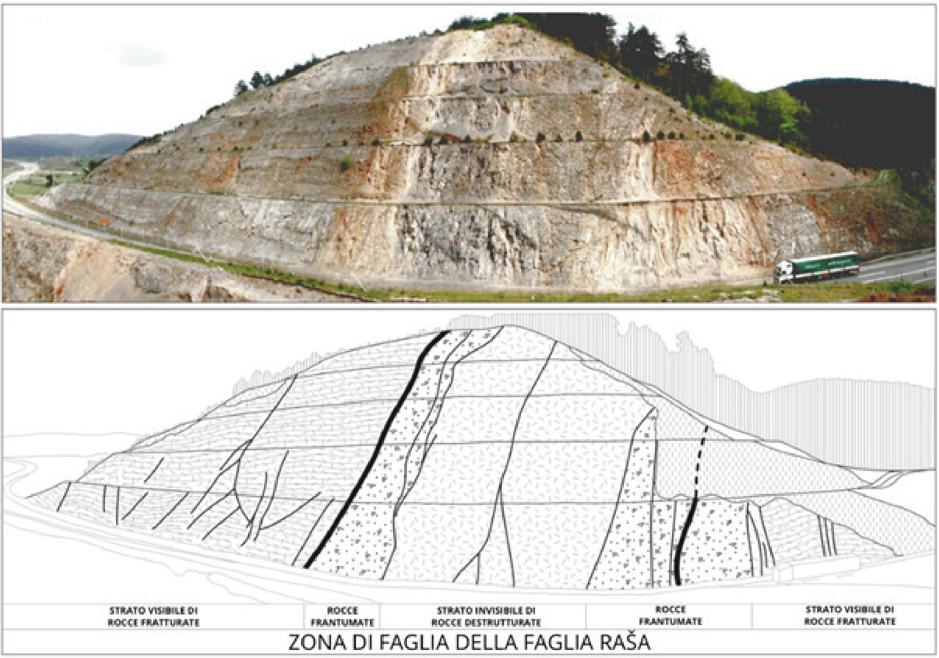


Fig. 10.13 – On the Zajčica section of the highway near Senožeče, we can see a cross-section of the almost 100-metre-wide fault zone. From the vantage point on the other side of the highway, where there is an explanatory board, we can see the typical zoning of rock deformation within the inner and outer fault zones. In the inner fault zone, we see crushed rock followed by the destructed rock in which the bedding is not preserved. In the fractured rock of the outer fault zone, the original bedding of the limestone is still visible. The northeastern tectonic block (left) consists of layered limestone of the Upper Cretaceous rudist limestone, and the southwestern block (right) consists of layered Upper Cretaceous-Lower Paleocene limestones (Photo: Ladislav Placer, Bogomir Celarc. Drawing: Ladislav Placer)

11. GEOLOGICAL ITINERARY: From flysch to flysch across the Karst anticline along the Way of St. James

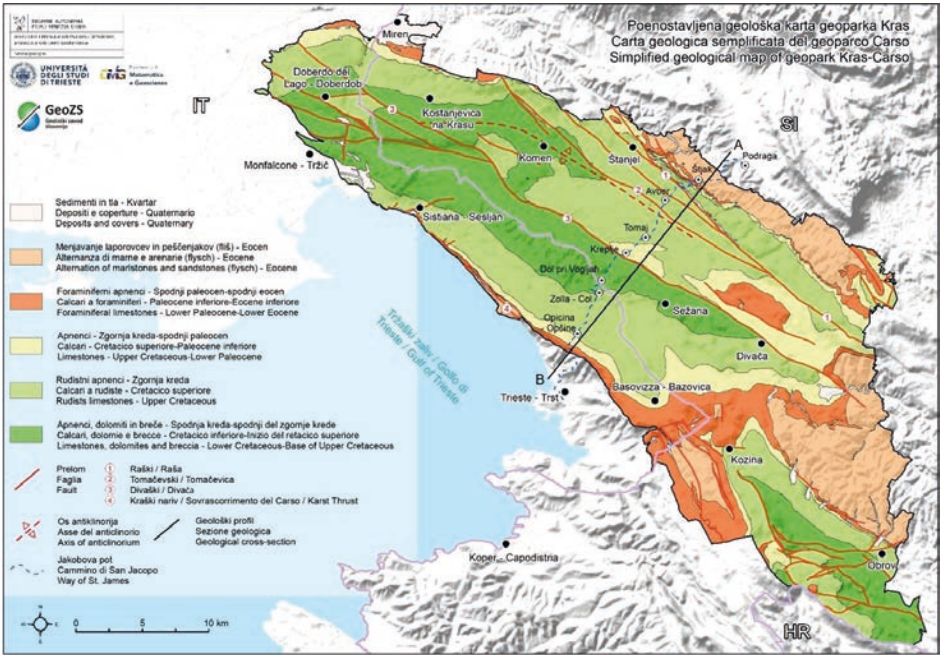
Authors: Matevž Novak and Bogdan Jurkovšek
Expert advisors: Jernej Jež, Petra Žvab Rožič

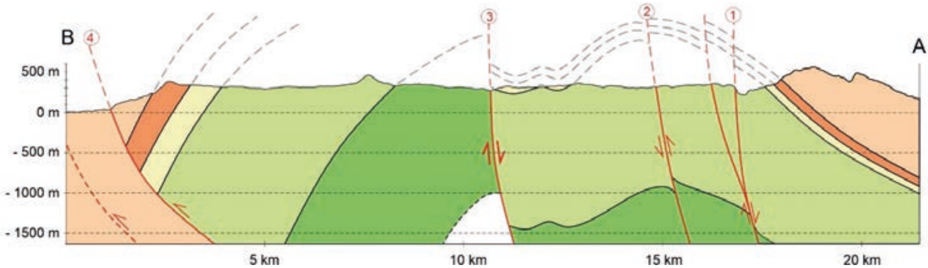
11.1 Introduction

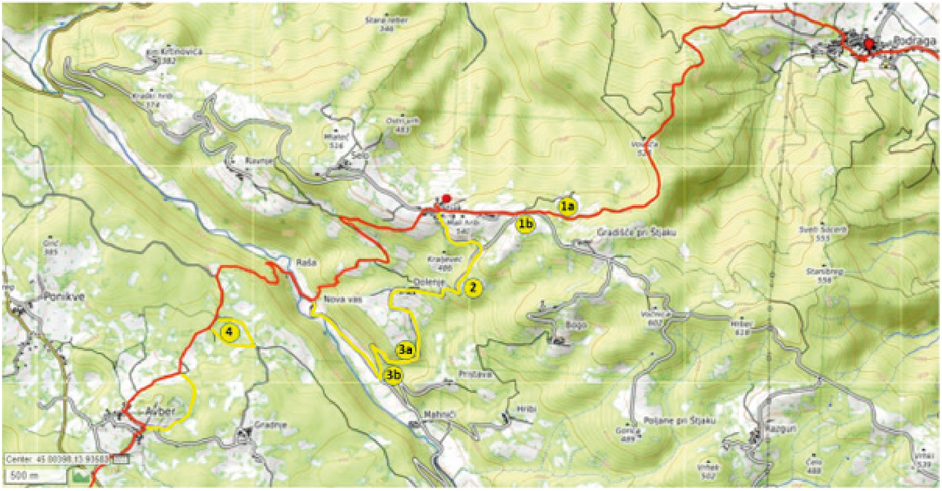
The main objective of this itinerary is to introduce visitors to the large-scale geological structure of the geopark by crossing the Karst anticline from the flysch of the Vipava Valley to the flysch of the Bay of Trieste. The best way for the visitors to get the glimpse of the symmetry that characterizes anticlinal folds is by crossing the anticline perpendicular to its axis. The one existing itinerary which perfectly corresponds to this condition, is the Way of St. James. The Littoral (Primorska) section of this trail leads from the youngest flysch rocks in the northeastern flank of the fold, across the older carbonate rocks of the Karst Plateau in the centre of the fold, and back to the youngest flysch rocks in the southwestern flank (see the trail trace on the geological map in Fig. 11.1). Although this trail does not traverse many of the geopark's geosites, it clearly exhibits all of the major geological units and many other phenomena related to geology.

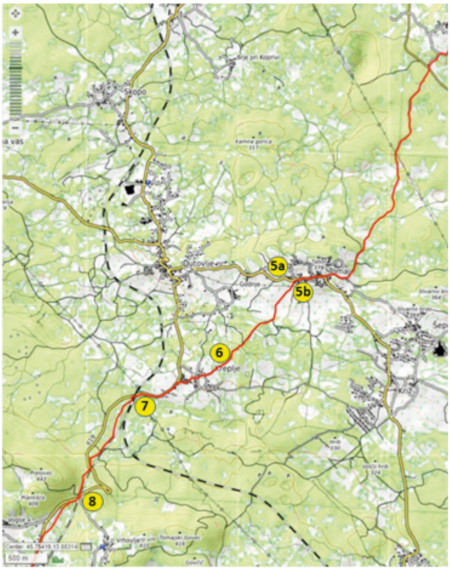
The Way of St. James has other advantages as well: it is a cross-border hiking trail of international renown (also known as the Camino de Santiago), it is well marked in nature with yellow arrows and trail blazes with a scallop, and in the open-street maps where its tracks and profiles are available online (Fig. 11.2; http://www.jakobova-pot.si/jakobs-way-slovenia/; http://www.jakobova-pot.si/jakobova-pot-slovenija-na-zemljevidu/; http://www.geopedia.si/#T1973_x413196_y66220_s12_b4).

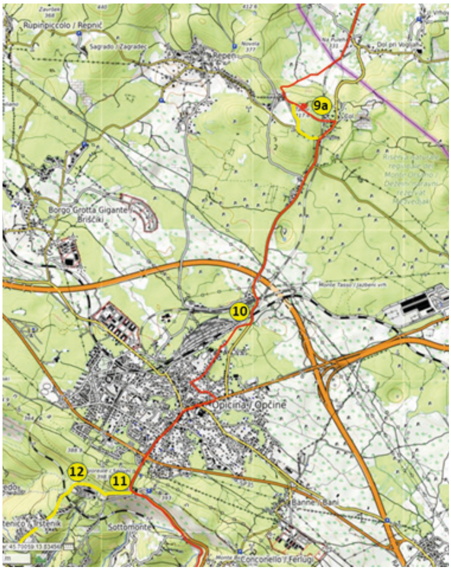
Fig. 11.1: The Way of St. James plotted on the simplified geological map of the Classical Karst and the geological cross section. Note that the scale of the cross section is vertically exaggerated by a factor of 2 to better show the anticline structure (Map adapted from Bensi et al., 2022; cross-section drawn by M. Novak)











Map data from OpenTopoMap.org.
Yellow line shows deviations from the route of the Way of St. James

The Way of St. James trail blaze with a yellow scallop

Fig. 11. 2: The itinerary with stops

The Littoral (Primorska) section of the Way of St. James, stretching from Štjak village to Trst-Trieste, is nearly 25 km long. Conducting a guided tour with observations and explanations covering its entire length in a single day could be quite challenging, if not impossible. Nevertheless, each shorter segment of the trail possesses unique geological attractions that can be explored individually. However, in order to achieve the goal of presenting the large-scale geological structure of Karst to the visitors, it should be explained in the context of the Karst anticline. To assist the guides, here are some visual aids with simple explanations. For a more detailed information about the tectonic processes that formed the Karst anticline, see Chapter 5.2: Today's geological structure of Karst.

The easiest way to describe the formation of an anticlinal structure is by using the models on Figure 11.3. In this process, rock layers, which were initially deposited horizontally (1), are subjected to compressional tectonic forces during orogenesis, and gradually, plastic deformation takes place forming a fold. The resulting upright (convex) fold is known as an anticline (2), while its opposite, the downward-bending (concave) fold, is referred to as a syncline. The surface erosion is gradually removing the "swelling" and revealing deeper layers that are progressively older from the limbs (flanks) towards the centre of the anticline (3).
The entire Classical Karst Plateau is one huge anticlinal fold, with its long axis running in the northwest-southeast direction. This is the easiest way to describe what visitors will observe on this itinerary.

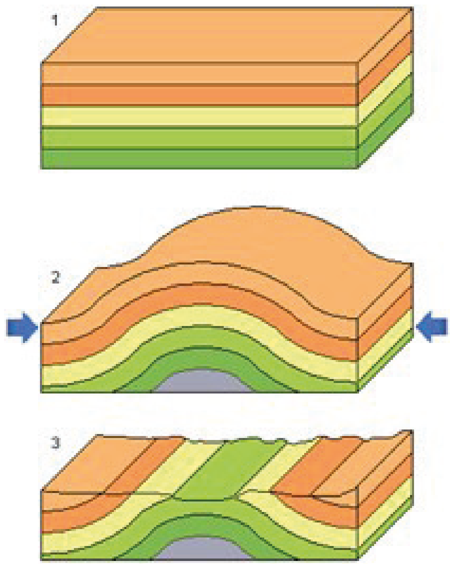
However, for a more complex introduction, compare the eroded surface of model 3 in Figure 11.3 to the simplified geological map of the geopark in Figure 11.1. The geological units in the map don't align as parallel and accurately as in the simplified model due to several reasons. The first reason is that the anticline is asymmetric, meaning that the axial plane is not vertical but inclined, resulting in one limb being steeper than the other (Figure 11.4). In the case of the Karst anticline, the limb that slopes towards the southwest is more inclined than the limb that slopes towards the northeast.

Further asymmetry is due to the plunging hinge line, meaning that the crest of the anticline is tilted from the horizontal position (Figure 11.5). In the case of Karst anticline, the hinge line plunges towards the southeast at a slight angle. As a result, progressively older geological units are exposed by erosion towards the northwest.

However, most damage to the perfect symmetry is due the fact that the Karst anticline is not a simple fold but an anticlinorium, named the Trieste-Komen anticlinorium. An anticlinorium is a big anticline which is folded internally into smaller folds, both anticlines and synclines. Additionally, the entire anticlinorium is dissected into smaller tectonic blocks by many steep faults, dominated by the Divača, Tomačevica and Raša faults in the NW-SE direction (see Fig. 11.1).

Finally, the Karst anticline is not something that can be seen in nature, not even from afar, such as from an airplane or on satellite images. It can only be visible through structural measurements of rock bed orientation and by knowing the age of each geological unit displayed on the geological map. Thus, don't forget to have a copy of the geological map with you while leading the tour.

Fig. 11.3: The process of formation of eroded anticline: 1. Horizontal rock layers before deformation; 2. Compressional forces fold layers and an anticline is formed; 3. Surface erosion of the anticline exposes older rocks at its nucleus while younger rocks are found at its flanks. Adapted from https://commons.wikimedia.org/wiki/File:Folds.png



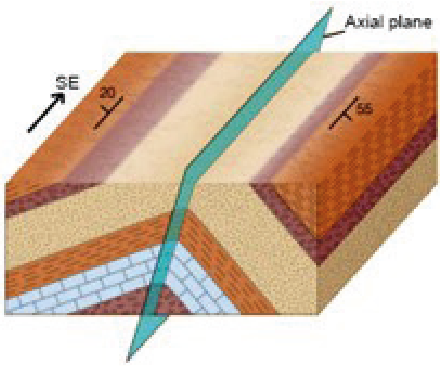


Fig. 11.4: Inclined anticline (Thompson Higher Education, 2007)

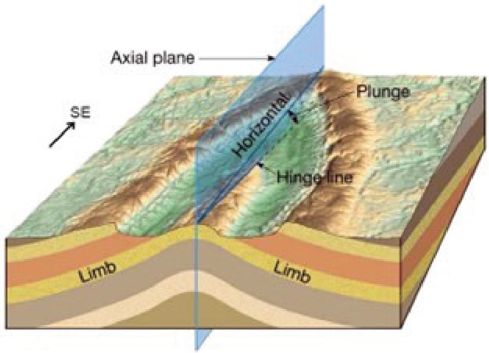


Fig. 11.5: Plunging anticline (adapted from Pearson Prentice Hall, Inc., 2005)

11.2 The itinerary and the observation points

The Littoral (Primorska) section of the Way of St. James enters the territory of the geopark on Vovšča hill (526 m a.s.l.) between the villages of Podraga in Vipava valley and Štjak on the ridge called Vrhé.

Stop 1 – Flysch at Štjak

The whole ridge of Vrhé is built of flysch beds, which is on this side of the Karst Plateau referred to as the Vipava Flysch. The term flysch does not refer to a rock, but to a characteristic sequence of different rocks that alternate in a characteristic fashion (see Chapter 4.5 for the explanation on the formation of flysch). At Stop 1a (Fig. 11.8), we can observe the alternation of thin brownish-grey marlstone and sandstone beds. Sandstone beds are harder and usually stick out like narrow bookshelves, while the softer marlstone is almost everywhere disintegrated. Flysch is typically very prone to weathering and often forms thick soil cover, ideal for vineyards, orchards, and other sorts of agriculture land. This we can observe all around Štjak. But this also has downsides on steeper slopes where the weathering residue easily slides down. A detailed account of a historic landslide from the slope above Podraga village in February 1969 is given by D. Radinja (1971). Under compressive tectonic forces, thin layers of flysch can easily be plastically squeezed into small-scale folds or completely crushed. Such deformation can be seen just above the main road at Stop 1b (Fig. 11.9).

Note that flysch beds are gently inclined towards NE as they form the outermost unit on the northeastern limb of the Karst anticline. The flysch is of early Eocene age, about 50 million years old, and thus the youngest of the geological units of the geopark, apart from the Quaternary slope scree and alluvial deposits. From here, our itinerary will first take us on a journey through geologic time "down the geological column" (Fig. 11.10) through the ever-older rocks towards the center of the Karst anticline. This is also a journey from the depths of the ocean basin to the pleasantly warm shallow sea on the Adriatic-Dinaric Carbonate Platform, bursting with life.

From Štjak, the Way of St. James has two alternative paths to the Raša valley, a footpath down the slope to Nova vas, and for the cyclists the road through the village of Dolenje. All described units can be observed on either of the two, but we suggest choosing the road as rocks are better exposed in the road cuts.

The change from the shallow marine sedimentary environment to the deep flysch basin was gradual and

A RECOMMENDATION TO THE GUIDES

The use of basic geological equipment

Most rocks in Karst lying by the roadside do not look particularly interesting: a rather featureless limestones, with little to show to the casual observer. For many geologists, the memory of the shock, and the thrill of minor discovery when they first looked through a hand lens at the fresh, wet surface of a limestone sample, is still fresh. Such treasures should not be withheld from visitors. To make their geological experience more exciting and your explanations more convincing, we strongly recommend the use of three basic pieces of geological field equipment: a geological hammer, a hand lens and a small dropper bottle containing dilute hydrochloric acid (Fig. 11.6).

The most common **geological hammer** is also called rock hammer or rock pick. The blunt hammerhead is used for breaking rocks and cutting small samples to get a look at a fresh surface for examination. The sharp pick end is only for light prying and digging in loose or weathered rock. Caution: the metal used in the manufacture of ordinary hammers is too brittle and sharp chips can fly off (a good reason to wear safety goggles). Geological hammers are made from specially hardened steel.

The **hand lens**, also called a loupe, allows geologists to examine rocks closely to identify small fossils and minerals. The most common ones have a small 10x magnifying glass folded into a metal or plastic case. To use the hand lens correctly, hold the lens close to your eye and then move the rock sample towards the lens until you get a good focus of the surface (Fig. 11.7).
Advice: Rocks should be examined on a fresh surface of a sample obtained by breaking the rock with a geological hammer. Wetting the surface makes fossil and mineral structures to stand out clearly, rather than being lost in the blur of a dry surface. Most geologists are accustomed to licking the rocks, but in a group of visitors this would be a rather inappropriate method. We therefore recommend the use of water from a bottle or, even better, a small plastic spray bottle.

Dilute hydrochloric acid (10% HCl) is used to perform the so-called acid test to distinguish the most common carbonate rocks, dolomite and limestone. Using a small dispensing bottle (a bottle with a dropper), a drop of 10% HCl is applied to a fresh rock surface and watched for bubbles of carbon dioxide gas to be released. The bubbles indicate the presence of carbonate minerals such as calcite and dolomite. The vigorous reaction distinguishes limestone from dolomite, which reacts very weakly or not at all.
Here's a tip: A household vinegar can be a safe, inexpensive, and easily obtained "acid" for identifying calcite and dolomite. Vinegar is dilute acetic acid (about 5% to 10%), that produces a weak reaction with calcite in limestone.

Fig. 11.6: Basic geological equipment (Photo: M. Novak)

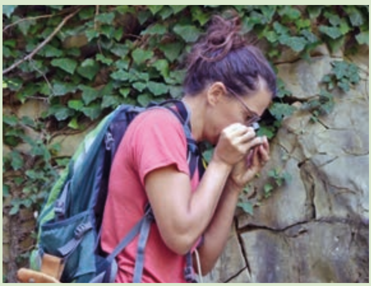


Fig. 11.7: The correct way to use a hand lens (Photo: M. Novak)

Fig. 11.8: Gently sloping flysch beds of alternating sandstones and marlstones at Stop 1a (Photo: M. Novak)

Fig. 11.9: Strongly folded and crushed flysch beds at Stop 1b (Photo: M. Novak)

thus we can observe exchanging horizons of thick limestone beds, marly limestone, and flysch beds after leaving Štjak. We call this lithostratigraphic unit the Transitional Beds.

Stop 2 – Foraminiferal limestones at Dolenje

From the last sharp bend in the road before Dolenje all the way to the village, we can observe mostly indistinctly bedded light grey to grey limestone. It is often possible to see many small fossils on the weathered surface, even with the naked eye. However, to examine these microfossils in their full splendor, we need to start using the geological equipment described. Break off a small piece from the limestone bed or loose rock, wet the fresh surface and look through the hand lens. In most specimens you will see many beautiful structures. Most of these are tests (calcareous shells) of foraminifera (see Chapter 3.2). They belong either to the very small miliolids, which look like little white rose blossoms (Fig. 11.11), or to one of the larger foraminiferal groups, the alveolinids, which look like little white volleyballs (Fig. 11.12), or the nummulitids, which look like little lips (Fig. 11.13) (see how they look like through the microscope in Figs 17 and 18).

On a weathered rock surface, nummulitids have a positive relief (they stand out from the surface), whereas alveolinids and miliolids have a sunken relief (they are incised below the surface level). This is due to the different composition of their tests. Alveolinids and miliolids have porcelaneous calcareous tests (three-layered high-magnesium calcite wall with randomly oriented needle-shaped calcite crystals forming a thick central layer (the "porcelain")), whereas nummulitids have hyaline tests formed by very small interlocking low to high-magnesium calcite grains. Because the stratigraphic range of many foraminiferal species is very short, they are used to give a relative age to the rocks in which they occur. On the basis of the foraminifera observed, these limestones are characterised by the globular alveolinid-dominated assemblages, which represent the lower (older) levels of the Late Paleocene-early Eocene foraminiferal limestone unit.

With some luck, other small fossils such as branch corals, bryozoans and corallinaceans (red algae), dasycladaceans (green algae) can be found in the same road cut. Along the NE margin of the Karst, these organisms, together with clams, gastropods and echinoderms, form lenticular bodies of light grey to white massive coral-algal limestone. It originates from small patch reefs in the inner part of the shallow Adriatic-Dinaric carbonate platform.

Not far from Dolenje, we will cross the next younger geological unit, the Limestones of uppermost Cretaceous to Paleocene age. This unit, which

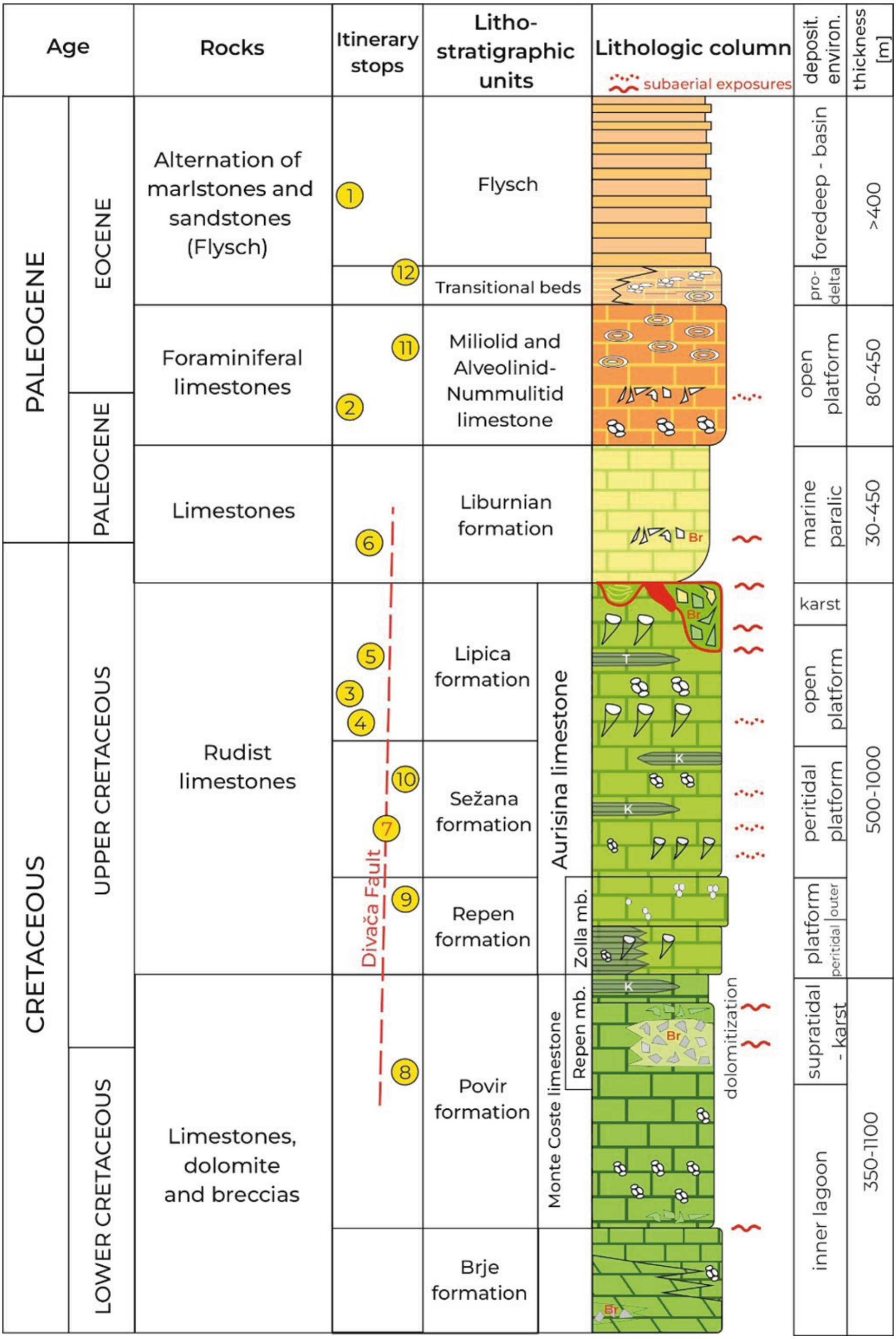

Age
Rocks
Itinerary stops
Litho-stratigraphic units
Lithologic column
subaerial exposures
deposit. environ.
thickness [m]
PALEOGENE
CRETACEOUS
EOCENE
PALEOCENE
UPPER CRETACEOUS
LOWER CRETACEOUS
Alternation of marlstones and sandstones (Flysch)
Foraminiferal limestones
Limestones
Rudist limestones
Limestones, dolomite and breccias
1
12
11
2
6
5
3
4
10
7
9
8
Divača Fault
Flysch
Transitional beds
Miliolid and Alveolinid-Nummulitid limestone
Liburnian formation
Lipica formation
Sežana formation
Repen formation
Povir formation
Brje formation
Aurisina limestone
Zolla mb.
Repen mb.
Monte Coste limestone
Br
T
K
dolomitization
foredeep - basin
pro-delta
open platform
marine paralic
karst
open platform
peritidal platform
platform peritidal outer
supratidal - karst
inner lagoon
>400
80-450
30-450
500-1000
350-1100

Fig. 11.10: Stops on the itinerary marked in the geological column of the geopark (Br - breccia, K - Komen limestone, T - Tomaj limestone) (after Jurkovšek et al., 2016 and Consorti et al., 2021)

corresponds to the Liburnian Formation, is better exposed around Kreplje, so we will examine it at Stop 6.

Stop 3 – Rudist limestone and the Raša Fault zone on the slopes of the Raša Valley

Where the road from Dolenje turns west, it cuts a long stretch of grey limestone (Stop 3a). Dark, ring-like structures can be seen from a distance. These are cross-sections of rudist shells, one of the most common and characteristic fossils of the Geopark (see Chapters 3.1 and 8 for descriptions). At first, we see mostly broken shells, but as we continue along the road, the shells are perfectly preserved (Fig. 11.14). Such an abundance of rudist shells is characteristic of only two lithostratigraphic units, i.e. the Lipica and Repen formations, which correspond to the Upper Aurisina and Zolla formations in the Italian part of the Karst. However, the rudists in the Repen Formation are different and much larger (see stop 9a). The cross-sections of the ones we see here often have spiny or lumpy protuberances, so that they look like flowers or stars. These are typical of the Late Cretaceous Lipica Formation (about 85 million years old). Note also that the limestone beds still dip to the NE, revealing that we are still in the north-eastern limb of the anticline.

Fig. 11.11: Miliolid foraminifera on a polished surface (Photo: B. Jurkovšek)

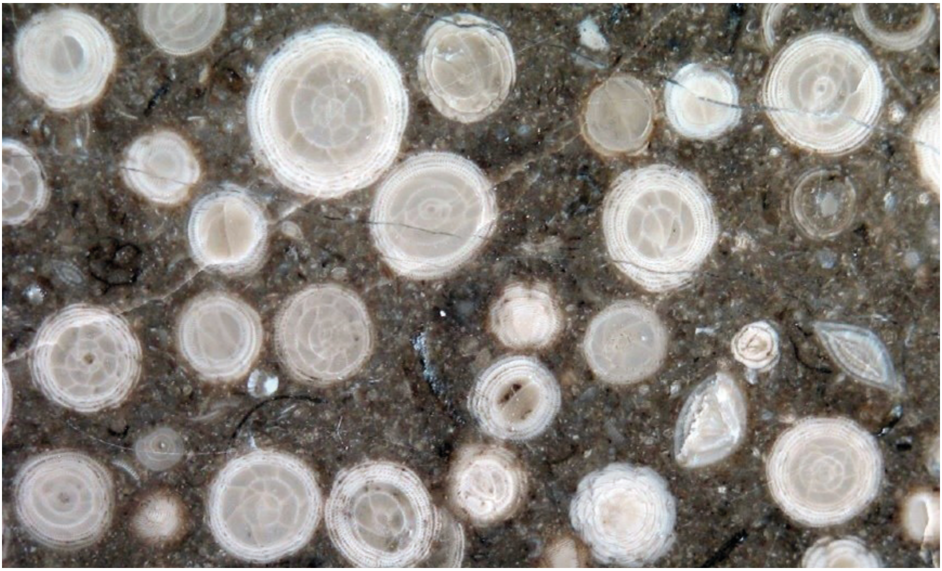


Fig. 11.12: Alveolinid foraminifera on a polished surface (Photo: B. Jurkovšek)

Fig. 11.13: Limestone with alveolinids (left) and nummulitids of genera Assilina and Operculina (right) (Photo: M. Novak)

The closer we get to the Raša Valley, the more the limestone layers are fractured and close to the bottom of the slope they become heavily crushed. We are entering an almost 100 metre wide fault zone of the Raša Fault. When the road reaches the Raša Valley, we see that the valley runs almost straight in a NW-SE direction. This is the direction of the so-called Dinaric structures, which are the result of the Dinaric orogenic phase (see Chapters 5.1 and 10). From where we are standing (Stop 3b; Fig. 11.15), the Raša Fault can be traced towards the northwest through Kobdilj and Štanjel into the Branica Valley and further on into the Friuli area, and to the SW to Senadode and south of Vremščica on to Ilirska Bistrica, and probably over the Velebit Mountains. But what does this fault, so well expressed in the morphology of the surface, really look like and what does it do? Imagine looking at the three-dimensional model beneath your feet. You would see strongly crushed limestone beds of the Lipica Formation, cut with an almost vertical flat surface, inclined about 80° to the NE. This surface is the main fault plane of the Raša Fault Zone. Now imagine that you were watching this process in the past. You would see that the whole region on the other side of the fault plane would slide past you to the right. If you were to jump across the fault plane, the region on the opposite side would again move to the right. Faults that move two blocks in this way are called right (or dextral) strike-slip faults. The Raša Fault is considered to be an active tectonic structure, meaning that it could trigger an earthquake at any time.

At Stop 3b, we leave the Way of St. James' Cycling Route, which continues towards Mahniči, and take a sharp turn towards Nova vas, back to the marked path. The Raša Fault in the Raša Valley runs along its southwestern edge, and in some places even cuts across the protruding parts of southwestern slopes. This is the case of Avberska reber, between Nova vas and Raša, where the path leads us up the slope.

Stop 4 – The delves of Avber

When we reach the plateau, we find trail signs of *"Pot kavadurjev"*. *Kavadur* is the local name for a quarry worker who, difficult conditions and using hand tools and simple equipment, breaks up blocks of stone and prepares them for further processing. This 5 km circular trail takes us to some of the 15 small quarries or delves (or *jave*, as the locals call them) that operated around the village of Avber between the 1st and the 2nd World Wars (here is the map with viewpoints: https://www.avber.eu/pot_kavadurjev.html). Today they are mostly overgrown with vegetation, and in many only large piles of loose stones (called griže by the locals) bear witness to quarrying activities.

Fig. 11.14: Limestone beds, full of rudist shells at Stop 3a (Photo: M. Novak)

Fig. 11.15: The morphological expression of the Raša Fault in the Raša Valley at Stop 3b (Photo: M. Novak)

We recommend that you follow the trail signs for *Pot kavadurjev*, as its eastern part almost coincides with the Way of St. James, with only short detours, and will take us to Avber. At our Stop 4 (corresponding to Stop 3 of *Pot kavadurjev*) we will examine the varieties of limestone in the remains of the Plavišče delve.

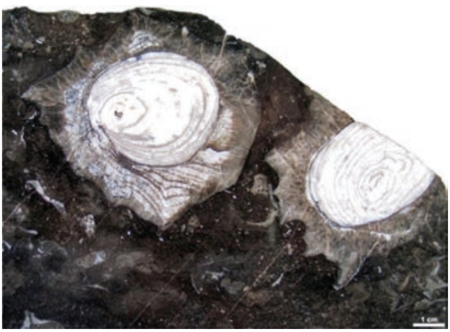
You will see that the structure of the limestone is the same as at our previous stop, and you will also find rudist shells. We are still in the Lipica Formation. However, the colour of the limestone we see here is much darker grey to almost black. This type of limestone, also called Kazlje Limestone or Avber Limestone, is found in the wider area between Ponikve, Avber, Gradnje and Kazlje. It was formed in closed lagoons or on their edges, occasionally low in oxygen, where a great deal of organic matter was preserved and finely dispersed between the sediment grains. It is this admixture that gives the limestone its dark colour. Breaking it with a geological hammer gives off a strong smell of bitumen. Mostly we see uniformly coarse-crystalline limestone composed of completely crushed rudist shells, fragmented into millimetre-sized grains. However, some layers contain well-preserved rudist shells (Figs 11.16 and 11.17). These are the same types of limestone as their lighter cousins, which are still extensively quarried in the large Lipica quarries. The first is known as "uniform" or "unito" limestone, and the second, whose rudist cross-sections resemble flowers, is called "rosy" or "fiorito" limestone (see Chapter 10).

Because of its rarity, good properties and decorative value, this limestone is mainly used as a boutique stone for small decorative elements in churches (altars, pillars, statues) and in noble buildings. The interior of the parish church of St Elija (1823) in the village of Kopriva is a good example.

On the way from Avber to Tomaj we will not see much difference in the rocks. As we walk on the Karst Plateau, we can enjoy the most characteristic karst landscape, a rugged terrain punctuated by dolines and crossed by dry stone walls. But something important is about to change. About halfway to Tomaj, the rarely expressed limestone beds change their orientation. Their gentle dip to the SW tells us that we are now on the other side of the anticline, on its southwestern limb. We have crossed the axial plane (i.e. the centre) of the anticline about 400 metres south of the main road between Ponikve and Dobravlje, but this is impossible to see in nature. In the introduction to the itinerary, we read that we will see the oldest Karst rocks in the centre of the anticline. But if we look at the geological column, we see that the Lipica Formation is still far from its base. Don't worry, a fault (a tectonic one) will soon take us there.

Fig. 11.16: Cross-section of a rudist thicket from northeast of Kazlje (Photo: B. Jurkovšek)

Fig. 11.17: Polished slab of Avber Limestone with a rudist species Eoradiolites avberi from Gradnje (Photo: B. Jurkovšek)



Stop 5 – Platy limestone at Tomaj

On the slope of the hill on which Tomaj rests, we enter a very peculiar geological unit, the Tomaj platy limestone. Platy limestone is a thin-bedded, generally dark-coloured, bituminous, laminated and fine-grained limestone. The beds are typically 1 to 10 cm thick. Lamination is a subtle structure within the beds, consisting of fine layers (~ 1 mm thick).

One of the characteristics of Tomaj platy limestone is the presence of chert, usually in the form of nodules, thin lenses, or thin layers (see Chapter 8). It can be easily recognised by its waxy lustre, a conchoidal (shell-shaped) fracture with very sharp edges, and by its relief from the weathered limestone surface. Another good way of distinguishing chert from other (carbonate) rocks surrounding it is to carry out a simple 'scratch test'. Chert will not only scratch glass, but will also leave a scratch on a steel geological hammer. Another characteristic of the Tomaj Limestone is its rich and highly diverse fossil content, represented by marine reptiles, fish, ammonites, planktonic stemless crinoids and macroflora (see Chapters 4.2 and 10).

Tomaj Limestone occurs in spatially limited sedimentary bodies (lenses and horizons), ranging in thickness from a few metres to 40 metres, within other thick-bedded limestones (see Chapter 4.2). As there are no good outcrops to study the Tomaj Limestone along our route, we will look at it and its architectural significance in two cultural heritage attractions.

Platy limestone is probably one of the oldest building materials in the Classical Karst area. In the past, there were many small quarries in operation in the area, but often the local people simply collected limestone slabs on the surface using picks and levers and were then used for building of dry stone walls, roofing and paving. The slabs used for roofing were usually from 15 x 20 cm to 30 x 35 cm in size and 2 to 5 cm thick. One of the most beautiful examples of a sacral building, covered with slabs (škrle in the local language) of the Tomaj Limestone, is the Church of the Virgin Mary (Fig. 11.18), just a step away from our trail (Stop 5a). Such examples of autochthonous Karst architecture are in great danger.

Due to safety standards and other regulations related to mining and quarrying, as well as natural preservation and conservation, the traditional use of stone is not possible today. There are many challenges to renovating or building a house in the traditional way, including a lack of knowledge about how to do it, legal restrictions and legal access to building materials. For these reasons, building stone is often used inappropriately or replaced by non-autochthonous stone and other materials. Characteristic architectural stone elements of such buildings are often damaged, destroyed or decaying. The loss of such stone-built heritage is a significant threat to the Karst cultural landscape.

As we leave Tomaj, we will pass another stone structure of cultural importance. The dry stone wall, built of Tomaj Limestone, with nicely visible laminations and chert lenses (Stop 5b; Fig. 11.19). The art of dry stone wall construction, knowledge and techniques, have been inscribed on the Unesco List of the Intangible Cultural Heritage of Humanity in 2018.

The cultivated land south of Tomaj owes its fertility to the Tomaj Limestone. Its weathering residue, the reddish-brown soil (terra rosa) containing chert, is particularly suitable for

Fig. 11.18: Church of the Virgin Mary in Tomaj (Photo: M. Novak)

growing vines. When the path leaves the fields, we encounter a new geological unit.

Stop 6 – Cretaceous-Paleogene boundary limestones at Kreplje

The grey to dark grey limestone, which is mostly well bedded, does not differ much from the Tomaj Limestone, and the change would easily go unnoticed if we were not observant. Only careful examination will lead us to the discovery that there are no cherts anywhere in these limestones. But there are fossils that reveal the true nature of these limestones. It is possible to find beds with thin shells of rudists, but beds with numerous shells of other groups of molluscs (clams and snails) are more common. However, the well-bedded limestone at Stop 6 (Fig. 11.20) hides tiny representatives of a very interesting fossil group. To find them, break off a piece, wet the surface and look through the hand lens. You will see many small circles with darker rims. If you are lucky, you may also find these fossils naturally leached out from the weathered surface. In this case you can see the true ovoid shape of these fossils with spirally twisted ridges (Fig. 11.21). These are reproductive organs of green algae of the family Characeae, equivalent to the seeds of land plants. They become fossilized through their calcified oospores, called gyrogoni-

Fig. 11.19: Dry stone wall at Stop 5b and the detail of dark chert layers in the laminated Tomaj platy limestone blocks (Photo: M. Novak)

tes. It is interesting to note, that the characean algae lived in freshwater and brackish environments. We know this from their living relatives, commonly known as stoneworts because they can become encrusted in lime. Indeed, the limestones of the Liburnian Formation were deposited in the alternating shallow marine, brackish and freshwater environments. In some places in Karst, such as in Vremski Britof, carbonised remains of macroflora from the freshwater and brackish phases of sedimentation resulted in the formation of coal beds.

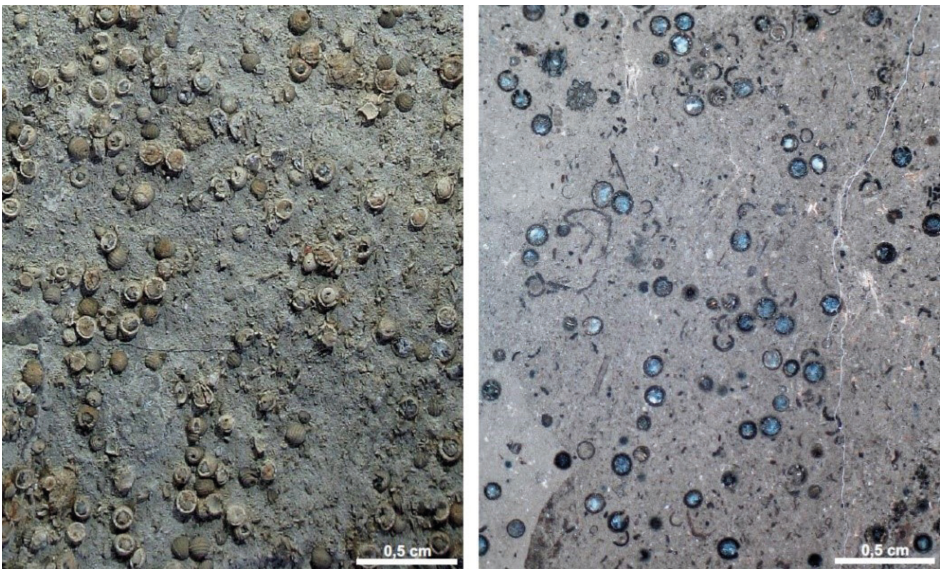
The studied limestone of Liburnian Formation is of Late Cretaceous to Early Paleocene age (about 65 million years old). This means that we are actually moving away from the centre of the anticline towards the younger geological units. Note also that the limestone beds dip to the SW, confirming that we are indeed on the southwestern limb of the anticline.

Stop 7 – The Divača Fault at Kreplje

At the last bend of the road before the railway underpass at Kreplje, our geological journey takes a drastic turn. As we approach, the limestone beds are badly fractured, and when we get to the bend, no bedding is visible in the completely crushed rock (Fig 11.22). If you remember what the fault zone of the Raša Fault looked like at Stop 3, you will easily recognise the similarity. We are in the central fault zone of the new major tectonic structure, the Divača Fault. And as if the railway underpass were some kind of time machine, when we pass through, we are standing on Lower Cretaceous rocks that are 45 million years older. So what happened? Although the Divača Fault is now a right-lateral strike-slip fault, like the Raša Fault, it originally formed as a normal fault in the Eocene, before the anticline was formed (see explanation in Chapter 5.1). Their weakened tectonic zones have been reactivated into lateral movement relatively recently, in a tectonic phase known as the Neo-Alpine, at the transition from the Mio-

Fig. 11.20: Bedded limestone of the Liburnian Formation at Stop 6 (Photo: M. Novak)

Fig. 11.21: Characean gyrogonites on a naturally weathered surface of characean limestone (left) and in a polished limestone slab (right) (Photo: B. Jurkovšek)



cene to the Pliocene ("only" about 5 million years ago). During the period of normal faulting, the entire northeastern "half of today's Karst plateau" was dropped by several hundred metres relative to the southwestern half. Thus, by crossing the Divača Fault, we find ourselves "climbing up" to reach the Lower Cretaceous limestones and dolomites of the Povir Formation, which are about 1,440 metres lower in the geological column. If this is difficult to understand, remember that we are walking on the surface of an anticline, the top of which has been removed by erosion. In order to have the Liburnian Formation on one side of the fault and the much older Povir Formation on the other at the same level, the northeastern tectonic block had to be lowered considerably.

Although the broken symmetry of the Karst anticline is mostly the fault of Divača Fault, it is also thanks to this fault that we will be able to see also some of the oldest rocks in Karst, starting the journey anew from the centre of the anticline towards its outermost geological unit on the southwestern limb.

Stop 8 – Limestone, dolomite and breccia of the Lower Cretaceous on the Preval Prelovec saddle

Walking towards the Preval Prelovec saddle, we see moderately well-developed beds of medium to dark olive-grey limestone. Locally, there are thin packages and beds of dark grey bituminous dolomite.

Where the path reaches the road over the saddle, there is a small stone chapel and to the sides of it we see rocks with a lumpy surface. Look closer and you will see that the lumps are angular pieces of rock, cemented together with a fine-grained matrix (Fig. 11.23). Such coarse-grained sedimentary rock is called breccia. If you break the lump with a hammer, you will see a yellowish-grey surface. Now how can you tell if this is limestone or dolomite? Remember the acid test from the introduction? A drop of 10% HCl will not produce any bubbles on the fresh surface, showing that these pieces of rock are dolomite. Such a dolomitic breccia layer occurs in the Povir Formation at the boundary between the Lower and Upper Cretaceous (100 million years old) across the Karst Plateau. Its origin is interpreted as tectonically and diagenetically formed by several phases of tectonic faulting. The lower part of the Povir Formation and the dolomitic breccia unit correspond to the Italian Monte Coste Limestone and Monrupino Formation respectively.

Fig. 11.22: Crushed limestone in the inner Divača Fault zone at Stop 7 (Photo: M. Novak)

There is another very interesting feature at this stop. Take a look at the road cut at the beginning of the narrower upper road leading to Vrhovlje. The grey dolomite breccia horizon is cut by several thick, almost vertical veins of yellowish material. You will find pieces of dolomite intertwined with flowstone (Fig. 11.24; see also Chapter 8). This is clearly a karst feature. But the karst weathering in this case has not happened recently, but in the geological past. Phenomena such as ancient karst cavities filled with sediments and flowstones are called paleokarst. As they could only form on land, they reveal periods of low sea levels, when parts of the Adriatic-Dinaric Platform were emerging (see Chapter 4.1). So, it is at this stop on our journey through the geological past that we come closest to sticking our heads out of the water.

The Way of St James continues through the predominantly dolomitic layers of the upper Povir Formation and crosses the border into Italy. On the Italian side, the path is not marked, so we have to follow the trail on the map.

Fig. 11.23: Dolomitic breccia at Stop 8
(Photo: M. Novak)

Fig. 11.24: Paleokarst features at Stop 8
(Photo: M. Novak)

Stop 9 – Rudist limestones around Zolla-Col

Surrounded by dolomite, the top of the Tabor hill, on which the splendid *Rocca di Monrupino* (Monrupino Fortress) stands, is built of limestone from the lowermost part of the Rudist limestones unit. It is called the Repen Formation in Slovenia and the Zolla Member of the Aurisina Limestone in Italy. As the geological characteristics of this limestone and the panoramic view from the fortress, are described in the Italian handbook (see Stop 4 of Itinerary 2), we will only mention the statue of the lookout (*Statua della vedetta*) that stands below the walls (Stop 9a; Fig. 11.25).

In the limestone from which this statue is carved, you can recognize the familiar fossil group of rudist clams. However, if we compare their transverse and longitudinal sections with those we have seen in the Lipica Limestone, they are much larger. Together with the much thinner and darker shells of other clams (mostly belonging to the species *Chondrodonta joannae*; see Chapter 3.1), they give this pale grey limestone such a distinctive look, that it is easy to recognize wherever you see it. And you can see it a lot, because it is widely used as an ornamental stone for flooring and walling, both indoors and outdoors. It is called Repen Limestone or Repen Classico Zolla after the town below the Tabor hill. Thanks to its very fine-grained structure, it is one of the most durable natural stones of Karst and is therefore extracted in numerous quarries in this very area. Many of the quarries are no longer in operation.

We recommend that you take the southern road past the Monrupino Cemetery to visit the geologically interesting Towers of Monrupino-Repentabor, described at Stop 3 of

Fig. 11.25: Repen Limestone in the statue at Stop 9a (Photo: M. Novak)

Italian Itinerary 2. Returning to the main road through Zolla-Col, just before the junction, there is a nice long outcrop of Repen Limestone. Its beds dip gently to the SW, as we would expect on the southwestern limb of the anticline. Heading south, we quickly cross the narrow belt of the Repen Formation, which is no more than 500 metres thick in this area. The next stop is already in the younger formation of the Rudist limestones unit. In Slovenia it is called the Sežana Formation, while in Italy it constitutes the lower part of the Aurisina Limestone. This limestone is even better known than the Repen Limestone, and Stop 9b, the Zolla Quarries, is devoted to some of the many excavation sites. For an explanation, see Stop 3 of Italian Itinerary 2.

Stop 10 – Rudist limestones at Opicina-Opčine

Following the Way of St. James along the main road to Opicina-Opčine, we see many exposures of limestone from the Sežana Formation. It usually forms medium-thick to thick beds, rather poor in larger fossils and rudist shells, where they occur, are mostly fragmented. We can see them best in the road cuts of the two underpasses under the railway (Fig. 11.26).

Just after the last railway underpass, we are surrounded by rocks of the youngest of the Rudist limestones. You already know them. They belong to the Lipica Formation. And so we are back to the oldest of the geological units, which we encountered in the centre of the broken Karst anticline NE of the Divača Fault. Here they appear in the southwestern limb and are followed, as if in a mirror image of the northeastern limb, by the younger limestone of the Liburnian Formation, the Foraminiferal Limestone and the Flysch, all of which are already familiar to us. We will not pay much attention to the first two units here, as outcrops are rare due to the city's infrastructure.

Stop 11 – Alveolinid-Nummulitid Limestones at the Obelisk of Opicina-Opčine

The limestone beds on which the Opicina-Opčine obelisk stands are full of white dots. Even nicer pieces of this rock can be found in the weathered loose rock around the obelisk (Fig. 11.27). Look closely and you will immediately recognise alveolinid foraminifera, the same as those we saw at Stop 2. They are accompanied by small lenticular nummulites. We are therefore back in the lower part of the Alveolinid-Nummulitid Limestone, where nummulites have not yet reached large sizes.

Let us mention here another rock that is offered to us for examination in the form of short stone pillars around the obelisk. They are made up almost entirely of fragments of rudist

Fig. 11.26: Limestone of the Sežana Formation with the horizon of fragmented rudist shells at Stop 10 (Photo: M. Novak)

shells. They give a very characteristic appearance to the limestone that we know under the name of Aurisina Limestone. This limestone belongs to the upper part of the unit, corresponding to the Lipica Formation. It was already quarried by the Romans in the famous *Cava Romana* quarry in Aurisina-Nabrežina, not far to the northwest. (see Chapters 4.2 and 6).

Stop 12 – Transitional Beds and flysch along the road to Terstenico-Trstenik

In order to properly observe the rocks that will end our exciting geological journey, we should deviate from the route of the Way of St James. Instead of going down to Trieste-Trst, we take the Via Bonomea to the west, to Terstenico-Trstenik. In the long road cut we follow the Alveolinid-Nummulitid Limestone. The well-developed beds dip relatively steeply (about 40 degrees) towards the SW (Fig. 11.28). This tells us that we are in the lower part of the limb of our anticline - look at Model 11.2 to see that the beds are horizontal in the centre of the anticline. The same geological unit is exposed along the Strada Napoleonica and is described at Stop 6 of Italian Itinerary 2, about 4 km NW from here.

Fig. 11.27: Alveolinid-Nummulitid Limestone beds and the weathered surface (Photo: M. Novak)

Where the slope flattens, the limestone beds suddenly end and a new rock appears. We are at the contact with yellowish-grey marlstone. In the last, i.e. the youngest, limestone beds we can find nice longitudinal sections of large nummulitids. Like what we saw at Stop 1, the marlstone is fractured and heavily weathered. The weathered surfaces are almost white (Fig. 11.29). We are now in the unit called Transitional Beds. They already resemble flysch, but there are no sandstone beds between the marlstones. This unit is very thin and discontinuous in this part of Karst. As we continue down the slope, outcrops are very rare, but here and there the typical sandstone beds of the flysch pop out and most of the stone walls are made of flysch blocks. The so-called Trieste Flysch forms almost the entire coast of the Gulf of Trieste.

Fig. 11.28: Uppermost Alveolinid-Nummulitid Limestone beds along the Via Bonomea with large nummulitids (Photo: M. Novak)

Fig. 11.29: Transitional marlstones at the contact with Foraminiferal Limestone (Photo: M. Novak)

At the end of the fascinating geological journey

And so we are back where we started our geological journey. Although the route we followed was not circular, but rather straight, the almost symmetrical structure of the Karst anticline brought us back to the same geological unit. Looking back on how we were able to determine the age of each geological unit reveals a fascinating paradox. Some of the largest geological structures, such as our great Karst anticline, can only be discovered with the help of some of the smallest fossil creatures, such as our single-celled foraminifera.

12. REFERENCES AND OTHER USEFUL SOURCES

Popular-scientific publications that provide overview descriptions of geological content of the Classical Karst:

Bensi S., Novak M., Otoničar B., Calligaris C., Cucchi F., Zini L., Bonini L., Barone V., Škrjanec S., Piano C. (eds), 2022: Geopark Kras = Il geoparco del Carso Classico = The Classical Karst geopark. Geological Survey - Central Directorate for Environmental Protection, Energy and Sustainable Development of the Autonomous Region of Friuli Venezia Giulia, 2022, Trst-Trieste; Geopark_Kras_SLO.pdf (regione.fvg.it)

Consorti L., Arbulla D., Bonini L., Fabbi S., Fanti F., Franceschi M., Frijia G., Pini G.A., 2021: The Mesozoic palaeoenvironmental richness of the Trieste Karst. 90. Congresso della Soc. Geol. It. - Trieste, 14-16 settembre 2021, Pre congress Field Trip N. 4. Periodico semestrale del Servizio Geologico d'Italia, ISPRA e della Società Geologica Italiana Geol. Field Trips & Maps 13/2.2, 40 pp; The Mesozoic palaeoenvironmental richness of the Trieste Karst (units.it)

Cucchi F., Pirini Radrizzani C., Pugliese N., 1989: The carbonate stratigraphic sequence of the Karst of Trieste (Italy). Mem. Soc. Geol. Ital. 40 (1987), 35–44.

Cucchi F., Finocchiaro F., Muscio G. (eds.), 2009: Geositi del Friuli Venezia Giulia, Ed. DiSGAM-Università di Trieste – R.A. Friuli Venezia Giulia, Tipografia Arti Grafiche Friulane/Imoco spa, Udine, 383 pp.

Cucchi F., Finocchiaro F., Zini L., 2010: Karst Geosites in NE Italy. In: Andreo B., Carrasco F., Duran J.J., La Moreaux J.W. (eds.), Advances in Research in Karst Media, 393–398.

Jurkovšek, B. & Kolar-Jurkovšek, T., 2002: Kras – pokrajina terana in fosilov: kaj kažejo najnovejša raziskovanja. Kras, 45, 37-39, Ljubljana.

Jurkovšek B. & Kolar-Jurkovšek T., 2021: Fosili Slovenije: pogled v preteklost za razmislek o prihodnosti = Fossils of Slovenia. Ljubljana, Geološki zavod Slovenije, 264 str.

Jurkovšek B., Cvetko Tešović B., Kolar-Jurkovšek T., 2013: Geologija Krasa = Geology of Kras. Ljubljana, Geološki zavod Slovenije, 205 str.

Pavlovec R., Pleničar M., Drobne K., Ogorelec B., Šušteršič F., 1989: History of geological investigations of the Karst (Kras) region and the neighbouring territory (Western Dinarides). Mem. Soc. Geol. Ital. 40 (1987), 9–20, Roma.

Geological maps and supplementary explanatory notes:

Cucchi F. & Piano C. (eds.), 2013: Carta geologica del Carso Classico (tratta dalla Carta di sintesi geologica alla scala 1:10.000 – Progetto GEO-CGT) e Brevi Note Illustrative della Carta Geologica del Carso Classico Italiano con Fanucci, F., Pugliese N., Tunis G., Zini L. (eds), Direzione centrale ambiente energia e politiche per la montagna, Servizio Geologico, Regione Autonoma Friuli Venezia Giulia, Trieste.

Cucchi F. & Zini L., 2002: Carta geomorfologica e strutturale del Carso Triestino alla scala 1:50.000. In: Hohenegger J., Melis R., Pervesler P., Pugliese N. (eds.), Field Excursion Guide of the Third Int. Congr. “Environmental Micropaleontology, Microbiology and Meiobenthology” - EMMM’2002 Trieste, 45 pp.

Jurkovšek B. 2010: Geološka karta severnega dela Tržaško-komenske planote 1 : 25.000, tolmač. = Geological map of the Trieste-Komen Plateau 1:25,000, explanatory book. Ljubljana, 72 pp.

Jurkovšek B., Toman M., Ogorelec B., Šribar L., Drobne K., Poljak M. & Šribar L., 1996: Formacijska geološka karta južnega dela Tržaško-komenske planote 1 : 50.000. = Geological Map of the Southern part of the Trieste-Komen plateau (Slovenia), 1:50,000. Inštitut za geologijo, geotehniko in geofiziko, Ljubljana, 143 pp.

Jurkovšek B., Biolchi S., Furlani S., Kolar-Jurkovšek T., Zini L., Jež J., Tunis G., Bavec M., Cucchi F., 2016: Geology of the Classical Karst Region (SW Slovenia–NE Italy). Journal of Maps 12, 352–362, 1 supl.; Full article: Geology of the Classical Karst Region (SW Slovenia–NE Italy) (tandfonline.com)

Placer L., 2015: Poenostavljena strukturno-geološka karta Krasa Kras, (slovensko), Carso (italjansko) = geografska enota. Geologija 58/1, 89–93; Poenostavljena strukturno-geološka karta Krasa Kras, (slovensko), Carso (italjansko) = geografska enota | Geologija (geologija-revija.si)

Scientific articles and monographs with descriptions of the geological structure and individual fossil groups of the Classical Karst:

Barattolo F., Bressan G., Burelli G., Carulli G.B., Cucchi F., Drobne K., Ogorelec B., Pirini C., Poli E., Pugliese N., Romano R., 2005: Cretaceous/Tertiary boundary and Paleocene deposits of Trieste Karst and Slovenia. Studi Trent. Sci. Nat., Acta Geol. 80 (2003), 39–64, Suppl. 1.

Caffau M., Pleničar M., Pugliese N., Drobne K., 1998: Late Maastrichtian rudists and microfossils in the Karst region (NE Italy and Slovenia). Geobios, Mem. Spec. 22, 37–46.

Calligaris R., 1992: I pesci fossili dei calcari ittiolitici di Comeno e di facies a questa correlabili conservati nelle collezioni del Museo civico di Storia Naturale di Trieste. Atti del Museo Civico di Storia Naturale di Trieste 44, 57–111.

Cavin L., Jurkovšek B., Kolar-Jurkovšek T., 2000: Stratigraphic succession of the Upper Cretaceous fish assemblages of Kras (Slovenia). Geologija 43/2, 165–195.

Debeljak I., Košir A., Buffetaut E., Otoničar B., 1999: A preliminary note on dinosaurs and non-dinosaurian reptiles from the Upper Cretaceous carbonate platform succession at Kozina (SW Slovenia). Razprave 40, 3–25.

Debeljak I., Košir A., Buffetaut E., Otoničar B., 2002: The Late Cretaceous dinosaurs and crocodiles of Kozina (SW Slovenia): a preliminary study. Mem. Soc. Geol. Ital. 57, 193–201.

Dobruskina I., Jurkovšek B., Kolar-Jurkovšek T., 1999: Upper Cretaceous flora of Slovenia. Annales 9/2, 243–256.

Dragičević I., & Velić I., 2002: The northeastern margin of the Adriatic carbonate platform. Geologia Croatica 55/2, 185–232.

Drobne K., Ogorelec B., Pleničar M., Zucchi-Stolfa M.L., Turnšek D., 1988: Maastrichtian, Danian and Thanetian beds in Dolenja vas (NW Dinarides, Yugoslavia). Mikrofacies, foraminifers, rudists and corals. Razprave 4. razr. SAZU 29, 149–224.

Drobne K., Ogorelec B., Pleničar M., Barattolo F., Turnšek D., Zucchi Stolfa M.L., 1989: The Dolenja Vas section, a transition from Cretaceous to Palaeocene in the NW Dinarides, Yugoslavia. Mem. Soc. Geol. Ital. 40, 73–84.

Gorjanović-Kramberger C. 1895: Fosilne ribe Komena, Mrzleka, Hvara i M. Libanona uz dodatak o oligocenskim ribama Tüffera, Zagora i Trifalja. Djela jugoslavenske Akademije znanosti i umjetnosti 16, 1–67.

Jurkovšek, B. & Kolar-Jurkovšek, T., 1995: Zgornjekredni skat Rhinobatos iz Lipiške formacije pri Dobravljah (Tržaško-komenska planota, Slovenija). Annales 7, 161-170, Koper.

Jurkovšek B. & Kolar-Jurkovšek T., 2007: Fossil assemblages from the Upper Cretaceous Komen and Tomaj Limestones of Kras (Slovenia). Neues Jahrbuch für Geologie und Paläontologie - Abhandlungen 245/1, 83–92.

Košir A., Goričan Š., Debeljak I., Otoničar B., Turnšek D., 1999: Vodnik po ekskurziji ob 50. obletnici ustanovitve Paleontološkega inštituta Ivana Rakovca ZRC SAZU. Ljubljana, Založba ZRC SAZU, 20 pp.

Ogorelec B., Dolenec T., Cucchi F., Giacomich R., Drobne K., Pugliese N., 1995: Sedimentological and geochemical characteristics of carbonate rocks from the K/T boundary to Lower Eocene on the Karts area (NW Adriatic platform). Proc. of 1st Croatian Geol. Congress, Opatija, 415–42.

Ogorelec B., Dolenec T., Drobne K., 2007: Cretaceous–Tertiary boundary problem on shallow carbonate platform: carbon and oxygen excursions, biota and microfacies at the K/T boundary sections Dolenja vas and Sopada in SW Slovenia, Adria CP. Palaeogeography, Palaeoclimatology, Palaeoecology 255/1-2, 64–76.

Otoničar B., 2007: Upper Cretaceous to Paleogene forbulge unconformity associated with foreland basin evolution (Kras, Matarsko Podolje and Istria; SW Slovenia and NW Croatia). Acta Carsologica 36/1, 101–120.

Placer L., Vrabec M., Celarc B., 2010: Osnove razumevanja tektonske zgradbe NW Dinaridov in polotoka Istre. Geologija 53/1, 55–86;

Pleničar M., 2005: Upper Cretaceous Rudists in Slovenia. = Zgornjekredni rudisti v Sloveniji. SAZU 39, 255 pp.

Pleničar, M. & Jurkovšek, B., 1997: Rudisti iz Lipiške formacije v kamnolomu Lipica I = Rudists from the Lipica Formation in the Lipica I quarry. Annales 11, 115-140, Koper.

Radinja D., 1971: Usad nad Podrago v Vipavski dolini: primer porušenega prirodnega ravnotežja v flišni submediteranski pokrajini. Geografski zbornik 12, 265–318.

Scotese C.R., 2014: Atlas of Paleogene Paleogeographic Maps (Mollweide Projection), Vol. 1 and 2, The Cenozoic and The Cretaceous, PALEOMAP Atlas for ArcGIS, PALEOMAP Project, Evanston, IL; Home Page (scotese.com)

Scientific articles and monographs with descriptions of the hydrogeology of the Classical Karst:

Aljančič M., Brenčič M., Gams I., Kranjc A., Lajovic A., Lowe D.J., Planina T., Sket, B., Šušteršič F. (eds.), 1998: Škocjanske jame - The Škocjanske jame caves. Naše jame 40, Bulletin of the Speleological Association of Slovenia.

Civita M., Cucchi F., Eusebio A., Garavoglia S., Maranzana F., Vigna B., 1995: The Timavo hydrogeologic system: an important reservoir of supplementary water resources to be reclaimed and protected. Acta Carsologica 24, 169–186.

Cucchi F., Zini L., Calligaris C., 2015: Le acque del Carso Classico/Vodonosnik klasičnega Krasa. Progetto/Projekt HYDROKARST, EdizioniUniversità di Trieste, 181 pp.

Gabrovšek F. & Peric B., 2006: Monitoring the flood pulses in the epiphreatic zone of karst aquifers: the case of Reka river system, Karst plateau, SW Slovenia. Acta Carsologica 35/1, 35–45.

Gams I., 2003: Kras v Sloveniji – v prostoru in času. Založba ZRC, Ljubljana, 516 pp.

Knez M., Otoničar B., Petrič M., Pipan T., Slabe T. (eds.), 2020: Karstology in the Classical Karst. Springer, Advances in karst science, 222 pp.

Kranjc A. (ed.), 1997: Kras - Slovene Classical Karst. Založba ZRC, Ljubljana, 254 pp.

Kranjc A., 1999: Uvod. In: Kranjc A. (ed.), Kras – pokrajina, življenje, ljudje. Založba ZRC, Ljubljana, 9–17.

Kranjc A., 2002: Zgodovinski pregled in opis jam (A Historical Overview and Description of the Caves). In the monograph Park Škocjanske jame (The Škocjan Caves Park), Škocjan Caves Park publi.

Mihevc A., 2001: Speleogeneza Divaškega krasa. Založba ZRC, Ljubljana, 180 pp.

Zupan Hajna N., 2021: Karst, Caves and People. Založba ZRC, Ljubljana, 173 pp.

Popular-scientific publications with descriptions of karst stone and the stone cultural heritage of the Classical Karst:

Belingar E. (ed.), 2014: Priročnik kraške suhozidne gradnje. Park Škocjanske jame, Škocjan, 31 pp.

Biolchi S., Cucchi F., Pieri F., Devoto S., Furlani S., Tunis G., Zini L., Gerdol S., Bavec M., Kolar-Jurkovšek T., Jež J., Jurkovšek B., Milanič B., Novak M., Šolc U., Peternelj K., Guštin M., Premrl B., 2014: Platy limestones: 10 case studies in the Classical karst. Trieste: Dipartimento di matematica e geoscienze, Università degli studi di Trieste, 48 pp.

Carulli G.B. & Onofri R., 1966: I marmi del Carso. Ed. Del Bianco, Udine.

Cucchi F. & Gerdol S., 1986: I marmi del Carso triestino. Ed. Camera di C.I.A.A. di Trieste, 195 pp.

Jurkovšek B., 2000: Kamnarstvo je del tradicije Krasa. Kras 37, 38–39.

Mirtič B., Mladenovič A., Ramovš A., Senegačnik A., Vesel J., Vižintin N. 1999: Slovenski naravni kamen. Ministrstvo za znanost in tehnologijo Republike Slovenije; Restavratorski center Republike Slovenije, 131 str., Ljubljana

Novak M. (ed.), 2015: RoofOfRock Final Thematic Report. Geological Survey of Slovenia, Dubrovnik. https://roofofrock.geo-zs.si/Publication/index.html

Novak M., Biolchi S., Čebron Lipovec N., Jež J., Peternelj K., Šolc U., Golež M. (eds.), 2015: Roof of rock. Ljubljana, Geološki zavod Slovenije; Dubrovnik, Neretva Regional Development Agency Dunea, 181 pp.

Pavlovec R. & Vesel J., 1992: Flowstone as Natural Stone. Acta Carsologica 21, 185–191.
Renčelj S., 2002: Kras: kamen in življenje. Koper, Libris, 162 str.

Vesel J., 1979: Repen. Geologija 22/1, 117–126.

Vesel J., 1987: Razširjenost nahajališč in stanje raziskanosti arhitektonsko-gradbenega kamna v Sloveniji. Geol. zbornik 8, 1–11.

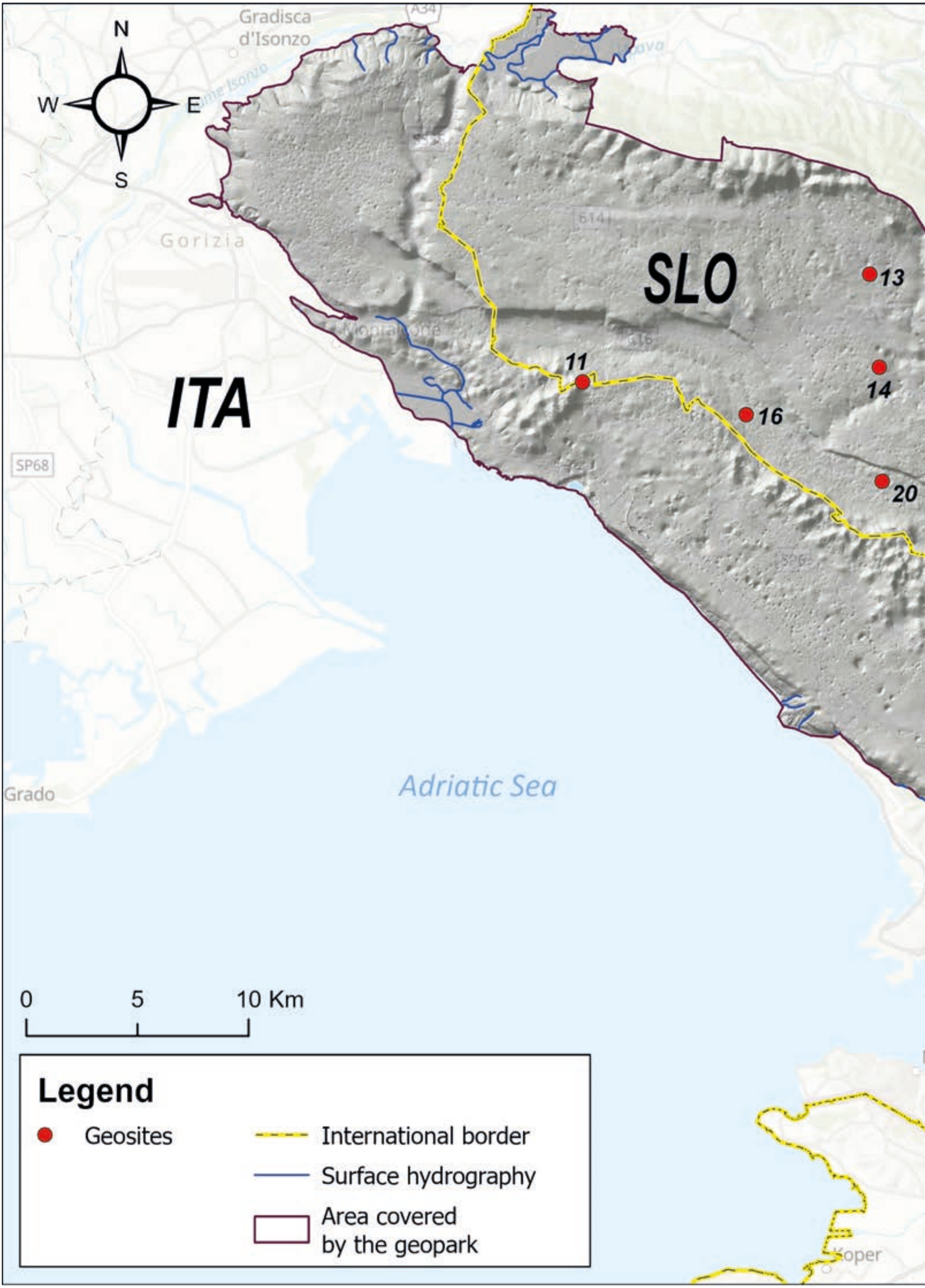
Websites:

Global Geoparks Network: http://www.globalgeopark.org/
Museo di Storia Naturale: https://museostorianaturaletrieste.it/civic-museum-of-natural-history/
Projekt Kras-Carso: https://www.krascarso-carsokras.eu/sl
Projekt RoofOfRock: https://roofofrock.geo-zs.si/Publication/index.html
UNESCO Global Geoparks (UGGp): https://en.unesco.org/global-geoparks
Visit Kras: https://www.visitkras.info/

13. LIST AND LOCATIONS OF GEOSITES

No. of Geosite	Geosite
11	Grofova Jama Cave
12	Paleokarst features and paleosoils of Trsteljska Brda Hills
13	Komen-Škrbina - Komen Limestone with fossil vertebrates
14	Doline at Debela Griža - Volčji Grad prehistoric settlement
15	Mali Dol dry valley
16	Rusa jama at Gorjansko - cave and abandoned quarry of flowstone
17	Outcrop of Komen Limestone at Skopo
18	Kopriva Quarry of rudist limestone
19	Raša valley with its tributaries
20	Veliki (Brestoviški) Dol
31	Repen limestones at Dolina quarry
32	Upper Cretaceous stratigraphic section along the Sežana-Vrhovlje road
33	Phantom Karst' (i.e., dedolomite) in the Povir Formation near Sežana
34	Kazlje Quarry of Tomaj Platy Limestone
35	Cretaceous/Paleogene Boundary section Dolenja vas at Senožeče
36	Fault zone of Divača Fault
37	Uvala Senadolski Dol
38	Raša fault
39	Rudist patch-reef at Senožeče-Gabrče
43	Bestažovca Cave
44	Small-size relief rocky features along the "Living Karst Museum" pathCarso"
45	Lipica 1 Quarry of rudist limestone

46	Vilenica Cave
47	Mines of black coal at Lipica
49	Kačna jama Cave
50	Risnik Collapse Doline
51	Denuded (roofless) cave at the Lipove Doline
52	Reka blind valley and collapse dolines at Škocjan Caves
53	The Škocjan Caves
54	Jama na Prevali 2 Cave (Mušja Jama Cave)
55	Stratigraphic section at Vremski britof
59	Beka - Ocizla Cave System
60	Paleokarst pit with fossil remains of vertebrates (dinosaurs and crocodiles) near Kozina
61	Matarsko podolje system of blind valleys
62	Divaška jama Cave
63	Dimnice Cave



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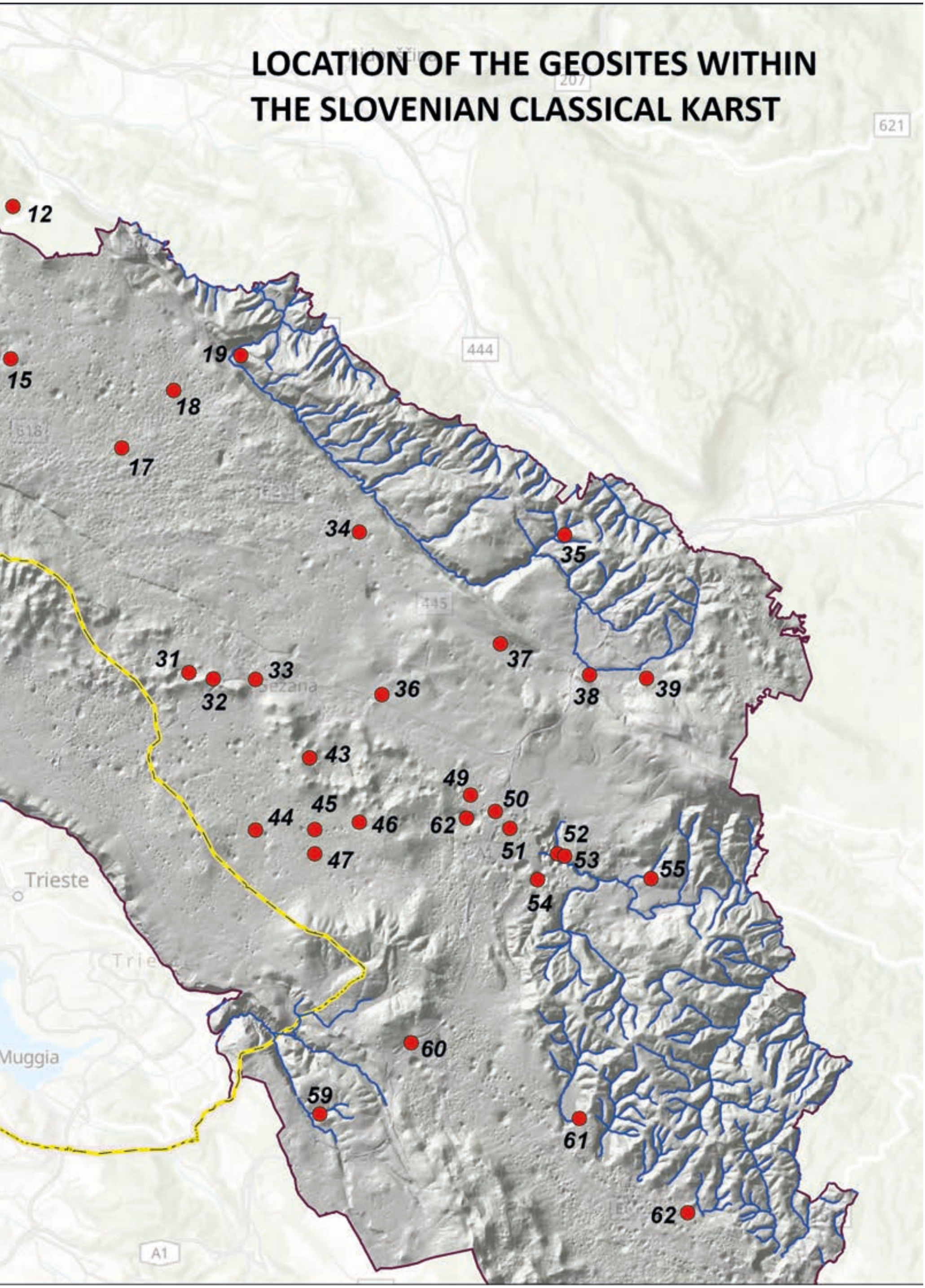
Geosites
International border
Surface hydrography
Area covered by the geopark


LOCATION OF THE GEOSITES WITHIN
THE SLOVENIAN CLASSICAL KARST
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Muggia
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