REGIONE AUTONOMA FRIULI VENEZIA GIULIA

OBČINA SEŽANA

KRAS CARSO GEOPARK

THE CLASSICAL KARST GEOPARK

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Foreword

This special book, entitled „The Classical Karst geopark“, bears witness to a successful cross-border cooperation that will lead to the creation of a cross-border geopark in the Karst region.

The publication is one of the results of the GeoKarst project, co-funded within the framework of the Interreg V-A Italy-Slovenia Cooperation Programme 2014-2020, while the contents produced by the Italian partners were financed by the Geological Survey of the Central Directorate for Environmental Protection, Energy and Sustainable Development of the Autonomous Region of Friuli Venezia Giulia (RAFVG).

The idea of a cross-border geopark originated during the definition of the proposal of the strategic project KRAS-CARSO (Cross-border Cooperation Programme Slovenia-Italy 2007-2013) and proved to be most appropriate during its implementation. In fact, the feasibility Study on the creation of the geopark showed in technical, economic-managerial and participatory terms that the integration of the Karst area could be achieved through the creation of a cross-border geopark as a development tool for the sustainable use of resources and the well-being of the people living on the Karst Plateau. In 2015 and 2017, the 5 Slovenian and 12 Italian municipalities, which comprise the area concerned, decided to create a cross-border geopark, so that, since 2018, the Geological Survey of RAFVG (coordinator for the Italian part of the geopark) and the Municipality of Sežana (coordinator for the Slovenian part) have been intensively collaborating on the creation and management of the cross-border Karst geopark.

The book describes all the main features of the Karst, which, as the “cradle” of karst studies, is of global significance from a cultural-historical and scientific point of view. In the book you will note the frequent use of bilingual place-names and toponyms, this reflects the rich history of the area, which stands at the intersection of various cultures. Nowadays, the inhabitants of the Karst are mainly Slovenians and Italians. Slovenian language and culture in the Italian part of the Karst is covered by a law protecting the linguistic minority.

Our sincere thanks go to all the contributors who have made this book possible.

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INTRODUCTION

Figure 1.1.1: The Karst in spring time, a view from the inside towards the Adriatic (Photo: Sara Bensi)

1.1 Geoparks and the UNESCO Global Geoparks Network

A geopark is a geographic area with well-defined boundaries and recognized geological importance, in terms of scientific significance, rarity, aesthetic or educational value of the sites of interest contained therein. In a geopark, the primary purposes - that is, the protection and enhancement of geodiversity - are combined with education and sustainable development objectives that particularly involve local communities. A geopark uses its geological heritage, in connection with all other aspects of the area's natural and cultural heritage, to enhance awareness and understanding of the key issues facing society, such as using the Earth's resources sustainably, mitigating the effects of climate change and reducing natural hazard-related risks. By raising awareness of the importance of the area's geological heritage in history and society today, Geoparks give local people a sense of pride in their region and strengthen their identification with the area.

The concept of Geoparks developed around the mid-1990s and is now promoted on an international scale by UNESCO. In the year 2000 the European Geoparks Network (EGN) was formed, which was later (2004) merged into the broader Global Geoparks Network (GGN).

The European Charter of Geoparks, which each EGN member is called on to accept and sign, provides for the development and experimentation of:

- methods of **conservation** of the geological heritage;
- partnerships with local companies to promote and support the creation and **marketing of new products** linked to the area's geological heritage;
- activities to promote **geotourism** and holistic economic development;

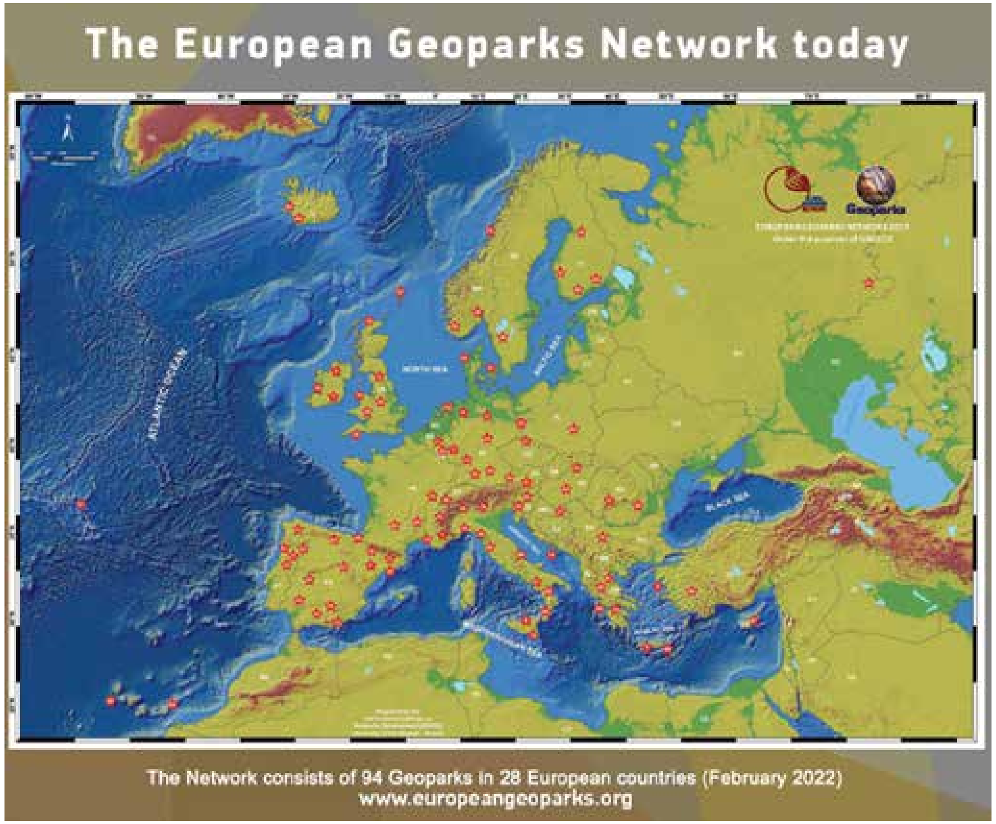


Figure 1.1.2: Map of the European Geoparks Network and, on the right side, the list of Italian and Slovenian Geoparks, including the location of the Classical Karst (from site: www.europeangeoparks.org)

✦ activities to promote **environmental education and scientific research** in the disciplines of Earth Sciences.

By 2022 there were 177 UNESCO Global Geoparks, distributed in 46 countries over four continents.

Italy and Slovenia are well represented on the international scene with 14 Geoparks recognized in the European Network and in the Global Geoparks Network under the auspices of UNESCO, and in the whole of Europe only 4 of which fall into the category of cross-border geoparks. Kras-Carso-Karst is also a cross-border area of unique geological and geomorphological characteristics of international importance, which has made it a “cradle” of the science of “Karstology” from a cultural-historical and scientific point of view and has been named the “Classical Karst”.

Figure 1.2.1: The underground watercourse of the river Reka/Timavo River at the bottom of Abisso di Trebiciano - Labodnica Cave was reached at 326 metres below the surface in 1841 (Antonio Federico Lindner 1841)

1.2 Why a geopark on the Classical Karst?

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

The main geological highlights of the Classical Karst geopark 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. As a matter of fact, modern speleology (systematic cave exploration and mapping) originated in this area, starting with the search for a water supply for Trieste. In 1841 the underground watercourse of the Reka/Timavo River at the bottom of the Grotta di Trebiciano-Labodnica Cave was reached at 326 metres below the surface (Figure 1.2.1). Due to the distinctive relief forms, local terms for karst phenomena, such as the words “*Kras*”, “*Carso*” and “*Karst*” themselves, while *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 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 (Figure 1.2.2). Comparable in their outstanding appearance and size is the Grotta Gigante-Briška jama Cave 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.

Figure 1.2.2: Škocjan Caves, on the UNESCO World Heritage List since 1986 (Photo: Borut Lozej - Photo archives Škocjan Caves Park)

The significant presence of geo-related resources of the Classical Karst is complemented by:

- about 80 geosites, many of which are recognized for their international importance and are visited and enjoyed by hundreds of thousands of visitors per year.
- the exceptional biodiversity of plant and animal species and the large number of rare and endemic species, places the Karst among the areas with the highest biodiversity in Europe. It is important for the conservation of habitats of endangered plant and animal species in Europe. The area also has great scientific and research significance for the study of cave flora and fauna.
- a significant natural heritage is also evidenced by 67% of the territory falling within the Natura 2000 network; with two Biosphere Reserves under UNESCO with the intergovernmental programme MaB – Man and Biosphere, namely the Škocjan Caves Park and the Marine Protected Area of Miramare.
- the cultural heritage, characterized by numerous archeological sites in the area; by the fortifications and defence infrastructure of the First World War, which in this area recorded one of the bloodiest pages in history, and by the typical local agri-food resources, from wines to oil, from cheeses to ham, strongly connected with the characteristics of the soil and geology.

CHARACTERISTICS OF THE KARST

2.1 What is karst?

"Karst phenomena" or more simply "karst" is the morphological expression covering all the processes of rock removal in which the dominant process is the chemical attack on carbonate rocks, with mechanisms which go under the name of karst corrosion or dissolution. Dissolution occurs where water is present in liquid form and therefore in temperate, subtropical and tropical climates. In areas with low rainfall precipitation, or where snow and ice predominate, the karst process is less effective than mechanical processes such as river erosion, glacial abrasion, etc.

In reality, we have to remember that all rocks are soluble in water, but only some lead, in certain morpho-climatic conditions, to the development of the typical karst forms. These rocks are, in order of importance, carbonates, composed of calcite, dolomite, etc., evaporitic rocks, composed of rock salt, gypsum, anhydrite, etc., and the quartzites composed of various forms of quartz.

Limestones and dolomites represent about a quarter of land, are widespread on all continents and are all more or less karstified.

On the surface, karst takes many forms, making it difficult for the average person to recognize. Some, however, are dramatic and scenic. Much of the karst landscape is also hidden below ground in caves. In most karst areas, there is usually no surface water, because most karst waters flow underground. All precipitation quickly infiltrates below the surface through open fissures and crevices. Even relatively large rivers may disappear into ponors in karst landscapes and their waters flow deep underground through known caves as well as through unknown channels and fissures. The karst surface is commonly rocky, without thick soil cover and therefore unsuitable for cultivation. Thus, karst areas have never been densely populated.

Figure 2.1.1: The Orleška Draga Doline and Mt. Nanos in the background (Photo: Roberto Valenti)

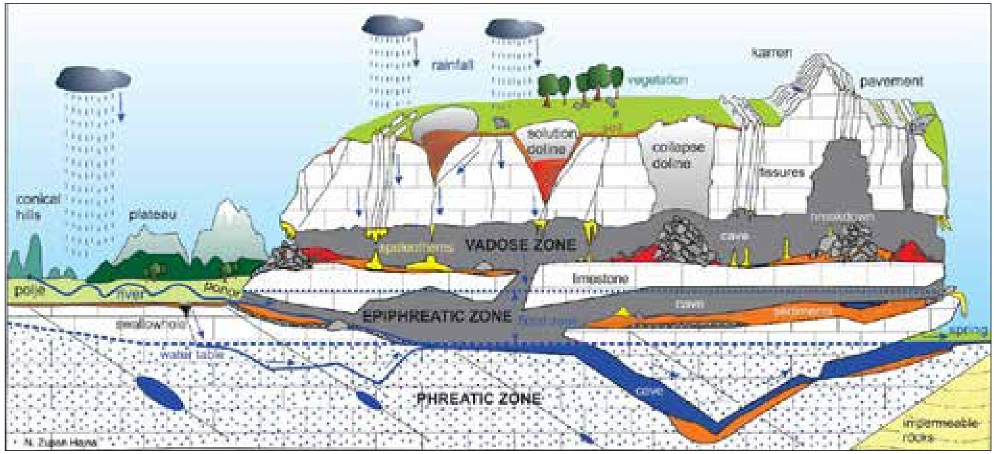


Figure 2.1.2: Conceptual model of the water flow in a karst aquifer with the main surface and underground geomorphological features (from N. Zupan Hajna, 2021)

The toponym "karst" originates from the Paleo-Indo-European word Kar (also Karra) which means rock or stone.

From a scientific point of view, karst is defined as a landscape with characteristic reliefs, caves and groundwater drainage, formed by dissolution processes (Figure: 2.1.2). The term originally referred to the limestone area northeast of the Gulf of Trieste in Slovenia and Italy, named *Carusadus* or *Carsus* in Latin and modified in various languages into *Karst* (German), *Carso* (Italian), and *Kras* (Slovenian). This term was later applied to all areas with similar characteristics. In Slovenian, *kras* means a rocky, bare and dry landscape. The name is often used as a toponym for this type of landscape in the northwestern Dinaric karst of Slovenia and Croatia.

2.1.1 Karst rocks

Dissolution of soluble rock is the most important karst process. Thus, the development of karst landforms is mainly limited to areas where carbonates (e.g., limestone (Figure 2.1.3A), dolomite, chalk, clastic carbonate rocks (conglomerate, breccia), marble, and carbonatite) or evaporites (e.g., gypsum, anhydrite, and salt (Figure 2.1.3C) occur. Of these, limestones and dolomites are the most common. The majority of carbonate as well as evaporite deposits are derived from tropical and subtropical areas where they were deposited on shallow marine carbonate platforms and coral reefs, similar to those found nowadays in the Bahamas (Figure 2.1.4), the coasts of Persian Gulf and Great Barrier Reef of Australia. Later these areas with carbonate platforms were transported from their original position to recent one by plate tectonic processes.

Important properties of carbonate rocks for the formation of karst include porosity, their mineralogical composition, structural and textural characteristics, the degree of impurities and the thickness of the bed in which they occur. Furthermore, the geotectonic regime of certain karstic regions and the geological structures - such as bedding plane partings, fissures, and faults - also play an important role in the formation of karst features and landscapes. Water percolates through open spaces (fissures, fractures, faults, bedding planes,...) in carbonate rocks and simultaneously enlarges them through corrosion processes. The purer the carbonate rock, the less insoluble residues it contains. Dolomite dissolves more slowly than limestone and is more prone to mechanical disintegration.

Figure 2.1.4: Underwater carbonate sand dunes, locally exposed on the land surface (W of Eleuthera Island, Great Bahama Bank, Bahamas (Photo: Bojan Otoničar)

Figure 2.1.3: Karst rocks; A) Upper Triassic bedded limestone of Dachstein Formation (Kanin Plateau, Julian Alps, Slovenia) (Photo: Bojan Otoničar), B) Cretaceous limestone breccia/ conglomerate (Učja Valley, W Slovenia) (Photo: Bojan Otoničar), C) Paleozoic salt (Queshm Island, Iran) (Photo: Bojan Otoničar)

2.1.2 Dissolution of carbonate rocks

The intensity of limestone dissolution is influenced above all by the quantity of precipitation and the partial pressure of the available CO_2, both dependent on climate, and the properties of the rock. In general, the more water and CO_2 to form carbonic acid that are available, the faster the rock dissolves. Water causes dissolution according to its chemical composition and mechanical properties, i.e., the quantity and nature of water flow and the characteristics of its contact with the rock. Karstification of carbonate sediments/rocks begins as soon they are exposed to freshwater or a mixture of fresh and salt water. In principle, limestone and dolomite karstification involve the dissolution of the minerals calcite and dolomite, while impurities remain as an insoluble residue. Rainwater enriched with CO_2 from the atmosphere and soil forms a weak carbonic acid. When percolating through carbonate rocks, this weak carbonic acid dissolves them, forming calcium and hydrogen carbonate ions. When the water enriched with the dissolved ions reaches an open cave environment, the difference in CO_2 partial pressure in the cave results in the degassing (bubbling) of the solution, which causes the precipitation of calcite in various forms of calcite deposit, i.e., different forms of flowstone.

Denudation (the uniform lowering of the land surface) of a karst surface indicates the removal of carbonate material from the surface in ionic form. Values are based above all on climate (quantity of precipitation, temperature), evapotranspiration, CO_2 partial pressure and the composition of the rock (minerals, texture, structure, impurities, etc.). According to field data in a temperate climate, the denudation rate of the karst surface is about 20 - 60 metres per million years.

2.2 Surficial and underground karst forms with karst terminology

Surface karst phenomena are formed by dissolution with rainwater (e.g., karren, dolines), by karst groundwaters (e.g., bottoms of poljes, levelled surfaces) and by transferring karst underground features on the surface (e.g., collapse dolines, unroofed caves). Natural cave entrances are part of the karst surface which lead to the underground. These include shafts, ponors, swallowholes, springs and openings in the floors of collapse dolines, as well as openings formed by the erosional intersection of caves and the karst surface. Caves exhibit different patterns depending on the local geology (rock composition and structures such as fissures, faults, bedding planes), location (latitude, elevation), groundwater characteristics (allogenic vs. autogenic…), the dominant mechanism of dissolution (prevailing acid, mixing corrosion, cooling of ascending water etc.), landscape evolution (different geotectonic realms), and climate (temperate, tropical…).

2.2.1 Karst surface relief features

The formation of karst features depends on the quantity of precipitation, the type of the host rock, the presence of soil and vegetation and the slope or inclination. Suitable conditions result in the formation of both small-scale dissolution features (e.g., flutes, meanders, solution pans, grikes in limestone pavements, etc.) and medium- and large-scale karst features (e.g., dolines, conical peaks, poljes, etc.).

2.2.1.1 Small-scale dissolution features

Small-scale karst features form on the surface of the rocks due to corrosion by water (precipitation) at the contact point with the rock surface (Figure 2.2.1). Their formation depends on the quantity of precipitation, the nature of the flow and the contact between the water and the surface of the rock.

Figure 2.2.1: Small-scale surface dissolution rock features (Photo: archive of IZRK ZRC SAZU): A) rain (solution) flutes (Classical Karst), B) solution grooves (Kanin, W Slovenia), C) solution pans (kamenitzas) (Classical Karst), D) corrosion grikes (Classical Karst)

Small corrosion features of various sizes form on the surface of the limestone, which makes the surface of the rocks uneven and rough (Figure 2.2.1A, B). Solution pans (kamenitzas) (Figure 2.2.1C) are formed on the flat surface of the bare rock, while grooves and larger gutters (Figure 2.2.1A, B) develop along the dip of the slope. If the grooves were formed under the soil that was subsequently removed - and in some places also moss - they are more or less rounded. When joints or other areas of lower resistance are enlarged by corrosion, grikes form (Figure 2.2.1D), which separate the rock into blocks of a range of sizes. Blocks are larger if the rock is thick-bedded or massive. Areas of chaotically dissected smaller stones or screes are also common especially on thin-bedded limestone (griže).

These small scale features are linked either to the active dissolution of the water flowing on slopes of variable steepness (dynamic solubility) or to the static dissolution by standing water in the depressions (static solubility). The former can be further divided into those set along lines of maximum slope and into those set along the discontinuity planes of the rock mass.

We can thus recognize:

- Solution flutes (Figure 2.2.1A)
  Minute forms represented by short straight furrows (about 1 cm deep, 1-4 cm wide, 5-50 cm long) with a rounded section. They are often grouped in complexes (comb, feather, bundle, island) and are separated by sharp ridges that act as a watershed. Their genesis can be traced back to rainwater corrosion due to dynamic solubility along lines of maximum slope.
- Solution grooves (Figure 2.2.1B)
  These are furrows (more than 5 cm wide, more than 3 cm deep, at least 100 cm long) that follow the maximum slope of the limestone surface. They have a varied morphology: the section is always in the form of a U and the development is usually straight but also tortuous or meandering, the latter more frequent on slightly inclined surfaces. The bottom is smooth, often hollowed out by a secondary groove (minimum percolation flow). These are “gutters”, the genesis of which is linked to the concentrated linear flow of runoff waters, so the morphology depends on the inclination of the flow surface, the presence of plant organisms, the type of climate. They are the classic effect of what is called accelerated corrosion.
- Solution pans or kamenitzas (Figure 2.2.1C)
  Small closed basins (depth from 2 to 50 cm, width from 5 to 200 cm), rounded, of variable diameter, shallow compared to the area covered. The floor is usually almost horizontal, the section is flat or bowl-like, widened towards the bottom. Often, they have an outlet. Their genesis is linked to the standing of water in a micro-depression, sometimes originating or favoured by phytokarst, that is to say the erosion of karst rocks by filamentous algae that burrow into them. They widen faster than they deepen as corrosion is more

active at the edges than at the bottom. At the base of the walls, protruding niches are often created, almost “corrosion grooves”, during the phases of progressive emptying of the solution pan due to the progressive deepening of the discharge groove.

- Grikes (Figure 2.2.1D)
  Deep openings, rarely linked to the anastomoses between holes, more often than the true preferential water outflows driven by fracturing. The sides are always very steep, the bottom is flat or V shaped and poorly opened. From the perspective of their genesis, they are similar to karst furrows, although, while in the furrows it is the maximum slope that guides the water flow, in grikes it is the discontinuities (normally those of fractures) which condition the direction of movement.
- Griže (‘*grih-zhe*’)
  Stony ground created by little rocky blocks isolated by karst along the discontinuity surfaces (stratification and fracturing) from the rocky substrate and developing in place, without transport.
- Limestone pavements
  Rocky outcrops in which there are several dissolutive morphotypes in association such as solution flutes, solution grooves, grikes, solution pans, solution runnels, etc.
- Limestone towers
  Isolated residual blocks (5-10 m in height), bearing witness to the ancient surfaces.

2.2.1.2 Medium-scale karst features

The doline is the most characteristic karst landform of middle latitudes (Figure 2.2.2). Those up to ten metres deep and as much as 50 metres wide prevail. These are closed funnel -or bowl-shaped depressions in karst landscape, the width of which is usually greater than its depth. Usually, their slopes are of a similar rockiness as the surrounding karst landscape with sediment or soil cover up to a few metres thick at the bottom. This same landform can be the outcome of a range of processes, such as dissolution, collapse, the washout of fine-grained sediments and the subsidence of strata above more soluble rocks. This said, many dolines are inherited forms of primary caves and shafts. The most common are solution dolines in which the water in them dissolves the rock from the surface and carries it underground in solution. These form at places where water percolates vertically into the depths and effectively dissolves the rock, mainly as a result of the presence of soil and biological activity. The density of dolines on the karst surface depends on the rock type (they are less frequent on dolomites and very numerous on pure bedded limestones), the inclination of slopes (dolines are not found on steep slopes) and the frequency of fractures. Dolines on limestones are rockier than those on dolomites and have less soil on their flanks. Soil typically accumulates at the bottom of dolines, where fields and vegetable gardens are often located.

Figure 2.2.2: Artificially transformed (levelled) doline for agricultural purposes (Bela Krajina, S Slovenia) (Photo: Bojan Otoničar)

Much bigger than regular dolines are collapse dolines (Figure 2.2.3). These are large karst depressions with steep or even vertical slopes, formed by the collapse of the ceiling of major caves. The presence of these morphotypes is mainly linked to the presence of groundwater flows which, as a result of erosion and dissolution, have removed the collapsed material. Collapse dolines do not usually form suddenly, but rather slowly, by the long-term falling of rock from the cave ceiling until a hole opens at the surface. The bottoms of collapse dolines are usually covered with the fallen rocks, which can block the cave entrances. However, through some collapse dolines underlying caves can be reached. During wet periods, when the underground water level is high, lower parts of collapse dolines can be flooded. Larger collapse dolines are between 50 and 200 metres deep and up to a few hundred metres wide. Their volume can reach millions of cubic metres.

Another typical karst relief form is the uvala, i.e., a larger elongated shallow depression with a U-shaped bottom and a higher perimeter. Uvalas are also common with dolomite as the host rock. They may form by the coalescing of several dolines which have enlarged towards one other. They may also have dolines on their floors, as well as a somewhat larger amount of sediment and thicker soil cover.

As was shown above, the surface of limestone karst is commonly rocky and rugged and therefore relatively impassable, the soil cover is thin or accumulates at the bottom of depressions. The surface of dolomite karst is formed through the reciprocal action of denudation processes and fluvio-erosional geomorphic processes. Thus, the surface of dolomite karst is usually smoother and less rocky (Figure 2.2.4), and traces of surface water flow may be visible. There, dells (*dolci*), typical inclined, elongated karst depressions, rather similar to dolines, are commonly found. On dolomite karst, there is more soil than in limestone karst areas and the landscape is therefore more suitable for settlements and cultivation.

Figure 2.2.3: Osp, collapse doline at the Karst edge (SW Slovenia). At high water the stream springs from a cave under the cliff (Photo: Matej Blatnik)

Figure 2.2.4: Slightly undulating surface on dolostone between Gorenje and Bukovje near Postojna (SW Slovenia) (Photo: Bojan Otoničar)

2.2.1.3 Large-scale karst features

A *polje* (Figure 2.2.5) is the largest type of karst depression with a levelled rocky floor, overlain with a thin cover of sediment and a typical karst drainage system. These can be several dozen kilometres long and wide. Usually it has an elongate perimeter and a sinking stream with springs on one side of the polje and ponors on the other. Most poljes are formed along regional tectonic structures and are widened by lateral dissolution of the base of the surrounding slopes. A fluctuating water level flattens the polje's floor by corro-

Figure 2.2.5: Cerknica karst polje, an intermittent lake, with Javorniki and Snežnik Mts. in the background (SW Slovenia. (Photo: Bojan Otoničar)

sion. Oscillation of the water table causes hydrological phenomena such as springs, ponors, estavelles and floods. When the ponors are no longer able to drain away the additional water carried by the sinking stream, intermittent karst lakes occur. In dry periods poljes are dry and the water level is below the surface.

Figure 2.2.6: -Doberdò-Doberdob Lake during low flow (Photo: Philippe Turpaud)

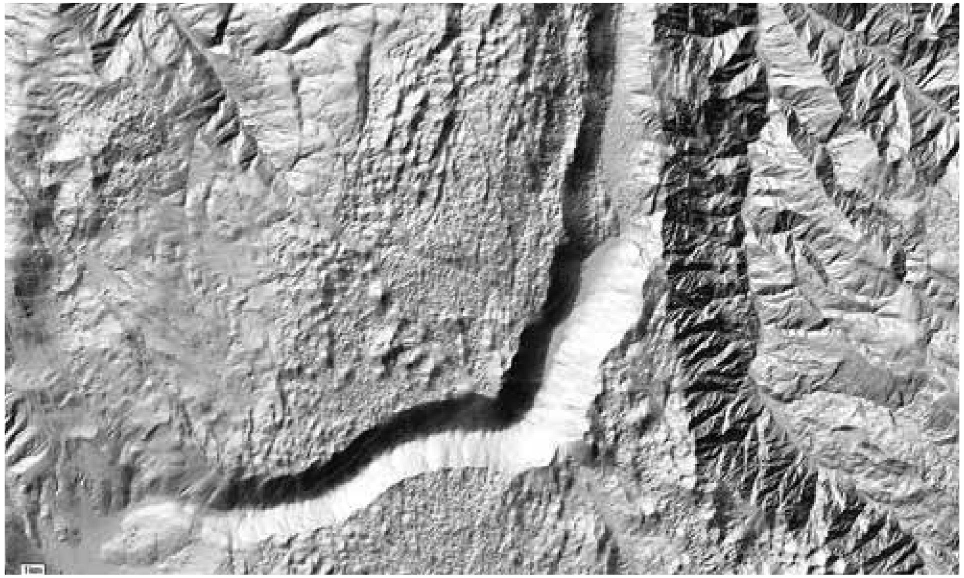
2.2.1.4 Morphological forms of contact karst

The area, where surface water flows from the river relief to the karst, is called a contact karst. Due to the large amount of water that flows into the typical karst marginal depressions, sinkholes, ponors, floodplains and sinks are formed at the contact with the surface river network developed between impermeable rocks and karst. However, typical relief forms of such contact karst are blind valleys. Due to large amounts of water, the dissolution of limestone in such places is faster than in those karst areas where only rainwater dissolves carbonate rocks.Their bottoms are leveled by the oscillation of groundwater and are usually covered by allogenic sediments brought by sinking rivers. As the conduits of the sinking rivers are formed by

average water flows, these cannot drain the increased inflow during heavy rains, and so floods are frequent here.

As a "non-karstic" element in the karst, dry valleys (Figure 2.2.7) can be considered to a certain extent. These are former river valleys that in the past crossed a given karst area. Old riverbeds, for at least part of the year, have no active watercourse for all or part of their length because the water is lost in the karst or is at a much lower level. The bottoms of the dry valleys are usually more or less karstified, so that dolines and other surface karst phenomena occur there.

Figure 2.2.7: Lidar DMR (Slovenian Environment Agency) of an almost 500 m deep incised dry valley, the Čepovanski Dol which crosses the high karst plateau of Banjščice (W Slovenia)



2.2.1.5 Karst plain

Karst plains (Figure 2.2.8) represent levelled surfaces, formed by erosion and corrosion. The complex processes that produce corrosion plains in karst have been termed "lateral solution planation" or "corrosion levelling" and involve a combination of vertical dissolution, lateral undercutting of slopes, and springhead sapping. Larger karst planes may cut and level different geological structures.

2.2.1.6 Coastal karst

Coastal karst develops where rocks that are above sea level are in contact with rocks that are generally below sea level. In these environmental conditions, all the karst features are enhanced by marine aerosols, microbial effects and wave motion, which accelerate all karst dissolution and erosion processes. The mixture of sea water and fresh groundwater also promotes the genesis and development of caves and springs.

Figure 2.2.8: View from Trstelj Mt. on slightly dipped, levelled Classical Karst Plateau surrounded by hilly areas (Photo: Bojan Otoničar)

2.2.1.7 Fluviokarst

A karst landscape where the dominant landforms are valleys cut by surface rivers. Erosion prevails over the dissolution processes.

2.2.2 Caves

The most characteristic karst phenomena, without which there is no "real" karst, are karst caves. By anthropogenic definition, caves are underground cavities large enough for humans to enter. They can be vertical or horizontal and filled with water. Caves consist of a series of interconnected passages (galleries, channels...) of various types, such as tubes, canyons, keyholes, fissures, and meanders. Caves can also widen into large cavities and chambers.

Karst caves are formed as a result of the dissolution of rocks along the route of subsurface water flow in various environments. The geological structures and lithological composition of carbonate rocks have a decisive influence on the formation and development of caves. The water in the rock mass follows the geological discontinuities (bedding plane partings, fractures, faults...) and the most soluble porous layers and, in the case of a karst aquifer, chemically and mechanically erodes carbonate rock on its way, forming channels, i.e., karst caves.

The characteristics of cave conduits, from which we can infer their origin, are mainly due to the hydraulic conditions in which they were formed. In the hydrological sense, caves are conduits in a karst massif in which a turbulent water flow is established as a result of dissolution. The water, pushed initially through hairline fractures by constant pressure, dissolves their walls. The flow thus increases and the fracture widens further, since the chemically aggressive water penetrates ever deeper. The continuation of this process leads, via the accelerated growth of the fracture, to a breakthrough point in which the rate of flow increases by several orders of magnitude in a very brief period. Cave channels can be formed in a constantly flooded (i.e., phreatic) zone, where they are created with a slow pressure flow below the karst water level. This is where most cave channels primarily form, while subsequently growing and transforming under a range of conditions, in occasionally flooded (i.e., epiphreatic)

Figure 2.2.9: Originally phreatic cave passages, subsequently located and modified in epiphreatic and vadose hydrological zones;

a) Oval and keyhole shaped phreatic channel now in periodically flooded epiphreatic zone (Amaterska Cave, Moravian karst, Czech Republic) (Photo: Bojan Otoničar);

b) Large canyon type (vadose) passage of Škocjan Caves periodically flooded to different levels with the open flow of Reka underground river (Karst) (Photo: Matej Blatnik);

c) Relict phreatic channel modified in epiphreatic (cave sediments) and vadose zones (flowstone) (Postojna Cave; SW Slovenia) (Photo: archive of IZRK ZRC SAZU) and non-flooded (i.e., vadose) hydrological zones. Although the phreatic zone is dominated by more or less horizontally orientated channels, vertical channels can also form under special conditions, resembling shafts in a plan view.

Conduits develop around their entire circumference, so typical phreatic passages are round or oval in shape (Figure 2.2.9a). In the epiphreatic zone, water usually flows faster through the channels. In the dry season, the water covers only the bottom of the channel or riverbed while during the rainy season the channels are flooded. The largest cave channels are formed in the groundwater fluctuation zones. These passages develop partly in phreatic conditions, i.e. symmetrically under pressure, and partly in vadose conditions, i.e. in a flow with an open surface. The typical shape of passages is usually a combination of the oval (phreatic) shape and the canyon type (vadose) passage (Figure 2.2.9a, b).

When the groundwater level drops for various reasons, the channels pass into the vadose zone, where the water flows according to the principle of free fall, except for perched phreatic horizons. The basic type of a passage in the vadose zone is a chimney and a slightly modified version of a shaft, but meanders are also formed, corroded and mechanically eroded by the perched water flows. In the vadose zone, mechanical erosion gains importance, and the walls of the caves are also strongly modified by collapsing processes. Sand and gravel in karst rivers can mechanically grind and significantly transform cave conduits. In the epiphreatic and vadose zones, cave channels may be filled with cave sediments and flowstones to varying degrees (Figure 2.2.9c). Sediments deposited around the circumference of the passage protect the walls against corrosion. If sediments are deposited on the floor, the passage generally extends in an upwards direction, where the walls continue to be exposed to corrosion. This type of passage development is technically known as "paragenesis".

Vadose caves also form between the karst surface and the karst water table. The water in this zone flows gravitationally and only washes a limited part of the cave ceiling. As a result, most of the caves in the vadose zone are shafts and meanders.

Since in karst areas the water table (and also the surface) commonly lowers over time, phreatic caves travel upwards through the hydrological profile, first into the zone of water table fluctuation (the epiphreatic zone) and then higher into the unsaturated or vadose zone (Figure 2.2.9c). Here they intersect with vadose shafts created by water percolating from the surface. Gradual lowering of the karst surface (denudation) and the water table exposes some karst channels, originally of phreatic origin, at the karst surface, where they form part of the surface karst relief (Figure 2.2.10). These so-called denuded or roofless caves can tell us much about the geological, geomorphological, hydrogeological, and climatic history of a given area, especially when filled with cave sediments. Mechanical sediments and flowstone in fossil cave channels of once phreatic and epiphreatic caves are similarly important. Thus, the term speleogenesis is used to describe the entire life cycle of caves, from their formation to their cessation.

Figure 2.2.10: Old denuded phreatic caves indicating long-lasting geotectonic, hydrogeological and climatic evolution of a given region:

A) completely denuded part of old phreatic cave filled with cave sediments (Kozina, SW Slovenia) (Photo: archive of IZRK ZRC SAZU),

B) partly denuded fossil phreatic cave filled with cave sediments (Kozina, SW Slovenia) (Photo: archive of IZRK ZRC SAZU)

2.3 Hydrogeological characteristics of karst

Karst areas occupy about 15% of ice-free land area. Karst aquifers supply water to about 20% of the world's population, 30% of Europeans, and over 50% of Slovenians. What makes these aquifers so prolific but yet so vulnerable?

Carbonate rocks are exposed to dissolution in groundwater and surface water throughout their life cycle, beginning in the saltwater-freshwater mixing zone of the marine environment. Karst massifs are part of the hydrological cycle. Water flowing through initially porous-fissured carbonates dissolves the rock along the pores or fracture walls, forming networks of dissolution channels (caves). Their development continuously adapts to the geological and hydrological conditions of the area. It can be said that the networks of conduits evolve to provide the optimum discharge from the recharge to the springs.

In a mature karst massif, the distribution of conduits is the result of the long-term geological evolution of the area, which includes uplift, faulting and fracturing, downcutting of the erosional base, changes in hydrological conditions, etc. The existing distribution of conduits in a mature karst aquifer, which largely determines the flow within, is extremely complex and unpredictable.

The recharge of karst aquifers can come from a range of sources. Some recharge always enters karst aquifers as distributed infiltration of precipitation. Many karst areas are also in contact with non-karstic fluvial regions at some point. Surface water in these regions is organised in a fluvial network. When in contact with karst, the evolution of the fluvial network and the evolution of the subsurface karst network may coevolve, one dictating the other and vice versa. The end result may be a river that sinks underground at the contact between soluble and insoluble rocks. In some situations, a surface flow may form within a karst basin and then sink underground as a concentrated flow. Karst springs are unique hydrological features. Karst aquifers are hierarchical, so that water from a large recharge area emerges in a very limited region or even at a single spring and only in karst landscapes can an entire river emerge from the spring with an average discharge of tens of cubic metres per second.

Roughly speaking, all aquifers are divided into a phreatic and a vadose zone. The phreatic zone is permanently filled with groundwater, while the vadose zone is air-filled and water flow is directed to the groundwater surface by gravity. Large fluctuations in recharge, especially in karst systems with allogenic recharge, can result in very large fluctuations in groundwater levels, which in extreme cases can rise as much as 200 m in less than a day.

Due to the large underground water conduits, there are often no surface waters in karst areas. The unsaturated zone in karst aquifers can be more than two kilometres thick. Drilling a few hundred metres from the surface to the water table is the rule rather than the exception.

Water flowing through the karst aquifer may follow a system of large conduit and channels from the inflow to the spring. It may also flow very slowly along systems of tiny fractures and enter hierarchically larger structures and conduits. In fact, most of the water in any aquifer is stored in fracture systems, while most of the water flows through the conduits. The time it takes for a unit of water to travel from the point of entry to the spring in the same aquifer can range from hours to millennia. As a result, karst aquifers are difficult to protect. A contaminant can pass through the aquifer in a matter of hours, but it can also remain in it for decades.

2.4 Types of karst

Different types of karst and caves develop under different geological, climatological and hydrological conditions. Three basic conditions must be met for karst formation: soluble rock, water, and the development of underground drainage. The availability of water is the most important climatic factor for the development of karst. Karst landscapes occupy about 20% of the surface of the continents where soluble rocks such as carbonates (e.g., limestone, dolomite) and evaporites (gypsum, salt) are available. Caves and solution features can also form in other rocks such as quartz sandstones or granites, but they are not formed by the same processes as karstic features of "common" as well as Classical Karst. Caves also form in glaciers and in lava, but with different processes from those that form the above mentioned features and landscapes.

Carbonate rocks cover 15% of the Earth's surface, but the global dissolution rates of limestone are determined by the amount of water and CO_2 in a given setting. Thus, global dissolution rates of limestone are determined by the amounts of water and CO_2 from vegetation available in the environment. Therefore, there are numerous variations of karst landscapes around the world. Their formation depends on geology and climate (precipitation, temperature, type of vegetation, and the amount of biogenic CO_2 in the soil), and this is usually related to their geographical position including their latitude, longitude and altitude. Karst occurs in areas where water is abundant; but aridity and extreme cold hinder its development. These two climatic conditions result in a lack of water in a liquid state, which limits dissolution, and therefore other geomorphological processes may dominate the area's morphological development. In contrast, in permanently or seasonally wet tropical climates, dissolution processes are much more rapid and exaggerated.

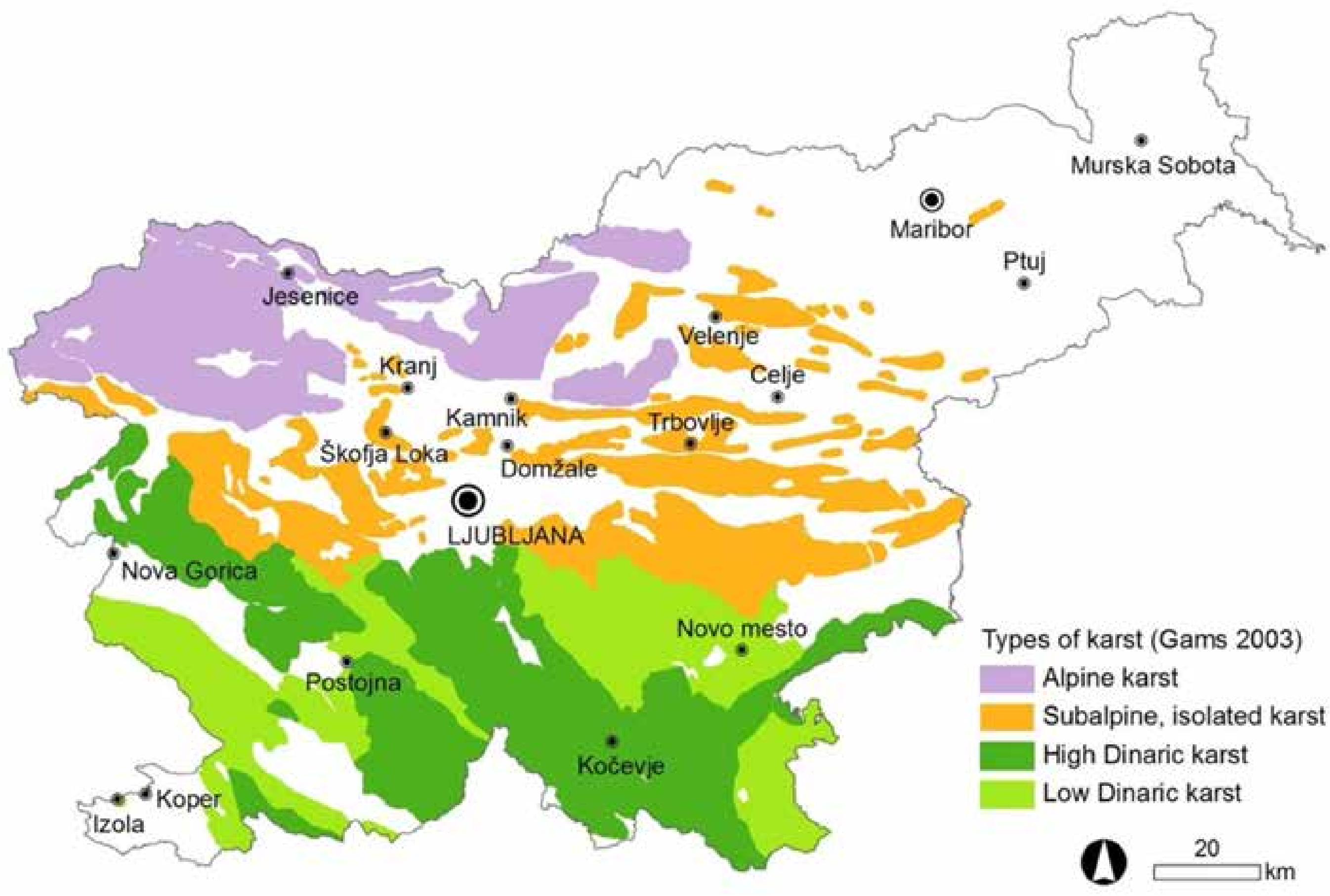


Figure 2.4.1: Map of different karst types of Slovenia (from Gams, 2003)

2.4.1 Main types of karst in Slovenia

Karst represents almost half the land area in Slovenia. According to Habič (1969), karst in Slovenia can be divided into three major units according to geological, hydrological, morphological and landscape settings (Figure 2.4.1): 1) Alpine karst - high mountain and mountain karst of the Julian Alps, Kamnik-Savinja Alps and Mt. Karavanke; 2) Dinaric karst - high and low Primorska, Notranjska and Dolenjska karst; and 3) pre-Alpine, intermediate and pre-Pannonian isolated karst (Idrija, Cerkno and Tolmin areas, Rovte Hills, Polhov Gradec Dolomites, Posavje Folds, Gorjanci and some areas in NE Slovenia), which are further divided into smaller regions according to morphological and hydrological characteristics.

Alpine karst or high mountain karst (Figure 2.4.2) is characterized by pronounced vertical gradients, and a mixture of fluvial, glacial, and karst elements in the landscape, resulting in fluvial valleys deeply incised into mountains and plateaus. It is formed in Devonian to Cretaceous carbonate rocks, while Triassic limestone and dolomite predominate. In the Slovenian alpine karst, characteristic high mountain karst features such as pavements, karrens, small depressions with vertical walls (*kotliči*) and large dolines (*konte*) occur. Underground, deep shafts and vertical cave systems are typical. The deepest caves in Slovenia are located on the Kanin and adjacent plateau (e.g., Čehi 2 is over 1500 m deep).

The Dinaric karst (Figure 2.4.3) is located in the southern part of Slovenia and is divided into Low and High Dinaric Karst (Figure 2.4.4). It is formed in Permian to Paleogene limestones and dolomites, while Cretaceous limestones and dolomites predominate. The main tectonic patterns of the area are represented by the Dinaric (NW-SE) and Cross-Dinaric (NE-SW) fault zones, S-N and NE-SW trending fissures and SW verging overthrust structures. The predominant relief features are extensive levelled surfaces at different altitudes, large closed depressions (e.g., poljes) and cone-shaped hills. Karst rivers occur only on the floors of the poljes. Allogenic rivers that, flowing from non-carbonate regions, either sink at the karst boundary and form blind valleys or cross the karst through deep karst valleys and canyons. There are numerous extensive and complex cave systems formed by sinking rivers and also connected to the surface by numerous vadose shafts. These represent both active and relict drainage pathways. Very well-known are the Škocjan caves, a UNESCO World Heritage Site, and the famous tourist Caves at Postojna, whose formations are associated with relatively large sinking rivers. Various deposits (e.g., allogenic sediments, speleothems) have ac-

Figure 2.4.2: High Alpine karst of the Kanin Plateau (NW Slovenia) (Photo: Bojan Otoničar)

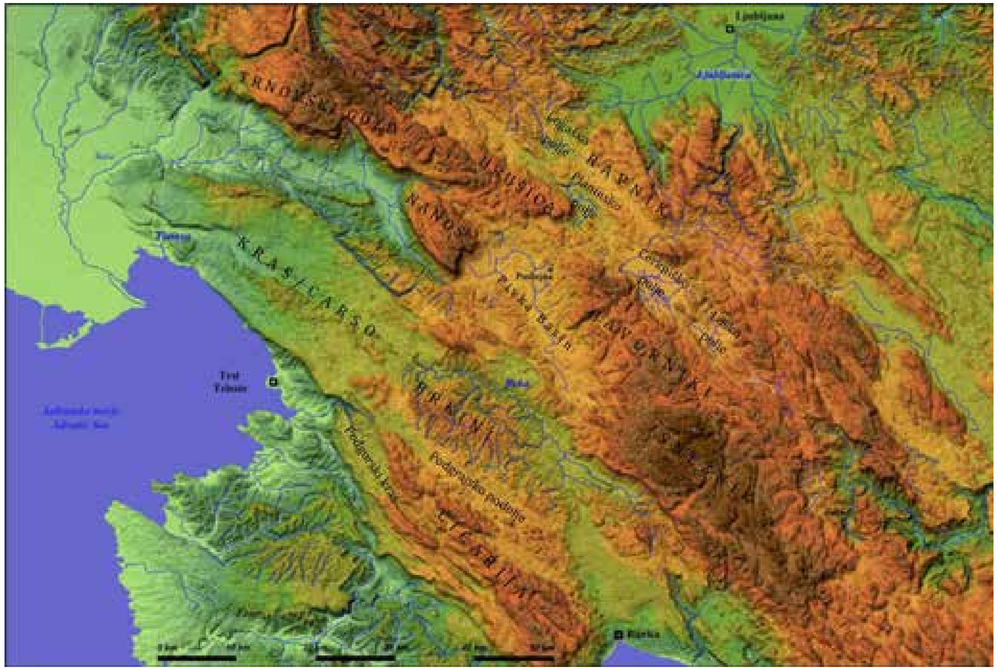


Figure 2.4.3: DEM of SW Slovenia (with parts of Croatia and Italy) showing different karstic regions of Dinaric karst including the Karst Plateau (archive of IZRK ZRC SAZU)

Figure 2.4.4: The Vipava Valley separates the Karst from the Forest of Trnovo and Nanos high Karst Plateaus (upper and right side of the figure) (Photo: Bojan Otoničar)

cumulated in the caves as a result of specific karst development. The morphology of the surface karst is characterized by abundance of karrens, dolines of various sizes, sometimes extensive collapse dolines, cave entrances, unroofed caves and so forth.

In contrast to the large extensively karstified regions of the Alps and Dinarides, intermediate and isolated karst occupy rather small areas. These are surrounded by non-carbonate rocks and developed under the influence of allogenic inflow. Horizontal caves are usually formed by sinking rivers, which generally have a high clastic sediment load. Ponors and springs are common. Karst hydrology and karst features are primarily determined by the location of an individual karst area, while the general evolution of large-scale relief is less important. Intermediate karst areas developed in limestones and dolomites from the Palaeozoic to Neogene age are located in the central part of Slovenia in a west – east oriented belt between the Alps and Dinarides. The main tectonic structures in this part are both Alpine, (E-W), and Dinaric, NW-SE oriented. Isolated karst occurs in smaller patches of carbonate rocks (mainly Miocene in age) in the central and eastern part of Slovenia, i.e., in the area of the Pannonian Basin.

2.4.2 Main types of karst in the Friuli Venezia Giulia Region

In the 7,850 km^2 of the Region there are outcrops of carbonate rocks covering approximately 1,900 km^2, affecting about 5,000 km^2 of mountainous and hilly areas. Almost 7,500 caves have been discovered in this area and inventoried, of which well over 3,000 are in the Italian side of the Classical Karst.

Using geological, morphological and hydrogeological criteria, about sixty karst areas - made up of limestone, dolomitic limestone, limestone dolomite, limestone breccias and conglomerates - have recently been identified and outlined.

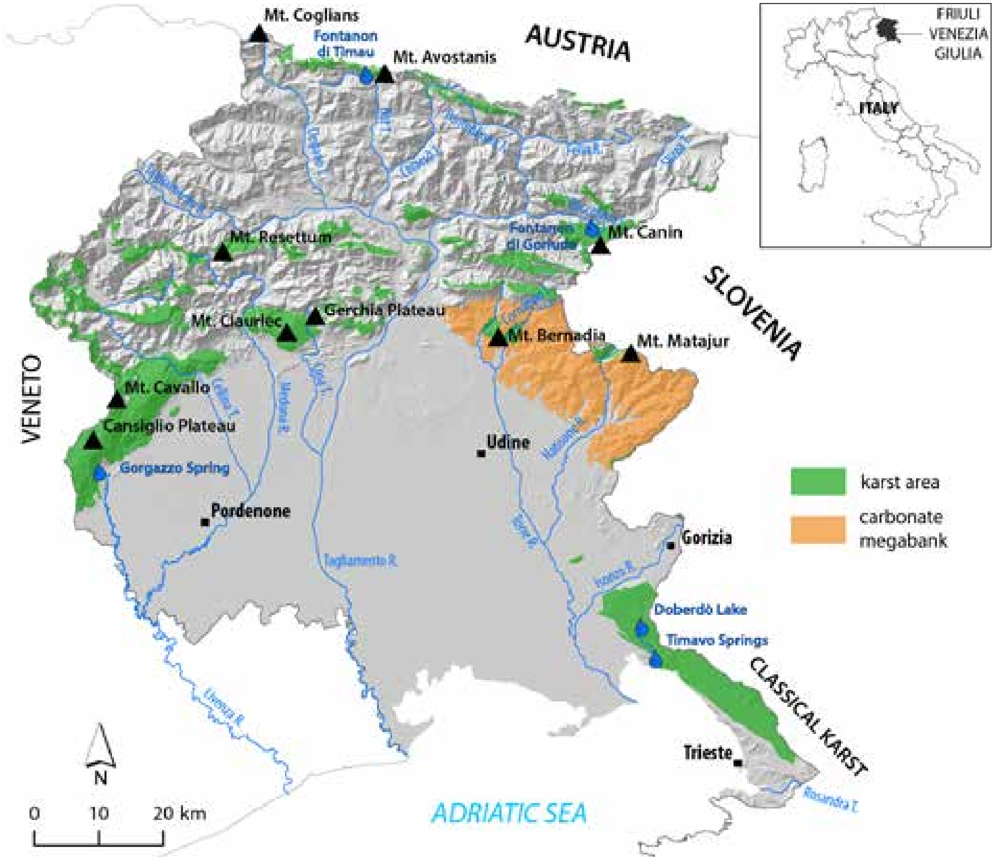


Figure 2.4.5: Karst areas in the Friuli Venezia Giulia Region (Cucchi and Finocchiaro, 2017)

Some 50 of these areas outcrop limestone or dolomite rocks in which karstification is ascertained by the presence of meaningful surface and/or hypogean karst forms (dolines, cave entrances, hypogean karst networks, karst springs, limestone pavements and small corrosion features, poljes, blind valleys, etc.). Of these, about ten are particularly important, with some of them being transboundary and, shared between Italy and Austria or Slovenia.

From a morphological point of view, and thus also from that of karstification, three types of karst areas can be recognised, namely alpine karst, prealpine karst and karst plateau.

Alpine karsts develop in the Carnic Alps in narrow areas aligned along the Austrian border and Julian Alps, shared with Slovenia. These are characterised by a high frequency of caves and intensely karstfied outcrops. They contain isolated but often water-rich aquifers. The regional pride is certainly the karst in the Triassic-Cretaceous succession of Mt. Canin-Kanin. Here, all the epigean karst features of the high mountains can be identified, often exemplary, accompanied by impressive underground systems, such as the Col delle Erbe Complex (over 23 km of development, with dozens of deep shafts reaching -935 m) and the Foran del Mus Complex (over 13 km of development).

In the Pordenone Carnic Pre-Alps and the Julian Pre-Alps there are numerous areas of wooded, pre-Alpine karst, with interesting cavities and widespread and varied surface karst including the areas around Pradis, Mts. Resettum, Ciaurlec, Bernadia and Musi, characterised by a high frequency of caves, dolines, and intensely karstified outcrops as well as rich aquifers. The karst developed in the limestone banks interspersed in the Paleocene and Eocene flysch of eastern Friuli is unusual. It hosts extensive systems of active caves whose springs are revealed by the river network, but for which there few pieces of evidence for karst on the surface.

Figure 2.4.6: The Alpine karst of Mt. Poviz (Photo: Giacomo Casagrande).

Figure 2.4.7: Limestone pavement and grikes on the highlands of Mt. Ciastelat (Pordenone Province) (Photo: Barbara Grillo)

There are two karst plateaus. One is facing the sea, represented by the Classical Karst, the other the vast Cansiglio-Cavallo Plateau, dominating the Friulian plain, whose geological boundaries transcend those of the Region. The polje of Piancavallo and the vast karstified cretaceous limestone outcrops are special. Among the widespread karst features present, the dolines which border the plateau on the eastern slope, symmetrical, dense, deep, with their sides dotted with splendid karrenfelds, and the limestone pavements of the northern sector (Mt. Ciastelat) are the most representative. Of the caves, the main abysses include Bus de la Lum and Bus de la Genziana and the Gorgazzo, Santissima and Molinetto springs, a Spring area of the Livenza River.

Figure 2.4.8: The Gorgazzo Spring at the toe of the Cansiglio-Cavallo karst area (Photo: Franco Cucchi)

GEOLOGY AND GEOMORPHOLOGY OF THE CLASSICAL KARST

3.1 The area covered by the Classical Karst geopark

The Classical Karst (*Kras* (Slovenian), Carso (Italian)) is a limestone plateau that runs north-west – south-east and is bordered by the Isonzo-Soča River (Italy and Slovenia) to the north, the Adriatic Sea to the west, the Brkini hills and the lower course of the Reka River to the south, and the Vipava Valley to the east.

The plateau is gently dipping toward the north-west from the 674 m summit of Mt. Kokoš-Cocusso down to the sea level at the springs of the River Timavo. It consist largely of limestone and dolomitic rocks, the latter outcropping less frequently, mostly in the hills.

The Classical Karst geopark covers 936 km2, 213 km^2 within Italy and 723 km^2 in Slovenia; it includes 17 municipalities, in some cases in their entirety, others only partially, such as the urban centres of Trieste and Monfalcone. On the Italian side there are 12 municipalities, while there are 5 on the Slovenian side of the border. The Italian municipalities involve both the Gorizian Karst (Savogna d'Isonzo-Sovodnje ob Soči, Sagrado, Fogliano Redipuglia, San Pier d'Isonzo, Ronchi dei Legionari-Ronke, Doberdò del Lago-Doberdob and Monfalcone), and the Karst of Trieste (Duino-Aurisina - Devin-Nabrežina, Sgonico-Zgonik, Monrupino-Repentabor, Trieste and San Dorlingo della Valle-Dolina). The five Slovenian municipalities within the Classical Karst are Sežana, Miren-Kostanjevica, Hrpelje-Kozina, Divača and Komen.

The Geopark is crossed by important infrastructural networks running both east-west and north-south. These are routes of continental importance, which on the one hand facilitate connections with other European regions and, on the other, increase its environmental vulnerability.

The landscape of the Karst is characterized by some peculiar aspects, that exhibit the full typology of karstology, and which can be summarized as follows:

1. **Underground waterways, springs and karstic lakes**, accompanied by a reduced surface area with a hydrographic network and a scarce presence of valley systems shaped by erosion.
2. **Irregular, undulating plateaus**, with rounded, domed reliefs and extensive flat areas, harsh in appearance.
3. **Closed, hollow depressions** (dolines).
4. **Broad rocky outcrops**: *Karrenfeld* modelled by various dissolutive forms, called microforms, to distinguish them from macroforms (dolines, uvalas and poljes).
5. **Cavities, potholes, abysses, caves and caverns**.

Figure 3.1.1: The movement of the morphologies of the Classical Karst (Photo: Roberto Valenti)

The landscape of the Classical Karst is also characterized by its tectonic setting, with a Dinaric structural trend. In Italy this structure has created a wide anticline with an axis running north-west - south-east, but asymmetrical, i.e. with a vertical south-western flank and a north–eastern flank much less inclined. It is precisely here that the Karst Plateau develops.

As a result of its proximity to the Adriatic and to Mediterranean climate, the Karst has been continuously inhabited since the Paleolithic Era. Due to its thin soils, rocky nature and the lasting summer drought, land use has traditionally been directed towards pastoralism and the rearing of livestock. Only on the richest land has agriculture developed, which in recent years has been marked by the excellence of its wines and olive oil. The city of Trieste, close to the area covered by the Classical Karst, is an important attraction for services, tourism and employment of the residents of the geopark. Geotourism has a long tradition in the area, linked in particular - but not only to - the presence of caves, amongst which the Škocjan Caves and the Grotta Gigante-Briška jama Cave stand out as attractions.

Figure 3.1.2: The area of the Classical Karst geopark with municipalities boundaries (by ZaVita d.o.o.)

Figure 3.1.3: The map of the infrastructures and the watercourses of the area of the geopark (by ZaVita d.o.o.)

3.2 A history of exploration and research on the Classical Karst

3.2.1 Geological investigations

Although pioneering, the first geological studies on the territory of the Classical Karst date back to the late 1700s and are well established by the early 1800s. Their value, however, is to be considered historical. More detailed and modern studies and investigations started in the second half of the 19th century when Austrian geologists and paleontologists laid the foundations for a geological cartography of use in the knowledge of the geological evolution of the area and its surroundings.

The first geological maps drawn up by Adolphe Morlot date from 1848 while those elaborated by Torquato Taramelli are from 1874, but the most significant advances in the geology of the Classical Karst and neighbouring areas are from 1859 to 1920 (Figure 3.2.1), and to Guido Stache, a talented geologist and paleontologist, who for a long-time was director of the *Geologische Staatsanstalt* (the Austrian Geological Survey). His volume *Die Liburnische Stufe und deren Grenz-Horizonte* (The Liburnian and its borders) printed in 1889 is a fundamental work, just as important as his other writings, and is an essential work for later geologists.

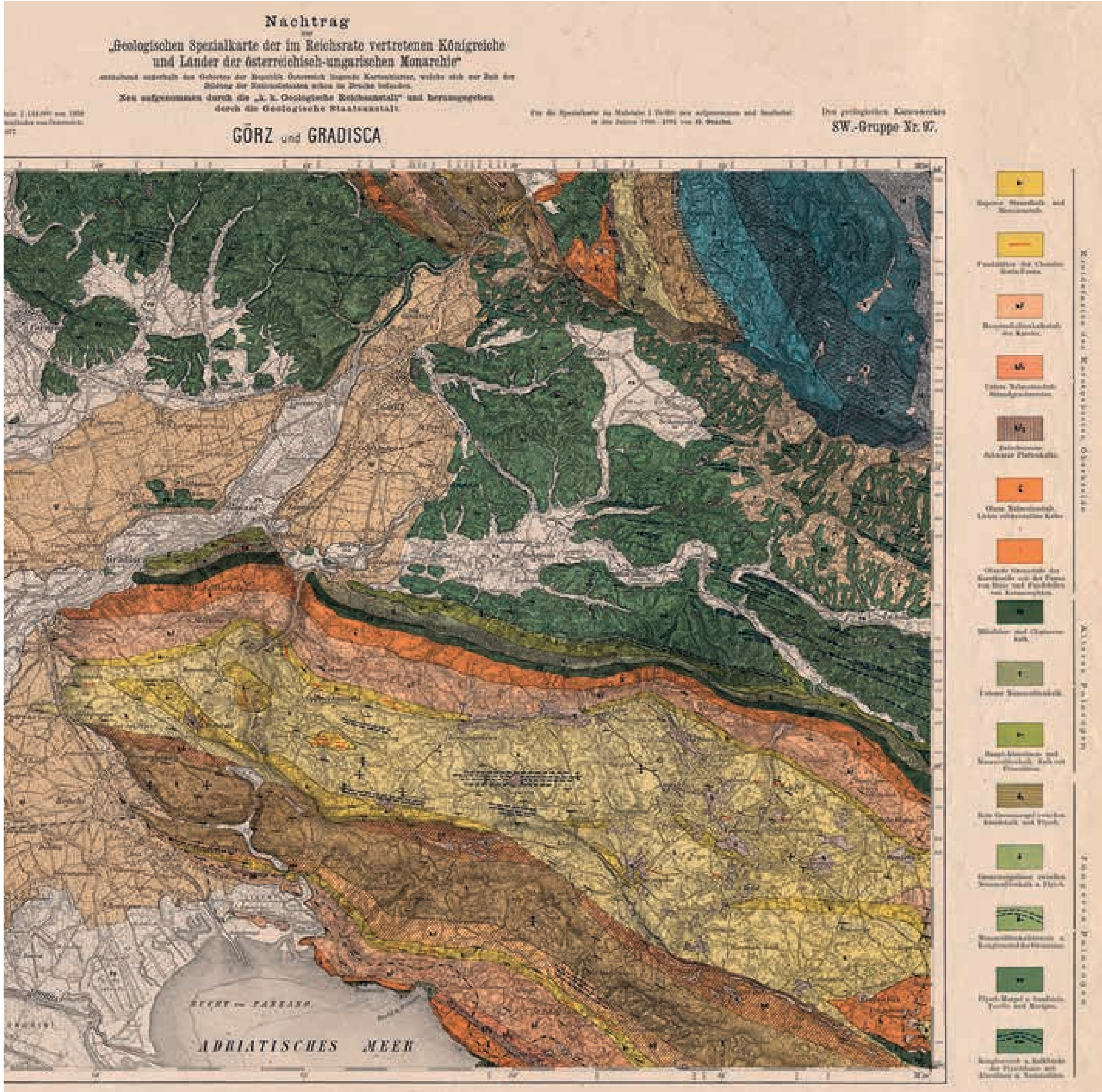


Figure 3.2.1: Extract of the map Gorz und Gradisca, *edited in 1920 by Guido Stache on behalf of the Austrian Geologischen Staatsanstalt.*

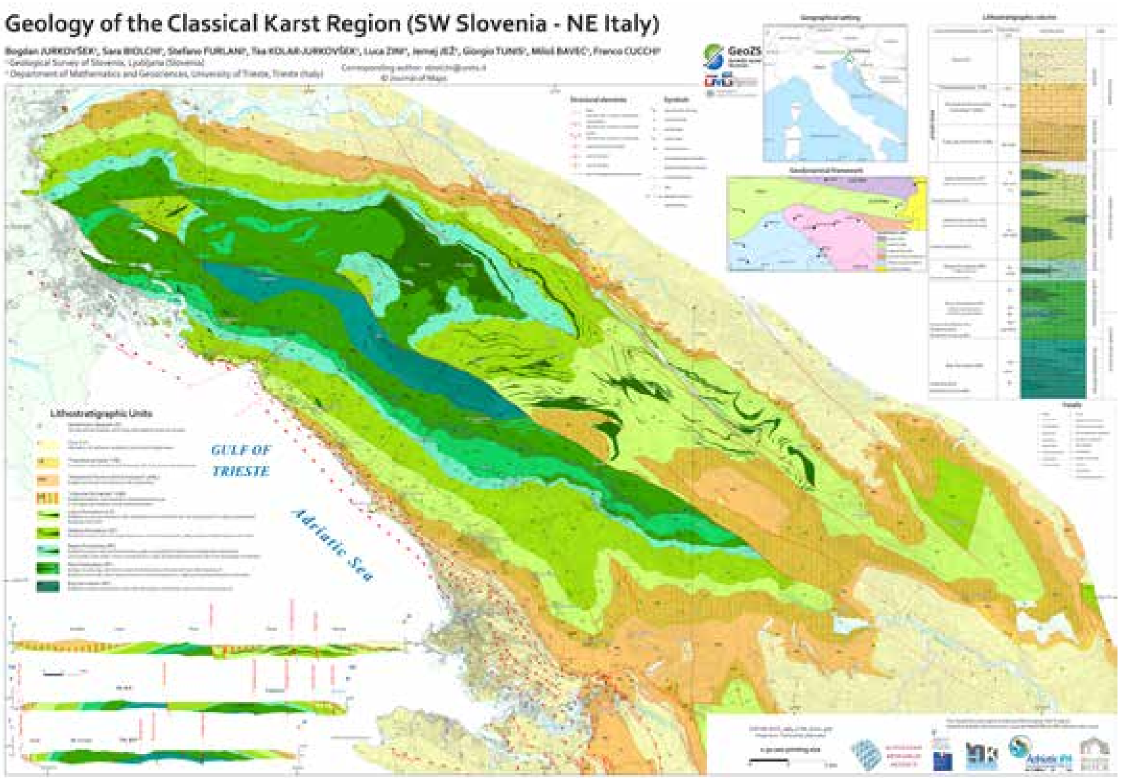


Figure 3.2.2: Classical Karst geological map realised in the aim of the INTERREG Italia-Slovenia Projects as HydroKarst and RoofOfRock (Jurkovšek et al., 2016)

In the second half of the 19th century, the special attention of paleontologists was attracted by finds of the fossil fish and reptiles in the laminated and platy limestones that occur within the various Cretaceous formations in Classical Karst. The first study was published in 1850 by J. J. Heckel, and the most comprehensive one in 1895 by C. Gorjanović-Kramberger, describing as many as 27 fish species from those layers.

After the World War I the Karst was studied in detail mostly by Italian geologists, such as Carlo D'Ambrosi from 1925 to 1955, Alvise Comel from 1927 to 1940 and the German-Austrian Franz Kossmat from 1935 to 1938. They wrote numerous sheets and related explanatory notes for the "*Carta geologica delle Tre Venezie*" at the scale of 1:100,000.

After the World War II, research by numerous Italian and Slovenian geologists continued, but separately, with the development of a new traditional local geological maps at the scale of 1:25,000 and 1:100,000. For Italy, research was led by Bruno Martinis from 1949 to 1975. In Slovenia, elaboration of geological maps were conducted within the scope of Basic Geological Maps project of the former SFR Yugoslavia (scale 1:100,000), led by Stanko Buser from 1967 to 1973 and by Mario Pleničar from 1969 to 1973. The last period of detailed geological research in Slovenia, beginning in the 1990s under Bogdan Jurkovšek, resulted in the production of geological maps of the southern and northern parts of the Trieste-Komen Plateau (Jurkovšek et al., 1996; Jurkovšek, 2008, 2010). Also the correct approach to problems related to the complex geological structure began in this period, especially by Ladislav Placer who, from 1969 to date, has produced numerous works on post-Cretaceous Alpine-Dinaric geodynamics.

Starting from 1999, the Geological Survey of the Autonomous Region of Friuli Venezia Giulia in collaboration with the University of Trieste, through the Technical Geological Map (*Carta Geologico Tecnica* - CGT) and GEO-CGT projects created new digitized geological maps at scales of 1:5,000 and 1:10,000 of some areas of the Region, including the topographic sheets “Trieste”, “Caresana”, “Gorizia” and “Grado”, which comprise the Classical Karst. As a result of the collective work, the geological map of the italian part of the Classical Karst in scale 1:50,000 has been published in 2013 (Cucchi & Piano, 2013).

In the early 21th century, through a series of INTERREG Projects, collaborations between Italian and Slovenian geologists have became more intensive. As a result of the aforementioned modern national maps and the cross-border collaboration, in 2016 a geological map, at a scale of 1:50,000 of the entire area of the Classical Karst was published (Figure 3.2.2).

3.2.2 Speleological and hydrogeological research

As far as geomorphology and speleology are concerned, Posidonius of Apameia (135-50 B.C.E) may be considered the first investigator of the Karst, but, regretfully, we know only that he mentions the Reka sink running to the Timavo. Only a millennium later, did Ferrante Imperato start to work at the Timavo springs to discover whether the Reka that sinks in the Škocjan Caves is the same that reappears at the Timavo Springs. He tried to prove it using floats and he published his observations in 1599. Athanasius Kircher illustrated his explanation of “hydrophylacia” as a theory of underground reservoirs connected with the sea by an example from the Rhaetian Alps. The picture includes the actual area of Slovenia, and the Timavo Springs rising beneath “*Timavus Mons*” are also drawn in. In the volume *Mundus Subterraneus* Kirchner (1964) mapped the mouths already declaimed by Virgil from which the Timavo flowed, recalling that it had long been assumed that the waters came from Škocjan.

The birth of scientific speleology in the Classical Karst area is down to the Slovenian Johann Weikhard von Valvasor, who in 1687 described the hydrogeology of Cerknica Lake and the surrounding territories and his most famous work *The Glory of the Duchy of Carniola* contains descriptions of the most famous caves of the Karst, such as that of Postojna and Škocjan. Although Valvasor (1689) did not take such a profound interest in the Karst as he did in in the karst phenomena of Notranjska and Dolenjska, his publications aroused a great interest in karst phenomena.

In 1748 the court’s mathematician Josef Anton Nagel, commissioned by Emperor Francis I, arrived in Carniola to see and to report on what was true in the news of “unusual and miraculous phenomena”. In his report from the Karst he described the Vilenica Cave which at that time had been a “show cave” for a good 100 years already. His description is accompanied by several fine illustrations. It should be remembered that this area is not only the cradle of scientific speleology, but also of speleological tourism. The first book of the signatures of visitors to the caves of Skocjan dates back to 1819, but there is a document from 1633 which indicates that Count Petazzi, then the owner of the land in which the Vilenica Cave near Lokev opens, ceded part of the proceeds from visits to the cave itself to the local community, which therefore can boast of being the first tourist cave in the world.

The evolution of Speleology in the area of the Classical Karst is linked with the economic life of Trieste. The granting of the status of Free Port by Charles VI in 1719, led to a significant increase in naval traffic and to the importance of the city: it is estimated that in 1780 a quarter of all the trade of the Empire passed through Trieste. Within a century the city underwent major transformations: the port was enlarged and new neighbourhoods were built. Consequently, the water requirements also increased.

The *Teresianischer Aquädukt* (the Maria Teresa aqueduct) had already been built in the mid-1700s, drawing water from the flysch slopes leaning against the Classical Karst and feeding fountains located in the main squares. However, the flow rates were never so high as to definitively solve the problems of water supply in the city and the port. The speleological research of the underground Timavo was linked to these issues.

At the beginning of the 19th century it was the research of individuals, enthusiastic and eager for knowledge that prevailed. A good example is Eggenhöfer who swam the Reka River from its ponor through Mariničeva and Mahorčičeva jama to Mala dolina in 1816. Soon after, collective and organised research started.

The involvement of the Municipality of Triest and the interest of some prominent figures of the city in this topic have been documented since the early 1800s. In 1828 a Commission for water was appointed in charge of evaluating the area's water resources, from Aurisina-Nabrežina to Škocjan. In 1838 A. F. Lindner started a systematic research on the places (blow holes) where, during the floods of the Timavo, the air was expelled by the rising waters in the oscillation zone of the underground aquifer. The goal was to identify an intermediate point along the underground Timavo. This was discovered in the Trebiciano-Lobodnica Cave. The exploration was an exceptional undertaking for those times, lasting 5 months of excavations with the opening of bottlenecks and even the use of mines. On April 5th 1841, Luca Kral of Trebiciano-Trebče and Anton Arich, a miner from Idrija, descended into the great cave of the Abyss, at the bottom of which flowed the Timavo at depth of 326 metres. Thus, the first window on the river's underground course was opened. The news went around Europe, so much so that until the beginning of the 20th century the cave was considered the deepest in the world.

During one of the first descents, specimens of *Pterostichus fasciatopunctatus* were collected, a beetle characteristic of the upper Timavo Valley, scientific proof of the connection between upper and underground Timavo and one of the earliest examples of a biological tracer.

But the discovery did not solve the water problems of the city, the altitude (12 m a.s.l.) was too deep to exploit. The construction of fixed stairs was financed and the characteristics of the water and the level of the river were studied to assess the extent to which the water could rise. In the following years, the construction of the *Südbahn* (Southern Railway) further aggravated the problem of Trieste's water supply, and the project of derivation from the caves of the Classical Karst was abandoned and it was decided to exploit the springs at Aurisina-Nabrežina. It is worth remembering that at the initiative of the Southern Railway constructors Adolf Schmidl started to explore the caves in the Classical Karst in the middle of the 19th century to discover the possibilities for cave tourism.

In the 1880s, numerous speleological groups belonging to the various mountaineering associations of Trieste were founded, which began to operate in the area in search and exploration of caves. In the early 1900s, through a series of experiments with chemical tracers, dyes and the radioactive marking of water, Renato Timeus demonstrated the water connection between the sinkhole of Škocjan, the Abyss of Trebiciano and the Springs of San Giovanni-Štivan. It was the scientific confirmation of the many hypotheses and attempts, often empirical, which, starting with those made by the pharmacist Ferrante Imperato at the end of the 1500s, and that had followed one another for three centuries.

In 1888 Kačna Cave was discovered and in 1889 cavers, guided by Anton Hanke (SK DÖAV) reached its bottom where high waters of the Reka appear.

In 1890 speleo-explorers reached the final siphon of the caves of Škocjan and the cave was almost entirely explored, with exception of the part called *Tiha Jama* which was only discovered in 1904. At the same time as the explorations, the cave was also prepared for tourist-mountaineering visits. In 315 days in the years 1894 to 1895 five local workers succeeded in building the wooden stairs and ladders down the 186 m deep vertical entrance shaft which allowed them to enter the cave without additional equipment. This construction was unique in the world and probably was their greatest technical achievement.

During the First World War the front reached the Karst. The explorations did not cease but were redirected for military purposes. A special group guided by Hermann Bock, a speleologist, prepared the plans for changing the caves into shelters, magazines, hospitals etc. Some projects were also implemented and in some caves there was enough room for 2,000 men!

The end of the World War I represented an epochal change for the city of Trieste and also for Karst research. In the following years the figures of Luigi Vittorio Bertarelli and Eugenio Boegan acquired ever more importance. In 1926 they published the volume *2000 Grotte* (2000 Caves), a synthesis of the speleological knowledge of the time and above all the first attempt to draw up a complete list of the caves of the Classical Karst. In 1929 the foundation of the state institute, the *Istituto Italiano di Speleologia* at Postojna contributed a lot of research. The Institute published the main Italian speleological journal, the *Grotte d'Italia*. In the following years Boegan deepened and synthesized his knowledge on the underground course of the Timavo and in 1938 he published *Il Timavo*, a volume that for decades has remained one of the best examples of "study on subaerial karst hydrography and underground", as the subtitle says.

After The Second World War, both the Slovenian and Italian sides of the Karst increased their research with the aim of spreading speleological knowledge and discovering caves of the underground Reka/Timavo system.

3.3 GEOLOGICAL HISTORY OF THE GEOPARK AREA

Paleogeography

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 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. But the trained geologist - with the aid of a handlens - is able to read fragments of the long book of geological history in every piece of these rocks. The nature of these layers and the contacts between them, and especially the rock's inner structure and tiny fossils, called microfossils, are the pages and letters of this geological chronicle. They convey fascinating information on the depth, temperature, salinity, and oxygenation of the ancient seas in which these limestones were formed, telling of what life and the environment in the geological past looked like and how it changed over time. We use the prefix "paleo-" to denote prehistoric phenomena, with words such as paleotemperature, paleoenvironment, paleogeography, or paleokarst, and indeed, the episodes of the chronicle of the geopark 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. They cover 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.

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. The Early 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 about 18.4 °C, more than 4 °C warmer than today. 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 boundary between the Cretaceous and the Paleogene, which also represents the boundary between the Mesozoic and Cenozoic eras, was marked by a major extinction event, associated with the impact of a large asteroid in the area now occupied by the Yucatan Peninsula in the Gulf of Mexico. This event drastically changed life on Earth, wiping out 73% of living species, including dinosaurs, ammonites, and many other organisms that had thrived on the continents and in the oceans for millions of years.

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

Madagascar 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 3.3.1).

In the Cretaceous, as a consequence of a warm climate and high sea levels, large portions of the continents that nowadays are emergent land were occupied by vast shallow, epicontinental seas (meaning "on continents"). This gave way to a vigorous burst of marine life, including those life forms that later, in the Cenozoic, would successfully conquer the Earth, such as corals, molluscs,

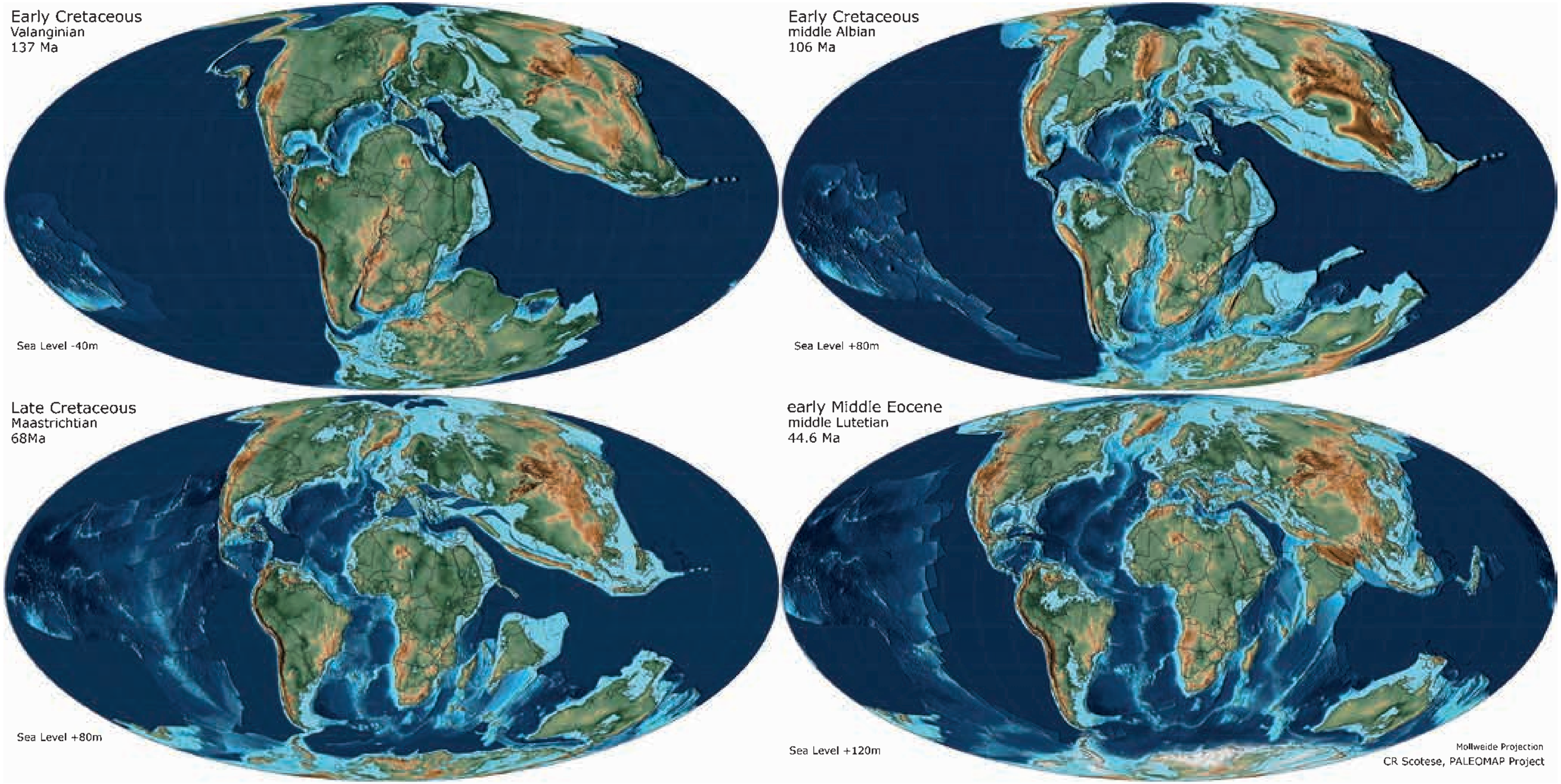


Figure 3.3.1: The changing world from Early Cretaceous to Middle Eocene, in times of formation of rocks that build the geopark (after Scotese, 2014)

echinoderms, crabs and fish. The Earth's poles were free of ice, and seawater had a weaker circulation and was less well-oxygenated. This, at times, led to the accumulation of black, organic-rich sediments on the seafloor.

The Classical Karst area is made up of sedimentary rocks of the former Adriatic-Dinaric Carbonate Platform (Figure 3.3.2). 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 or the Great Barrier Reef in Australia. The Adriatic-Dinaric Carbonate Platform was indeed a large example, as evidenced by its rocks outcropping from northeastern Italy, along the entire length of the Dinarides, as far down as Montenegro. The platform developed when the breakup of the mega-continent called Pangea brought about the formation of two separate continental masses, Laurasia and Gondwana, with the opening of the Tethys Ocean. At first the Tethys was a gulf that later became a broad seaway that stretched approximately east - west at tropical latitudes. One of constituent parts of Gondwana was the African Lithospheric Plate. The Adriatic-Dinaric Carbonate Platform formed on the Adria Microplate, which was initially connected to the African Plate and became an independent plate from the Mesozoic onwards. 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. The platform existed for millions of years, from the Jurassic to the early Eocene until tectonic movements connected to the collision between the lithospheric plates brought about the rise of the Alpine chain and to the platform's foundering in the oceans. This event is testified to by the sandstones of the flysch that derive from

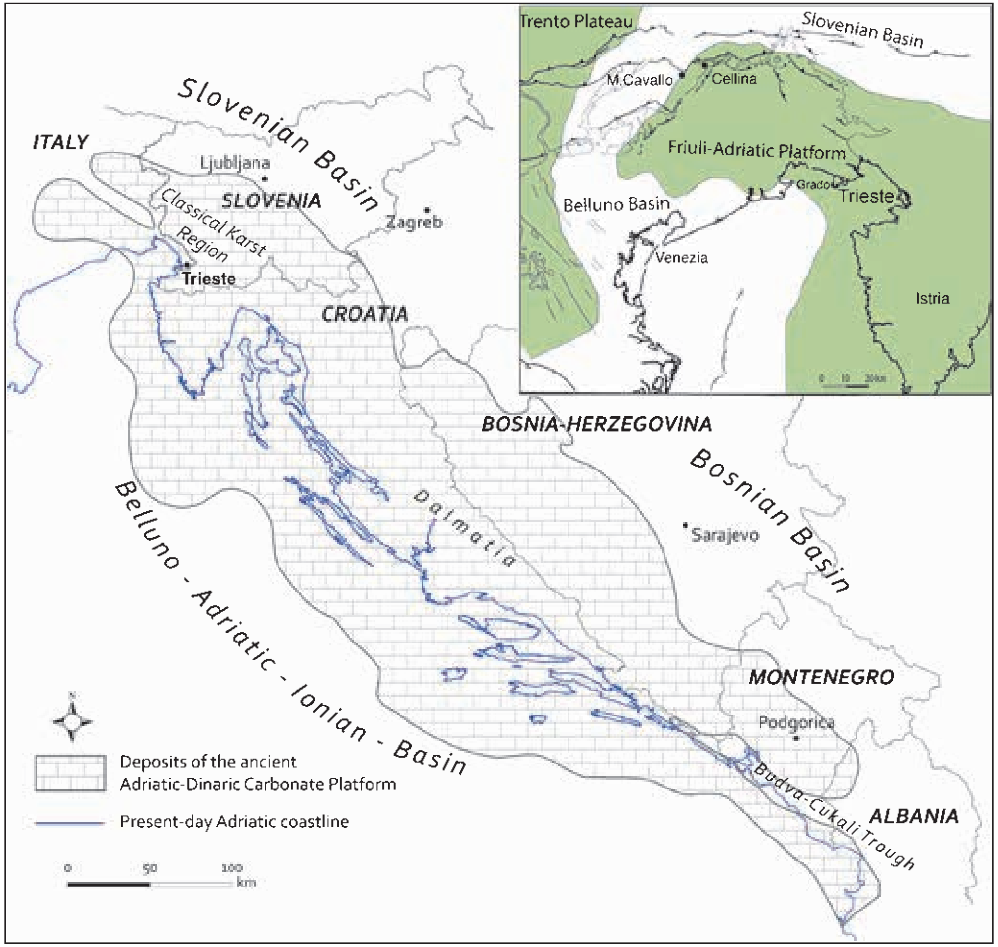


Figure 3.3.2: Present-day geographic map overlain by one showing the extent of the Adriatic-Dinaric Carbonate Platform deposits (modified from Dragičević & Velić, 2002) and a detail of the northern part with the Friuli-Adriatic Platform (modified from Consorti et al., 2021)

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).

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 the Classical Karst area is also called the Friuli Platform and corresponds to the northwestern limb of the Adriatic-Dinaric Carbonate Platform that, during the Cretaceous, was bordered by two stretches of deep sea: the Slovenian Basin to the northeast and the Belluno Basin to the west (Figure 3.3.2). 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.

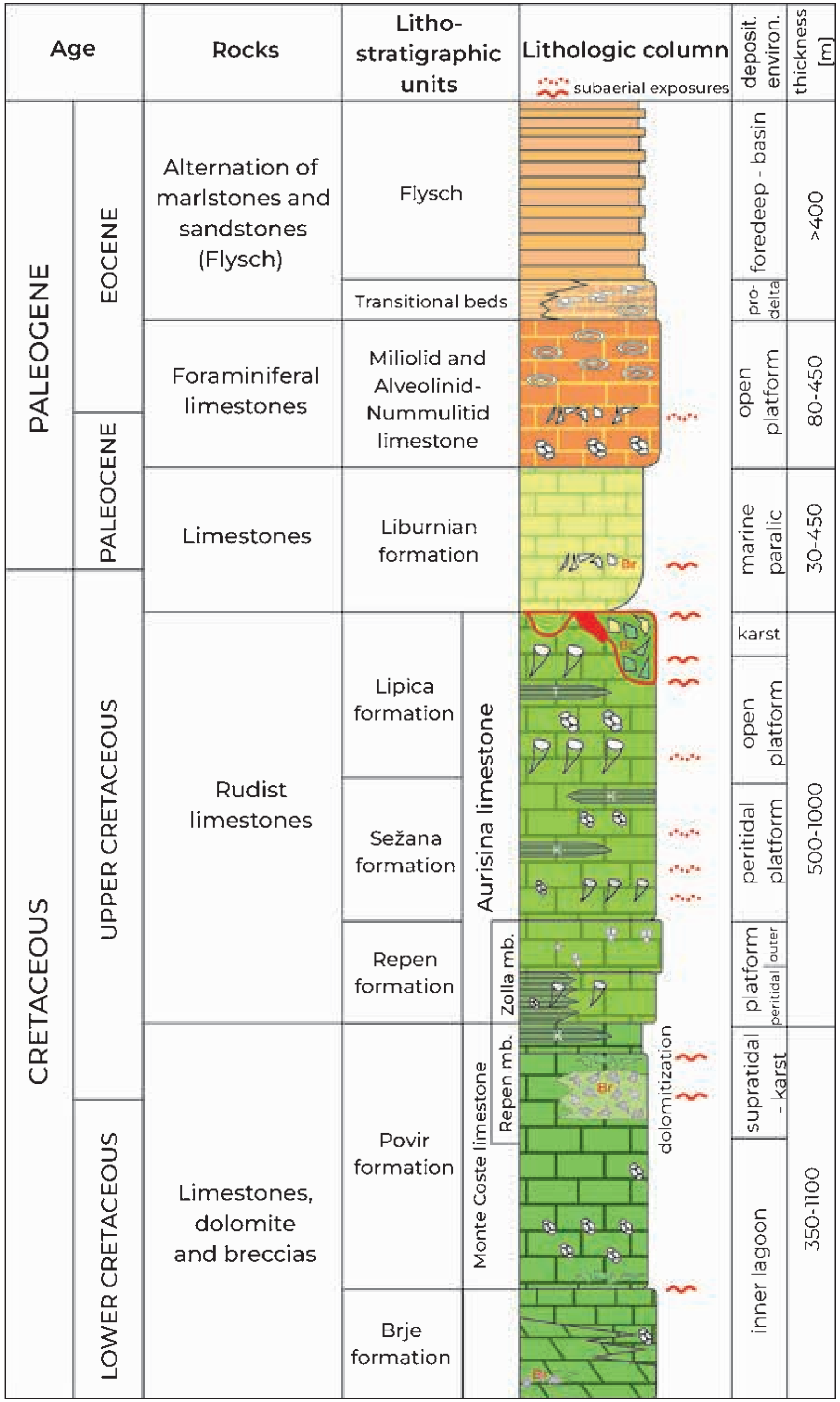


Figure 3.3.3:
Geological column, depicting geological units building the geopark (Br – breccia, K – Komen limestone, T – Tomaj limestone) (after Jurkovšek et al., 2016 and Consorti et al., 2021)

Rocks and fossils 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. The characteristics of these sediments unequivocally tell geologists that they were deposited in a warm, shallow sea. In these waters microscopic organisms, such as foraminifera, coccolithophorids and diatoms thrived. On the carbonate platform, thousands of forms of corals, echinoderms, brachiopods, crustaceans, and other animal groups were abundant. In addition to them, a peculiar group of clams (technically bivalve molluscs), called rudists developed. These unusually shaped bivalves first appeared at the beginning of the Cretaceous, but flourished in the Late Cretaceous and, together with many other plants and animals, became extinct at the end of the period. The rocks of the Classical Karst also show evidence of multiple short- and long-lasting subaerial exposures, times in which the platform top emerged above sea level.

The succession of rocks of the Classical Karst, nearly 1500 m thick, has been subdivided into several geological units, that group together rocks that are genetically related. One way of representing such units, called *formations* by geologists, -sometimes further subdivided into smaller parts called *members*, or grouped into larger ones called *groups*, is the lithostratigraphic column (Figure 3.3.3). In this type of representation, formations are depicted from the oldest at the bottom to the youngest at the top. The lithostratigraphic column of the Classical Karst highlights the main phases of the evolution of the environment in this area in a period of over nearly 100 million years. The physical distribution of formations is shown in the geological map. For some of these units, Slovenian and Italian geologists use different names and some parts of the succession are also subdivided differently. In this book, a simplified scheme was adopted in which the rocks of the Classical Karst are subdivided into their most distinctive units. The following description presents them in stratigraphic order, that is from the oldest to the youngest.

✦ Lower to Upper Cretaceous limestones, dolomites and breccia

These are the oldest carbonate rocks of the Karst Plateau deposited during the Early Cretaceous, between approximately 140 and 90 mya, mainly in a calm, shallow lagoon environment that resembled that of today's tropical islands. Most of these rocks are limestone, although there is also dolomite. 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. It is not uncommon to encounter dark grey dolomite among the oldest rock units of the Classical Karst.

The environment during the Cretaceous did not change dramatically in the area occupied by the Classical Karst, but, being very shallow-water, it was easily exposed when sea level oscillated. 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. There are also longer scale phenomena that can cause these variations. 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. In times when sea level dropped, large portions of the 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, such as karst cavities filled with sediments and flowstones, are called paleokarst and a trained eye can recognize them in the rocks of the Classical Karst. There is actually evidence that this area of carbonate platform emerged multiple times during the Cretaceous, but 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). It is testified to by a layer of breccia (a sedimentary

Figure 3.3.4: Breccia testifying to the important emersion episodes that the carbonate platform underwent (west of Povir) (Photo: Bogdan Jurkovšek)

rock composed of angular rock fragments cemented together) that outcrops in a narrow band stretching across the Classical Karst. This breccia probably formed because the rocks of the platform, once exposed, were fragmented and eroded into cavities produced by the ongoing karstic dissolution (Figure 3.3.4).

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

In some places within this carbonate succession brownish stained irregular bodies of calcite mineralisation occur in the otherwise dolomite host rock. It represents calcitized dolomite or so called dedolomite.

✦ Upper Cretaceous rudist limestones with fossiliferous platy limestone layers

Limestone also continued to accumulate in the shallow sea on the Adriatic-Dinaric Carbonate Platform during the Late Cretaceous. The circulation of waters on the shallow lagoon of the ancient Classical Karst was, however, not evenly distributed. There were areas where water circulation was more sluggish and thus oxygen concentrations were lower. Furthermore, although the seafloor topography was rather flat, some parts were characterized by deeper waters. This led to the formation of some of the most interesting and paleontologically important rocks in the geopark, the platy limestones. The dark-grey, thin-bedded, laminated limestones contain thin layers or lenses of chert, a hard, dense flint-like rock composed of microcrystalline quartz, and can smell of bitumen when broken (Figure 3.3.5). 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 shallow-water limestones which belong to the different Upper Cretaceous formations between 95 and 80 million years ago. One of them, 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 Gorjanović-Kramberger in 1895) contains the remains of fishes, various reptiles, and plants in an exceptional state of preservation (Figure 3.3.6).

Another, slightly younger platy and laminated limestone with thin lenses or layers of chert is the Tomaj Limestone. It frequent-

Figure 3.3.5: Upper Cretaceous platy and laminated Komen Limestone with chert at the village of Skopo (Photo: Stanko Buser)

Figure 3.3.6: 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.*

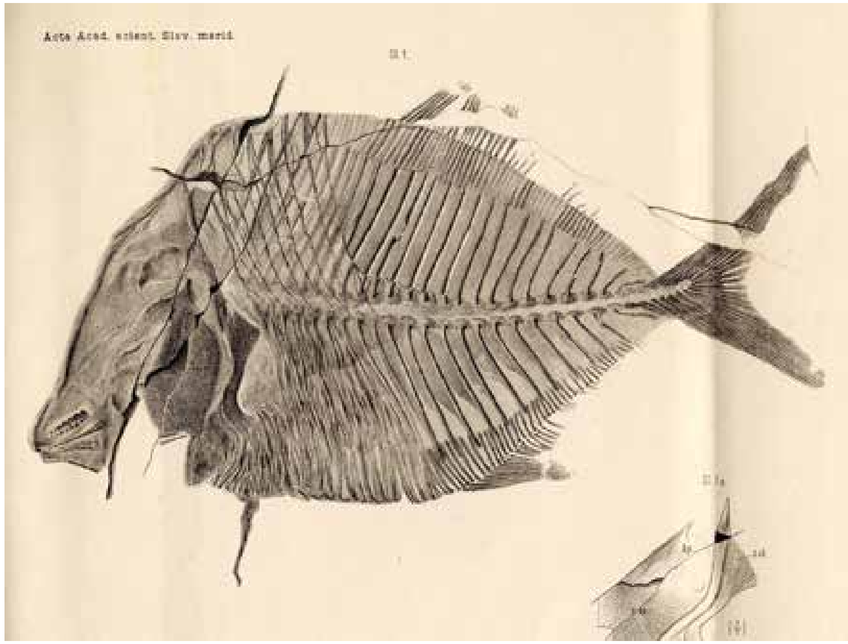
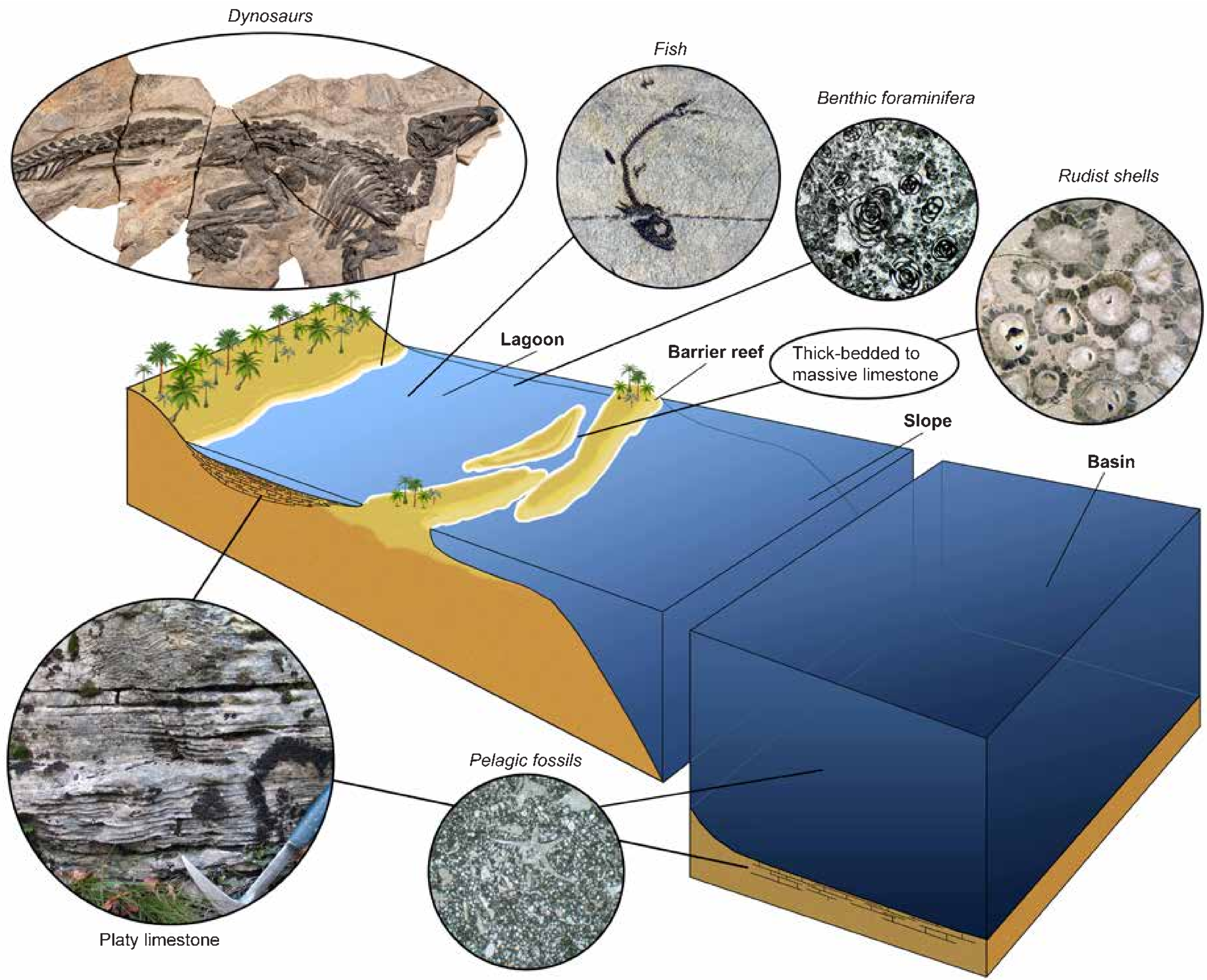


Figure 3.3.7: Reconstruction of a Late Cretaceous shallow-sea environment with typical inhabitants found as fossils on Karst Plateau (Drawing: Barbara Jurkovšek)

ly contains numerous and well-preserved fossil fish, ammonites, planktonic crinoids, and other inhabitants of the open sea (Figure 3.3.7). The presence of fossil plants with conifers dominant indicates the close proximity of land to the south of the lagoon (Figure 3.3.8; see also Chapter 4).

These rocks are mostly found in the central and northern areas of the Classical Karst Region (Figure 3.3.9). The Komen and Tomaj

Figure 3.3.8: 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, Civic Museum of Natural History Trieste)


Dynosaurs
Fish
Benthic foraminifera
Rudist shells
Lagoon
Barrier reef
Thick-bedded to massive limestone
Slope
Basin
Pelagic fossils
Platy limestone

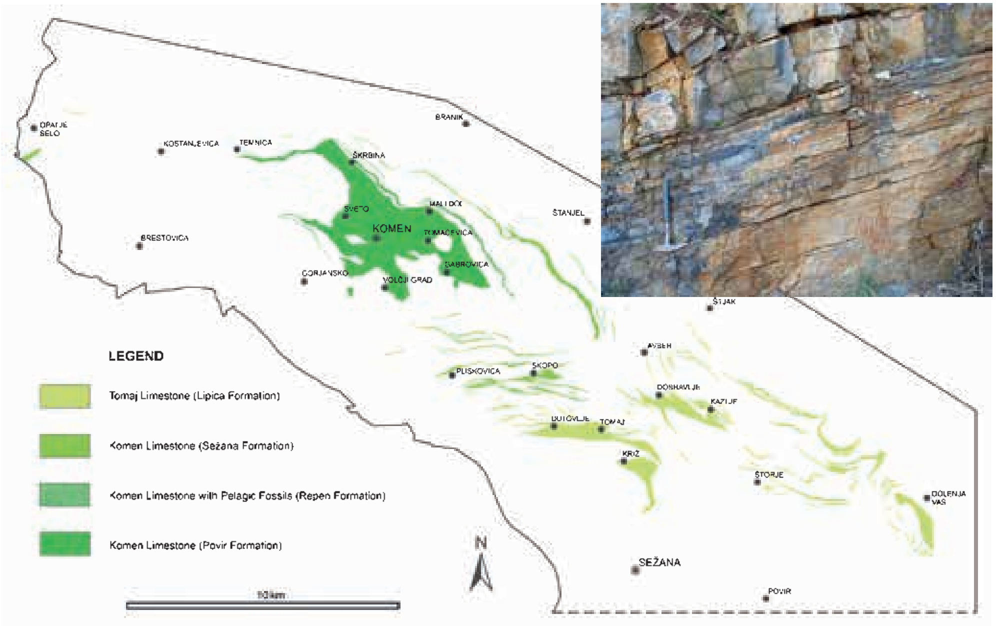


Figure 3.3.9: Upper Cretaceous platy limestones of different age in the Slovenian part of the Karst area (modified from Jurkovšek et al., 2013). Top right: Laminated Komen limestone with chert lenses at Škrbina (Photo: Bogdan Jurkovšek)

Figure 3.3.10: Rudist limestone in the road-cut at Divača (Photo: Bogdan Jurkovšek)

limestones are undoubtedly one of the oldest building materials in Classical Karst region. Even in the late 19th and early 20th centuries, local people collected slabs of these rocks for paving and roofing. A thick layer of reddish-brown soil called *terra r*ossa can form when these rocks are exposed to atmospheric agents. The vines are growing very good on this soil.

Besides these peculiar black, laminated rocks, most of the Upper Cretaceous of the Classical Karst is represented by grey and pale grey limestone. One of the most striking features of this rock is the abundance of rudists. During this period rudist bivalves, perfectly adapted to living attached to a variety of substrates, evolved into an amazing number of species with different shapes, 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. During the Upper Cretaceous rudists thrived in the shallow waters on the carbonate platform and formed extensive colonies. 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 (Figures 3.3.10 and 3.3.11).

Extensive deposits of rudist limestone in in the Classical Karst area are found, for instance, near Lipica, Kazlje, Vrhovlje, Povir, Gorjansko, Aurisina-Nabrežina, Borgo Grotta Gigante-Briščiki Col and Repen and these rocks are still being extracted in many quarries as a valuable architectural stone.

In the limestone, rudist shells can be more or less abundant, fragmented in pieces of various sizes or preserved whole. Depending on this, the colour of the rocks and their appearance when they are cut and polished, makes them more or less suitable to being carved. This has brought about many local names that are used by quarriers

Figure 3.3.11: Polished slab of Lipica Limestone displaying a cross-section of rudist cluster (Photo: Bogdan Jurkovšek)

Figure 3.3.12: Upper Cretaceous limestone with chondrodont shell fossil from north of Sežana (Photo: Bogdan Jurkovšek)

to identify the rocks they are extracting and selling. Some examples include Lipica (Figure 3.3.11), Repen, Kopriva and Granitello (see Chapter 5.1).

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. The Cava Romana Quarry at Aurisina-Nabrežina in Italy dates back to the 1st century B.C.E.. The largest quarry of Lipica/Aurisina Limestone today is Lipica 1 in Slovenia, where large blocks of massive rudist limestone are extracted (see Chapter 4).

Other typical fossils that can be found in the Upper Cretaceous limestone include those of the bivalve *Chondrodonta ioannae*. These fossils appear as leaves with many lobes and can be several centimetres long (Figure 3.3.12). Abundant accumulations of chondrodont shells can be found near Sežana and at the Monrupino-Repentabor sanctuary.

Figure 3.3.13: 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 (freshwater wetland) limestone (Photo: Bojan Otoničar)

✦ Upper Cretaceous-Paleocene limestone, a witness to major changes at the Cretaceous/Paleogene boundary

Major environmental changes took place at the end of Cretaceous. 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 3.3.13). This happened because the movements of the plates of Earth's crust were causing the African continent to move towards the European one. This would ultimately result in the formation of the Alps and of many other mountain chains such as the Pyrenees, the Carpathians, and the Himalayas. 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 paleontological content of these rocks which is very diverse and features animal and plant fossils indicative of environments that could be terrestrial or aquatic with brackish or saline water. 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 Basovizza- Bazovica, Lipica and Štorje areas. These were mined in the 19th and early 20th century.

The existence of many 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 Pescatore-Ribiško naselje in Duino Aurisina-Devin Nabrežina Municipality (Figure 3.3.14). There, two complete skeletons of the hadrosauroid

Figure 3.3.14: Laminated limestones near Villaggio del Pescatore-Ribiško naselje, in which dinosaur fossils were found (Photo: Sara Biolchi)

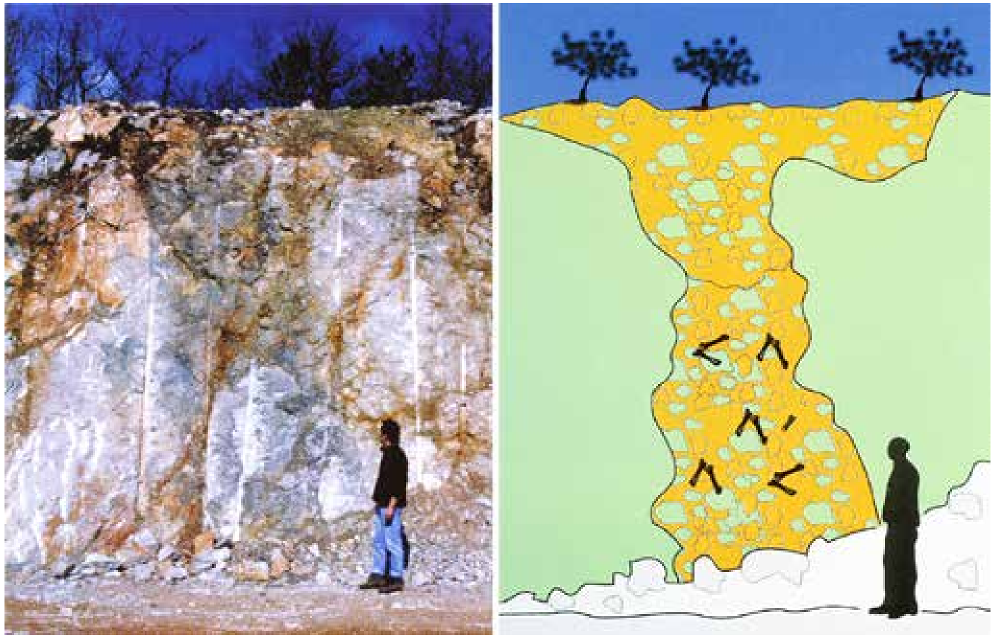


Figure 3.3.15: The locality of dinosaur bones in the breccia with limestone clasts of the Liburnia Formation that fills the paleokarstic cavity in limestones of the Lipica Formation in the road-cut at Kozina (after Košir et al., 1999)

Figure 3.3.16: The bones of dinosaurs, crocodiles 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)

Figure 3.3.17: Slivia-Slivno old quarry exposing paleokarstic breccia (from Consorti et al., 2021) (Photo: Maurizio Ponton)

species *Tethyshadros insularis* were found. Besides the hadrosaurs, this limestone also contains the remains of pterosaurs, crocodilians, fish, and other vertebrates (see Chapter 4). Fossil remains of Upper Cretaceous vertebrates, mainly dinosaur teeth and bones, have also been found in limestone breccia in a paleokarstic shaft near Kozina (Figures 3.3.15 and 3.3.16).

The Slivia-Slivno abandoned quarry exposes breccia made up of disorganised limestone blocks (Figure 3.3.17). 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.

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 and coinciding with the impact of a large asteroid. 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. Numerous animal and plant species, both on land and in the oceans, went extinct including dinosaurs and ammonoids as well as the rudists that cannot be found in rocks younger than this event. In the Classical Karst the, K-Pg boundary is well exposed at Dolenja vas.

✦ 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. Another sequence of limestone records this phase of the history of the Classical Karst area. Fossils in the Paleocene and Eocene rocks tell us how life in the seas changed after the end of the Mesozoic era. 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. As a result of the presence of a range of large benthic (seafloor-dwelling) foraminifera, in some strata these accumulated in large numbers, these limestones are easily identifiable (Figure 3.3.18). Some of the foraminifera resemble ancient coins and therefore were given the name of Nummulitids (from the Latin word *nummus* meaning the coin) (Figure 3.3.19) by paleontologists, while others, called Alveolinids, had a peculiar structure characterized by the presence of numerous cavities that, when observed with a hand-lens, look like small circular holes (Figure 3.3.20). There are actually many different species of these fossils which again helps geologists to assign an age to the rocks in which they occur.

✦ Flysch of the middle Eocene deep ocean basin

The youngest of the rocks that characterizes the Classical Karst area 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 that is well known by the term flysch (Figure 3.3.21).

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 events. They were therefore eroded and, through rivers, brought down to the sea. At times such sands

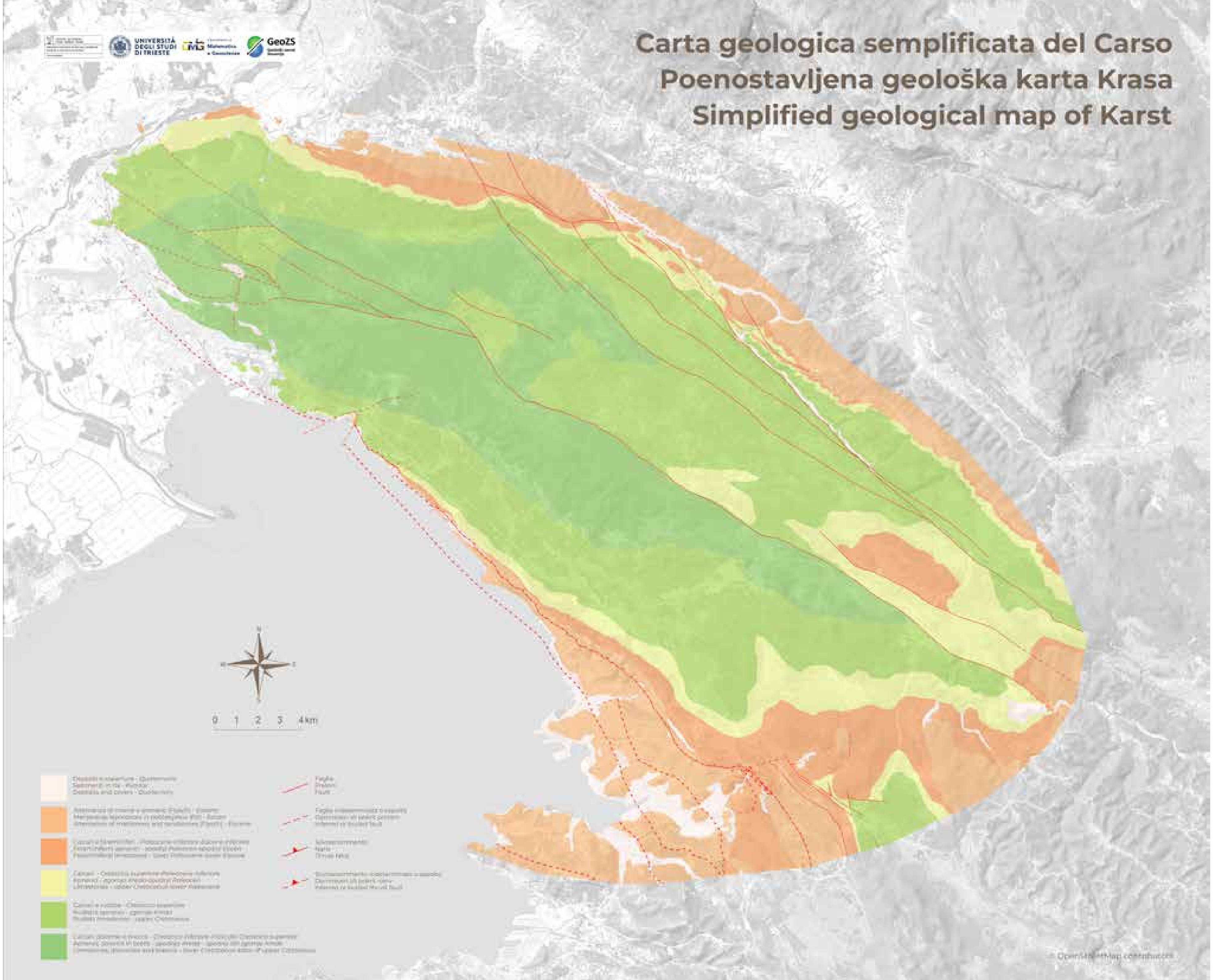
Figure 3.3.18: Foraminiferal limestone with Nummulitids and Alveolinids from west of Kozina (Photo: Matevž Novak)

Figure 3.3.20: Alveolinid foraminifer as seen through the microscope (Photo: Matevž Novak)

Figure 3.3.19: Nummulitids, resembling coins, naturally isolated from weathered rock (Photo: Matevž Novak)

Figure 3.3.21: Alternation of marlstone and sandstone beds composing a flysch sequence south of Gora (Photo: Bogdan Jurkovšek)

and clays, when they were not yet lithified, slid down the continental slopes in the form of submarine landslides. 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 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. On the surfaces of some layers, traces of crawling and burrowing can be seen, mostly made by unknown animals in the former sandy seabed. 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. In the vicinity of the Miramare Castle, some large blocks of the limestones rich in Nummulitid and Alveolinid fossils can be found. Geologists have observed that these blocks are underlain and covered by flysch, characterized by folds and deformations. This indicates that these blocks are actually parts of a large landslide that slid while flysch was still depositing. Such evidence testifies that, somewhere, the uplifting causing the rise of the Alps had brought the Cenozoic platform rocks to the surface and that they had collapsed into the sea where the turbidites of the flysch were accumulating (see Chapter 4).


Carta geologica semplificata del Carso
Poenostavljena geološka karta Krasa
Simplified geological map of Karst
0 1 2 3 4 km

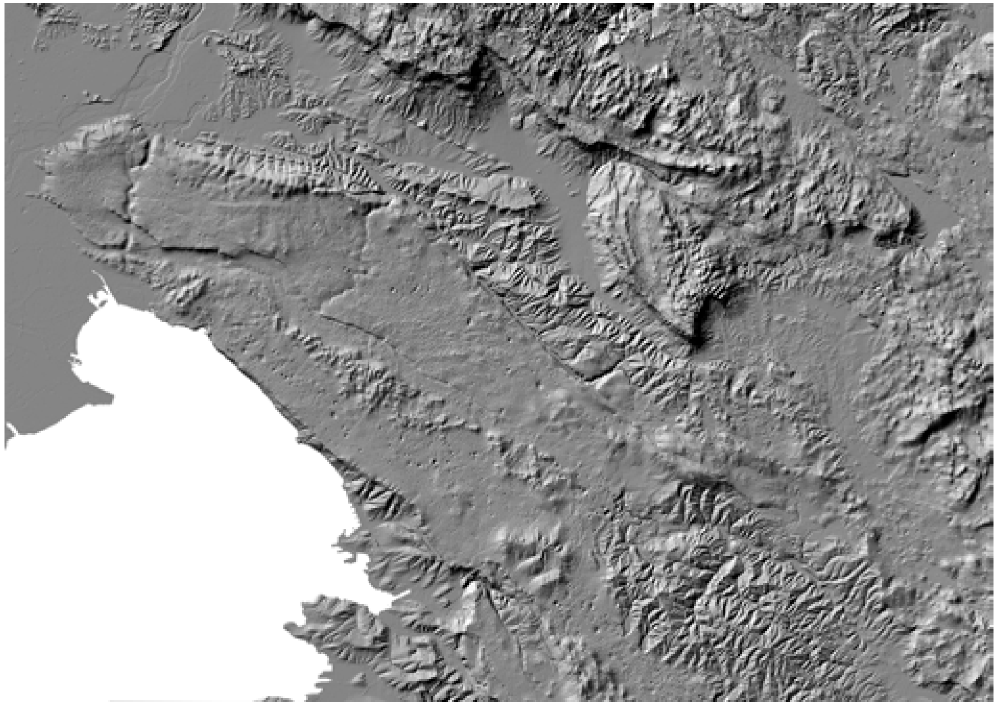


Figure 3.4.1: Shaded relief of the Classical Karst and surrounding area realised in the framewrok of HYDROKARST Interreg Italia-Slovenija 2007-2013 project

Figure 3.3.22: Simplified geological map of the Karst area, made for the geopark visitor centre at the Natural History Education Centre of Basovizza-Bazovica; the legend consider the same simplifed grouping of lithologies of the geological column in the Figure 3.3.3

3.4 Structural setting of the Classical Karst area

The present-day morphology of the Classical Karst area results from a long history of deformation that began millions of years ago. However, its structure can be summarized simply as a wide plateau with an area plunging to the southwest where the city of Trieste and the Gulf of Trieste are located (Figure 3.4.1).

This lay-of-the-land derives from the 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, that is to say, the northernmost segment of the African plate, and the Eurasian plates (Figure 3.4.2).

3.4.1 The Dinaric orogeny

One orogenic phase produced the Dinaric chain, a mountain belt that begins at the Italian/Slovenian border and finishes where Albania ends and Greece begins (Figure 3.4.2). The Classical Karst is located in the northern sector of the Dinarides. As mentioned before, the Dinarides result from the convergence between two plates. During the Cretaceous (70-80 million years ago), these plates were separated by an ancient ocean called the Tethys. When the two plates started to converge on each other, the rocks of the oceanic floor began to subduct. Note that the oceanic crust is denser than that of the continental plates. This is why when a continental plate collides with an oceanic one, the oceanic plate dives beneath the continental one, sinking into the Earth's interior. During the evolution of this convergence, the process of creating a mountain belt reaches its apex when all the denser (oceanic) rocks have been subducted and the two equally dense continental plates collide. In geology, the subducting plate is named the lower plate, the second the upper. To describe the development of orogeny and the accretionary mechanisms of the mountains in simple terms, one can imagine the upper plate as a bulldozer or snowplow that tears away some

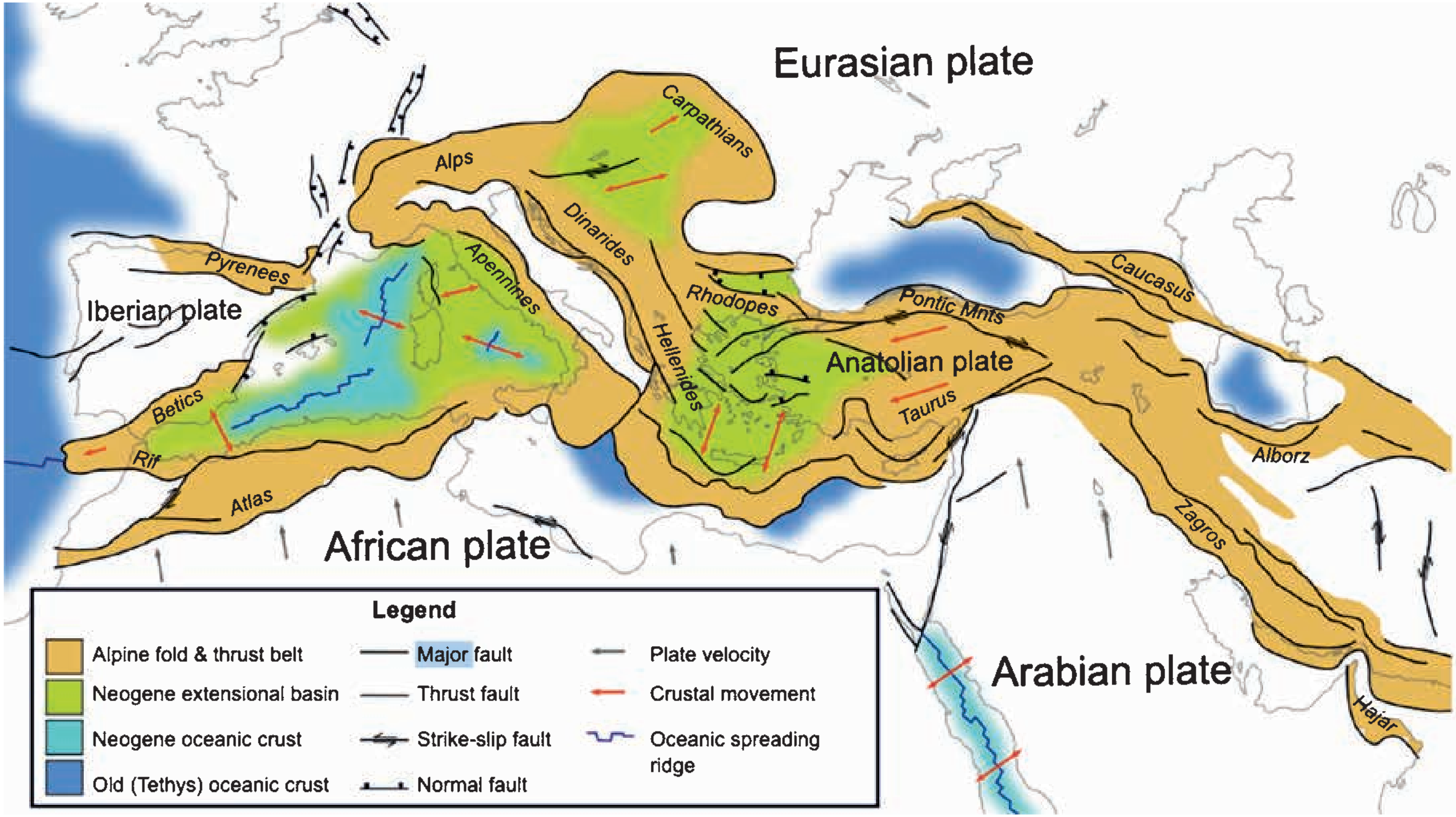


Figure 3.4.2 : Tectonic map of Europe

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. 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 Classical Karst. This natural bulldozer moved above a subducting plate at a rate of a few millimeters 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 accommodation space for sediments that derived from the erosion of this huge

Figure 3.4.3: Simplified evolutionary sketch of the Dinaric orogeny

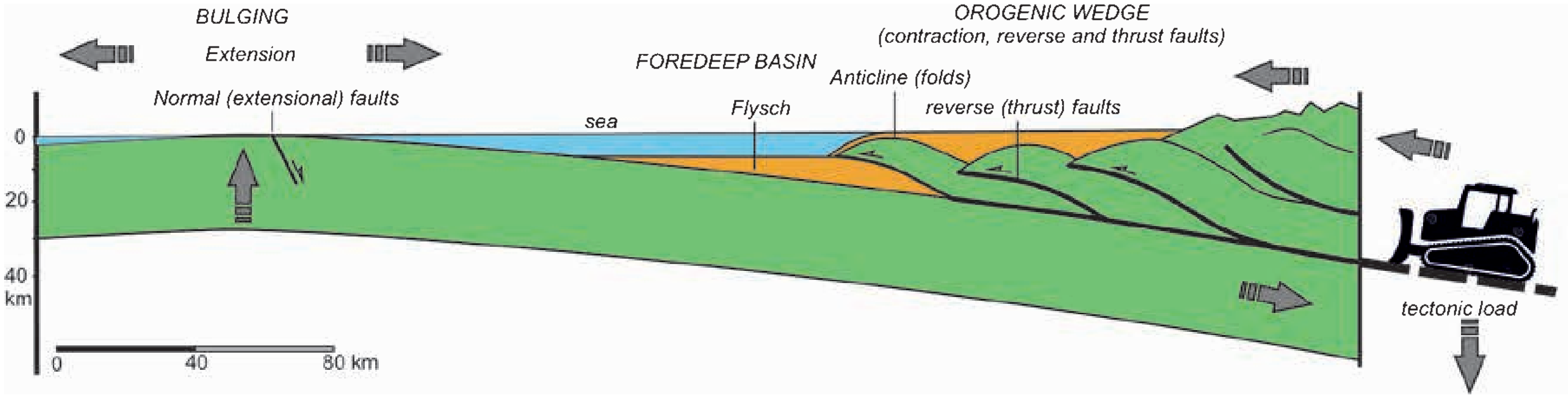
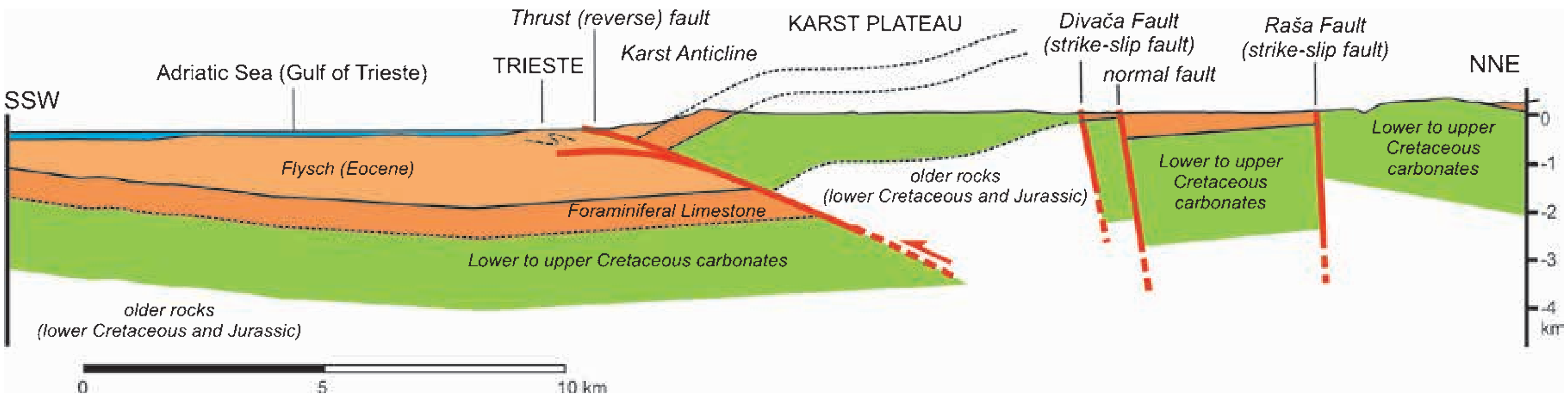


Figure 3.4.4: Geological cross-section



wedge (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, depicting a large asymmetric fold, namely an anticline (a fold with a shape of A) with its southern limb more inclined than its northern one.

3.4.2 The structure and the history of the Classical Karst

If we imagine vertically cutting through the Karst, we would observe its internal structure, namely the Karst anticline (Figure 3.4.4).

As mentioned, this 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

Figure 3.4.5: Mechanism showing the generation of a fold deforming a towel

to southwest. To understand this process, one may imagine moving a towel on a table (Figure 3.4.5). 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, in the center of the Karst Plateau outcrop the geological map shows the older rocks, i.e., the Lower to Upper Cretaceous rudist limestones with fossiliferous platy limestone layers (see Section 3.3; green areas in Figure 3.3.22), and moving towards the edges of the Karst the younger rocks are present (orange rocks in the geological map of Figure 3.3.22).

The geological map also shows red lines crossing the area. These red lines are the major faults. In general, faults represent fractures in the rocks that are formed as a consequence of compressional or extensional tectonic phases during the geological evolution of the area. Faults may be classified as 1) reverse faults that are surfaces in which a rock block moves up relative to another block; 2) normal (extensional) faults in which a rock block moves down with respect to another block and; 3) strike-slip faults, in which the two blocks move laterally. In the Classical Karst area, all these types of faults exist. 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 contractional 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 (see Chapter 4). These are strike-slip faults generated during a younger phase, during which ancient normal faults are reactivated (reactivation means that a fault changes its kinematic during the geological time, e.g., a fault that was a reverse fault due to the change of tectonic forces in the geological time may be removed as a normal fault or strike-slip fault). This means that the Divača and Raša faults at the start of their history were normal faults and then altered their movement in a horizontal mode. Note that, in general, extensional faults form when the rocks are stretched. However, only a contractional phase has been described, namely the Dinaric orogeny and the contractional structure (reverse and thrust faults).

To understand the tectonic mechanisms that generated the normal faults, it is necessary to look at the simplified sketch of Figure *3.4.3* and the bulldozer. The bulldozer creates the contractional wedge and the folds and reverse (thrust) faults. However, the thickening of the wedge increases the load on the lower plate, inducing bulging and stretching in the foreland area, hence the condition for the development of extensional (normal) faults. These normal faults are involved in the contractional wedge when the bulldozer reaches its position. Now only one question remains unsolved, namely why the Divača and Raša faults are now strike-slip faults. After the end of Dinaric orogeny's major contraction phase, the movement of the Adria plate continued, slightly changing its direction, i.e., from northeast to the north (the neo-Alpine phase). This change induced a rotation of the rocky blocks and a strike-slip reactivation of the ancient normal faults.

3.5 Geomorphology of the geopark area

The Karst is a low carbonate plateau lying between the Gulf of Trieste and the Vipava Valley at an altitude ranging from a few metres and about 500 m above sea level (a.s.l.). It is bounded to the southwest by the Gulf of Trieste and a low-lying non-carbonate flysch landscape, and to the northwest by the alluvial Friuli Plain. Flysch hills over 600 m above sea level separate the Karst from the Pivka basin. To the southeast, the Karst is well separated from the flysch areas of Brkini and the Reka Valley on one side, while on the other, more southerlyn side, it gradually merges with the karst areas of Čičarija, the Podgorski Kras and the Matarsko Podolje. The Karst Plateau stretches for 46 km southeast to the northwest and is also inclined in this direction, from Lokev at 450 m a.s.l. to Doberdò-Doberdob at 98 m a.s.l.. It is up to about 15 km wide and covers about 750 km^2.

The Classical Karst belongs to the Mediterranean area and has a Mediterranean climate, influenced by its location far to the north and the altitude. Summers are hot and dry, while winters are quite cold with a characteristic cold northeasterly wind - the *bora*. Most of the rain falls in autumn. In the central part of the Karst, in Komen, which is only ten kilometres from the sea, the average annual temperature is 12°C at an altitude of 290 metres. The amount of precipitation is relatively high, as the long-term averages range from 1,400 to 1,650 mm per year, with 1,000 mm per year on the coast.

The Classical Karst's karstification has been evolving for more than 10 million years and the original morphologies across the surface are today recognized only with difficulty. The karst surface features, just as they appear today, are the result of the predominant lithological conditionings and partially due to tectonic-structural ones.

Starting from the sea and running in a northeastly direction, it is possible to encounter different morphological units, all oriented NW-SE:

- a coastal karst between Duino-Devin and Aurisina-Nabrežina;
- a hilly alignment of the San Primo-Sv. Primož Mt. – Gurca-Gorka Mt. – Belvedere-Banovski Mt. – Calvo-Globojnar Mt.;
- the levelled landscape between Sistiana-Sesljan, Aurisina-Nabrežina and Basovizza-Bazovica;
- the hilly area which goes from Mt. Ermada-Grmada to Mt. Volnik-Lanaro as far as Mt. Tabor;
- the wide, levelled landscape between Doberdò-Doberdob, Kostanjevica na Krasu, Komen, Dutovlje and Divača on the southern side of which is a further structurally depressed area related to a range of faults between Colle Nero-Jamlje, Brestovica and Divača is present;
- the hilly northern alignment dividing the Classical Karst from the Vipava Valley.
- Separated from them are the fluviokarstic Rosandra-Glinščica Valley and northern part of levelled karstic plane of Matarsko Podolje with blind valleys on its NE edge.

As a result of the solubility of karst rocks and geological unconformities in them, the large amounts of precipitation and inflows of allogenic waters from peripheral non-carbonate rocks, a great number of characteristic surface and underground karst forms have developed here. Their study is important for understanding the geological, hydrogeological and climatic dynamics, not only of the Classical Karst, but also of the wider area.

Small-scale surface relief rocky features

The most distinctive karren fields were formed on the thick-bedded to massive Upper Cretaceous limestone in the wider Lipica, Opicina-Opčine, San Pelagio-Šempolaj and Borgo Grotta Gigante-Briščiki areas and in part of the Karst around Divača. As a rule, this type of limestone does not disintegrate as quickly on the surface and beneath soil cover as the younger, usually thinner-bedded Paleocene limestone, which is therefore more frequently reshaped as a result of karst surface processes. The larger rock masses of Cretaceous limestone have remained largely intact. However, most of the land surface has been deforested and the area around the karrens was primarily used for grazing. Karrens consist of rock masses ("stone teeth") up to 5 metres high, formed between fis-

Figure 3.5.1:
A) Karrenfeld close to the Colognatti Abyss (Photo: Furio Finocchiaro);
B) Rain flutes and solution pans have been carved out by rainwater (Repen) (Photo: Bojan Otoničar)

sures. The subcutaneous rock features that shape the rock relief of the lower parts of the karrens and, in some places, the peaks that have been reshaped under the soil, represent the oldest phases of karren/stone teeth formation. The subaerially exposed rocks have been reshaped by rainwater and thus solution flutes and runnels as well as kamenitzas cover the surface of the rocks (Figure 3.5.1 A and B). Overgrowth of the once mostly bare karst surface associated with direct exposure to rain has transformed them beneath lichens, mosses, and soil. Thus, the rock relief provides traces of the evolution of the karst surface and its use (from deforestation to grazing to reforestation).

Medium-scale karst surface features

In detail, the Classical Karst is dissected by numerous closed karst depressions. Among them, dolines predominate, and collapse dolines, uvalas (*doli*), dry valleys and conical hills are also frequent (Figure 3.5.2). The surface is often rocky because the thin soil is not continuous and the rocky floor is not completely covered.

Dolines of a range of shapes, fills (*terra rossa*) and anthropogenic transformations (cleared with dry stone walls around them, archeological sites, vineyards, vegetable gardens or cultivated fields) (Figure 3.5.3) are very frequent in the Classical Karst. Since the soil in the Karst is often present only at the bottom of the dolines, vegetable gardens and cultivated fields are often planted. The bottoms of the dolines were levelled, while stones were removed from the slopes and buried or piled up to form dry stone walls (Figure 3.5.3). The floors of dolines were often also used for water storage (i.e., ponds or, in slovene, “*kal*”) (Figure 3.5.4).

Figure 3.5.2 :
Solution doline near Padriciano-Padriče village
(Photo: Furio Finocchiaro)

Figure 3.5.3: Anthropogenically transformed doline immediately below the walls of the prehistoric settelment of Debela Griža near Volčji Grad pri Komnu (Photo: Bojan Otoničar)

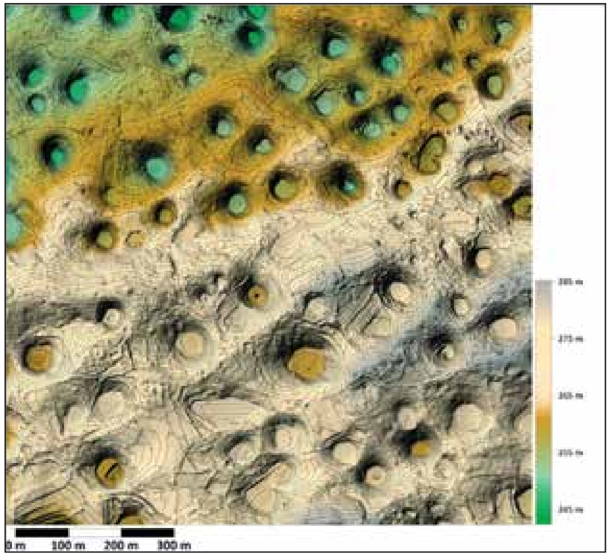


Figure 3.5.4:
The pond on the bottom of the Percedol-Prčendol Doline near Opicina-Opčine (Photo: Furio Finocchiaro)

Figure 3.5.5:
DEM of Lipiški Ravnik in the southeastern part of the Classical Karst is characterized by dolines with steep rocky slopes and anthropogenically flattened floors. In some dolines soil has been dug and taken to nearby villages for use in vineyards and gardens.
The contour interval is 1 m.
(from Mihevc & Mihevc, 2021)

More than 22,400 dolines have been identified with 5,900 on the Italian side and 16,500 on the Slovenian side of the border, covering a total area of about 20 km^2. In some areas of the Classical Karst Plateau, such around Basovizza-Bazovica, Opicina-Opčine, Divača, Borgo Grotta Gigante-Briščiki, Gorjansko, Doberdò-Doberdob and San Martino del Carso-Martinščina, the density of dolines is greater than 70 per km^2.

Most dolines, 62%, have an average diameter up to 50 m, 31.5% have a diameter between 50 and 100 m (Figure 3.5.5) with only a dozen have a diameter larger than 500 m. Their average depth is about 30 m. Larger collapse dolines in the Classical Karst are 50 to 200 m deep and as much as a few hundred metres wide, with a volume of as much as several million m^3. Collapse dolines are distributed throughout the Classical Karst area. The largest concentrations of 27 major collapse dolines are located in the Divača area, in the hinterland of the river Reka ponors, and near Sežana. They mark a path of the underground river Reka and some of the largest caves in the Classical Karst, such as the Škocjan Caves - Kačna Cave system. There are also some smaller concentrations of collapse dolines in the northern part of the Classical Karst such as those south of Kobjeglava, and in the area between Kazlje and Štorje. In the selected area of the Divača Karst (31 km^2), collapse dolines were found to account for about 4% and dolines for about 7% of the total area, but it is estimated that the total volume of collapse dolines is more than four times the total volume of dolines.

In the levelled area between Aurisina-Nabrežina and Basovizza-Basovica, the depressions exhibit a very large range in diameters and depths according to their genesis (solution or collapse) and age (evolution).

A high concentration of dolines (with a frequency greater than 40 per km^2) can be found in the wide plateau of the Gorizia-Monfalcone area. Located at an altitude of 100 - 200 m a.s.l., the plateau is characterized by a large number of dolines that are similar in size and depth, with an average diameter between 50 and 80 m.

Although the surface of the Classical Karst is densely covered with dolines (Figure 3.5.5), they account for less than 10% of the total area (excluding the hilly part of the Karst). The simple interpretation of the origin of the relief in the Classical Karst is complicated by the rather frequent occurrence of denuded caves, indicating that in some places a significant portion of the surface relief features were actually created during the transformation of underground caves.

Like denuded caves, collapse dolines could also be considered a reflection of the underground karst on the karst surface.

Apart from the already mentioned level surfaces, there are no karst forms of larger dimensions in the Karst iself, with the possible exception of the uvala near Senadolice (Figure 3.5.6). Uvala Senadolska dolina or Dol represents an elongated, closed karst depression, a little more than 5 km long and, on the perimeter over a kilometre wide, running SE-NW, at the bottom of which there are several beautifully shaped dolines. It is open only to the NW, where it turns a slight bend at Senadolice to a level area almost 100 metres lower than the SW part of the Karst.

The formation of the uvala can be attributed to the accelerated dissolution in the area of the fissure zone compared to the slower dissolution of the clayey and brecciated, crushed or broken inner zone of the Raša Fault, or it may even be a remnant of the old blind valley that drained water from an already completely eroded adjacent area of flysch.

Contact karst and dry valleys

In the Classical Karst area, the most famous sinking river is the Reka (becoming the Timavo in Italy at its re-emergence), which vanishes underground at the end of the great Vreme Valley into the Škocjan Caves (Figure 3.5.7). Some smaller streams also sink at Dane and Senožeče. The Vrhpolje Valley near Kozina can be considered a „fossil" blind valley. However, the best known and most typical are the blind valleys along the northeastern flank of Matarsko Podolje along the not clearly defined southeastern border of the Classical Karst.

Although there are a number of smaller dry valleys in the Classical Karst, often still active and more or less pronounced in relief, two stand out. Pletni Dol (Mali Dol) (Figure 3.5.8), which crosses the Classical Karst between the Branica Valley and Brestoviški Dol, and the most pronounced and largest, Vallone-Doberdobski Dol that crosses the Gorizia-Gorica-Monfalcone Karst between the Vipava Valley and Monfalcone.

The genesis of these dry valleys is still debated. Some authors believe that these valleys are what remains of ancient riverbeds, others believe they may be a trace of ancient unroofed caves which originat-

Figure 3.5.6: Uvala Senadolski Dol near Senadolice in the southeastern part of the Classical Karst runs NW – SE direction along the Raša Fault (Photo: Bojan Otoničar)

Figure 3.5.7: Blind valley of Reka River before it sinks into the Škocjan Caves. Note the levelled surface dipping slightly towards the NW of the Karst (central part of the figure) with a hilly landscape on the sides (Photo: Matej Blatnik)

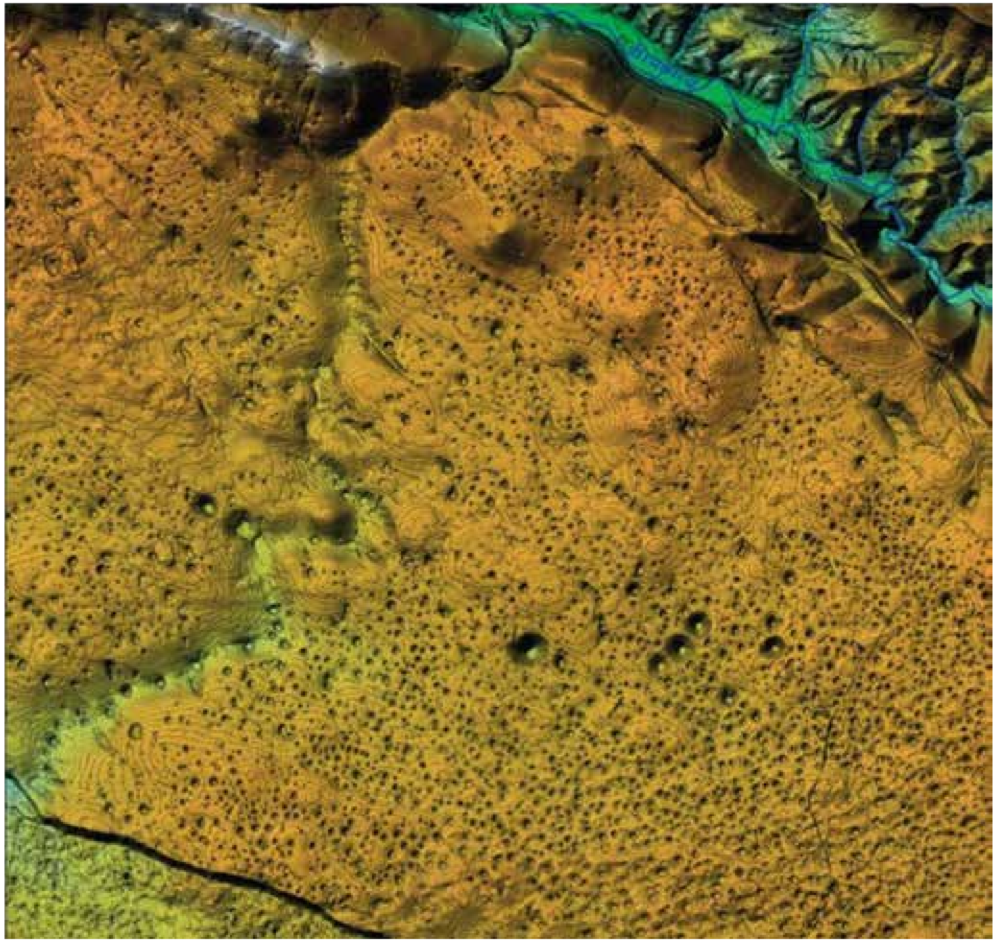


Figure 3.5.8: DEM of levelled landscape of the central part of Classical Karst with numerous dolines and Mali Dol dry valley. A doline has also formed in the dry valley. The escarpment in the lower left corner of the figure has developed along the Divača Fault. The contour interval is 5 m (from Mihevc & Mihevc, 2021)

ed by the lowering of the karst surface, others suggest the interconnection of different karst depressions such as polje, caves and uvala.

The already mentioned Brestoviški Dol (Figure 3.5.9), where the Slovenian part of the Classical Karst reaches its lowest altitude, only a few dozen metres above sea level, and where the Classical Karst region is supplied with water, is a tectonically induced depression developed along the regional Divača Fault.

Figure 3.5.9: Veliki or Brestoviški Dol in the NW part of Classical Karst is a tectonically-induced depression developed along the regional Divača Fault which is especially well reflected in the relatively steep NE flank of the depression (left side of the figure) (Photo: Matej Blatnik)

Figure 3.5.10: The Rosandra-Glinščica fluviokarst Valley (Photo: Franco Cucchi)

Fluviokarst Rosandra-Glinščica Valley

“Klinš’ca”, as the local inhabitants call it, or, simply, “Valle” as the people of Trieste call it, is at the extreme eastern side of the Classical Karst Plateau (Figure 3.5.10). It is a canyon-like valley, excavated in the Cenozoic limestone by the Rosandra-Glinščica torrent and represents a rare example of a karst river valley with surface hydrology. Its origin is mainly due to the presence of faults and overthrusts and the different predisposition to erosion between the limestone and

marls, making it a beautiful example of lithological and structural control on morphogenesis. The whole area, and in particular Mt. Stena, is characterised by surface and underground karst features. 100 caves have been surveyed, some of which are more than 100 metres long. Among them, one of the most beautiful is the Savi Cave, rich in speleothems, the growth axis of which are characterised by geochemical and physical changes (controlled by climate as well as by the dynamics of the host karst system). The Valley was also known in the past and was used to carry the salt from the coast to the inland villages. Caves with prehistoric remains, the ruins of castles and hillforts, mills, country churches, the ruins of the Roman aqueduct and abandoned quarries demonstrate the intense and ancient settlement of the area. The Rosandra-Glinščica Valley's peculiar climatic and geomorphological conditions and its geographical location make it a special and important habitat.

Coastal karst

Along the coastline between Aurisina-Nabrežina and the Villaggio del Pescatore-Ribiško Naselje the limestones, that outcrop widely, are rich in epigean and hypogean karst features. Marine aerosols contribute to the development of all karst features by enhancing their shape. The mixture of freshwater and seawater not

Figure 3.5.11: The Duino-Devin Cliff (Photo: Rodolfo Riccamboni)

only promotes the genesis of notches, but also of caves and springs. The moderately sloping coast up as far as Sistiana-Sesljan becomes a high cliff as far as the small port of Duino-Devin (Figure 3.5.11). The chromatic contrast of rock, sea and vegetation creates a unique and fascinating landscape in every season.

Caves

In the Classical Karst within the geopark, more than 4,000 caves have been explored, with 3,000 in Italy and almost 1,800 in Slovenia. The numerical difference is due to the fact that in Slovenia only those caves that are longer or deeper than 10 metres are recorded in the cave cadastre while in Italy smaller ones are also included. Only about ten caves are longer than 1,000 m.

The analysis carried out has highlighted that about 45% of the caves have a prevailing horizontal development, while 30% have a prevailing vertical one. About 25% have a complex shape in which shafts alternate with horizontal sections.

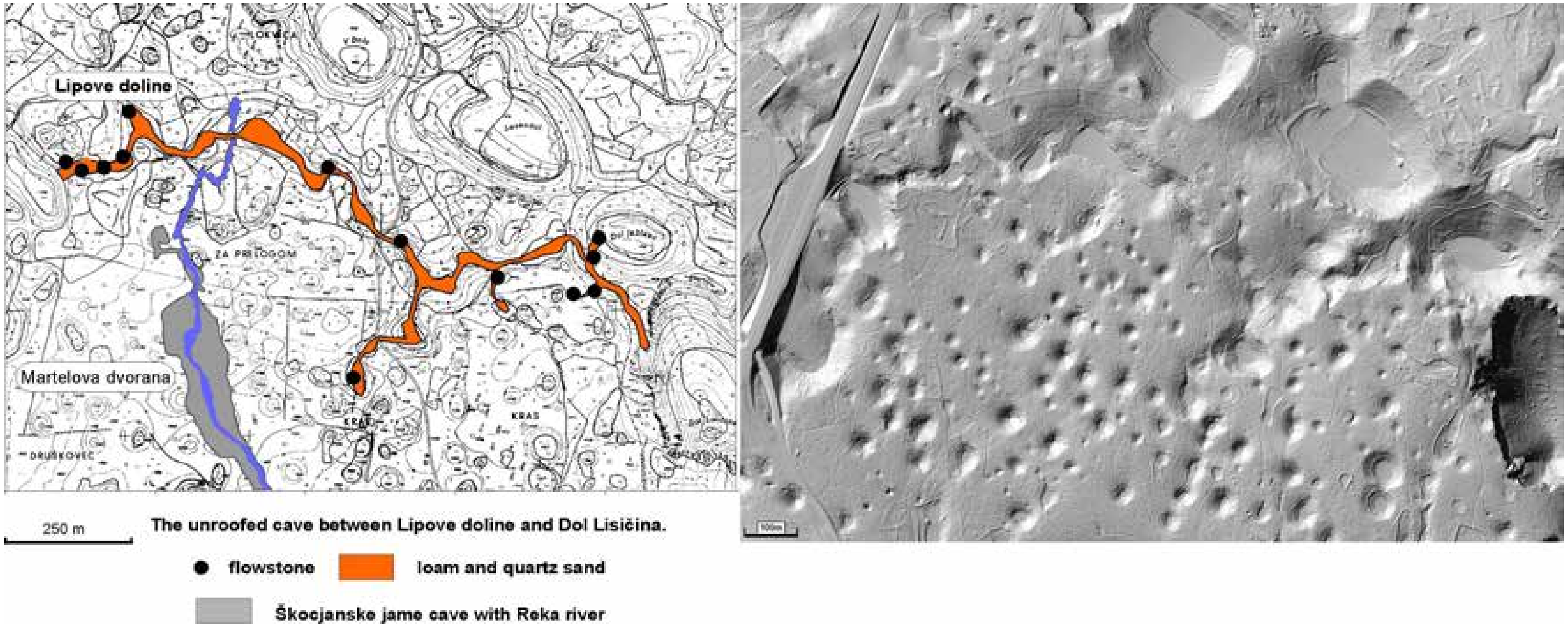
The basic data of caves/shafts are kept in the cave cadastre of the Slovenian Speleological Association, which is managed and directed by the Karst Research Institute ZRC SAZU, and in the Regional speleological cadastre of the Friuli Venezia Giulia Region, managed by the Geological Survey of the Autonomous Region of Friuli Venezia Giulia.

The longest cave network in the Classical Karst is the 20,200 m long cave Kačna jama while the deepest is the 378 m deep Claudio Skilan Cave.

Today in the Classical Karst there are caves that were primarily formed in the flooded or phreatic hydrological zone in different levels and zones. A special element of global value of the caves around Divača and Sežana - Opicina-Opčine, together with the Škocjan Caves, are the phreatic caves, which are found at various levels and are of exceptional importance for the study and understanding of karst hydrogeological systems and the associated geological evolution of a particular karst and karst/fluvial contact areas. The deepest karst features identifiable below the surface are the caves, the lower parts of which are still permanently or intermittently flooded. These can be intersected by ponors and collapse dolines (Škocjan Caves) or by deep stepped shafts and steep fossil epiphreatic channels (Kačna jama, Jama 1 v Kanjeducah, Brezno v Stršinkni Dolini -Jama Sežanske Reke, Trebiciano-Labodnica Abyss and the Lazzaro Jerko Cave). Shallower caves, just below the surface, and thus older, are dry, subhorizontal or slightly dipping caves, now in the vadose zone, and which represent fossil or relict phreatic channels which in the past drained a significant proportion of karst groundwater to springs. Caves of this sort include the Divaška jama, Vilenica, Jakofčičeva jama, Gustinčičeva jama v Blažčevi dolini, Lp2 (at Lipica), Lipiška jama, Škamprlova jama, Grotta Claudio Skilan, Grotta di Padriciano, Grotta Impossibile, Grotta Lindner, Grotta Gigante-Briška jama, Grotta Torri di Slivia-Pejca v Lascu and the Grotta Noè-Pečina v Rubijah. These caves are often accessible through vertical shafts or are so close to the surface that karst denudation has opened the cave ceilings (Figure 3.5.12).

Figure 3.5.12: The denuded cave entrance of the Grotta Azzurra-Zidaričeva pejca Cave (Photo: Furio Finocchiaro)

Figure 3.5.13: Topographic map with location of the denuded cave at Lipove Doline above Škocjan Caves (left) (from Mihevc 2001) and a Lidar DEM (Slovenian Environment Agency) of the same area (right)



The related relative raising of the territory or lowering of the erosion base and simultaneous lowering of the karst surface due to denudation is confirmed by the numerous denuded caves or caves without ceilings (e.g. the denuded cave with stalagmite in the Lipova dolina above Škocjan Caves (Figure 3.5.13), a large denuded cave near Povirje, various denuded caves near Sežana, and a denuded cave with stalagmites in Borgo Grotta Gigante-Briščiki). Today, these caves are part of the karst surface, but their form is basically a relic of the phreatic/epiphreatic underground karst, which was later transformed into a vadose hydrogeological zone, and subsequently even on the karst surface and subject to surface processes. The denuded caves and the caves observed today in the vadose zone may have been formed at the same time and be of the same age, separated only by a later different location according to the morphology of the surface. The oldest caves in the Classical Karst today are those closest to the karst surface, including the caves in the area of Tabor, Monte Lanaro-Volnik Hills and Mount Ermada-Grmada where the Grofova jama Cave, with a sedimentary fill at least 10 million years old, is particularly interesting and important.

Cave shafts are numerous in the Classical Karst and represent vertical channels that can be independent or represent entrances to horizontal caves. Here it is worth mentioning the entrance to the longest cave in the Classical Karst, the Kačna jama Cave, the Abisso della Volpe Shaft and the independent shaft of Lipiško brezno. The entrance to the Kačna Jama is located in a large doline at the bottom of which opens a 186 m deep system of parallel shafts, the Abisso della Volpe is 181 m deep, while the Lipiško brezno shaft is an independent cave feature and, at 210 m, probably represents the deepest known single vertical shaft in the Classical Karst.

The origin of large shafts in the Classical Karst is not yet fully understood, since it is not clear whether they are shafts that originated in the vadose zone, created by percolating water from the surface or whether they are actually subvertical phreatic or epiphreatic channels.

3.6 Hydrogeology of the geopark area

The Classical Karst aquifer

Every time you walk along the Karst Plateau you will be amazed by the uniqueness and variety of landscapes that surround you. Sometimes just a few steps are enough to pass from forest to arid, stony ground, from spires and hums to chasms and depressions, from soft meadows to impervious *karrenfelds*. Everything tells a story lasting millions of years, in which water, as a tireless sculptor, has modeled every rocky outcrop, making it original and unique. Water, however, only stays on the surface for short periods of time. The extensive network of discontinuities (layers, 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 this aquifer are the Timavo Springs, that, with their average flow rate of 30 m^3/s, represent the most important source in the area of the geopark.

But where does all this water come from? And why does it come out at this particular place?

To answer this question, we need to turn to geology.

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 silici-clastic rocks, here represented by flysch (an alternation of marl and sandstone in which the silicatic component prevails over the carbonate one). These two geological units have different hydrogeological characteristics and 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 Hydrogeological Map (Figure 3.6.1), note how the flysch is present in an almost continuous fashion, both in

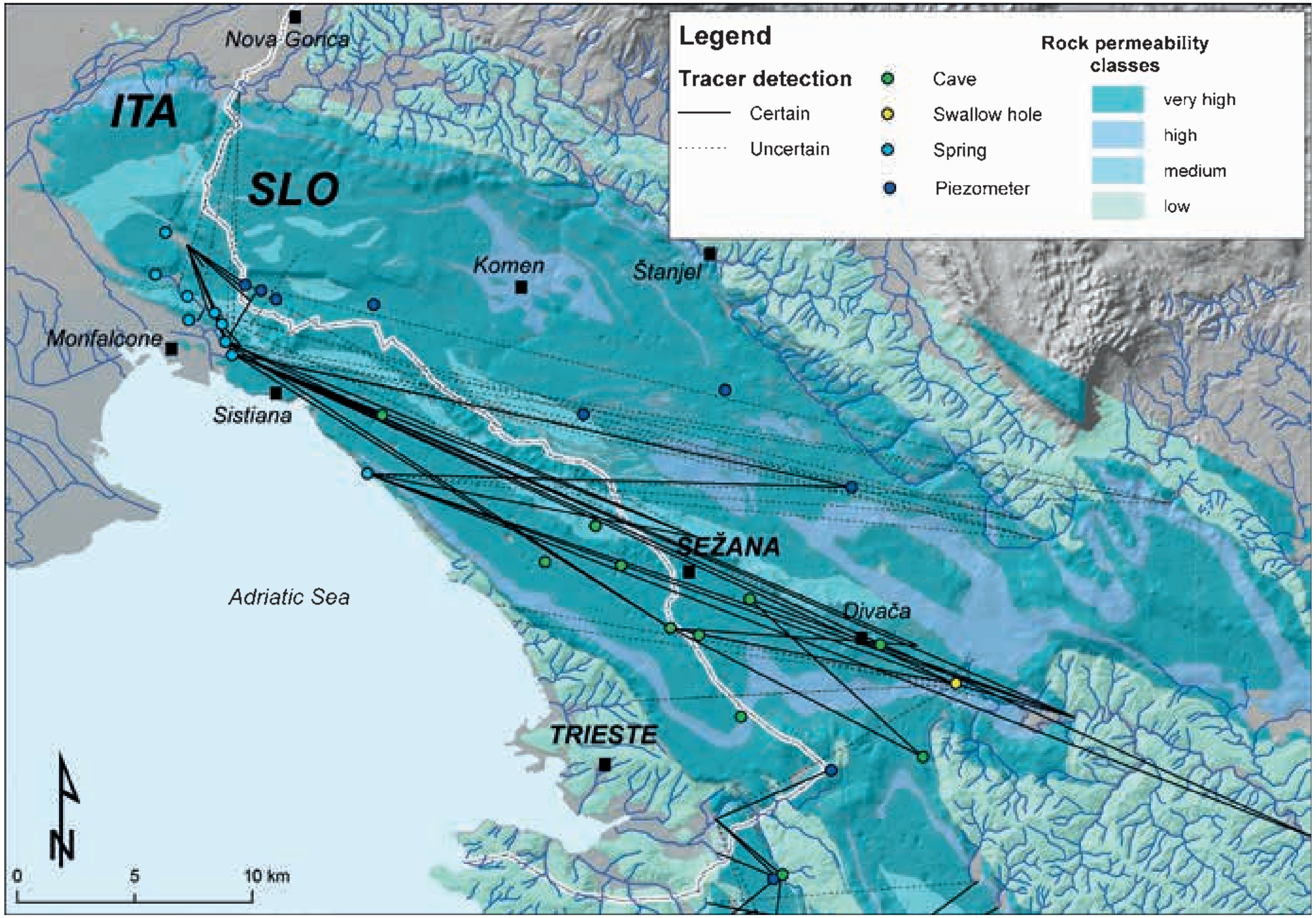


Figure 3.6.1: The hydrogeological map of the Classical Karst (modified from Zini et al., 2022)

the northern and eastern sector of the Classical 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 sector in correspondence of the area between Aurisina-Nabrežina and Monfalcone where the barrier is lacking and the groundwater can re-emerge in numerous springs.

The aquifer recharge

The aquifer is recharged by three distinct contributions: rainfall, water from the Reka and Raša Rivers, and inflows from the Isonzo Plain aquifer (Figure 3.6.2).

Given the extension of the Karst Plateau and the heavy rainfall in this region, precipitation represents the main contribution to the re-

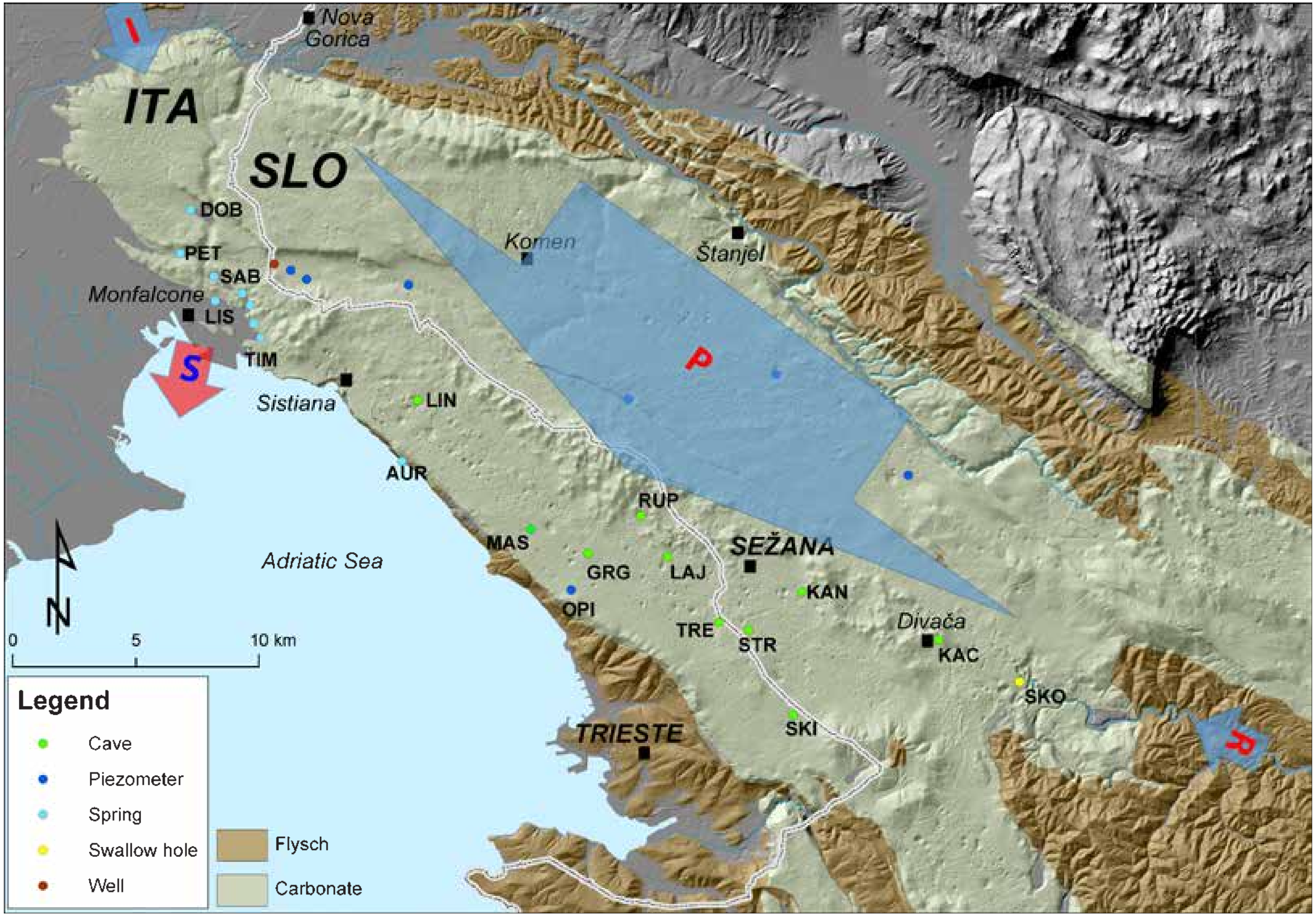


Figure 3.6.2: The hydrostructure of the Classical Karst with the main water points: SKO Škocjan Caves, KAC Kačna jama-Abisso dei Serpenti Cave, KAN Jama 1 v Kanjaducah Cave, SKI Claudio Skilan Cave, STR Brezno v Stršinkni dolini - Jama Sežanske Reke Cave, TRE Trebiciano-Labodnica Cave, LAJ Lazzaro Jerko Cave, GRG Grotta Gigante - Briška jama Cave, RUP Rupingrande Abyss, OPI Opicina piezometer, MAS Massimo Abyss, LIN Lindner cave, AUR Aurisina Springs, TIM Timavo Springs, LIS Lisert Springs SAB Sablici Lake, PET Pietrarossa Lake and DOB Doberdò Lake. The blue arrows identify the various contributions to feeding the aquifer and the red arrow the average flow values of the various springs (modified from Zini et al., 2022)

Figure 3.6.3: Vreme's swallow hole. Tracing test using a fluorescent green dye (uranine) (Photo: archive of the Department of Mathematics and Geosiences - University of Trieste)

charge of the Classical Karst aquifer, which is located in a transition area between the Mediterranean and continental climate, where the average rainfall varies from about 1000 mm/year along the coast to 1800 mm/year inland and to values over 2000 mm/year in the Reka basin. Due to the intense and widespread karstification of the rock mass, the low vegetation cover and often the negligible amount of soil, there is no hydrographic network on the surface, but rainwater quickly infiltrates, recharging the groundwaters.

An important contribution can be observed in the north-western sector of the Karst between the towns of Merna and Sagrado where the waters of the Isonzo-Soča and Vipacco-Vipava Rivers are in direct contact with the limestone. In this area a series of swallow holes activates the transfer of surface and groundwater towards the karst aquifer. The water infiltrates at numerous points and in this way has created a complex karst network that brings the waters towards the springs between Mucille-Močile and the Timavo Springs themselves.

The contribution of the Raša and Notranjska Reka (Upper Timavo) Rivers to the aquifer is the most interesting from a hydrodynamic point of view. These watercourses flow on the surface as long as they pass over the flysch, but when they reach the limestones, a series of sinkholes drain their waters at depth. The Raša discharges are relatively modest and even for long periods the riverbed remains dry, while those of Reka are decidedly greater, and represent on average more than a quarter of the recharge of the entire karst aquifer.

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 process is active 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 are swallowed and downstream the riverbed is dry (Figure 3.6.3).

When the flow rate is higher than about 1 m^3/s the Vreme swallowhole is unable to capture all the water which continues its flow towards Škocjan Caves. The Reka enters the Škocjan Caves, which are more than 6 kilometres long, at an altitude of 317 meters above sea level (a.s.l.), crosses some very deep collapse dolines (the Mala dolina is 120 metres deep and the Velika dolina is more than 165 metres deep) and after having covered about 3.5 kilometres of a gigantic gorge, 10 to 60 metres wide and over 100 metres deep, it disappears into the siphon of the Dead Lake at 212 metres a.s.l.

The *Notranjska Reka* has an extremely variable flow rate, ranging from over 380 m^3/s during floods to 0.18 m^3/s in dry periods. The flow rates can be so high that sometimes the underground conduits cannot drain all the water. The groundwater rises abruptly, flooding sections of caves that are usually inactive. The air in the cavities is expelled abruptly giving rise to what, in 1800s, were referred to using the German term "*luftloch*" (blow-hole) (Figure 3.6.4). Using these points speleologists discovered and explored the caves, reaching the Timavo's underground conduits including the Kanjaduce Cave (Jama 1 v Kanjaducah), the Abyss at the Stršinkna dolina-Jama Sesanke Reke, the Trebiciano-Labodnica Abyss and the Grotta meravigliosa di Lazzaro Jerko (Wonderful Cave of Lazzaro Jerko). Furthermore, the Timavo can also be reached in the cave system of Brezno treh generacij (Three Generations Abyss, B3G) - Kačna jama (Snake Cave, KAC).

Kačna jama is an enormous hypogeous complex that developed in Cretaceous limestone about 1 km west of the village of Divača and about 800 m west of the Dead Lake. The abyss opens at an altitude of 435 metres a.s.l. and has an access shaft 186 metres deep, leading to a larger system of conduits distributed on two levels reaching a depth of 280 metres.

The upper level is hydrogeologically inactive but richly concreted. The lower level, which is accessed from the upper one through a series of shafts and conduits, develops sub-horizontally and consists of a complex system of conduits. Here, in low water conditions, the Reka/Timavo flows freely up to a siphon located at 156 metres a.s.l. The siphon can drain a maximum flow rate of 15 m^3/s. With higher flow rates the water level in the cave rises and a series of overflow conduits are activated, and drain flow rates up to 130-150 m^3/s. For higher flow rates the water level increases further still and even the gorge of the Škocjan Caves begins to flood.

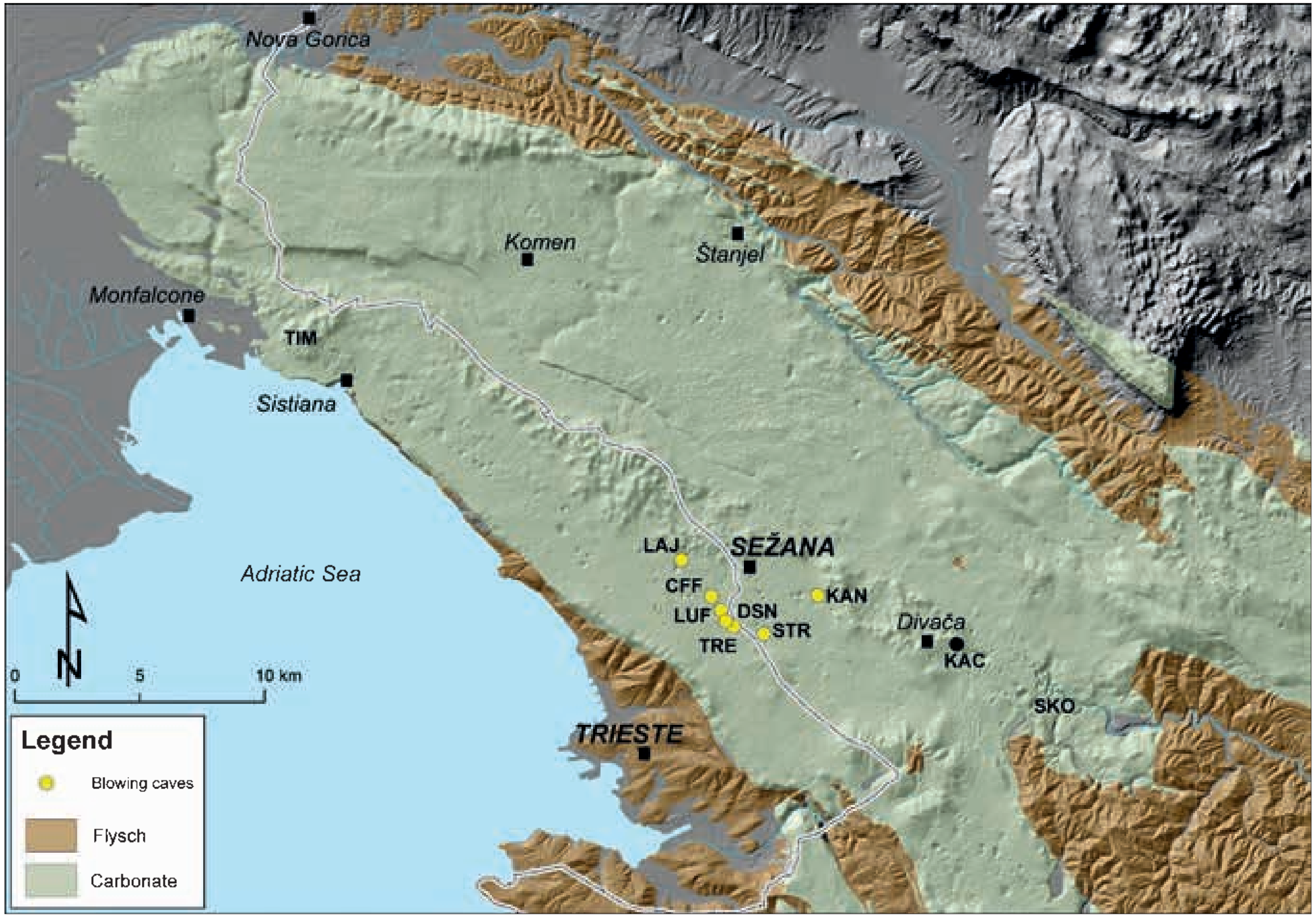


Figure 3.6.4: The "Luftloch" or blowing holes. SKO Škocjan Caves, KAC Kačna jama-Abisso dei Serpenti Cave, KAN Jama 1 v Kanjaducah Cave, STR Brezno v Stršinkni dolini – Jama Sežanske Reke Cave, TRE Trebiciano-Labodnica Cave, DSN Sette Nani Doline, LUF Luftloch Cave, CFF Pozzo presso il Casello ferroviario di Fernetti–Grotta Decapitata-Abisso Nagasaki Cave, LAJ Lazzaro Jerko Cave

In 2010, the Brezno treh generacij Abyss was discovered. It is connected with the new galleries of the Kačna jama Cave and forms an underground system of more than 20 km in length. It owes its name to the fact that during the explorations speleologists found traces of old excavation works, probably created at the end of the 19th century.

Five kilometes downstream of the Kačna jama Cave is the Kanjaduce Cave (Jama 1 v Kanjaducah). This is a 330 metre deep cave with a development of 1.5 km. At the bottom of the cave, at an altitude of about 20 metres a.s.l, there is a large conduit (600 metres long, 50 metres wide and 60 metres high) through which Reka/Timavo water flows. After a further 2.6 km we reach the underground system, the Jama Sežanske Reke - Brezno v Stršinkni Dolini, at the bottom of which the waters of the Reka/Timavo flow at about 15 m above

Figure 3.6.5: Reka/Timavo at the bottom of the Trebiciano-Labodnica Abyss (Photo: Alberto Maizan)

sea level along a wide tunnel. The cave has two separate entrances: the first, Jama Sežanske Reke, opens at 354 m a.s.l, and leads to the entrance siphon, while the second, Brezno v Stršinkni Dolini (344 m a.s.l.), leads to the exit siphon. The entrance siphon was explored by cave divers to a depth of 60 metres. From this cave, through a series of siphons, some of which are still unknown, you can reach the Trebiciano-Labodnica Abyss. This is the best known cave on the Karst and played an important role in karst hydrogeology research. Explored in 1841, for over eighty years it was the deepest cave in the world. Today it has a total planimetric development of more than, 2,400 m and a depth of 370 m (Figure 3.6.5). Recent cave-diving explorations have ascertained the presence of large flooded conduits that reach 40 m in depth, well below sea level, and several hundred metres in length.

One more cave that intercepts Timavo waters is the Grotta Meravigliosa of Lazzaro Jerko Cave, which opens in Col in Monrupino-Repentabor at an elevation of 302 m above sea level and 3.5 km north of the Trebiciano-Labodnica Abyss. The cave is mainly vertical, with numerous shafts that lead to two large halls, on the bottom of which water flows at an altitude of about 4 metres a.s.l.

Lazzaro Jerko is the last known cave in which it is possible to observe the Reka/Timavo directly. This is probably due to the fact that downstream the Timavo conduits are completely flooded and below sea level. The connection between all these caves with the Aurisina-Nabrežina, Timavo and Sardos Springs was confirmed by a series of tracer tests made with a range of tracers on several occasions.

During floods, however, and in concomitance with the increase in flow rates at the Škocjan sinkhole, the groundwater level can rise by tens of metres (up to over 100 m), flooding the deepest sections of some caves such as the Rupingrande and Massimo Abysses, the Claudio Skilan and Federico Lindner Caves, Dolenca jama and the Drča jama Caves.

The springs

Along the coastline from Aurisina-Nabrežina to the town of Monfalcone, 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 Classical Karst aquifer can be observed. Starting from the south-east, the first spring zone to be found is the Aurisina-Nabrežina Springs (Figure 3.6.6). These total 9 springs, which develop on a front of about 350 m, located near the limestone/flysch contact zone, which in this area is found on the beach. The waters today are collected in an artificial drainage trench which is parallel to the coastline, and which served as the aqueduct of the city of Trieste from 1857 to 1971.

From Aurisina-Nabrežina to Villaggio del Pescatore-Ribiško naselje there are other numerous outflows, often below sea level and not always permanent, with an estimated average total flow of 0.5-1 m^3/s and an extremely variable outflow depending on the regime. 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, a complex system of springs, karst lakes, and sinkholes can be observed, giving rise to a unique hydrogeological system and ecosystem (Figure 3.6.7).

Lake Doberdò-Doberdob is the northernmost of this series of karst lakes that also includes Mucille-Močile, Pietrarossa-Prelosno, and Sablici-Sabeljsko. These depressions, the bottom of which is located at altitudes between 1 and 5 m a.s.l., bring light to the waters of the karst aquifer. In each of the lakes there are permanent spring areas and sinkholes that regulate the water regime. During the periods of spate, the flow rate of the springs increases quickly and the sinkholes sometimes fail to drain all the water that pours into the lakes, making the level rise to over 10 m in a few hours.

This behavior characterized the whole area until the 1960s. The later construction of drainage canals in Pietrarossa-Prelosno and Sablici-Sabeljsko modified the hydrodynamics of this area, limiting the increase in water levels.

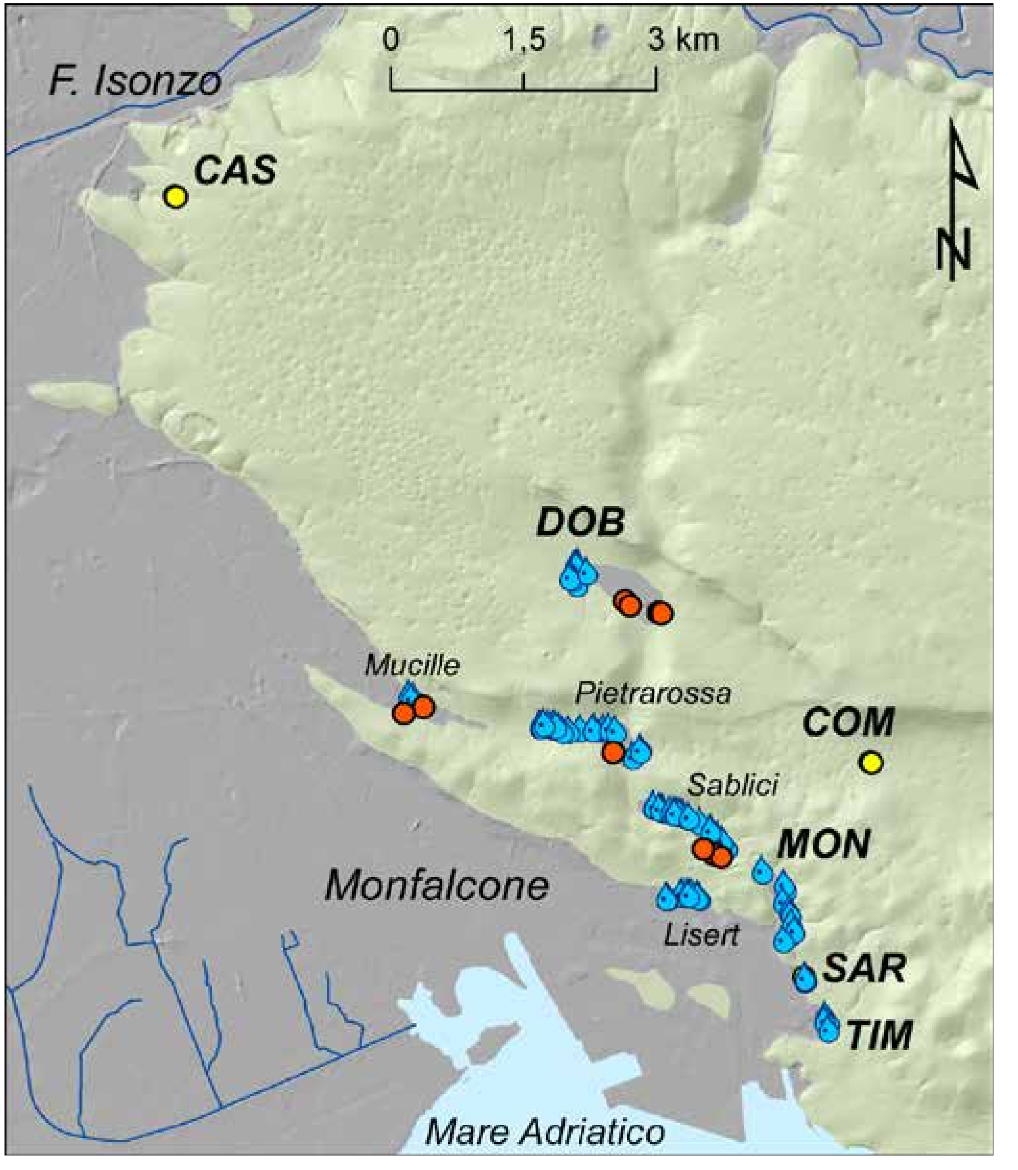


Figure 3.6.7: Springs and water points of the western sector of the Classical Karst.

Figure 3.6.6: Aurisina-Nabrežina Springs in flood condition: note the muddy waters that flow through the beach (Photo: archive of the DMG- Department of Mathematics and Geosciences - University of Trieste)

In San Giovanni di Duino-Štivan there are the Timavo Springs, which represent the main emergence of the Classical Karst. The sources consist of four springs collected in three branches that flow into a single channel that after 3 kilometres flows into the sea in the Gulf of Monfalcone. From the three branches of the springs there is a complex and articulated network of wide conduits that reach a depth of 83 m below sea level and a development of over 1500 metres.

In addition to the Timavo springs, the area also includes the Sardos Springs (Figure 3.6.8) and since 1929 the whole area is tapped for the water supply of the city of Trieste.

The hydrodynamics of the aquifer

The Timavo Springs represent the central junction of the hydrogeology of the whole Classical 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 and Vipacco Rivers, and the waters linked to the precipitations of the whole Classical Karst flow together with different regimes.

Each flood, however, has a unique behaviour, since the flow of water within the aquifer is related not only to the amount of rainfall, but also to the hydrogeological conditions prior to the single event (low water conditions, flood,...) and the distribution of rainfall over the entire area.

The waters of the Reka River - swallowed at Škocjan Caves - affect the entire eastern sector of the Karst up to the area of Duino-Devin. In their subterranean course they mix with the waters of the precipitation that infiltrates the plateau and finally emerges in all the coastal springs from Aurisina-Nabrežina to San Giovanni di Duino - Štivan (Figure 3.6.9).

During the most intense flooding events some overflow conduits are activated, which causes this water to also flow from the Sardos Spring. However, the waters of the Reka/Timavo cannot reach the westernmost sector of the Karst (the Isonzo Karst) where other contributions prevail.

Figure 3.6.8: Sardos Springs (Photo: Luca Zini)

Figure 3.6.9: Timavo Springs during flood (Photo: Luca Zini)

The waters that flow in the Isonzo Karst, in fact, are basically fed by two contributions, with the waters dispersed by the Isonzo-Soča and Vipacco-Vipava Rivers and the precipitation that infiltrates in this area. The waters of the Isonzo-Vipava system are the main source of supply in this sector of the Classical Karst and sustain the flow rates of all the springs from the Mucille-Močile to the Moschenizza-Moščenice Canal. During dry periods, when the flows of the Reka in Slovenia are very low (a few hundred litres per second), the Timavo Springs are also largely fed by this source.

In this framework, the Sardos Spring represents the point of contact between the western system fed by the Isonzo/Vipava system and the eastern one linked to the Reka/Timavo, and according to the different hydrogeological regimes we observe the prevalence of one contribution over another or their mixing.