Karst Surface

The formation of the karst surface is a result of surface dissolution of rocks, removal of the rock in form of solution and of the underground flow of water through the voids caused by corrosion, i.e., caves. Thus, the relief shows the organisation and form of the underground drainage system or the type, size and distribution of cavities, which are otherwise not accessible or known to men.

Due to tectonic raising of the entire Classical Karst and geomorphological development of the surface and underground, the underground drainage paths changed in the past; new paths were formed, while the old, now inactive caves were preserved. By studying the current hydrological conditions, old cavities cannot be detected because they were formed under different hydrological conditions. The existence of such caves can be deduced from the relief forms of the surface and from the geomorphological development of the relief.

The area of the railway route contains fluvial relief on flysch rocks and karst relief on limestone. From the relief forms and from the impact of the fluvial relief on the karst, we can deduce the geomorphological development of the entire territory and indirectly also the development of the karst underground or distribution of karst porosity.

We have mapped and analysed the characteristic or diagnostic karst forms on the surface above the first two tunnels, and studied the broader area where development of the relief is connected with development of the karst on the tunnel route. We focused our attention primarily on the location of larger, flat segments of the surface, and on the size and distribution of dolines and collapse dolines.

Special attention was devoted to mapping the caves, which the karst denudation had opened up to the surface. Today, these are hydrologically inactive caves that bear witness to the oldest developmental stages of the karst. Observations and measurements have shown that the greater part of dissolution of karst rocks, around 90 %, takes places in the upper metres of the karst or on the very surface of the karst. This results in the surface of the Classical Karst being lowered by some 20–60 m per million years. As the surface is being lowered, it cuts through numerous old cavities that thus become a part of the present karst relief. Such caves were compared with the current, known caves and in Podgorski kras also with the density of the caves discovered at the Črnotiče quarry.

In addition to the individual relief forms, larger groups of forms that are connected to a special geological structure and share common morphological development features are also important. Such morphostructural or morphogenetic karst units on the route of the tunnels are Divaški kras, Gradišče, the edge of Matarsko podolje lowland, and Podgorski kras or Petrinjski kras (Fig. 1).

1 Geomorphological Analysis of the Territory

1.1 Relief Forms and Groups of Relief Forms

1.1.1 Small Corrosive Forms

Corrosion features of various sizes are formed on the surface of limestone and create an uneven and coarse surface of the rock. These forms are mostly rain flutes and karren. With their help we can deduce the solubility of the rock and the speed of the corrosion of the surface.

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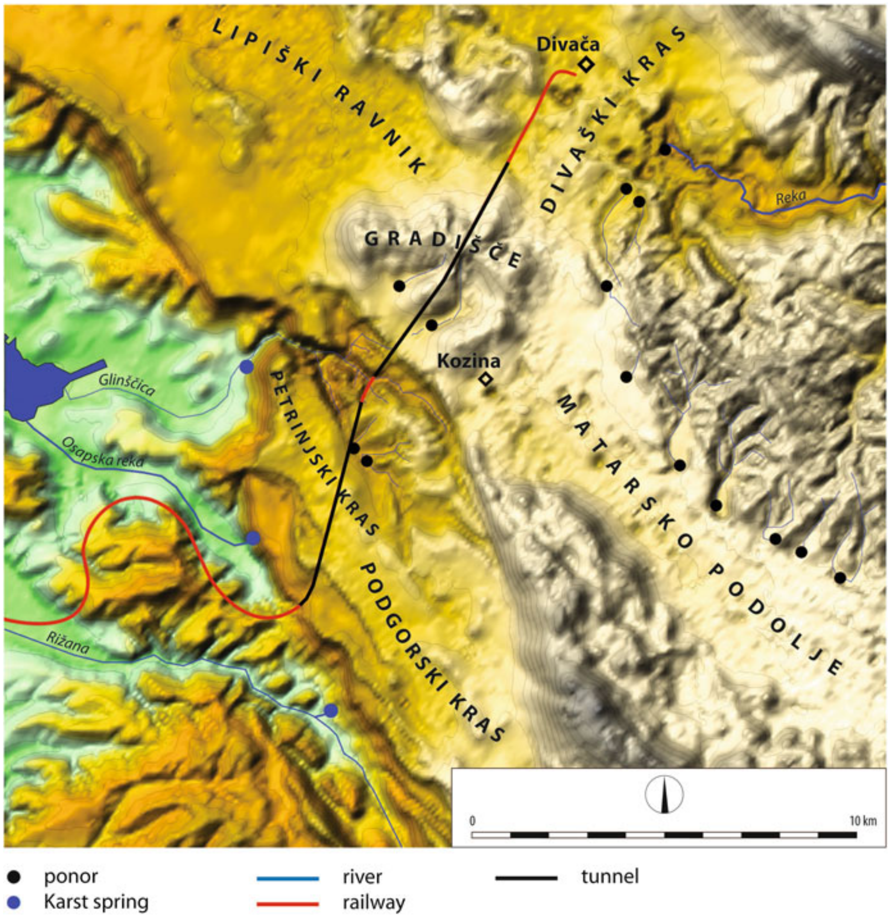

Fig. 1 Digital elevation model (DEM). Areas of the planned railway line and tunnels *T1* and *T2*. Larger relief units have been marked

1.1.2 Karst Hollows

Dolines are the most common karst depressions. They are funnel-shaped or kettle-shaped, mostly up to 10 m deep and with a diameter of up to 50 m. Based on their formation, dolines are divided into corrosion dolines, collapse dolines and dolines that were formed from cavities by denudation.

Solution dolines are formed where dissolution of rock is the strongest and where percolation into the karstified rock is possible. Solution dolines are formed by the locally concentrated dissolution of limestone, due to thicker soil. A larger quantity of CO_2 dissolved in water dissolves more limestone beneath the soil, is released in it, and thus a hollow is formed. These dolines have solid, compact floors beneath them. The majority of the dolines on the route are of this type.

Dolines are most commonly found on karst flatlands and very rarely on slopes or not at all on steeper slopes. These forms are a surface phenomenon; the only condition for their formation is draining of torrential water through the karst (Fig. 2).

When studying dolines in a specific territory, we first have to genetically separate different types of dolines and then, based on them, see the type of karstification.

Collapse dolines are large depressions that were formed with slow collapsing of roofs above larger underground cavities and afterwards with

Fig. 2 A typical doline in the karst of Divaški kras near the location where the tunnel *T1* will commence

transformation of slopes. They are from 50 to 200 m deep and up to 500 m wide, while their volume amounts to several million m^3. Seeing that their dimensions are much greater than dimensions of the largest known halls, and since the majority of the collapse dolines are located near larger underground flows, it seems that the formation of collapse dolines is not only the result of the collapse of the karst cavity, but also above all the result of dissolution and carrying away of the collapsed rock in the depths. The study of collapse dolines and large collapse halls near the Škocjanske jame caves and in the Kačna jama cave near Divača has shown the dual role of karst water in the formation of the collapse dolines (Fig. 3).

Fluctuation of water in the underground, for example over 100 m in the karst area of Divaški kras, causes the water to flow from the main channels into the side channels and into the tectonically fractured zones as the flood rises. When the water level drops, the water withdraws from the fissures. This constant alternation of water causes substantial corrosion and enables formation of rock instability in the depths. Another important role of the proximity of the main waterways is the carrying away of collapsed rock in the form of a solution or partially in the form of particles. The collapse dolines, therefore, point to the proximity of larger water flows.

The surface area of collapse dolines in the karst area of Divaški kras comprises around 6 % of the entire surface area. Their volume is substantial. Near Divača, the large valleys of Risnik, Radvanj and Bukovnik are located. Their bottoms are situated between 360 and 380 m above sea level. Beneath the Bukovnik valley, there are the lower passages of Kačna jama; directly beneath it, one of the passages ends in a large collapse. Here, the river is located 154 m above sea level or 230 m beneath the bottom of the collapse doline.

Favourable conditions for the formation of collapse dolines in the vicinity of the planned route were found only in the karst of Divaški kras.

Collapses that would lead to collapse dolines were not detected from the morphology anywhere along the route. However, collapses may appear where the tunnels will run close to an underground cavity.

1.2 Karst Levelled Surfaces

Large, flat surfaces can be formed only where a greater part of the corrosion ability of the water, precipitation

Fig. 3 Risnik collapse doline (Divača is in the background). The surface is levelled at around 420 m and the *bottom* of the collapse doline at 365 m *above* sea level

or sinking streams is used upon the surface. This can occur when the karst is situated at a low altitude or dammed up with impermeable or poorly permeable rock. Such a position causes the level of the karst water to be located shallowly beneath the surface; the low gradient creates branched out cave systems.

Numerous flat surfaces have been formed on the study area. The main are Divaški kras, Matarsko podolje and Podgorski kras. When afterwards the level of the karst water dropped by several hundred metres, the surface became dissected into numerous dolines, yet preserved the basic flatland shape.

1.3 Contact Karst

Contact karst is karst formed at the contact between surface and underground drainage. The quantity, regime and sediments of the allogenic rivers that flow onto the karst have modified the karst processes. The result of this are special relief forms, e.g. blind valleys and border flatlands, and phenomena such as sinking of water, floods and depositing of sediments onto the karst.

The development of cavities in the karst, which is passed by the tunnel route was influenced by the contact karst along the edge of the Brkini hills, the contact karst of Ocizla and the contact karst near Gročana and Vrhpolje.

Characteristic for the contact karst beneath the Brkini hills are the large levelled surface Divaški kras next to the ponors of the Reka River and the large blind valleys along the lowland Matarsko podolje, which have similarly shaped bottoms and slopes.

The surface forms of the contact karst of the Reka River are limited mainly to the Vremska dolina valley where a large blind valley was formed at around 370 m above sea level.

The bottoms of the blind valleys along the edge of Matarsko podolje are situated at 490–520 m above sea level. Across a span of some 20 km, the bottoms of the blind valleys vary by several tens of metres, while the system of valleys is raised by 200 m. These heights undoubtedly point to a common level, to which deepening and development of blind valleys along the edge of Matarsko podolje were carried out.

The contact karst near Vrhpolje was formed along the edge of a small patch of Eocene flysch, which enables draining away on the surface. Along the edge of the flysch, beneath Vrhpolje, at the altitude of some 450 m, and near Gročana, two streams sink into small indistinct sinkholes.

The contact karst along the Ocizla sinking streams is a large, elongated relief depression with the characteristic name Loke, which continues above a pass, only 30 m higher, into a deeply incised fluvial valley of Griža, a tributary of the Glinščica River. The shape of the depression shows that the stream initially flowed on top of the contact and did not sink. When the stream began to sink, its erosion ability decreased, and the deepening of the valley stopped at an altitude of some 380 m. Afterwards, the top part of the valley was drained away only karstically and became lowered to the level of the present ponors, whereas the non-karstic part of the Botač valley continues to be incised intensively. The developmental stages are also expressed in the morphology of the cave passages of the Ocizla sinking streams.

From the flysch ridge between Beka and Ocizla villages three larger streams and one smaller stream flow into Loke, which was formed along the contact between limestone and flysch. The Ocizla sinking streams drain water from a 3.5 km^2 catchment area on the flysch. The streams flow in from the watershed at the altitude of up to 500 m, while the ponors are situated at the altitude of around 350 m.

Due to the high gradient in the karst, the streams do not flood in front of ponors and do not deposit sediments.

1.4 Unroofed Caves

An unroofed cave is a cavity that has been opened up to the surface by dissolution and lowering of the surface (Fig. 4). Karst caves that were formed deep beneath the surface, usually no longer change after the water course abandons them. However, the surface does change; due to karst denudation, it constantly and evenly continues to lower. The surface lowering rate in the area of the karst is said to range from 20 to 60 m per million years. If presupposing that there were at least 100 m of the roof above the currently denuded caves, then these caves are from 2 to 10 million years old. These ages are confirmed by palaeomagnetic dating in the caves in the Črnotiče quarry and near Kozina.

If a cave had been filled with sediments, it is often not detected in the relief morphology; it is identified only by the typical sediments, mainly by flowstone (Fig. 5), lesser rockiness of the surface where the cave passages have been unroofed and by different use of land in the past, as they were often connected with smaller, elongated patches of arable land. The shape of unroofed caves depends on the size and shape of the cavity (passage, oblique passage) and on the incline of the surface (flat surface, slope), which had cut through the cave.

The findings of denuded remains of the caves on the surface testify to the perforation of the karst segment at this altitude. The dimensions and sediments found in the unroofed caves can lead to conclusions regarding the palaeographic conditions under which they had been formed. We can determine the flow rate through the cave and the sediments can tell us whether a sinking stream ran through it and where its surface catchment area was. Subsequent sediments, flowstone, red loam, rubble and remains of collapses bear witness to the subsequent dry stage of the cave's development and its disintegration, as it was reached by the surface's denudation front.

There have been 17 larger unroofed caves identified in the karst area of Divaški kras. The biggest one, the unroofed cave in Lipove doline, is situated between 420 and 440 m above sea level.

It is filled up with flowstone, gravel and sand, which had been deposited in the cave by a sinking stream, a predecessor of today's Reka River. The cave had passages with sections up to 20 × 20 m.

Near the route lies an unroofed cave, a continuation of the Divaška jama cave. Several unroofed caves were also found on the route between Divača and Lokev.

Less explored are the unroofed caves in Matarsko podolje lowland where several of them were explored during the construction works for the motorway north of Divača.

The highest density of unroofed caves is on the surface above the tunnel on the karst of Petrinjski kras between the Beka-Ocizla cave system sinking streams and the Črnotiče quarry (Fig. 6). Most of the caves have been filled up with loam, sand and gravel; quite a lot of flowstone has also been deposited there. In relief they are shown as shallow, yet long, elongated, 4–8 m wide depressions. They connect dolines, which means that the dolines were likewise formed by transformation of caves in the area of the surface denudation front.

A similar density of unroofed caves and similar surface forms continue in the Črnotiče quarry where we were also able to observe the cross-sections of 16 such caves and study the sediments in them (Fig. 7).

In the quarry we monitored the excavation of a 180 m long cave with a profile of 15 × 15 m. The cave was entirely filled up with massive flowstone, loam and quartz sand. These sediments have not been cemented. The cave and its sediments reached the surface where it was detected as an unroofed cave prior to its destruction.

In addition to horizontal caves, five vertical shafts were also opened up during the work in the quarry. Shafts are more difficult to detect because they were immediately filled up during the work in the quarry. The biggest shaft had a profile of 10 × 8 m and was around 60 m deep. The shaft could not be explored because the area around the entrance to the shaft was

Fig. 4 During the construction of the motorway numerous unroofed caves were discovered near Divača, i.e. caves above which limestone has already dissolved. The proof that they are caves, are the remains of flowstone and stalagmites, and stalactites found inside them, in addition to the other sediments deposited underground by the former sinking stream

heavily blasted. The bottom of this shaft reached the altitude of around 340 m above sea level (Fig. 8).

2 Morphostructural Units

In geomorphology this term denotes larger relief units, the scope and size of which are undoubtedly connected with geological structures. In the terrain in question, they are mostly contacts of various rocks, while the units are often limited with distinct neotectonic lines. The relief forms of one morphostructural unit usually underwent a common geomorphological development, which is why the term morphogenetic units can also be used to describe them.

The morphostructural or morphogenetic units usually exhibit similar relief forms, which is why they often have their own names. The tunnels' route passes through the karst area of Divaški kras, Gradišče and the edge of Matarsko podolje, it crosses the Glinščica valley and runs across the karst of Podgorski kras. For deeper understanding, the morphostructural units of the Brkini hills, the Slavnik mountain and the Taborski griči hills are also important (Fig. 9).

2.1 Divaški Kras

Divaški kras is a lower and rather flat karst plain, situated between the Vremska dolina valley, where the Reka River sinks, and the north edge of the Brkini, Taborski hribi and Gradišče hills. The surface of Divaški kras is located at the altitude between 450 and 400 m. It is more or less flat, with numerous dolines cut into it. Despite the relatively high number and density of dolines, the flat surface cover over 80 % of the total surface area, whereas the dolines cover a small portion, around 6 % (Fig. 10).

The tunnel route will contain a greater number of dolines, i.e. 15 dolines with non-load-bearing sediments at the bottom. Some of these dolines might have been formed from shafts filled with sediments. The problem of dolines is the low load-bearing capacity of the floor, which is why all the sediments must be removed, so that the base of the route lies on rock.

Collapse dolines were formed near the planned route only in the karst area of Divaški kras. Near Divača the large valleys of Risnik, Radvanj and Bukovnik are located. The volume of the collapse dolines is large. Risnik has around 1,700,000 m^3 and Radvanj

Fig. 5 A stalagmite in an unroofed cave in the Lipove doline near Divača. The stalagmite is standing in the open because the rock formation above the cave and the cave roof were dissolved by precipitation water

around 9,000,000 m^3 of volume. The connection between the large collapse dolines and the underground flow of the Reka River is evident. Their bottoms are situated between 360 and 380 m above sea level. Beneath the Bukovnik valley, there are the lower passages of the cave Kačna jama; directly beneath it, one of the passages ends in a large collapse.

The large collapse dolines were formed when roofs caved in over larger underground cavities or underground channels of larger rivers, which carried away the crumbled fragments of rocks. Such is the Radvanj collapse doline, which is located to the east, beyond the route (Fig. 11); however, it indicates that we can expect large passages, perhaps even large halls, at around 350 m above sea level. This should not affect the route as it is located deep beneath the surface across which the railway line will run.

Several larger unroofed caves have been identified in the karst area of Divaški kras. Most of the unroofed caves were discovered during the works on the route of the road near Divača, Dolnje Ležeče and near Povirje. Near the route lies an unroofed cave, a continuation of the cave Divaška jama.

The route of the railway line crosses only one large unroofed cave. The latter is located in the northeastern continuation of Divaška jama. This cave will probably be manifested in the transverse profile as a cavity up to 20 × 20 m large and filled with sediments with poor geomechanical properties (Fig. 12).

2.2 Lipiški Ravnik

Lipiški ravnik is an expansive, flat surface between Lokev, Sežana and Orlek. The surface of the plain is situated at the altitudes between 450 m near Lokev and 400 m near Sežana. The surface is finely dissected with numerous dolines.

The route of the railway line runs across only a section of this plain. Collapse dolines are no longer present here; there is only one unroofed cave on the surface, which partially reaches into the route area at 3.5 km. It is a cave passage filled with sediments of poorer mechanical properties (Fig. 13).

2.3 Gradišče

It is a vast elevation between Matarsko podolje, the Lipiški ravnik plain and the karst of Divaški kras (Fig. 14). It consists of a series of peaks, the highest one being Veliko gradišče (741 m) (Fig. 15). It is made up of Cretaceous and Palaeogene limestone; there is also a patch of Eocene flysch on top, which enables draining away of water on the surface. That is why, in addition to the karst relief, a fluvial relief was also formed on top of it; small brooks flow towards Gročana and Vrhpolje where they sink.

Beneath Vrhpolje, a valley with a flat bottom was formed, which resembles a blind valley. There a brook sinks from the flysch into indistinct holes; during

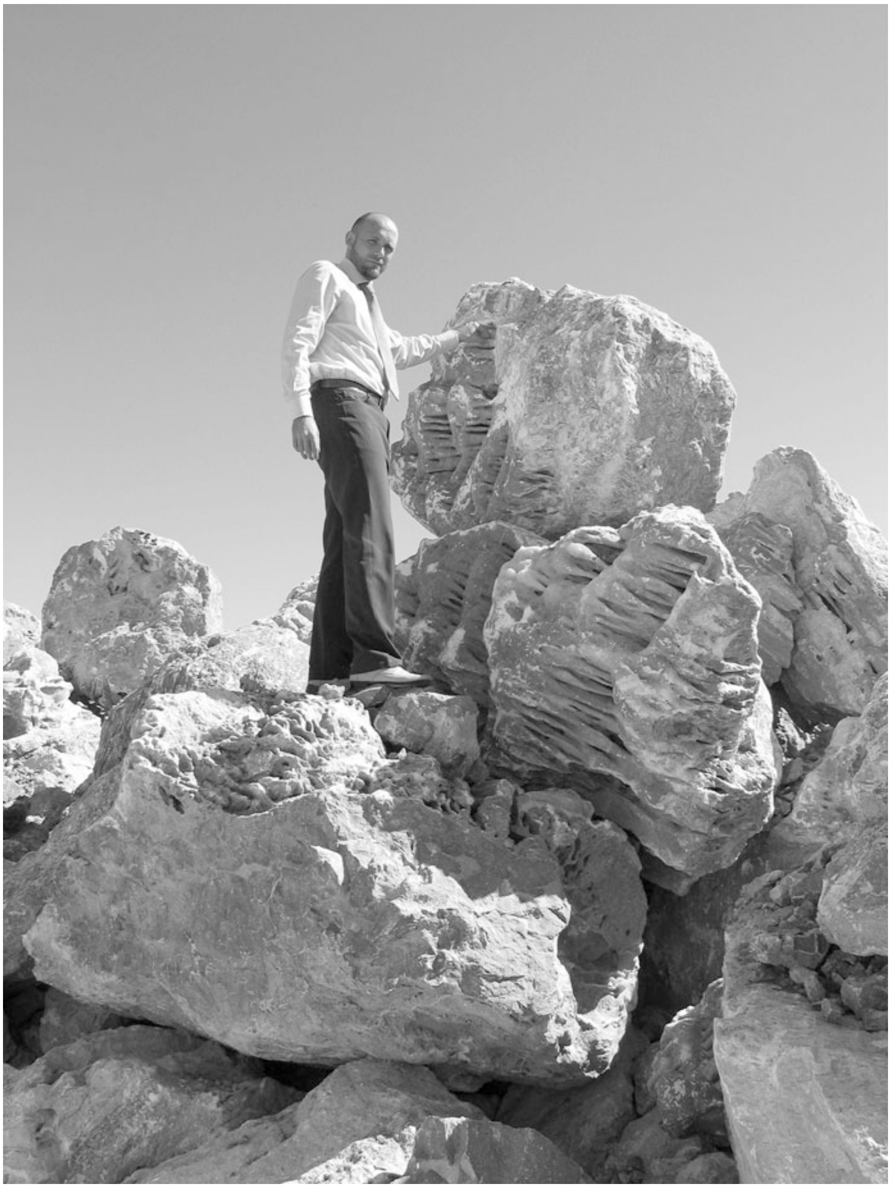

Fig. 6 Workers in the Črnotiče quarry often come across large caves; this can be seen from the pieces of stalagmites and stalactites which they treat as tailings

higher water levels it flows across the surface to the Glinščica valley.

In the area of the village Krvavi potok or the valley Vrhpoljska dolina (from 7.5 km to the contact with the flysch at 8.8 km), the tunnel T 1 runs around 150 m beneath the surface. The surface, the edge of Matarsko podolje, is levelled at around 450 m above sea level and dissected with only a few dolines. They cannot be used for deducing the underground conditions in this part of the karst (Fig. 16). Two unroofed caves on the surface nearby point to the existence of cave passages, up to several metres wide and high, on the current surface; therefore, one can expect such passages even deeper, at the level of the tunnel.

Fig. 7 Remains of a cave in the wall of the Črnotiče quarry. The passage had a 15 × 15 m profile and was partially filled with loam, sand and flowstone. In the photograph these sediments can be easily distinguished from the surrounding limestone

2.4 The Glinščica Valley

The Glinščica valley was formed in flysch rock between the foothills of the Slavnik mountain and the edge of Matarsko podolje and the karst of Petrinjski kras or Podgorski kras. The Glinščica River gathers the surface inflows on flysch of the karst of Podgorski kras near Podklanec and then deepens into two narrow valleys into flysch and limestone. This valley was formed after the neotectonic sink of the Gulf of Trieste had been formed, into which the valley opens up near Boljunec.

2.5 Podgorski Kras or Petrinjski Kras

It is a distinct karst plateau at the foothills of the Slavnik mountain. The western edge of the plateau drops down into the valley of the Rižana River and Osapska reka River in two sharp folds formed at the overthrust of limestone on flysch. Towards the north it is sharply limited by steep slopes above the Glinščica valley or the neotectonic sink of the Gulf of Trieste above the town of Dolina.

The karst area of Podgorski kras is made up of several larger and smaller overthrusting slices of flysch and limestone. The biggest slice of limestone is the 2 km wide karst area of Petrinjski kras between the flysch of Ocizla and the flysch slice of the Karst Edge between Kastelec and Črnotiče (Fig. 17). The planned route runs across it from the contact with the flysch beneath Ocizla to the exit of the tunnel at Črni Kal. The flysch slices were of great importance in the past development of the karst area of Podgorski kras. They dammed the water in the limestone and enabled the levelling of the surface. Today, the flysch lenses contribute to the disintegration of the plateau; the Glinščica River, which had cut shallow valleys into it, collects water on top of them and at the edge deepens into a deep, eroded valley. The sinking streams of Ocizla also collect water on top of the flysch belts.

Doline-covered flatlands were formed on limestone, while a fluvial relief was formed on flysch. A segment of flysch flows off on the surface into the Glinščica valley; due to the high gradient, it formed deep valleys.

The karst area of Podgorski kras or Petrinjski kras is a large flatland at the altitudes between 400 and 450 m. The tunnel pipes run across a section of it, between 11.5 and 16.0 km. Petrinjski kras is a 2 km wide section of Podgorski kras (Fig. 18). It is situated between the flysch of the Beka-Ocizla streams and the flysch slice of the Karst Edge near Črni Kal. The surface of the karst of Petrinjski kras is flat; small, rare

Fig. 8 A cut cave passage, an unroofed cave in the wall of the Črnotiče quarry. The passage was filled up with loam and sand by the sinking stream, while a 7 m *thick* bed of flowstone and stalactites was deposited on *top* of it. In the section, the passage is 17 m high and up to 5 m wide. The *light green dot* and the letter *M* mark the spot where 2-million-year-old mammal fossils were found in the sediment. Such passages, the unroofed caves, are common in the karst of Petrinjski kras

dolines exceed 50 m in width and 10 m in depth. Also common are very shallow dolines, up to 5 m deep.

The density of the dolines is relatively low, under 10 per km^2. The dolines differ with regard to their genesis. In the Črnotiče quarry, where we have been monitoring the progress of the quarry for several years, we have observed the excavation of several dolines. It has been shown that the majority of them were formed from the former caves (Fig. 19).

The tunnel runs beneath the karst of Petrinjski kras between 12.0 and 15.0 km. Unroofed caves are typical of this entire surface. In this section, the tunnel is located around 200 m below the surface. Although it cannot be precisely determined whether there is a

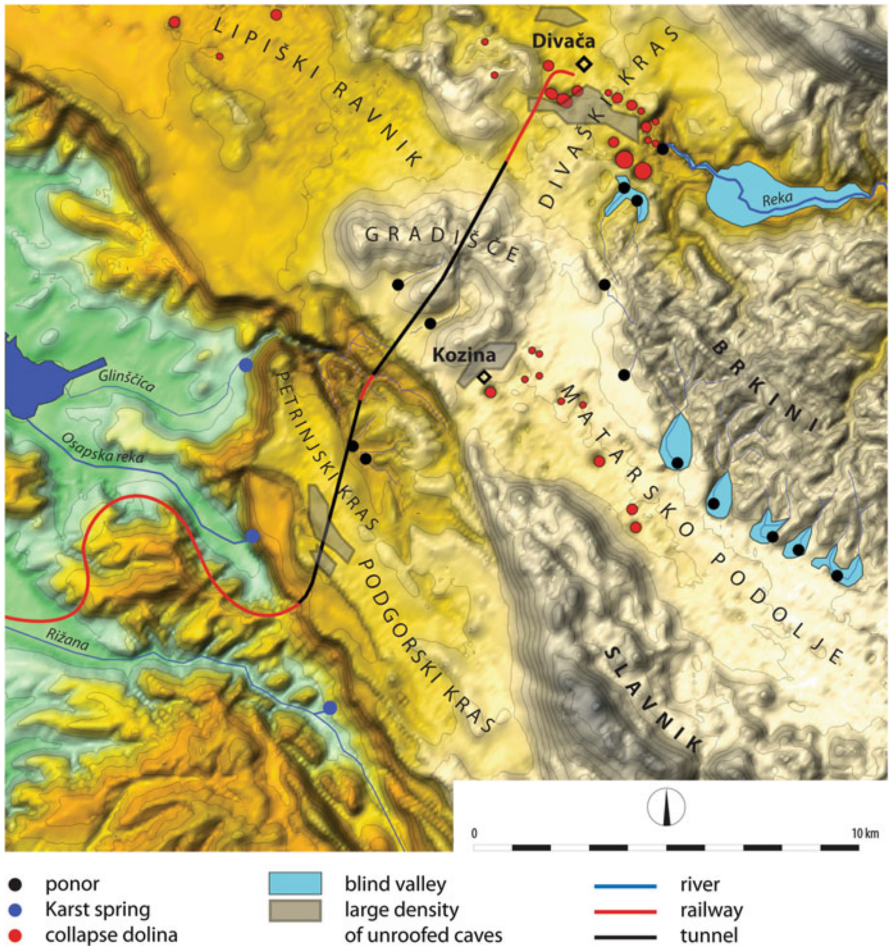

Fig. 9 Morphostructural units in the tunnels' *T1–T2* impact area. Divaški kras, 0.0–3.5 km

similar density of caves in the depths, it is very likely that such a density of cavities accompanies the contact of flysch and limestone also at the height of the tunnel.

2.6 Matarsko Podolje

The Matarsko podolje lowland is a 20 km long and 2–5 km wide flatland between the flysch Brkini hills and the Slavnik mountain chain. Its doline-covered and curved bottom rises steadily from around 490 m at Kozina to 690 m at Starod. At its edge, 17 separate streams flow in from the Brkini and sink into the edge of the lowland. The bottom of the lowland is more or less flat and finely dissected with dolines, collapse dolines and blind valleys.

The lowland and the bottoms of the blind valleys were formed near the level of groundwater; the depth of the accessible caves shows that today the water table of karst water is at least 50–100 m beneath the bottom of the lowland. The bottom of the Jazbina pri Materiji cave is dry and situated 350 m above sea level. The water table of karst water is probably much lower, at around 300 m. The tunnel route runs along the outer northwest edge of Matarsko podolje by the foothills of the Gradišče mountain.

3 Development of the Karst Relief

From individual relief forms, and primarily from the relief groups, we can reconstruct the development of the relief of the entire area of the south edge of the

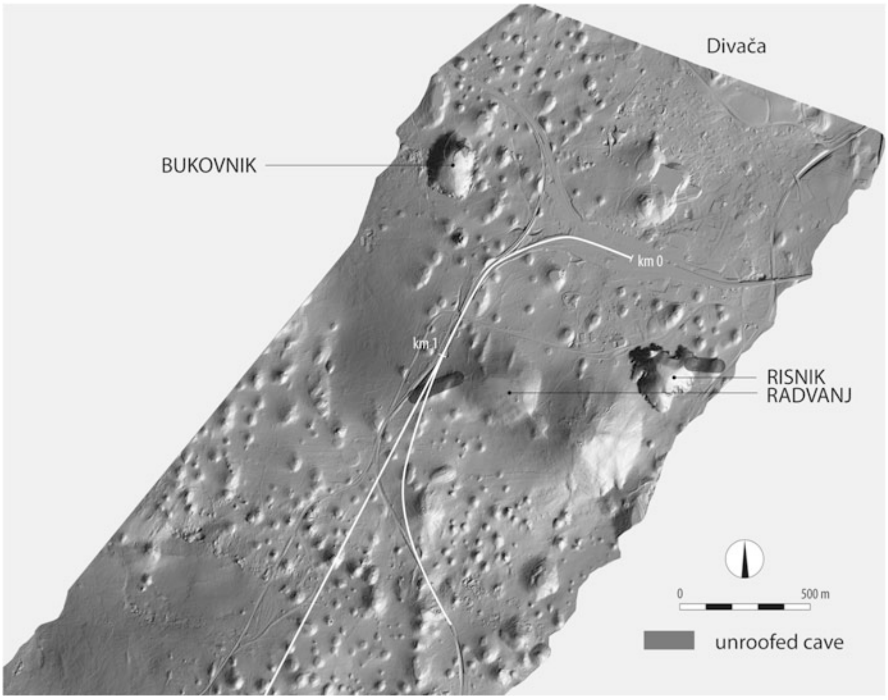

Fig. 10 DEM of the surface of Divaški kras. The large collapse dolines of Bukovnik, Risnik and Radvanj stand out. Dolines are small and evenly distributed across the flat relief. Larger unroofed caves can be found only to the west of Radvanj. A large series of dolines in the N–S direction was formed along the important fissured zone

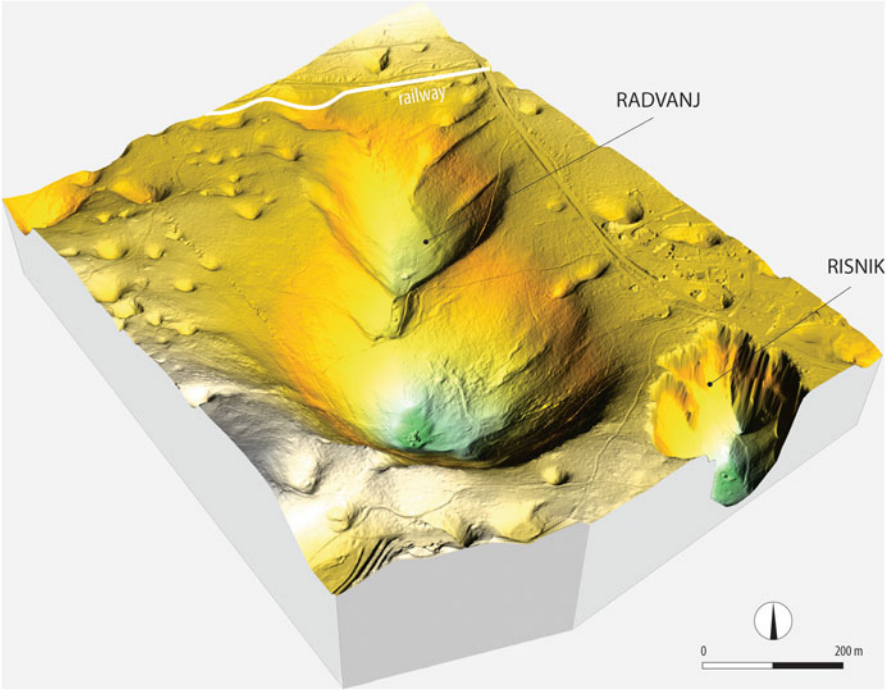

Fig. 11 The double collapse doline of Radvanj and Risnik near Divača. The railway route runs beyond the area of the collapse doline, merely crossing a larger unroofed cave

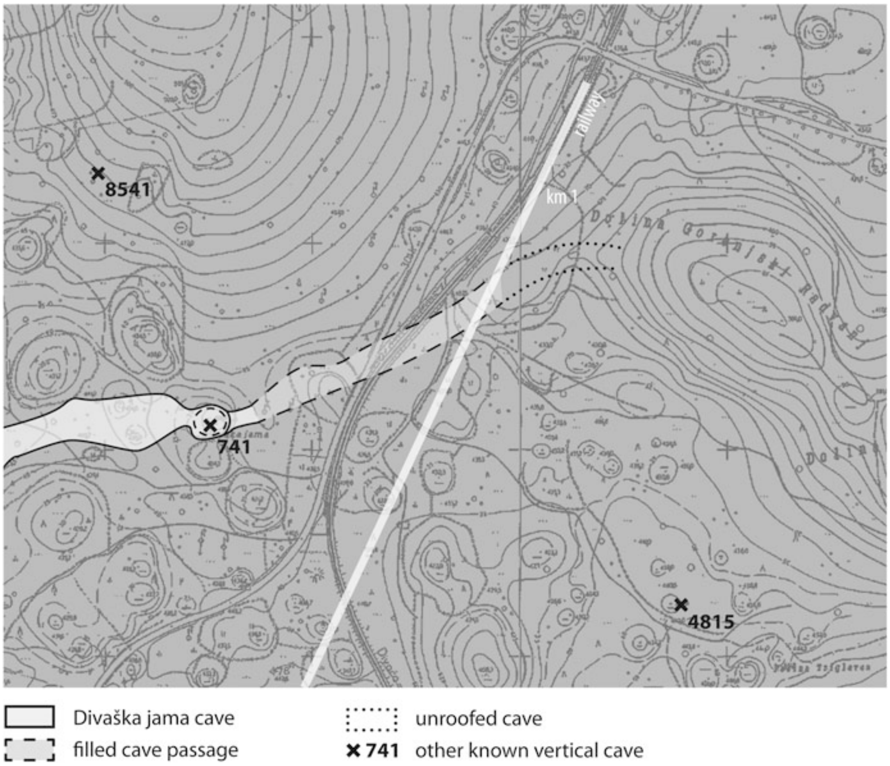

Fig. 12 Divaška jama is marked on the map with an unbroken *black line*, while the outline of its passages is marked with *grey*. The cave filled with sediments, which was detected with geoelectrical tomography, is marked with a *broken line*. Its continuation, i.e. an unroofed cave filled with sediments, which was detected in relief, is marked with a *dotted line*. The entrances to the caves are marked with *black crosses*, next to them, the Cave Registry number is written

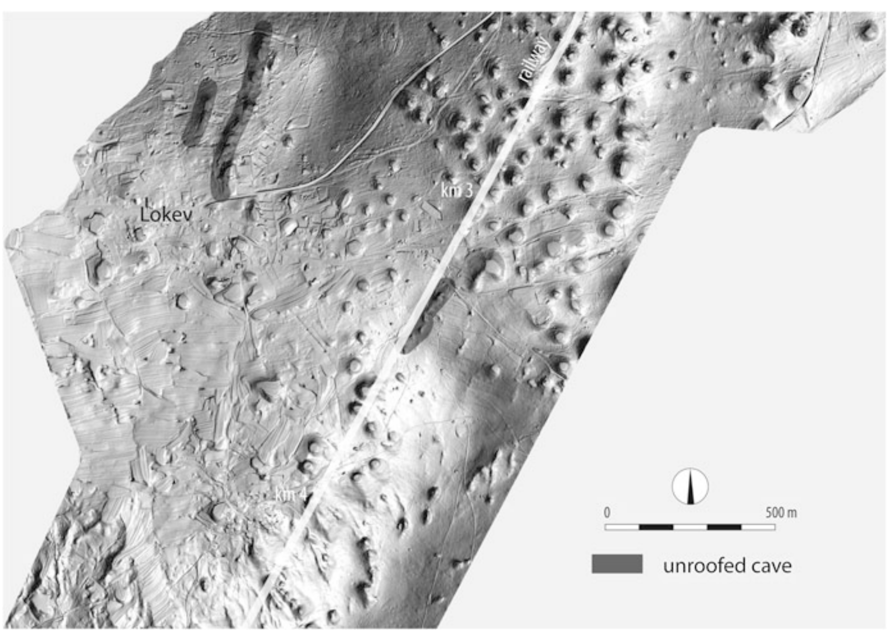

Fig. 13 DEM of Lipiški ravnik, Divaški kras and a part of Gradišče. Larger unroofed caves are marked with a *dark grey* colour

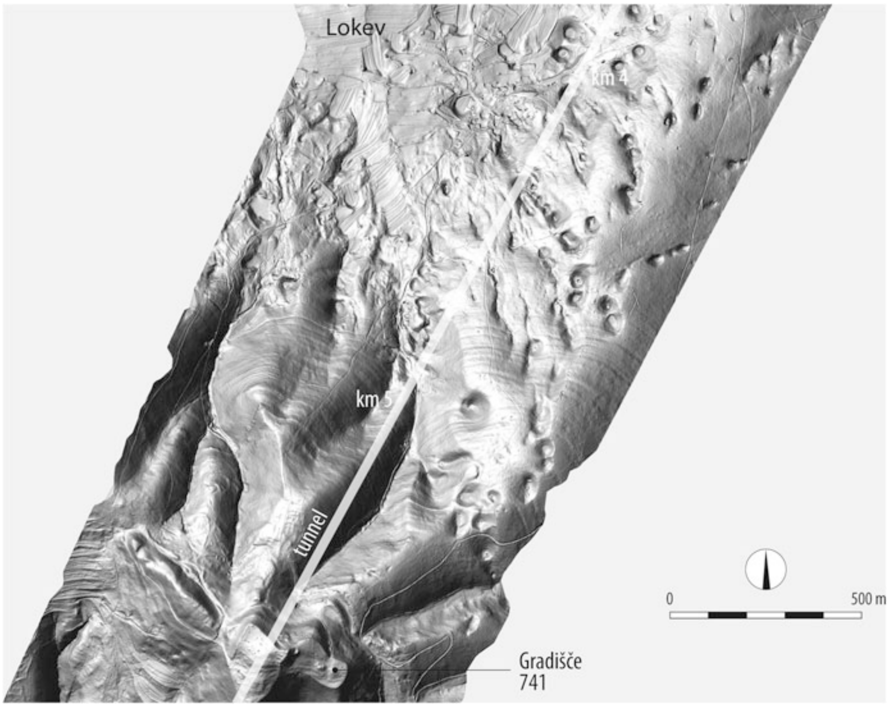

Fig. 14 DEM of Gradišče. The spike is located in the *bottom* part of the model on flysch rocks with a fluvial relief. The ridge running in the northeast direction is made up of limestone, which contains a few shallow dolines

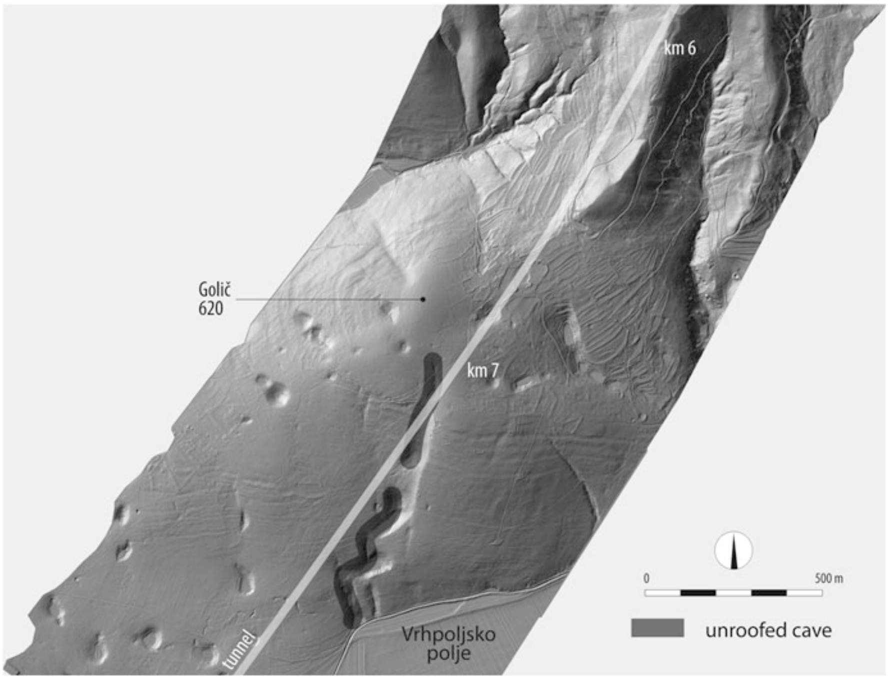

Fig. 15 DEM of the southern slopes of Gradišče. In the northern part they exhibit characteristics of a fluvial, ridge relief; in the southern part, dolines and a flat polje were formed on limestone near Vrhpolje. An unroofed cave or a more perforated limestone zone is indicated in the slope

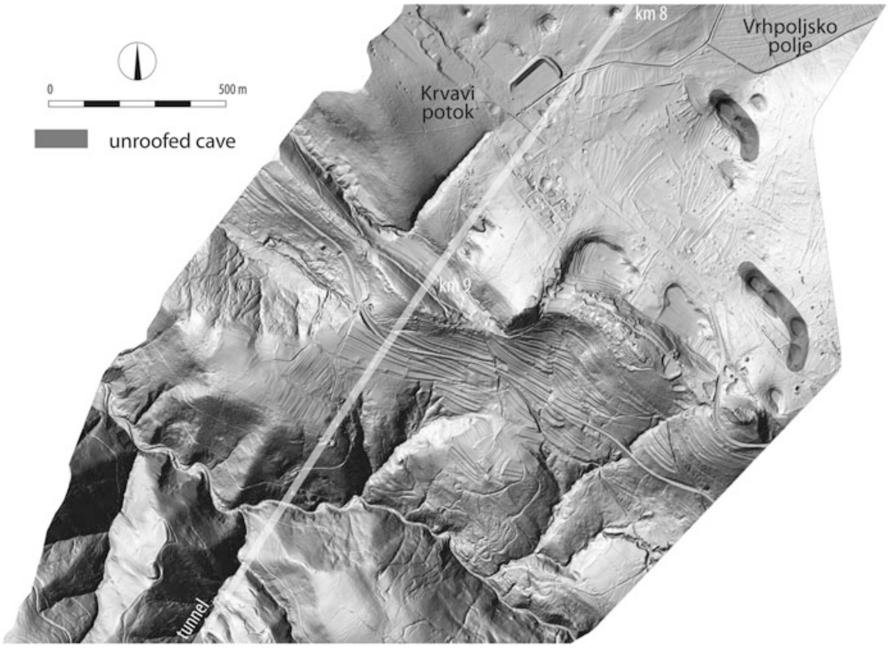

Fig. 16 DEM of the passage of Vrhpoljsko polje into the Glinščica valley. Two unroofed caves marked with *dark grey* colour are likely connected with the sinking of the brook that flows across Vrhpoljsko polje and largely also sinks there. Only during high water levels it flows across the now levelled riverbed on the surface into the Glinščica River

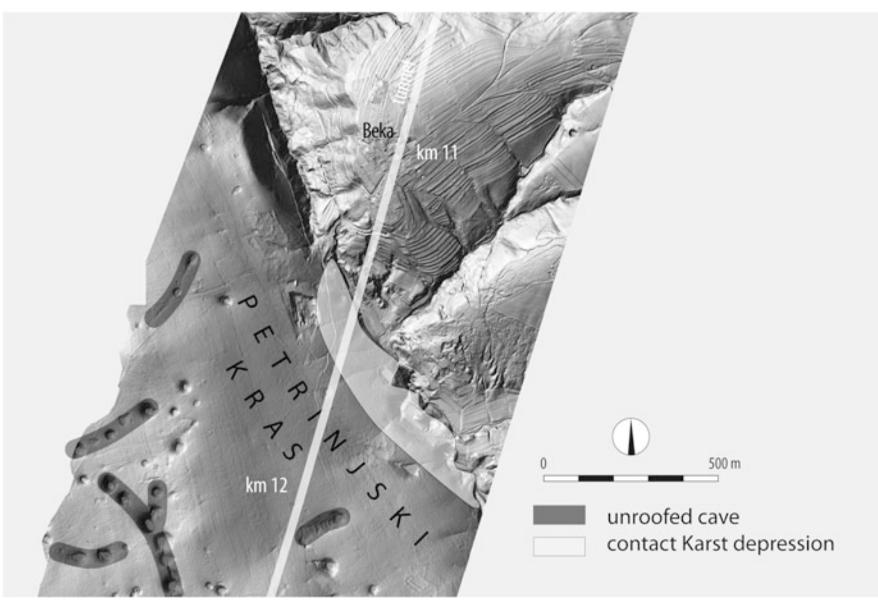

Fig. 17 DEM of the contact of the karst of Petrinjski kras and the flysch relief at the sinking streams of Ocizla. The unroofed caves are marked with a *dark grey* colour, while the hollow of the contact karst at the sinking streams of Ocizla is marked with *light grey* colour

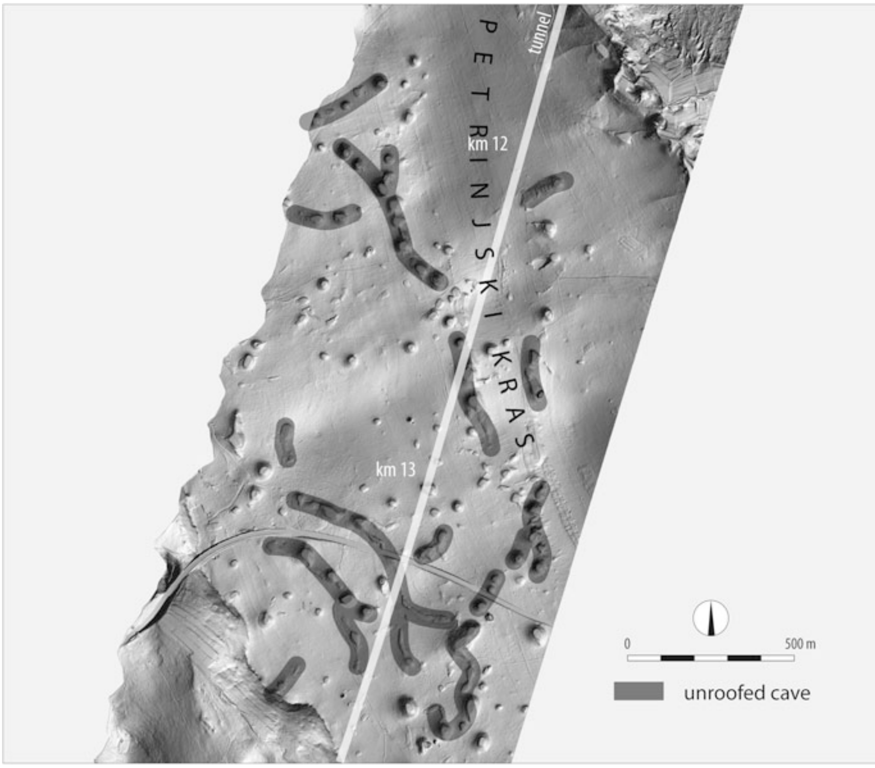

Fig. 18 DEM of the karst area of Petrinjski kras, a part of the karst area of Podgorski kras. Unroofed caves, which are visible on the surface as elongated depressions or a series of depressions, filled up with clay and sands, are marked with a *dark grey* colour. A similar density of cavities can be expected at the height of the planned tunnel

Classical Karst, which is intersected by the route of the tunnels. With reconstruction of the development of the karst relief we can anticipate where the more perforated zones and types of cavities are to be expected.

The morphology shows at least two morphological stages of development. In the first morphological stage, still preserved in the relief, the surface was formed under the conditions of the dammed karst. On the west side, the Classical Karst was dammed by the flysch, which is why the waters had to flow towards the northwest. Due to the low gradient, the initially more diverse relief was flattened. Thus, the surfaces of the karst area of Divaški kras, Lipiški ravnik and Matarsko podolje were formed; higher segments of the relief, the Gradišče and Slavnik mountains, remained among them. Sinking streams flowed in from the Brkini hills. The inflow of rivers from the flysch caused great fluctuation of the groundwater, which was reflected in the formation of collapse dolines near the main drainage paths. At that time the area was probably drained towards the northwest, the Matarsko podolje lowland, towards the karst area of Divaški kras and afterwards to the Lipiški ravnik plain. The main drainage paths most likely avoided Gradišče.

At the karst area of Podgorski kras, which is structurally determined by narrow zones of flysch among limestone, the waters flowed along these contacts, which resulted in a high density of cave passages.

Later, a profound change occurred. It was probably triggered by tectonic movements, primarily the sinking of the Gulf of Trieste, which opened up the Classical Karst laterally towards the west. This enabled the drainage of the karst towards the rivers of Rižana and Osapska reka and the village of Boljunec. A high gradient was formed, which was used by the Glinščica

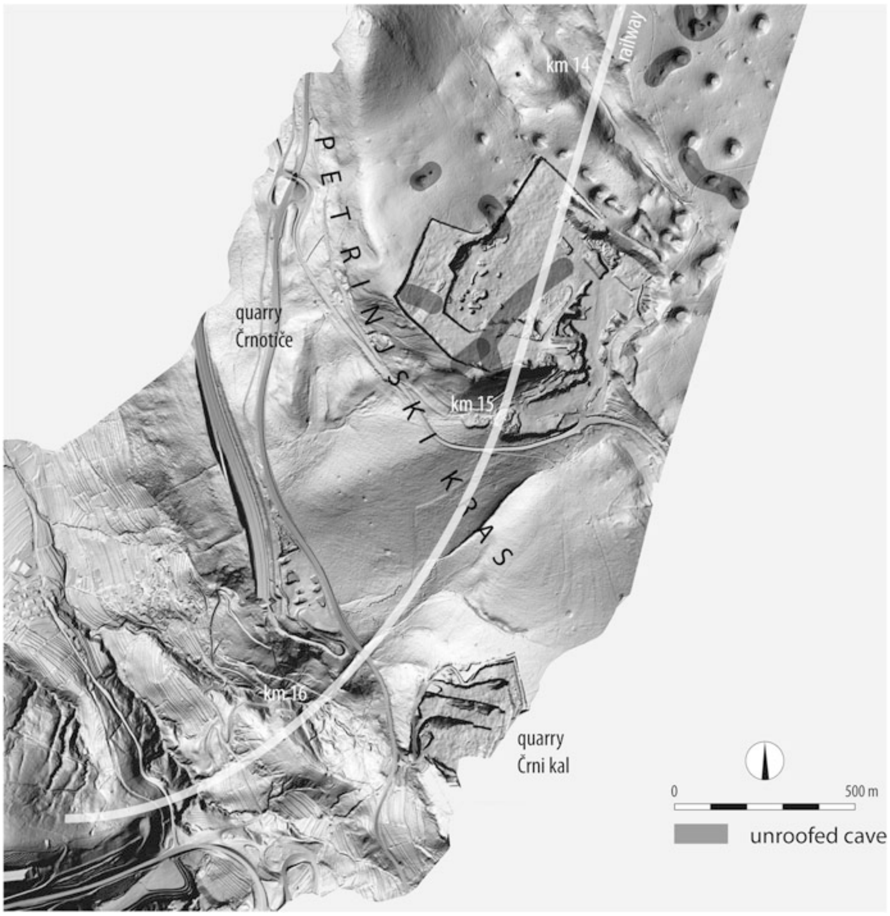

Fig. 19 DEM of the karst area of Petrinjski kras and of the Karst Edge near Črni Kal. This section contains the large Črnotiče quarry and south of it the Črni Kal quarry. Unroofed caves are marked with a *dark grey* colour. A similar density of cavities can be expected at the height of the planned tunnel

River on the surface, while in the underground the water level of karst water lowered, and hence the main channels descended lower down.

Under the present conditions, most of the relief is formed under the influence of precipitation. Throughout, the water table of karst water is located deep beneath the surface. It is similar in the karst area of Podgorski kras where deep, dry caves are accessible. Sinking rivers have no longer direct impact on the surface, except in proximity to ponors.

Current erosion is causing the oldest caves to open up to the surface. In exceptional cases the sections of their passages reach 20 × 20 m. Because the development of the deepening of the passages went on continuously and because these passages are also located in accessible, currently active caves, we can expect such passages to be spread throughout the karst massif.

4 Railway Construction on the Karst Surface

With a geomorphological analysis of the karst and non-karst surface above the planned route we cannot precisely determine where and of what kind the cavities exist in the underground. The morphological analysis is complemented with speleological and hydrological observations and enables the determination of zones and levels at which one can expect greater porosity or the location of important cavities.

The chief geomorphological findings that we must bear in mind are the following:

- The topography of the surface on the limestones indicates that today all the precipitation water from the area of the tunnels flows through the limestones karstically. This percolating water flows dispersedly to a great depth and does not create larger cavities. Creviced corrosion shafts are possible anywhere on the tunnel route.

- The route passes through larger morphological units that point to common developmental features and in which one can expect similar types of cavities.
- Larger cavities may be located throughout the entire limestone mass; however, greater density is probable beneath the surface of flatlands, in the karst area of Divaški kras, in the Lipiški ravnik plain (0.0–4.0 km) and in the karst area of Podgorski kras (11.5–16.0 km). There are not enough morphological signs for the area of the Gradišče mountain and the edge of the Matarsko podolje lowland near Vrhpolje (4.0–9.0 km) from which one could deduce the type and dimensions of the karst cavernosity.
- In the karst area of Podgorski kras or Petrinjski kras (11.5–16.0 km) the main courses on the surface of the unroofed caves run parallel to the contact with the flysch. Similar conditions can be expected at the depth at which the tunnel T2 will be dug.
- During the construction of the railway line on the surface, the route may encounter cavities, either empty or filled up with fine sediments, yet this cannot be predicted with the morphology of the surface.

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