Development and Karstification of the Karst Aquifer as Discovered Between Klanec and Črni Kal

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Between Klanec and Črni Kal, on a 6.5 km route of the motorway, 67 caves opened during earthworks, road cutting and tunnel digs (Fig. 2.1). The majority consisted of old caves, i.e. caves which once had water passing through. Two thirds of these caves were filled with alluvium. Research carried out in these caves augmented our knowledge about the development of this part of the Karst region. A cave system extending more than 500 m, which we tried to preserve in full, opened in the Kastelec tunnel near the Brezno na Škrklovici Shaft. Underneath the road, the passages of this system are connected with concrete tubes which are accessible via a gully at the side of the road.

Due to the construction of the tunnel and extensive roadcuts, the impact of the activities affecting the Karst Edge and its hinterland was significant, in several places leading to the unearthing of today's epi-karst and a part of the vadose zone, both of which are also intersected with old caves. Besides the palaeo-karst, these caves provide the oldest traces of karst development in this area. The caves which were discovered during construction gave us new insights about the cavernosity of the Karst and its development.

2.1 Karst Surface and Karstification

The route runs through alveolinid-nummulitid limestone and, to a smaller extent, flysch rock. It crosses several thrusting deformations between carbonate rock and Eocene flysch.

After Eocene flysch had been deposited in the Pyrenean phase, the rock underwent NW–SE folding. Later, the folds were deformed due to thrust, normal and longitudinal faults. The area between Petrinje and Črni Kal belongs to the imbricate structure of Čičarija thrust unit (Pleničar et al. 1969). The motorway route crosses folds, thrusts and fault deformations (mostly oriented NW–SE and NE–SW). Up to 100 m wide fissured zones striking N–S are mostly made up of open fissures along which shafts and karren systems have developed. These fissures are highly conducive to karstification (Fig. 2.2).

2.1.1 Alveolinid-Nummulitid Limestones

The alveolinid-nummulitid limestones representing the end of carbonate sedimentation in southwest Slovenia lie concordantly on miliolid limestone. The limestone is dominated by the fauna from the Alveolinidae and Nummulitidae families to such a degree that it has given this type of limestone its very name.

The bedding thickness changes in a lateral direction, with medium and thick beds being predominant. In some places, the bedding cannot be determined. The upper part of the alveolinid-nummulitid limestone in particular is more compact and homogenous; the bedding is also less prominent.

The biomicritic and biosparitic limestone, mostly packstone, is usually light brown, light grey or yellowish white in colour. It features numerous fossils of

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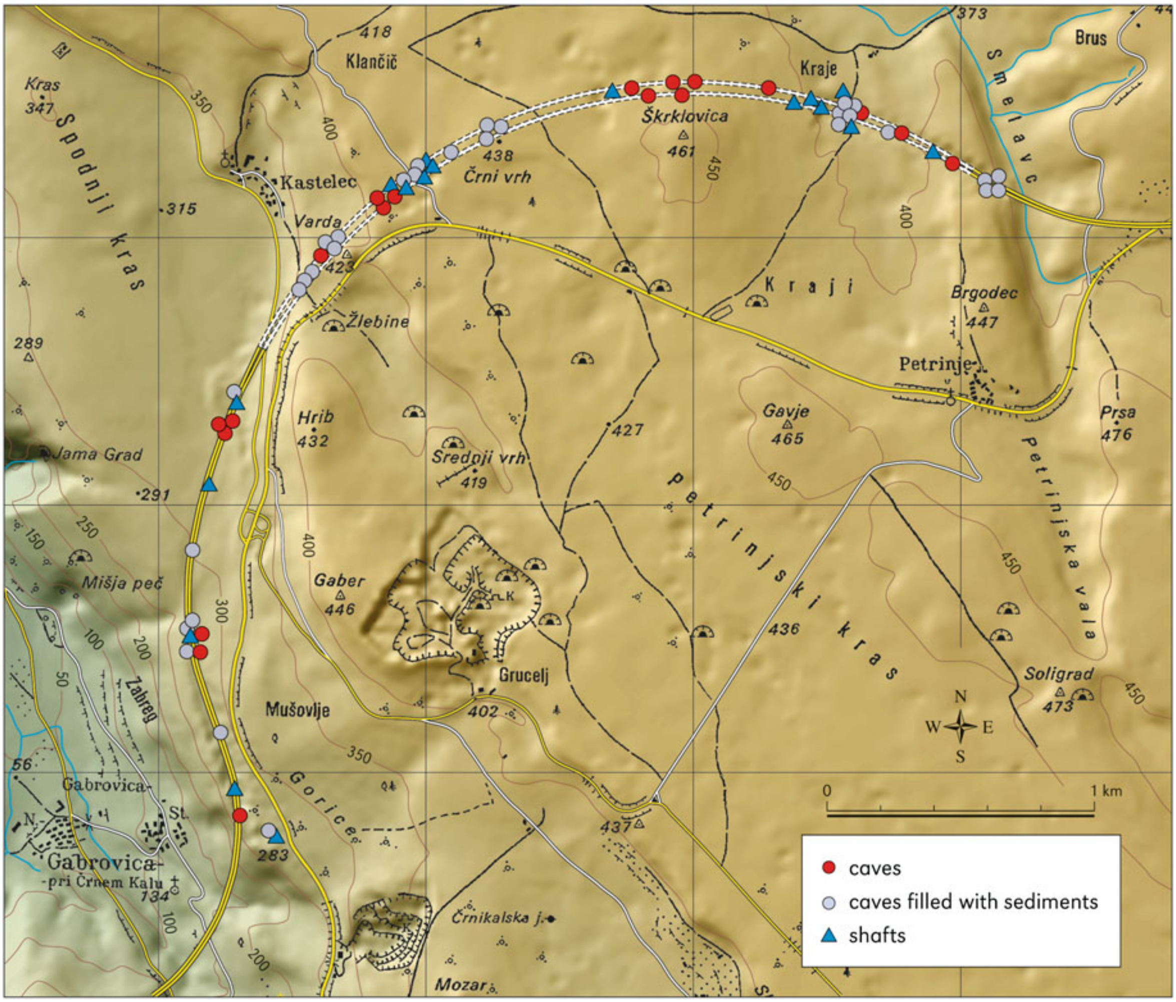

Fig. 2.1 Caves in the route uncovered during motorway construction

alveolinids, nummulitids and discocyclinids. Typically, one can locally also find in this limestone brachiopods, echinoids, corals, lithothamnians, various lamellibranchs, etc.

In most cases, the alveolinid-nummulitid limestone has deposited on the miliolid limestone continuously. Considering the limestone type, it was established that the sedimentation took place in an open and shallow shelf, while elsewhere the sedimentation conditions were more subtle. There, sedimentation took place in sheltered areas of the open shelf or, perhaps, in small lagoons (Jurkovšek et al. 1996).

Nummulites are the most common fossil remains in the alveolinid-nummulitid limestone with beds varying laterally from a few metres and up to 300 m. Usually, however, the genera Nummulites, Operculina and Assilina occur in a mix with all three genera present. There are areas where nummulites are predominant and others where operculines prevail. It follows that the former limestones could be termed nummulitid and the latter operculinid limestone. Assilines are usually featured in the rocks to a smaller degree.

2.1.2 Flysch

Along the border with flysch, we observe transitional beds of carbonate and non-carbonate rock, of mainly marl and marly limestone, often containing

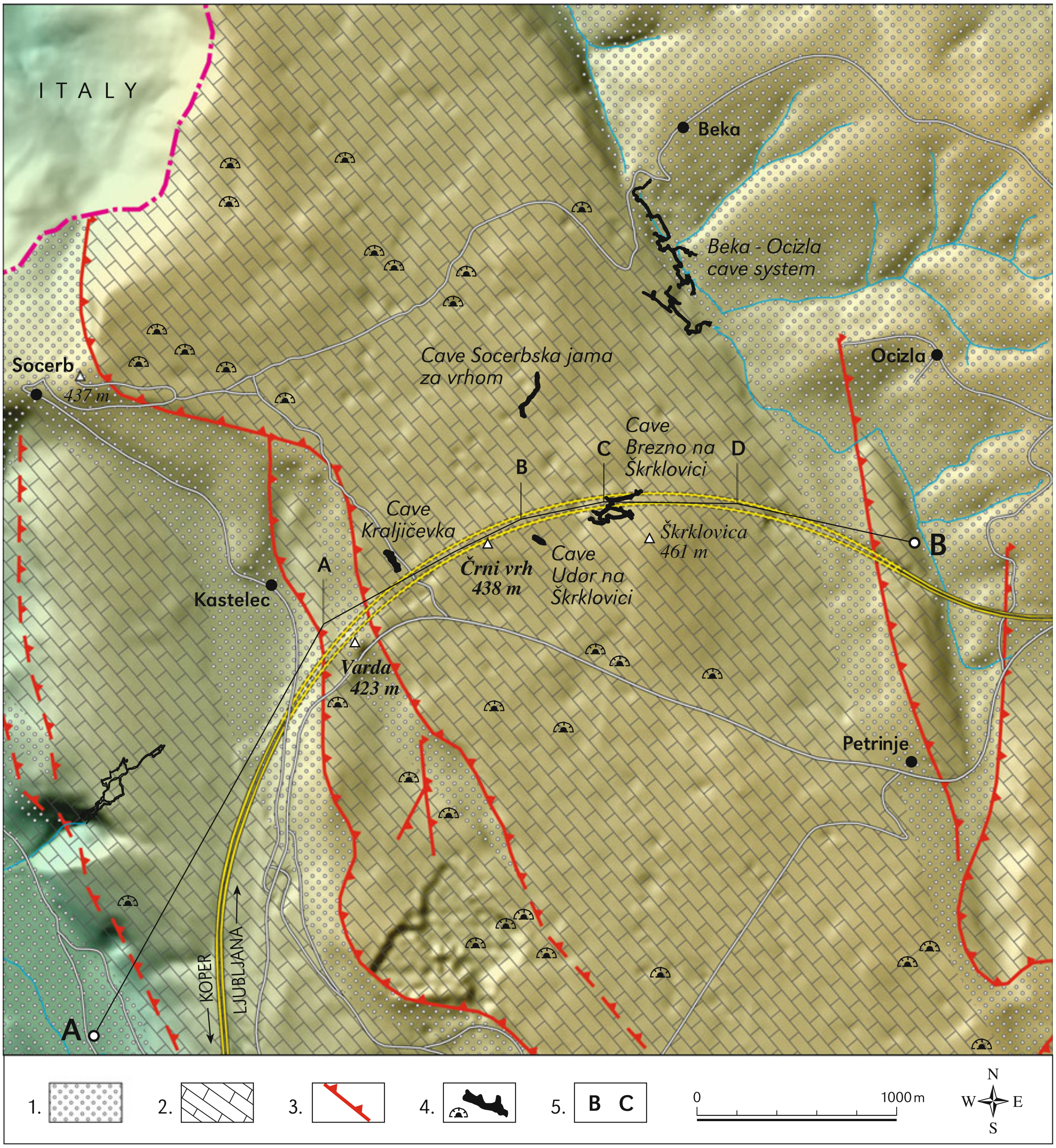

Fig. 2.2 Fault zones and already known caves in the studied area (the legend provided in Fig. 2.9)

abundant pelagic Foraminifera. Nevertheless, a longer or shorter hiatus may occur laterally between the two formations.

The flysch, marked by alternating sequences of marl, sandy siltstone, and coarse-grained carbonate sandstone with intermittent thicker or thinner insertions of breccia and conglomerates, was thrust-imbricated onto the alveolinid-nummulitid limestone. The area of contact was important for the typical speleogenetic development. It was established that in contact with impermeable rock, limestone is not just a water barrier as it is where runoff collects, carving from larger drainage channels through which the material is washed off below the ground.

2.1.3 Karstification of the Alveolinid-Nummulitid Limestone

In light of current research, it was found that alveolinid-nummulitid limestone is more resistant to erosion compared to the stratigraphically closer adjacent limestone. In most cases, it was only the surface that was subject to karstification, and the area directly below. Only on rare occasion does karstification occur deeper down. Surface karstification is heavily pronounced on inclined terrain where diluvial sediments occur. One can however topographically distinguish alveolinid-nummulitid limestone from the underlying miliolid limestone based on the more pronounced surface karstification and the numerous karren dissecting the rock surface.

The weathering of alveolinid-nummulitid limestone is platy; the limestone breaks up into rubble or displays irregular disintegration. The soil overlying the bedrock is often only a few 10 cm thick.

A detailed study of the influence of the rock type on the number of cave entrances was conducted in the immediate vicinity of the surveyed area. It was established (Knez 1995, 1996) that the Liburnia Formation beds, featuring alveolinid-nummulitid limestone, have a considerably smaller karstification depth than the Cretaceous beds. The average number of caves in the examined area is 1.01 cave/km^2, and the Liburnia Formation reaches 75 % of the average, but the alveolinid-nummulitid limestone only 0.43 cave/km^2. The significantly higher figures from the Senonian (2.42 cave/km^2) and from the Turonian (2.18 cave/km^2) should be noted.

In order to assess the cavernosity of the Karst region between Petrinje and Črni Kal, we measured the karst caves, uncovered in the course of quarry works, in the Črnotiče quarry with a laser theodolite. This involved shafts, horizontal caves and vertical fissures, mostly completely filled with cave sediment and flowstone. The passages were up to 220 m long with a diameter of up to 15 m. Some caves were situated immediately below ground, while others had opened a few metres deeper. Also, some were filled with sand and alluvial clay, while other instances featured rubble, and sometimes flowstone, deposited over sand and clay. Some of the karst caves which had not been completely filled with sediments were subject to measurements and mapping, later, however, these caves were destroyed and removed by quarry work.

Cavernosity was calculated using the geodetic measurements of the caves in the quarry. It was calculated that the total volume of the cave passages for 13 geodetically measured caves in a select block of rock (300 × 400 × 19 m) amounts to 89,074 m^3 or 3.9 %.

2.2 Epikarst

Underlying a thin layer of soil and overlying poorly fractured rock, subsoil karren with a characteristic subsoil rock relief (Slabe 1998a) had formed. The massively fractured rock has already disintegrated into individual, mainly smaller, pieces which were reshaped, i.e. rounded off, below ground; their surface, which was exposed to even weathering, indicates the composition of the rock. As it were, Palaeogenic fossils are often found sticking out of the surface. Along the contact of limestone and flysch, subsoil channels and scallops had formed. Above-sediment anastomoses are typical of the lower faces of the basal conglomerates in the flysch.

In Kozina, the former Palaeokarstic surface was unearthed directly below the present surface and revealed remains of dinosaurs and other animals (Debeljak et al. 1999).

2.3 Discovered Caves

On a 6.5 km route of the motorway, 67 caves were opened during earthworks, roadcuts and tunnel excavation. In terms of numbers, old caves—once marked by through-flowing water—were predominant (49); two thirds of these were filled with fine-grained alluvium and occasionally with coarse rubble.

Old caves opened as unroofed caves (Knez and Slabe 1999a, b, 2000, 2001c, 2002a, 2004a, b, 2005, 2006a, 2008, 2009b, d, 2010b, c, d, f, 2011, 2012b; Knez and Šebela 1994; Knez et al. 2012; Kogovšek et al. 1997; Mihevc 1996; Mihevc and Zupan Hajna 1996; Mihevc et al. 1998; Slabe 1996, 1997a, b, 1998a; Šebela and Mihevc 1995; Šebela et al. 1999).

Fig. 2.3 Walls of a cave network that was filled with alluvia and flowstone

Caves also opened at the perimeter of the roadcuts and during the excavation of the tunnel. Their passages reached up to 8 m in diameter.

A larger system of caves opened on the eastern side of the south entrance to the Kastelec tunnel. A part of the system was already missing the roof, one part consisted of hollow passages, and the other part was filled with sediments and flowstone (Figs. 2.3, 2.4 and 2.5). The rim of the passages had been characteristically reshaped above the sediments (Slabe 1995). From the largest passage, 18 alluvium samples were collected for palaeomagnetic study (Fig. 2.6). With regard to the location within the region and the development of this part of the Karst region, it was established that the deposits, much like other cave deposits in the immediate vicinity, consist of flysch deposits (Bosák et al. 2000a, b). The uppermost part of the profile is made up of a 3 m thick rubble layer. Below lies a 2 m layer which is sandier, whereas the lowermost layer is argillaceous. The sediment is yellowish brown (10YR 5/6) to light olive grey (5Y 6/2) in colour. From the bottom of the profile up, at a depth of 4.5–5 m, lies a 10–20 cm thick connective layer of clay that is of a darker shade (brownish yellow 10YR 6/8) than other sediments in the profile. The altitude of the deeper samples is 395 m a.s.l. Individual, unroofed parts of the cave, which were doline-like, were clearly distinguishable on the surface even before works began.

However, the largest cave system, stretching over 500 m (Figs. 2.7, 2.8 and 2.9), opened in the tunnel not far from the already known Brezno na Škrklovici Shaft (Reg. No. 1391; The Cave Registry of the Speleological Association of Slovenia and the Karst Research Institute ZRC SAZU) has distinct signs (large scallops) indicating that the water flow in the water-filled cave must have been slow. Three large passages opened in the tunnel, however they were not

Fig. 2.4 Section of the cave network that was filled with alluvia and flowstone

interconnected. Still, it appears that they are all part of a single cave system. The shape of the inclined passages (up to 8 m in diameter) suggests that the cave was shaped by the flow of water and that its reshaping by percolating water was less pronounced. The large scallops are the result of a slow water current, which was in fact the main culprit for the present shape of the cave, while the ceiling cups indicate that the cave was once completely filled with water. The ceiling cups are of various shapes, they run narrow and extremely high (up to several metres) along the cracks; they have relatively level tops and are often clustered into smaller or larger ceiling cupolas. Originally, the passages were filled with fine-grained alluvium, which had mostly been flushed out by now.

At the surface, specifically at the entry shaft to the Brezno na Škrklovici Shaft, the beds of alveolinid-nummulitid limestone dip 20° to the southeast. In the cave, in the left tunnel tube, the beds dip 30° or 40° to the east or northeast. At a vertical distance of 80 m, the bedding dip direction has thus slightly changed.

While making way for the roadcut, an old cave opened next to the steep karst edge, which was in fact, a system of minor passages with a round cross-section, their roofs criss-crossed by cups and cupolas—features dating back to when the cave had been shaped below the ground water level. Occasionally, a small conduit can be found on the bottom of the passage, created by the through-flow of small quantities of water over the rock bed—suggesting a more recent cave reshaping.

Many of the caves are characterized by cracks along vertical fissures, either hollow or filled with alluvium. Often they were 1–2 m, rarely 3 m, wide but they could run up to several tens of metres deep. Those that were filled with fine-grained deposits had supra-alluvial scallops along their rim.

Fig. 2.5 The wall of the passage that has formed along the alluvium, with the passage being filled with fine-grained alluvium

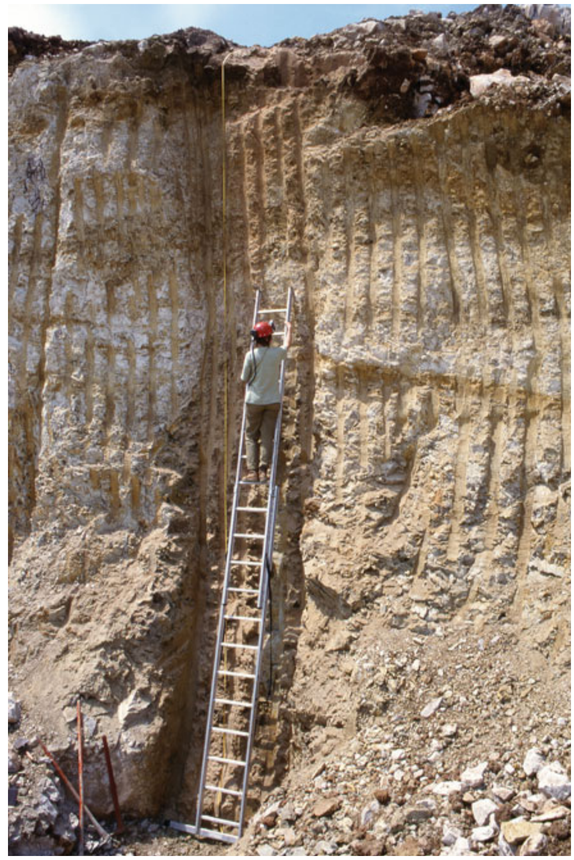

Fig. 2.6 Alluvia in an unroofed cave

In addition, there was a shaft with a diameter of 4 m located within the perimeter of the described cave system, before the tunnel (Fig. 2.10). It was completely filled with fine-grained alluvium. Its walls showed traces of percolating water and were only occasionally reshaped under the alluvium.

Caves also emerged along the contact of limestone and flysch. In places where limestone overlies flysch, most of the respective caves had formed in flysch. The caves had a diameter of 2 m, and they were completely filled with flowstone and fine-grained alluvium.

Eighteen shafts had opened, the deepest two exceeding 60 m each. Shafts were either simple or gradient. Some displayed old flowstone which had been corroded by water running down the walls.

2.4 Aquifer Development

Caves, which were opened during the construction works, reveal the most important periods in the development of this part of the Karst. The epikarst and the upper part of today's vadose zone are intersected by traces from different periods of karst development. The oldest caves demonstrate distinct traces of cavernosity of the aquifer, suggesting that the preserved part of the Karst was entirely shaped below the ground water table—which is today 230 m deep underground. As a result of the lowering of the karst surface, some of the caves have already lost their roofs (Knez and Slabe 2002a). The shapes of the other caves suggest formation in a phreatic zone. However, most

Fig. 2.7 A cave that was uncovered during the tunnel digging (*Photo* Feruccio Hrvatin)

of them were filled with fine-grained deposits which were later in part washed out. The alluvial fill in the caves is associated with ground water level rises following the Messinian Event (Bosák et al. 2000a, b). It appears that the shaft, which was filled with fine-grained alluvium, reveals a distinct period of formation of the upper part of the aquifer in vadose conditions before it had been reached by floodwaters.

A relatively swift transition of the formation of this part of the Karst region into permanent vadose conditions followed. Apart from alluvial traces, particularly deposits and rare traces of faster water currents, the caves show no distinct signs of formation in epiphreatic or vadose conditions. Today, this part of the Karst region is subject to formation with dispersed water percolating down from the karst surface. Water caves develop only at the contact area of flysch and limestone, which is crossed and entered by streams. It is safe to say that the development of this part of the Karst is closely connected with the rapid decrease of the ground water level.

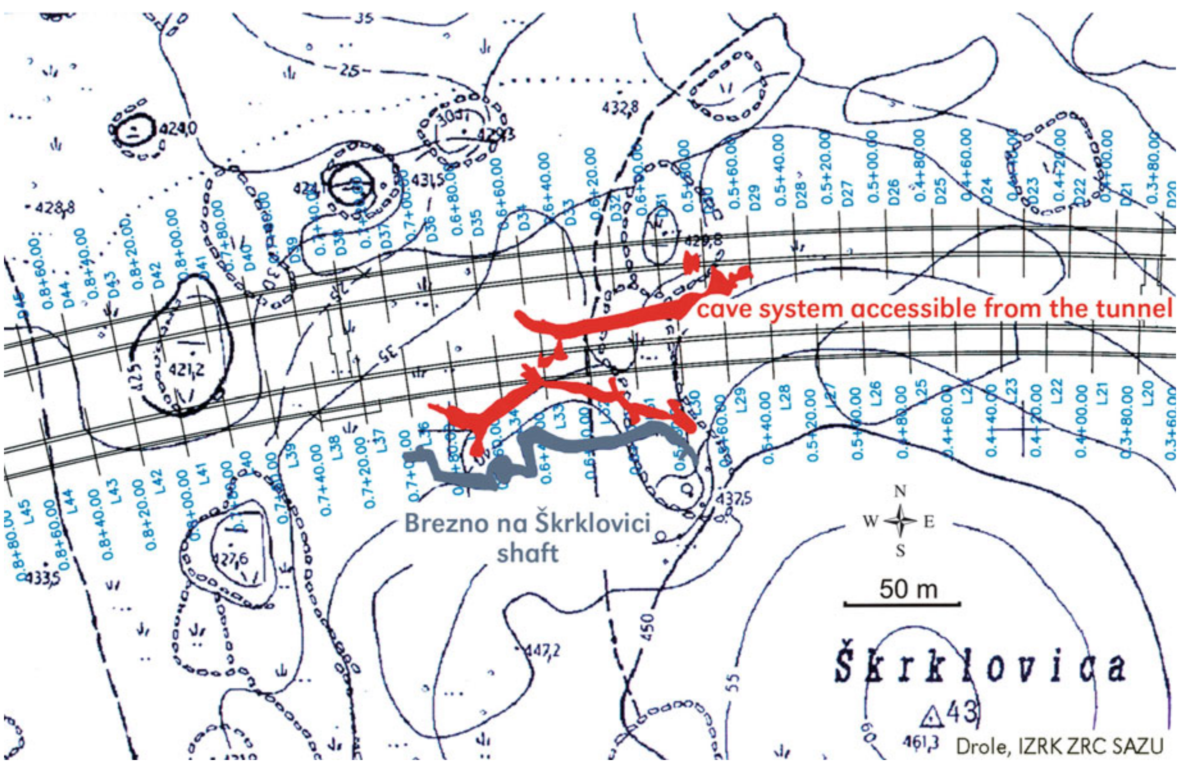

Fig. 2.8 A preserved cave network accessible from the tunnel

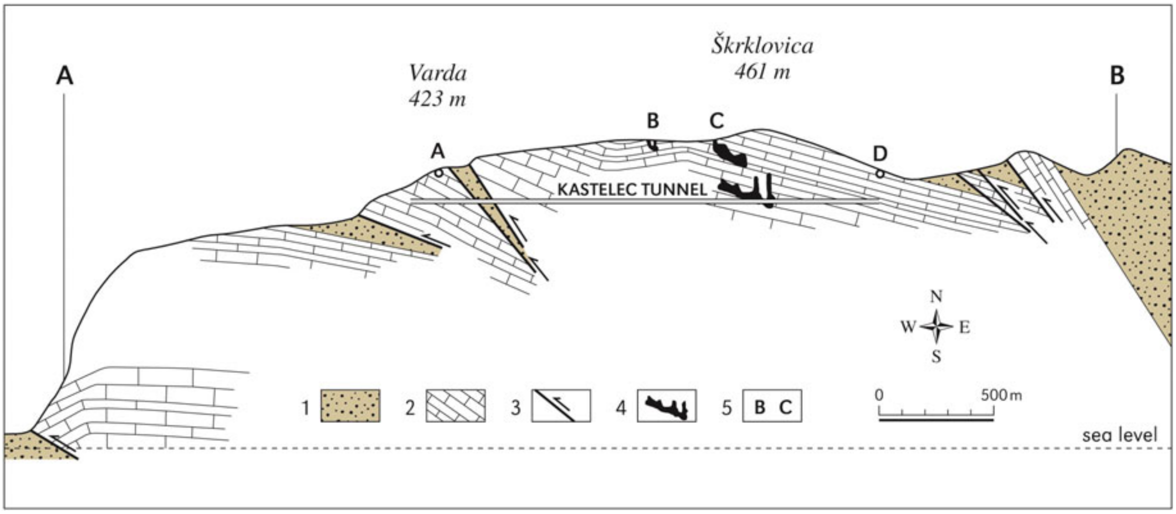

Fig. 2.9 Cave cross-section AB. The height of profile is enlarged by a factor of 3 relative to the length. Legend: *1* Eocene flysch, *2* Eocene alveolinid-nummulitid limestone, *3* thrust, *4* karst cave, *5* labelled points on the profile (B—Cave Udor na Škrklovici, C—Cave Brezno na Škrklovici)

Fig. 2.10 An old shaft filled with fine-grained alluvium

A part of the old caves is filled with coarse rubble which came about as a result of rock disintegration in the cold Pleistocene periods.

In several instances, it was observed that the water, percolating from the surface and trickling down the walls of the shafts—either independent shafts or such dissecting older caves—dissolved the flowstone which had once covered these walls. Will further research reveal that this is merely the result of the widening of cracks, of changes affecting the karst surface, or perhaps even the result of human impact due to the removal of vegetation?

2.5 Cave Preservation

All the caves discovered during the motorway construction were measured, mapped out (Fig. 2.11) and explored. Supported by road builders, we tried to preserve as many as possible. Now they are hidden behind rock embankments at the edges of respective roadcuts, and behind concrete rims inside the tunnel. Caves located under the road, with narrower openings and, despite blasting, a relatively unfractured rock rim, were covered with concrete slabs. We made efforts to preserve the largest cave system in the tunnel in full. The passages of this system are connected by concrete tubes running under the road, accessible through a shaft located at the side of the road in the tunnel.

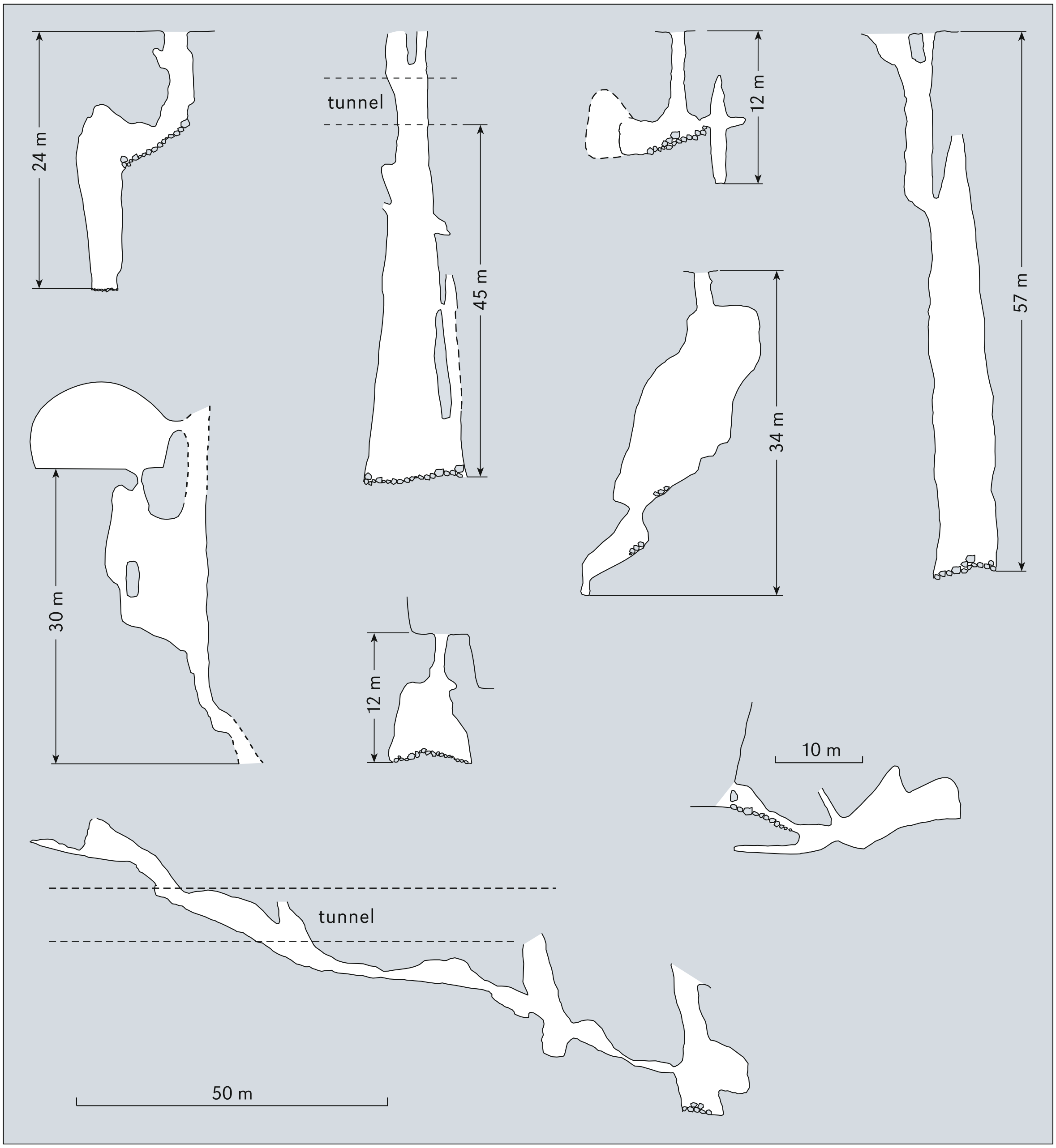

Fig. 2.11 Cross-sections of caves uncovered during tunnel-digging

2.6 Conclusion

On a 6.5 km stretch of the motorway, a total of 67 caves opened during the construction works, of which 49 caves, i.e. the majority, showed signs of having had water flowing through at one point. Inside the Kastelec tunnel a large cave system was discovered in the NW part of the Škrklovica hill (461 m), and proven to be genetically connected to the previously discovered Brezno na Škrklovici Shaft. A great portion of the caves was filled with fine-grained alluvium. Most of the motorway route runs over alveolinid-nummulitid limestone which is relatively resistant against karstification, accounting for the fact that in most cases only its surface and the parts close to the surface are distinctly karstified. The signs of karstification from various periods are evident in the epikarst in the upper part of today's vadose zone. The oldest caves still contain evidence of the cavernosity of the aquifer, when the part of the karst, which is still preserved today, was shaped entirely in the phreatic zone. Some of the caves consisting of a system of smaller passages with a circular cross-section, have ceilings that feature ceiling cups and cupolas, i.e. shapes dating back to the time when the caves had been formed below the former ground water table. This was followed by a relatively swift drop of the ground water level which led to the reshaping of the older signs of development in vadose conditions.

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