



Structural–Geological Mapping of Karst Areas

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For understanding geological structure of karst areas (Palmer 2007), it is inevitably to have detailed geological maps. But karst areas are mostly geologically mapped only as parts of basic geological maps (1:100,000 in Slovenia). If we deal with the example of Slovenia, we need to stress that besides basic geological maps we have tectonic maps and sketches of smaller areas in SW Slovenia, which help to better understand the tectonic and geodynamic situation (Placer 1981, 1982, 1996; Placer et al. 2010; Čar 2018). And we have a geological map of the southern part of the Trieste–Komen Plateau (Cretaceous and Paleogene carbonate rocks) in the scale 1:50,000 (Jurkovšek et al. 1996). But detailed structural–geological maps of karst areas in the sense of Čar and Gospodarič (1984) are still rare. For understanding development of karst features, it is thus significant to make very detail structural–geological maps in scales as 1:5,000, 1:1,000 or even 1:500 of caves and of the karst surface.

After the Second World War, karst areas of Slovenia were primarily studied by stratigraphy. In this sense, Pleničar (1960) described stratigraphic development of the Cretaceous rocks of the Notranjska region and determined that passages of the Postojna Cave are mostly parallel to the beds (Pleničar 1961).

The dependence of the origin and formation of cave passages on the faults and fissures of the Postojna Cave, including the wider area of SW Slovenia, has been researched in particular by Gospodarič (1963, 1964, 1965, 1968,

1969a, b, 1976). He produced detailed maps of the lithostratigraphic units of both the Postojna karst surface and underground as well as maps of the Postojna anticline structure together with the faults and fissures intersecting the anticline.

In the SW Slovenia field mapping of karst surface expanded in 1980s in the scale 1:5,000 (Čar 1982; Čar and Gospodarič 1984). Čar (1982) divided tectonically fractured zones into fissured, broken and crushed zones regarding different intensities of tectonic change of the rock. In fissured zones, the carbonate rocks are least fractured, and stratification is still visible. Broken zone is more fractured zone where rock often occurs as blocks, which may be physically displaced. Crushed zone is most fractured where stratification has been destroyed and rocks are crushed to the degree of tectonic breccia and clay. Fractured zone properties may change from one pattern to another in horizontal and vertical directions (Čar 1986).

By using the method of detailed tectonic–lithological mapping of the surface at a scale of 1:5,000, cave passages of the caves Planinska Jama, Črna Jama and Pivka Jama were connected with the already determined tectonically fractured zones on the surface with some degree of accordance (Čar 1982; Čar and Gospodarič 1984).

In 1990s, the method of detailed structural–geological mapping was transmitted to karst caves, such as Predjama (Šebela and Čar 1991; Šebela 1996) and Postojna Cave (Šebela 1992, 1998) owing to good speleological maps. This was an important progress in understanding the formation of karst caves regarding the structural–geological elements. The mapping was carried out according to Čar's (1982) classification of tectonically fractured zones. For the first time, this method was used experimentally in the cave passages and chambers of Predjama at a scale of 1:1,000. At a vertical distance of about 100 m, some tectonically fractured zones in the cave with outcrops on the surface by means of the longitudinal sections of the cave and those of the surface above were connected (Šebela and Čar 1991).

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After structural–geological mapping of Predjama, Postojna Cave was selected to be mapped in detail. An advantage of the Postojna Cave was its good cartographic base–ground plans, cross sections and longitudinal sections at a scale of 1:500 which were made by Gallino Petrini and Sartori in 1933–34, and supplemented by Hribar and Michler in 1948–60 (Caves Registry). Additional modifications and improvements were made in 1972 and 1983–84 by Kenda, and were supplemented in 1989–98 by Drole (Caves Registry).

Positions of Postojna anticline and interbedded slips due to thrusting and folding deformations were shown as important structural–geological elements that influenced the formation of cave passages. On the basis of the cross sections in the tourist part of Postojna Cave and those of the cave section of the underground Pivka River, it was established that 41.2% of the cross sections have been developed in tectonically fractured zones (Šebela 1998).

The importance of selected bedding planes for the formation of phreatic channels was determined as well by Knez (1996) in the case of Velika Dolina collapse doline in Škocjan Caves.

Surface structural–geological mapping was as well going on, and geological–structural position of vertical karst objects was presented for the area above Pivka and Črna Jama of the Postojna Cave system (Čar and Šebela 1997). Geological maps of the karst springs at the contact between non-carbonate and carbonate rocks in the Vipava Valley were presented by Janež (1997) and Janež and Čar (1997). Different cases of shaping of dolines regarding structural–geological conditions on the karst surface were shown by Čar (2001) and Šebela and Čar (2000). Development of karst at thrust contact limestone–dolomite was presented in 2001 (Čar and Šebela 2001).

Based on detailed structural–geological cave maps, Šušteršič et al. (2001) determined that position of collector channels is dependent on deflector fault, which in Postojna Cave has a Dinaric trend (NW–SE). The collector channel gathers underground streams that should cross the broken zone of the deflector fault (Šušteršič 2006).

Structural–geological map of the Škocjan Caves has been published by Šebela (2009). This was a compilation map of field mapping from the period 1991–2009 where field mapping represented big challenges due to high (up to 120 m) and big cave passages and due to the lack of good visibility.

Connections between underground cave passages, structural geology and hydrology of water channels were shown with structural–geological mapping in the 1:5,000 scale above passages of the cave Kačna Jama near Divača (SW Slovenia) (Žvab Rožič et al. 2015).

Recently, LiDAR tool is enabling important geomorphological upgrade for karst regions (Zlot and Bosse 2014; Mahmud et al. 2016), which helps geological field mapping

but cannot completely replace it. By using LiDAR and UAV (unmanned aerial vehicle) in semi-arid Brazil karst fracture system, connection between development of karren features and fracture systems was shown (Silva et al. 2017).

Detailed structural–geological cave and karst surface maps are the base for other karst-related researches as karst hydrology, chemistry of percolated waters in caves, geophysical research in karst (georadar, geoelectricity, seismicity), displacement monitoring of active tectonic structures, hydraulic modelling of karst areas, etc.

1.1 Case Studies

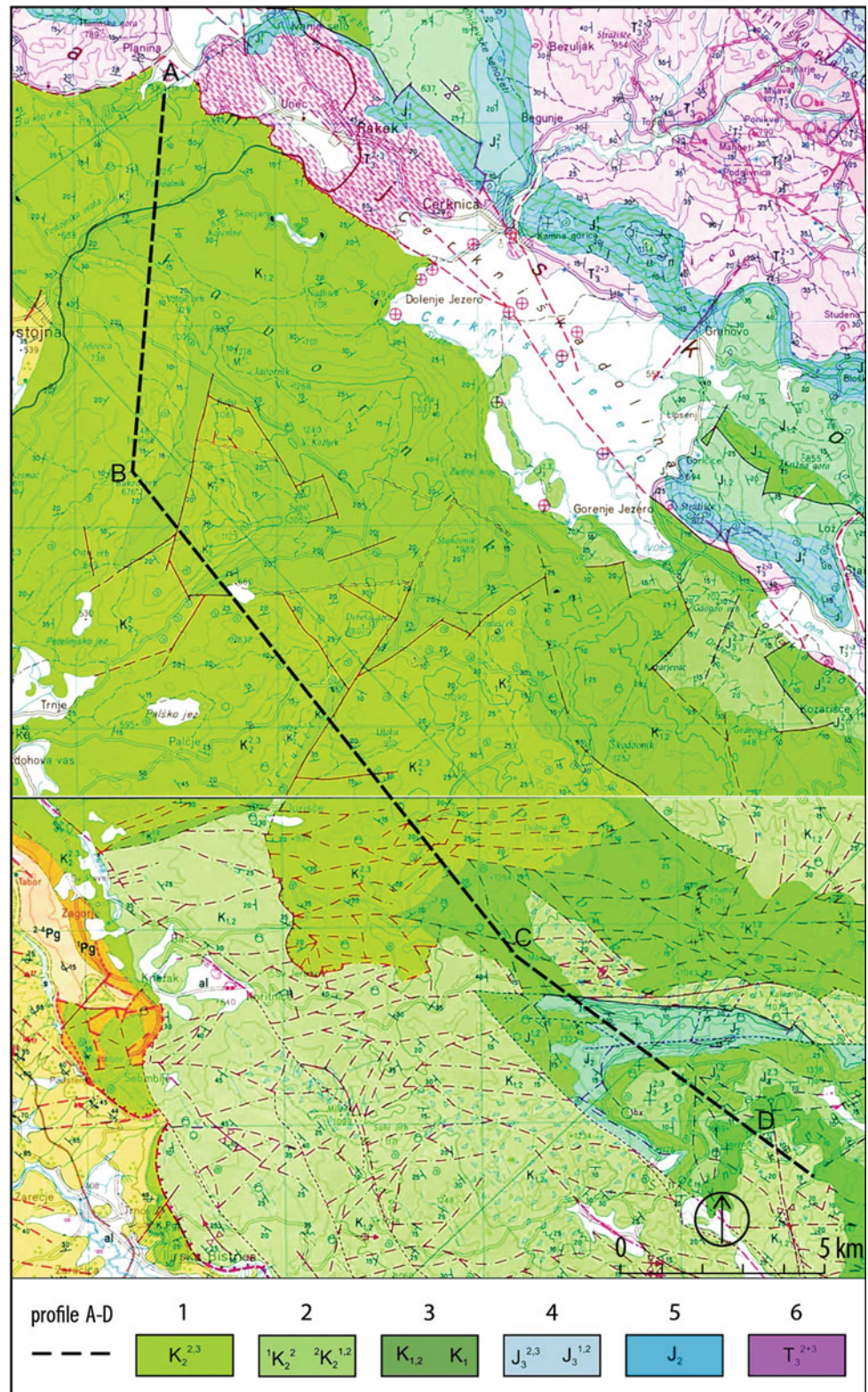
1.1.1 Longitudinal Geological Cross-Section Snežnik Mountain–Planina Cave

In the case when a geological map is needed for understanding oscillations and direction of groundwater flow in the mountainous karst area, basic geological maps can help, especially if no other more precise geological maps are available and if there is not enough time or financial support to perform time-consuming detailed field geological mapping in forested and mountainous area. Here, we present the karst area of Snežnik Massif–Javorniki Mountains (Fig. 1.1) in SW Slovenia (Petrič et al. 2018) between Snežnik Mountain (1796 m a.s.l.) and Malni karst spring at the base of Planina polje (448 m a.s.l.), where carbonate rocks can reach the thickness of up to 3,300 m (Pleničar 1970; Šikić and Pleničar 1975).

In tectonic sense, this area is part of External Dinarides. Thrust fault structure typical for NW part of External Dinarides is conditioned by paleogeographical conditions of the Adriatic–Dinaric carbonate platform (Placer et al. 2010). Thrust deformations started at the end of Cretaceous and especially after deposition of Eocene flysch. In the area of Snežnik Massif–Javorniki Mountains neotectonic structures as Predjama Fault as well as folds as secondary structures of the thrusting are detected. Faults show multi-phase tectonics with reactivations. This area is tectonically active (e.g. an earthquake on the western side of Javorniki Mountains in April 2014 with $M = 4.4$).

The area was studied because of the location of Poček (Fig. 1.2), which is a military training area in Slovenia and completely belongs to karst (Kogovšek et al. 1999). A principal underground water flow from Poček is in the direction towards north to the Malni spring, which is a principal drinking water catchment for Postojna town. At Poček, carbonate rocks are tectonically broken in two principal fault orientations: NW–SE and NE–SW. For the vertical and horizontal water flow, the most favourable are tectonic zones in N–S and NE–SW orientations. Those are open fissures, which developed in relaxation tectonic conditions.

Fig. 1.1 Course of longitudinal geological profile A–D (A Malni, B Poček, C Mašun, D Snežnik) on selected sector of basic geological maps 1:100,000 Postojna (Buser et al. 1967) and Ilirska Bistrica (Šikić et al. 1972). *Legend* 1 $K_2^{2,3}$ —Cretaceous limestone with rudists and thinner dolomite layers; 2 $^1K_2^2$ and $^2K_2^{1,2}$ —Cretaceous limestones with some dolomites; 3 $K_{1,2}$ —Cretaceous limestone with layers of bituminous dolomite, limestone and dolomite breccias on Snežnik Mountain, K_1 —limestones and partly dolomites; 4 $J_3^{1,2}$ and $J_3^{2,3}$ —Jurassic limestone; 5 J_2 —Jurassic dark grey dolomite in alteration with grey limestone; 6 T_3^{2+3} —Upper Triassic dolomite



To make the longitudinal geological profile A–B–C–D, morphology was taken from the 1:50,000 morphological map. Lithological and tectonic data were taken from more sources as the Basic geological map Postojna (Buser et al. 1967)

and Ilirska Bistrica (Šikić et al. 1972), from the structural–geological map of Čar and Gospodarič (1984) and from the tectonic map of Poljak (2000). Elevation of cross section of the Rak water channel at Planina Cave was added according to

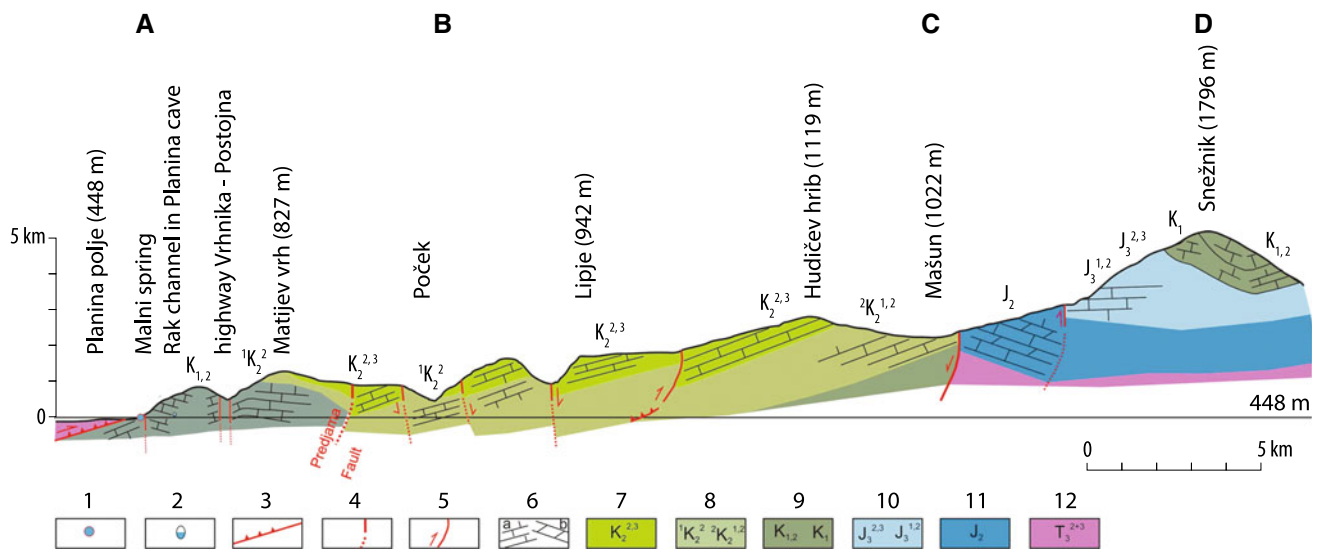


Fig. 1.2 Longitudinal geological profile A–D (A Malni, B Poček, C Mašun, D Snežnik). *Legend* 1 Malni spring; 2 cross section of the Rak channel in Planina Cave; 3 thrust fault; 4 a fault with possible continuation; 5 vertical movement along a fault; 6a limestone; 6b dolomite; 7 $K_2^{2,3}$ —Cretaceous limestone with rudists and thinner dolomite layers; 8 $1K_2^2$ and $2K_2^{1,2}$ —Cretaceous limestones with some dolomites; 9 $K_{1,2}$ —Cretaceous limestone with layers of bituminous

dolomite, limestone and dolomite breccias on Snežnik; K_1 —limestones and partly dolomites; 10 $J_3^{1,2}$ and $J_3^{2,3}$ —Jurassic limestone; 11 J_2 —Jurassic dark grey dolomite in alteration with grey limestone; 12 T_3^{2+3} —Upper Triassic dolomite. Longitudinal cross section modified by S. Šebela after Buser et al. (1967), Čar and Gospodarič (1984), Poljak (2000), Šikić et al. (1972). Profile heights are not in the same scale as the profile length

speleological data. Direction of fault movements was determined regarding the position of stratigraphic units and the dip angle of bedding.

We see that some extent already existing geological maps with some additional self-made longitudinal sections can help in specific karst-related studies.

1.1.2 Detailed Structural–Geological Mapping of the Postojna Cave Area

The area of Postojna Cave (cave and surface) was first mapped by Gospodarič (1965, 1976). Besides lithology, he studied fault planes and fissures in the cave which were not described as zones. The new tectonic–lithological mapping of Postojna Cave was done in the scale 1:500 (Šebela 1998). For the development of cave passages, importance of interbedded movements (flexural slip) which represent secondary deformations of the Postojna anticline with axis orientation NW–SE was specially stressed (Šebela 1998, 2012).

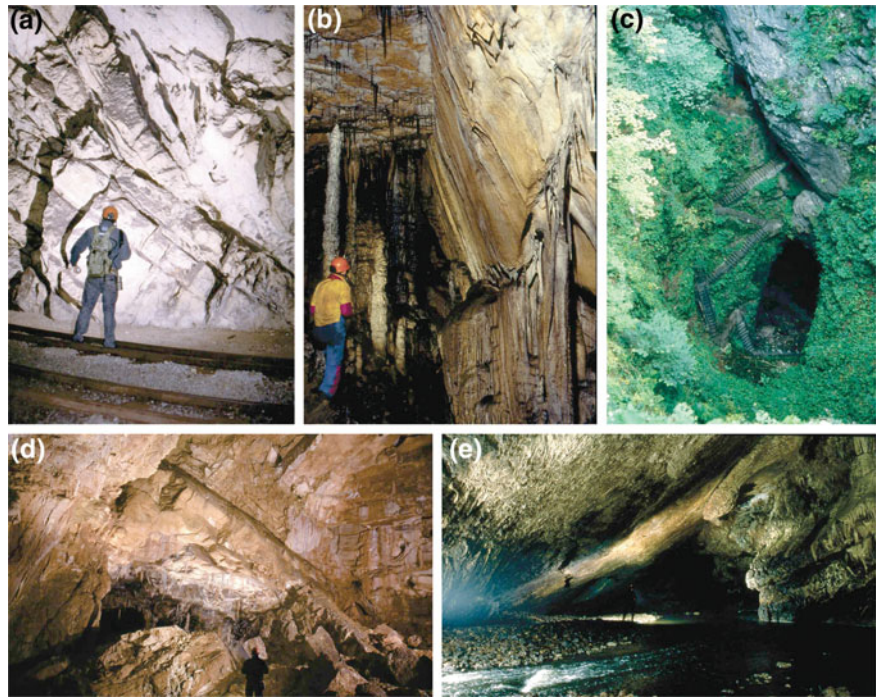
Duplex in Postojna Cave (Fig. 1.3a) is attributed to the period of overthrusting of the Upper Cretaceous limestones over Eocene flysch rocks. This was the same period that caused the vergence of the Postojna anticline axis towards SW for 7° – 14° (Šebela 1998).

A result of detailed structural–lithological mapping of karst caves is a very precise structural–geological map. An example of such map is presented in Fig. 1.4. This is a hand-drawn map from 1994 of the part of Postojna Cave. We can see that there are numerous fissures that are combined to zones. When we put fractured zones on the cave map, we are able to get the image of different directions of the fractured zones and connections between them (in the sense which fractured zone is cut by another zone).

With studies of 93 cross sections in Postojna Cave (Šebela 1998), it was determined that 37.6% of cross sections are shaped according to bedding. It was shown that selected cave passages are formed along bedding planes (Fig. 1.3e), moved bedding planes and connective fissures. The advantage for speleogenesis of some bedding planes and moved bedding planes is represented with their connection into penetrative effective porosity in specific structural block (Čar and Šebela 1998).

In the same period as geological mapping of the cave, structural geological mapping of the surface directly above Postojna Cave was accomplished (Šebela 1998, 2012). Principal fault zones on the surface were connected with fault zones mapped in cave passages. If we add LiDAR map on geology and cave ground plan, we get a clear detailed morphological and structural–geological map of the area above Postojna Cave (Fig. 1.5).

Fig. 1.3 Geological structures in Postojna Cave. *Legend* **a** Duplex due to overthrusting in Stara Jama, **b** fault plane is building a cave wall in the passage Rov brez imena, **c** entrance to Pivka Jama is developed along fault zone, **d** fault plane with low angle dip in Pisani rov collapse room, **e** underground Pivka River channel follows direction of bedding planes visible on the cave ceiling



According to the Basic geological map (Buser et al. 1967), the limestones which make up the Postojna Cave as well as the surface above may be attributed to the Upper Cretaceous, i.e. the Turonian and Senonian $K_2^{2,3}$ and Cenomanian K_2^1 age. *Chondrodonta* lumachelle horizon may be observed in a road cutting between Risovec blind valley and the cave Pivka Jama. The horizon is attributed to the Upper Cenomanian by Rižnar (1997). In Fig. 1.5, we left this horizon inside Turonian (K_2^2). Čar (2018) divided K_2^3 horizon into K_2^3 and $K_2^{3,4}$. In Fig. 1.5, we did not divide Senonian K_2^3 horizon. Regarding recent field observations, Maastrichtian (the most upper part of the Upper Cretaceous) carbonate rocks are present in the area of Postojna karst (Otoničar, pers. comm. 2019).

To understand dependence between formation of karst surface and underground features on structural–geological features, generations and type of regional tectonic activity must be included. Within the area between Postojna, Planina and Cerknica, Čar and Gospodarič (1984) determined generations of fault zones and the structural geometry of the Snežnik thrust sheet between the Idrija and Predjama faults. They established four generations of deformations from the Neogene and supposedly the Quaternary. The tectonic conditions of the treated terrain are divided into

- older movements,
- thrust structures and folds, and
- fault deformations.

At the end of the Eocene or in the Oligocene, the Alpine–Dinaric region was subjected to intense overthrusting. The beds were first folded and subsequently were broken. During the Miocene and Pliocene, the overthrusting was accompanied by folding (Placer 1982).

The faults of the first generation trending NE–SW were active in all the tectonic movements, probably even up to the Holocene. The influence is thought to be present also in collapse dolines around Vodni dol and in those around the blind valley Risovec, as well as in the orientation of the water channels in Črna Jama and Pivka Jama caves. In all these cases, we deal with active water channels which are perpendicular to the folded beds (Čar and Gospodarič 1984).

The Predjama Fault (Fig. 1.5) is steep NW–SE trending fault which is one of the most significant regional faults and runs along the NE part of the Pivka basin, passes Postojna and proceeds to the SE (Placer 1981).

Wider Predjama Fault zone passes Postojna Cave where tectonic micro-displacements are continuously measured since 2004 by TM 71 extensometers (Šebela et al. 2010). In the period 2004–2018, we detected 0.07 mm of dextral horizontal and vertical movement (in the sense of normal fault) along Dinaric oriented (NW–SE) fault zone in Velika Gora collapse chamber. This shows that some tectonic zones in Postojna Cave belonging to wider Predjama Fault zone (Fig. 1.5) are still tectonically active (Šebela 2008; Sasowsky et al. 2003).

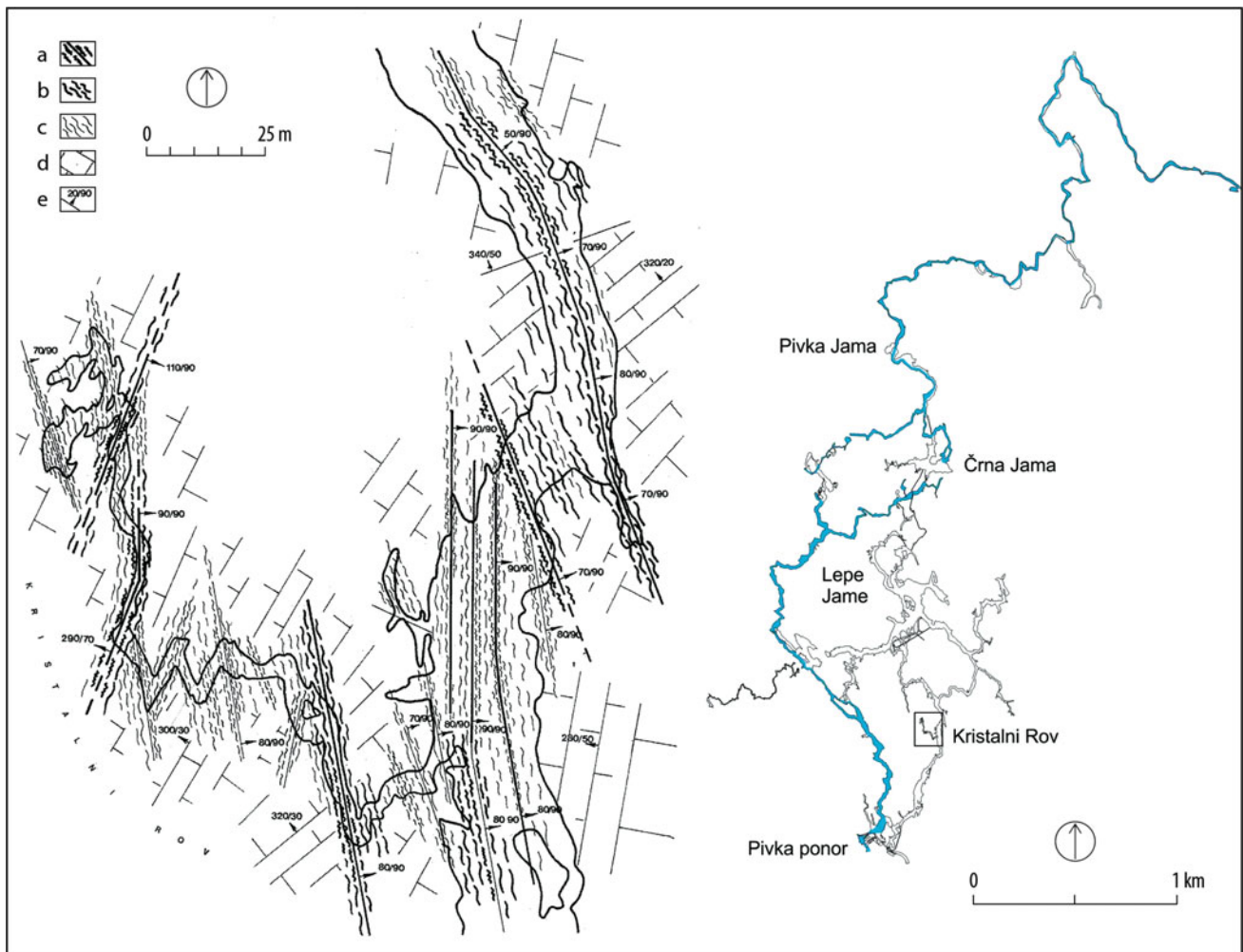


Fig. 1.4 Detailed structural–geological map of Kristalni Rov in Postojna Cave. Legend *a* crushed zone, *b* broken zone, *c* fissured zone, *d* Upper Cretaceous limestone, *e* dip direction and dip angle of bedding planes. Geology mapped and drawn by Šebela in 1994

1.1.3 Folding Deformations and Caves

It is obvious that many cave passages formed accordingly to regional structural geology. Detailed tectonic–lithological mapping in the scale 1:1,000 of the three big cave systems in SW Slovenia (Postojna Cave system, Predjama Cave and Škocjan Caves) showed connections between bedding planes and development of cave passages. Cave passages of the Postojna Cave are developed on both flanks of the Postojna anticline. Syncline axis is expressed north from Škocjan Caves passages, while in the area of Škocjan Caves we can only see dipping of the syncline axis as gentle folds. Relation between eastern passage of Predjama and Stara Jama caves shows the position of anticline axis (Fig. 1.6).

Formation of the Postojna anticline is post- or co-thrusting period of the Upper Cretaceous limestones over Eocene flysch. The same is probably the case in Predjama Cave. Additionally, in Predjama's western passage there is a

thrust fault where Upper Triassic dolomite is thrust over Upper Cretaceous limestones. Predjama's anticline deformation can be related to this even older deformations as well. In the Cave Stara Jama interbedded slips due to folding deformations are well visible and responsible deformation for passage development. Postojna anticline axis is Dinaric oriented (NW–SE), while anticline axis in Predjama is for 55° declined towards north (Fig. 1.6) regarding Postojna anticline.

Syncline axis in the area of Škocjan Caves has cross-Dinaric orientation (NE–SW) and can be related to near-faulting deformations (Divača Fault running in the vicinity), because contact between Eocene flysch and Upper Cretaceous and Paleocene limestone is further away as in Postojna and Predjama Caves.

In all three caves, some passages are characteristically formed along interbedded slips which developed due to folding. Bedding planes, especially those deformed by

Fig. 1.5 Geological map of the area above Postojna Cave. *Legend 1* surface Pivka River, *2* underground Pivka River, *3* anticline, *4* syncline, *5* thrust fault, *6a* fault dip direction and dip angle, *6b* supposed fault dip direction and dip angle, *7* overturned beds, *8* Eocene flysch rocks, *9* limestone breccia and conglomerate (Pc_2, E_1), *10* Upper Cretaceous limestone–Senonian (K_2^3) after division by Čar (2018), *11* Upper Cretaceous limestone–Turonian (K_2^2), *12* upper Cretaceous limestone–Cenomanian (K_2^1)

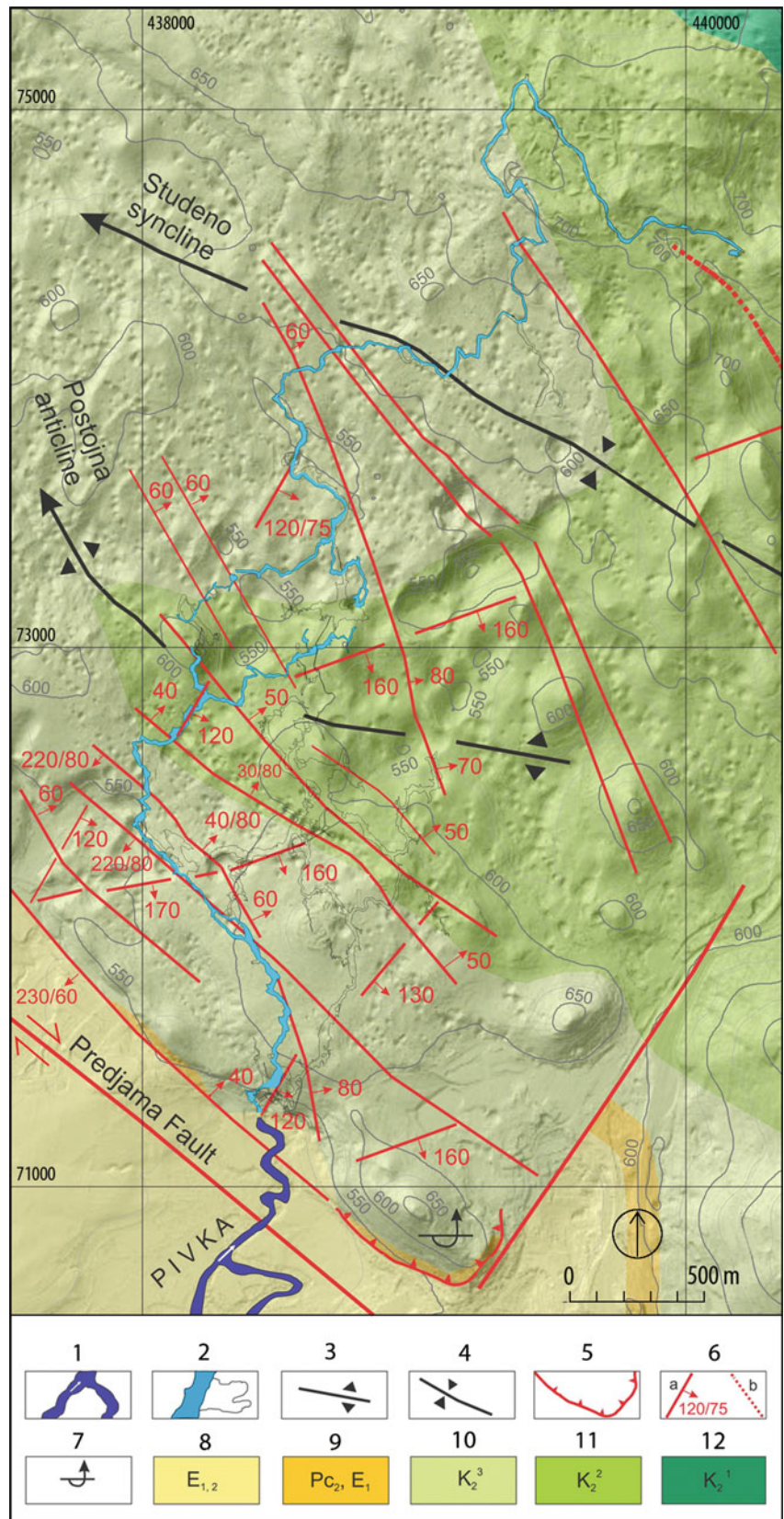
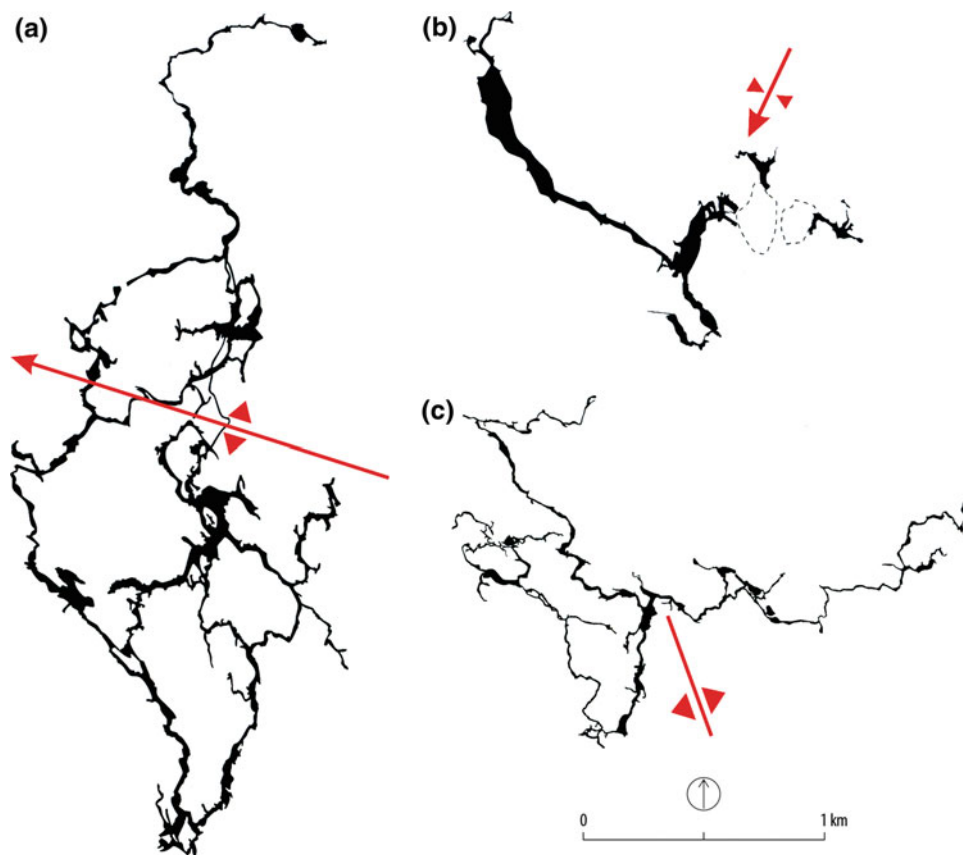


Fig. 1.6 Ground plans of **a** Postojna cave, **b** Škocjan caves and **c** Predjama cave with anticline (**a** and **c**) and syncline (**b**) axis



interbedded slips, are one of the most important structural elements inside or along which cave passages developed. Cave passages of studied caves are formed on both flanks of folds. Anticlines resulted due to compression in folding tectonic events and are primarily not related to younger faulting.

1.2 Conclusion

Fundamental knowledge about the karst forms cannot be separated from an understanding of the geological structure. Karst areas can be regarded as a dynamic, spatial, geological–hydrological and speleological–succession systems, which are under the constant influence of ongoing tectonic movements (Čar 2018).

Detailed field geological mapping of karst in Slovenia in the last 40 years showed strong connection between geological structure and formation of karst surface and underground features. Cave passages are developed according to geological structural elements such as joints, faults, folds, bedding planes and interbedded slips. In studied caves (Postojna Cave, Predjama and Škocjan Caves), tectonised bedding planes play an important role for cave passages formation. Principal regional folds are Dinaric oriented

(NW–SE) in Postojna and Predjama Caves. Due to folding interbedded slips or flexural slips developed what represented the weaknesses in carbonate massif used by waters to form underground paths–karst caves. Bedding planes especially those deformed by interbedded slips are one of the most important structural elements inside or along which cave passages developed. Cave passages of Postojna Cave and Predjama are formed on both flanks of anticlines.

Surface tectonic and karst features are well seen on LiDAR maps, but only this information cannot replace field hard-rock geological mapping. Development of digital tools (as photogrammetry) in karst geology is very applicable (Triantafyllou et al. 2019), but detailed field structural–geological mapping cannot be completely exchanged with some kind of automatic method yet. Basic knowledge of karst geology is still waiting for us in the field.

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