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GEOLOGICAL STRUCTURE OF THE DIVAČA AREA AND ITS INFLUENCE ON THE SPELEOGENESIS AND HYDROGEOLOGY OF KAČNA JAMA

GEOLOŠKA STRUKTURA NA OBMOČJU DIVAČE IN NJEN VPLIV NA SPELOGENEZO TER HIDROGEOLOGIJO KAČNE JAME

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Petra Žvab Rožič, Jože Čar & Boštjan Rožič: Geological Structure of the Divača Area and its Influence on the Speleogenesis and Hydrogeology of Kačna jama

Caves develop along sedimentary and tectonic discontinuities within soluble rock mass. In the Slovene Classical Kras (Karst), the primary lithologies are limestone and dolomite. Previous research of cave systems in SW Slovenia indicated a clear relationship between cave channel directions with local structural elements, which is also documented in the mapped area. Kačna jama is the longest cave of the Kras Plateau and represents an important part of the underground flow of the Reka River. For structural mapping, we applied a method adopted for the surface of karstic terrains. We documented three NW–SE oriented faults and additionally an equally oriented fracture zone. These structures are parallel to the regional Divača Fault, which was detected in the NW edge of the mapped area. Between them, the cross-oriented fracture zones run, and occasionally bend, towards N–S orientation. The described structure is explained using a complex, divergent-convergent, dextral strike-slip fault-wedge. Among the detected structures, we focus on the Risnik Fault along which the Risnik and Bukovnik collapse dolines are developed, whereas in the Kačnja jama the same fault is manifested by several rock-fall accumulations. During dry-weather conditions groundwater is drained through the fault in the terminal sump at the end of the Ozki rov channel. Whereas during floods, the same fault acts as a hydrogeological barrier, because the previously mentioned terminal sump is no longer capable of transmitting sufficient quantities of groundwater, which in such conditions flow along the fault through a well-developed system of channels in the NW direction. We propose that the Risnik Fault acts as a deflector fault.

Keywords: Kačna jama, Kras (Karst) Plateau, structural mapping, speleogenesis, deflector fault.

Izvleček UDK 551.435.84(497.471)

Petra Žvab Rožič, Jože Čar & Boštjan Rožič: Geološka Struktura na območju Divače in njen vpliv na spelogenezo ter hidrogeologijo Kačne jame

Jame se razvijajo vzdolž nezveznosti, sedimentarnega ali tektonskega izvora v zaporedju topnih kamnin. Na Klasičnem Krasu slednje predstavljata apnenec in dolomit. Predhodne raziskave kraških terenov jugozahodne Slovenije so pokazale jasno povezavo med smerjo jamskih kanalov in lokalnih strukturih elementov, kar se je pokazalo tudi na prikazanem območju kartiranja. Kačna jama je najdaljša jama Klasičnega Krasa in predstavlja pomemben del podzemnega toka reke Reke. S strukturnim kartiranjem površine nad jamo, ki je prilagojeno kraškim ozemljem, smo ugotovili potek treh SZ–JV prelomov in ene vmesne razpoklinske cone v enaki smeri. Te strukture so vzporedne regionalnemu Divaškemu prelomu, ki smo ga zaznali na skrajnem SV delu raziskanega območja. Med njimi potekajo prečno usmerjene razpoklinske cone, ki so deloma povite do smeri S–J. Opisano strukturo razlagamo s kompleksnim divergentno-konvergentnim desno-zmičnim prelomnim klinom. Posebej obravnavamo Risniški prelom, ob katerem sta razviti udornici Risnik in Bukovnik, ter nekaj večjih podorov v jami. V odtočni sifon na koncu Ozkega rova nizke vode odtekajo skozi Risniški prelom v smeri regionalnega gradienta. Medtem za visoke vode isti prelom predstavlja hidrogeološko zaporo, saj prej omenjeni odtočni sifon ne zmore več prevajati zadostnih količin podzemne vode in ta odteka vzdolž preloma po dobro razvitem sistemu kanalov v NW smeri. Menimo, da ima Risniški prelom vlogo zapornega preloma.

Ključne besede: Kačna jama, Kras, strukturno kartiranje, speleogeneza, zaporni prelom.

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INTRODUCTION

It is generally accepted that high radon exhalation is related to the underlying geology and often coincides with large-scale geological structures such as fault systems (Burton *et al.* 2004; Šebela *et al.* 2009; Vaupotič *et al.* 2010). In the last few decades, comprehensive studies of indoor radon were completed across Slovenia (Vaupotič 2010) and elevated radon values were detected in the Divača Railway station (Žvab *et al.* 2006). For establishing the relationship between elevated indoor radon levels and potential fault systems, a detailed structural map of the Divača area was made and it evidenced that the Divača Railway station is situated directly above the intersection of NW–SE (Dinaric direction) and NE–SW to N–S striking fracture zones. A specific microlocation was emphasised as a potential factor for locally elevated degassing of the geological interior (Žvab *et al.* 2006). After its elaboration, the structural map was placed over the floorplan of the Kačna jama (jama means cave in Slovenian), which consists of more than 15 km of investigated channels, is the third longest cave system in Slovenia, and spreads below the Divača town and its surroundings. A comparison showed a fairly clear overlapping of the geological structure with the cave system pattern, which encouraged further research and the existing structural map was expanded over the major area above the cave system. This paper presents the results of the structural mapping of the Divača karst area and discusses the relationship and influence of the structure on the speleogenesis and hydrological behaviour of the Kačna jama system.

GEOLOGICAL SETTING

Divača is located on the Kras Plateau, the region that gave the karst phenomenon its name. In the Divača area, the karst features are strongly expressed. The surface is characterised by numerous dolines and collapse dolines and shafts connect it to the cave systems several hundred meters below, which are part of the large hydrogeological system of the Reka River. The most famous of these cave systems are the Škocjanske jame, where the Reka River sinks and flows through a spectacular underground canyon. From the terminal sump in the Škocjanske jame, the flow continues along unexplored flooded galleries and reappears in the Kačna jama, which is the focus of this study. After leaving the Kačna jama, the Reka River flows through several smaller caves (Jama 1 v Kanjaducah, Brezno v Stršinkni dolini, Labodnica, and Jama Lazzaro Jerko) and finally reappears in the Timavo Springs near

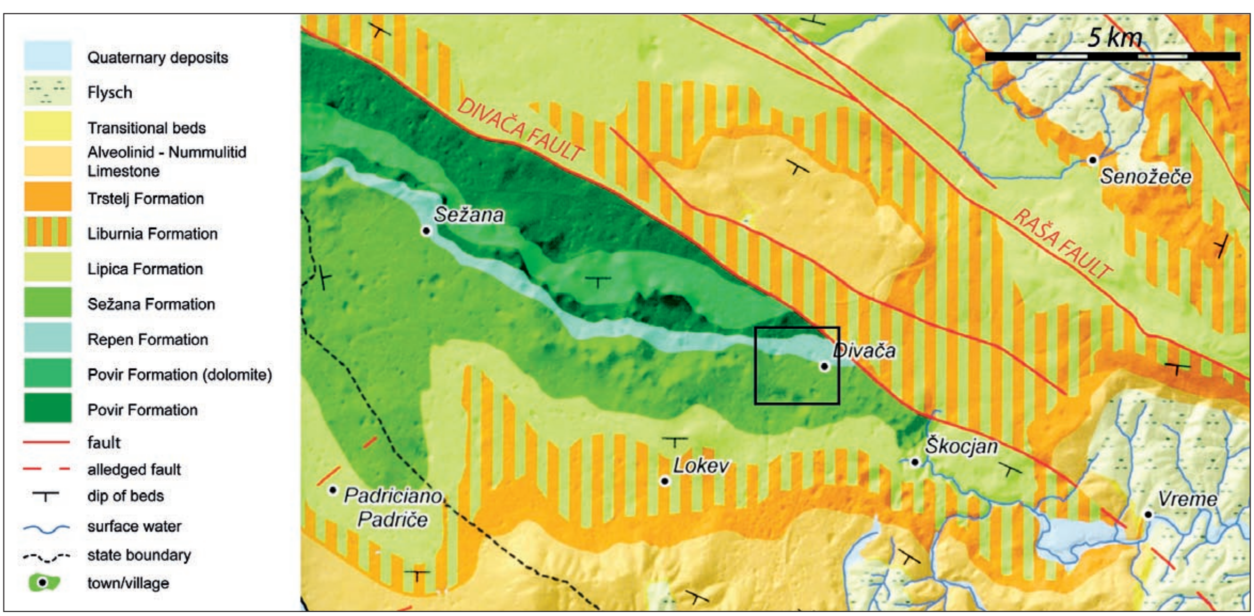

Fig. 1: Geological map of the SE part of the Kras (Cucchi 2015, based on Jurkovšek et al. *1996). The boxed area represents mapped territory.*

Trieste (Mihevc 2001; Gabrovšek & Peric 2006; Zini *et al.* 2015).

The Kras Plateau is characterised by a thick Cretaceous to Lower Paleogene succession of the Dinaric Carbonate Platform (Buser 1973; Jurkovšek *et al.* 1996, 2013; Jurkovšek 2010; Cucchi *et al.* 2015). In the Lower Cretaceous, limestone is often altered to dolomite, whereas the overlying succession becomes dominated by the limestone (Fig. 1). In the mapped area, the outcropping succession is oldest in the NW and becomes younger towards the S/SE. It begins with the upper part i.e. Superchondrodonta limestone of the Povir Formation, which is bedded limestone with local rudist shells present. The overlying Repen Formation is characterised by alternation of bedded pelagic limestone and Repen Limestone i.e. massive, partly recrystallised limestone with displaced rudist shells. In the southern part of the mapped area, the Sežana Formation outcrop is present. While it locally begins with oncoidal limestone, the major part is composed of bedded limestone with rare rudist biostromes. At the northwestern edge of the mapped area, the tectonically delineated latest Cretaceous to early Paleogene Liburnia Formation occurs (Jurkovšek *et al.* 1996).

The carbonate-dominated Kras Plateau is surrounded by Eocene flysch (Buser 1973; Jurkovšek *et al.* 2013). In the NE, the boundaries are stratigraphic and marked by drowning unconformity. Consequently, the carbonates of the Kras Plateau, together with the flysch of the major part of the Vipava Valley, belong to the same geotectonic entity known as the Komen thrust sheet, which northwardly passes into the flysch-dominated Vipava Syncline (Buser 1973; Placer 1981). In the southeast, the transition is marked by a complex Čičarija imbricated structure, where carbonates are overthrust on flysch in numerous small-scale thrust sheets, among which the Črni Kal thrust fault is considered as the most prominent (Placer 2007; Placer *et al.* 2010). Two regional NW-SE extending strike-slip faults are recognised on the plateau. In the northwest, the Raša Fault is traced along the Raša River valley, it outcrops spectacularly on the highway roadcut in the SE, and branches into several faults towards the NW. Through the central part of the plateau, including the mapped area, the Divača Fault is recognised (Jurkovšek *et al.* 1996, 2013; Poljak 2000). The Sežana and Lipica Formations, northwest of the Divača Fault, contain pelagic Komen and Tomaj limestone, whereas the southeastern block is absent of these intercalations, which promotes a neotectonic reactivation of the original Mesozoic fault (Jurkovšek *et al.* 1996, 2013).

METHODS

The geological structure of the Divača area was elaborated using the special mapping method adopted for the karstic realm. The methodology is based on the recognition of three degrees of tectonic fracturing in limestones; crushed, broken, and fissured/fractured zones (Čar 1982; Čar & Pišljar 1993) as well as the connection of differently sized and shaped dolines with individual fault zones (Čar 2001). Structural elements were drawn on topographic basemaps with a 1:5000 scale. The mapped area covers 2 km^2 including a major part of the surface above the Kačna jama cave system (Figs. 2 and 3). In the NW part of the Kačna jama, above the recently explored Rov za zrcalom, surface structural mapping was not possible due to anthropogenic alternation of the surface. The area is covered by the Gorenje Village that is towards the NW and is followed by meadows on which rock outcrops were cleaned and used for the construction of drywalls.

GEOLOGICAL STRUCTURE OF THE DIVAČA AREA

The structural map of the Divača area is presented in Fig. 2, while Fig. 3 shows the Kačna jama plan with the names of the channels discussed in this paper. The most prominent structure of the investigated area is the NW–SE oriented Divača Fault. It runs through the NE edge of the mapped area, which is covered and altered by a densely urbanised Divača town, therefore making lateral tracing of the geological structural elements virtually impossible. However, in the SE outskirts of the town, the outcrop of the broken zone of the Divača Fault was observed.

Parallel to the Divača Fault, three stronger faults cross the mapped area and the intensity of displacements

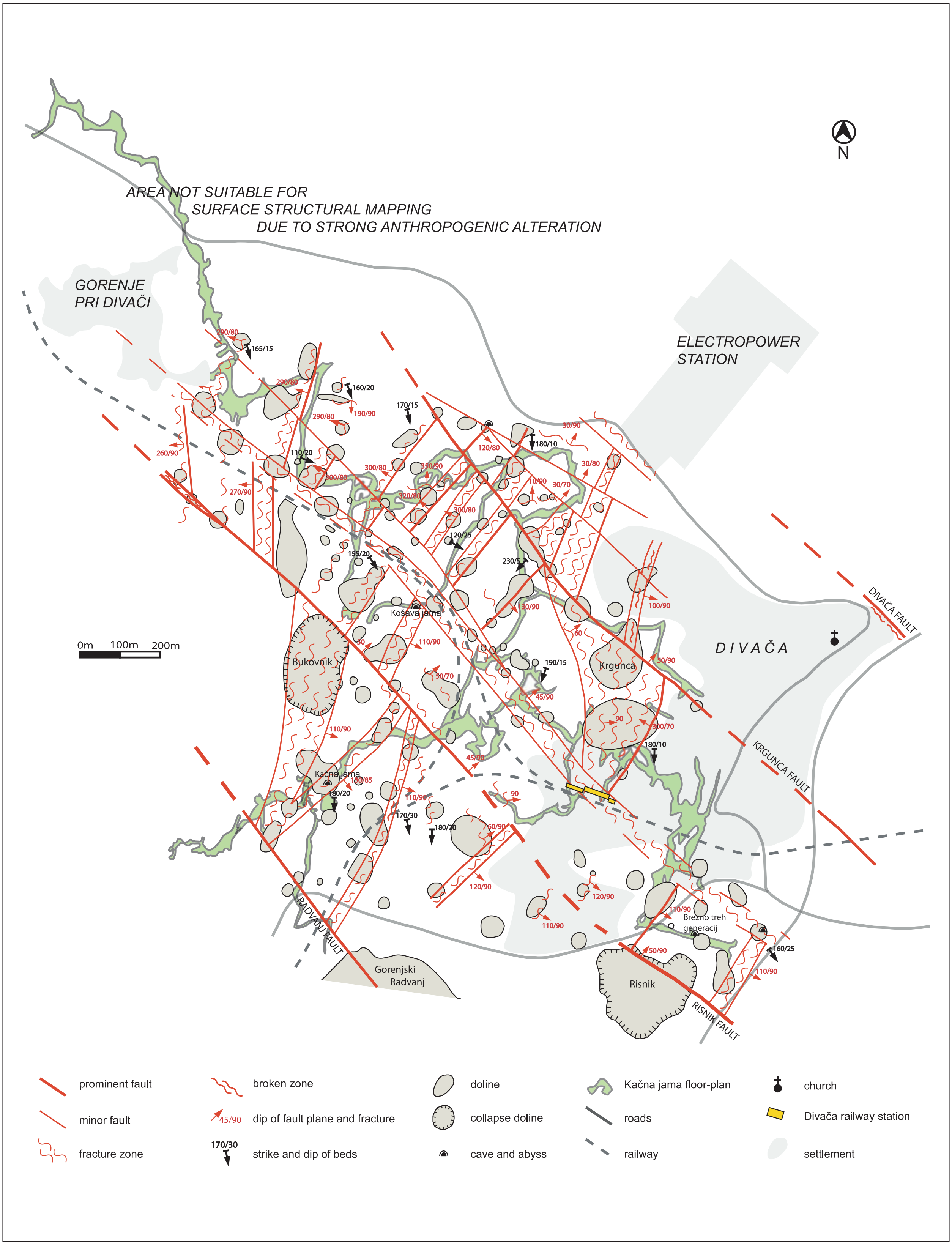

Fig. 2: Geological structure of the surface above the Kačna jama channel network. The structure is dominated by NW–SE Dinaric strike-slip faults and connecting NE–SW to N–S stiking fracture zones.

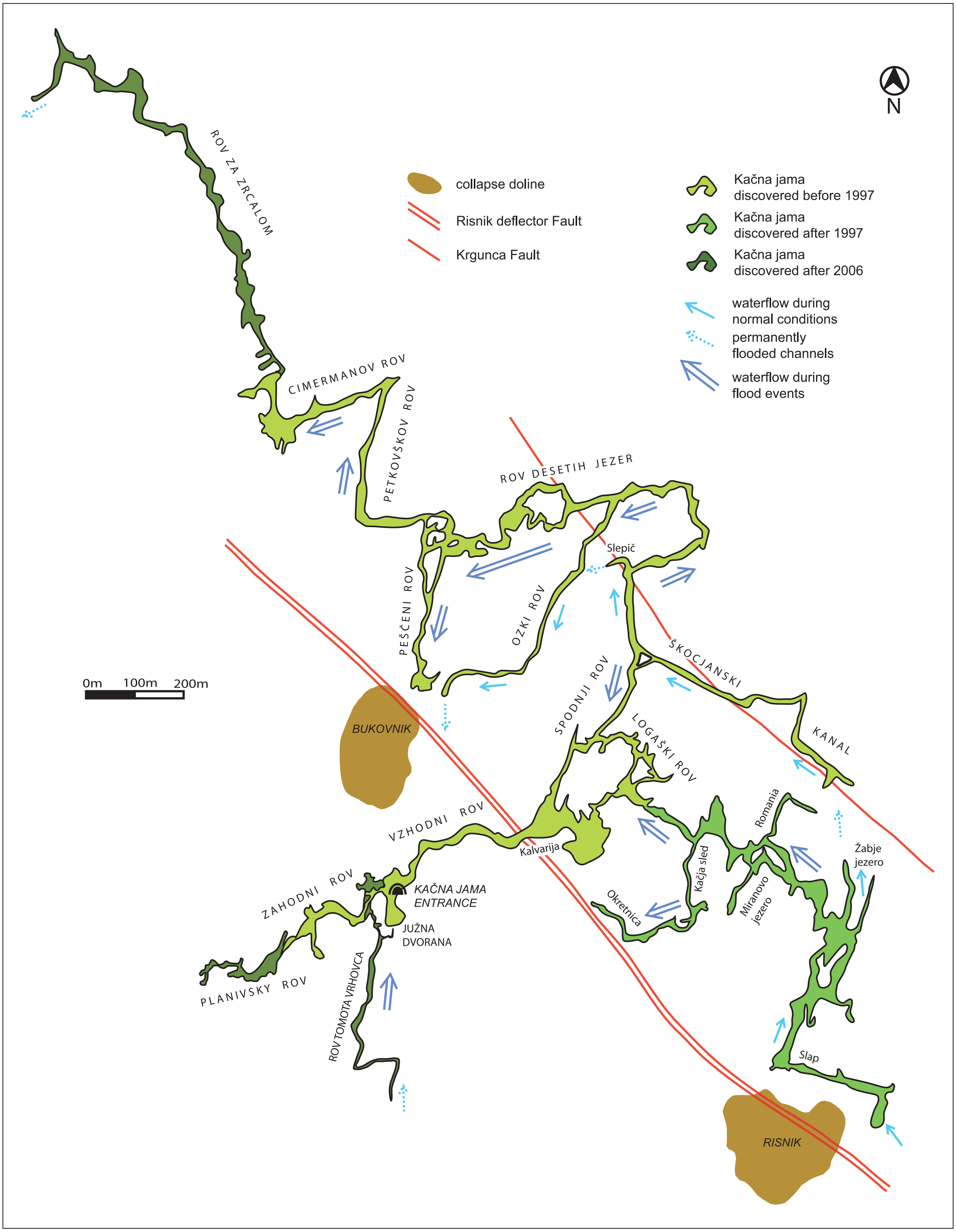

Fig. 3: Map of the Kačna jama with the main groundwater flow (Source: Slovenian cave cadaster, water flow is redrawn mainly from Mihevc, 2001) and the position of crucial surface detected structural and geomorphological elements which influence and/or indicate the hydrological characteristics of the Risnik Fault, Krgunca Fault, and collapse dolines.

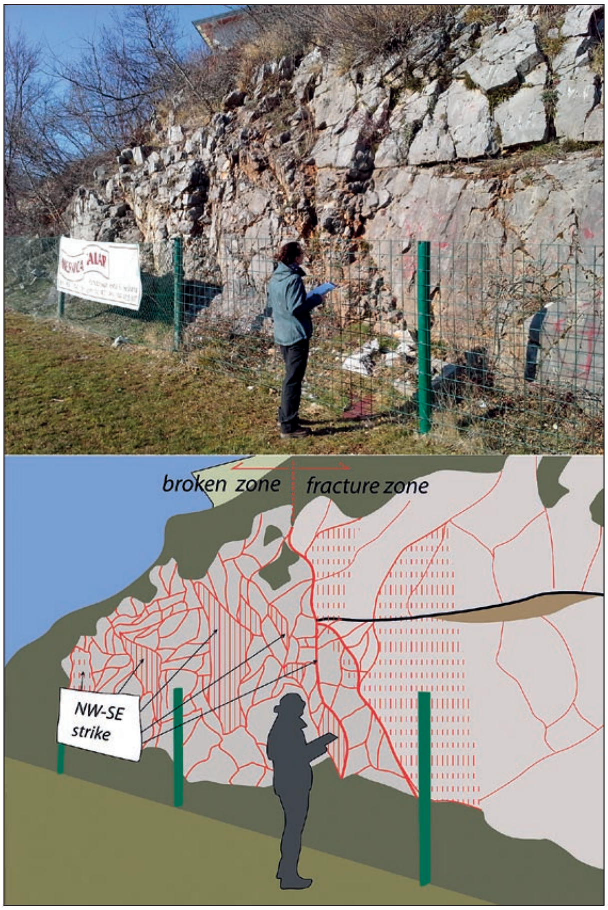

Fig. 4: Photography (above) and reconstruction (below) of the Krgunca Fault outcrop at the Divača football ground.

was assessed by the rate of deformation. The closest, the Krgunca Fault, is named after the largest doline that it runs through. Its inner fault zone is best exposed near the football ground at the Krgunca Doline (Fig. 4) and along the railway. The second Risnik Fault runs along the NE cliffs of two collapse dolines, the Bukovnik to the NW, and the Risnik (Fig. 5) to the SE of the map. The third fault was detected in the SW corner of the mapped area and is named after the extensive Radvanj Doline to which it enters at the edge of the map. Across the bottom of the Radvanj Doline, an Electrical Resistivity Imaging (ERI) profile was constructed and it indicated a vertical zone of very low-resistivity, which points to the existence of a fault zone (Stepišnik 2008).

Between the Krgunca and Risnik Faults, the parallel fault is reflected in the wide fracture zone that runs directly below the railway station and separates into two branches towards the NW. Similarly, between the Krgunca and Divača Faults, several fracture zones exist i.e. minor faults running subparallel to the main fault in the Dinaric direction. However, in this area outcrops become rare and tracing of these structural elements becomes more speculative.

Between the described faults, pronounced fracture zones and small faults appear with strikes generally perpendicular (approximately SW−NE) to the main fault direction. Structures in the SW−NE directions are predominant and they vary within 30 degrees and tend to bend towards the N−S direction. The dip of the fractures is subvertical, whereas in the NW part of the map, it can be steep towards the NW, but rarely in the opposite di-

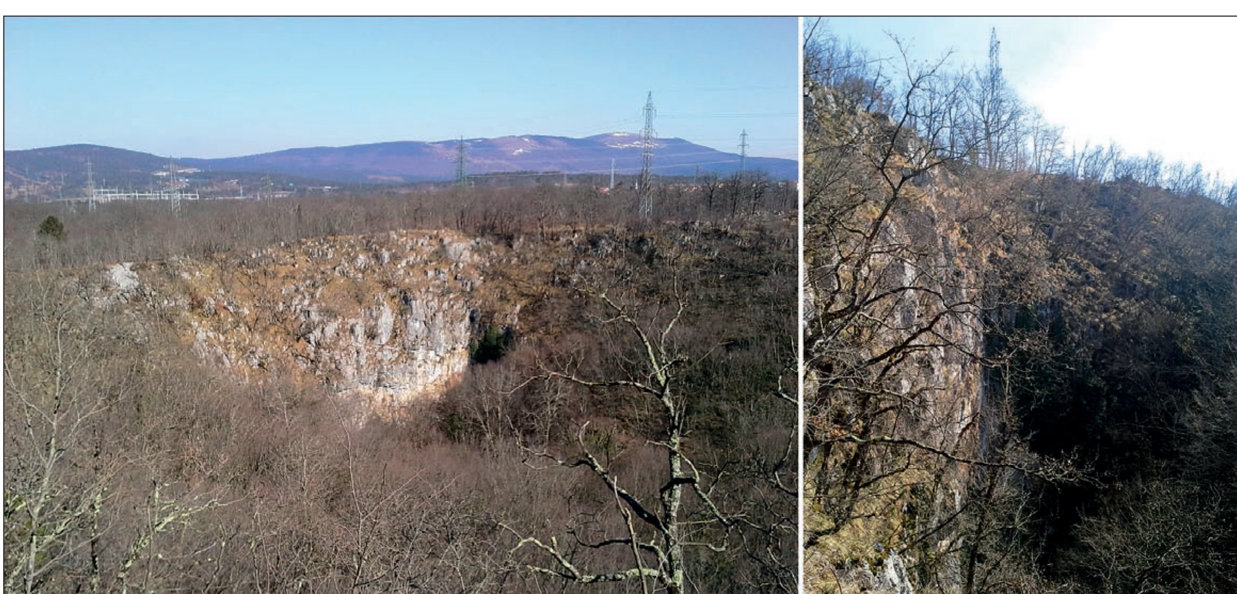

Fig. 5: Frontal (right) and lateral (left; towards the SE) view of the cliff originating along the Risnik Fault plane in the Bukovnik collapse doline.

rection. Particularly wide fracture zones were detected in the Krgunca Doline, where they terminate along the faults. A wide fracture zone reappears towards the NW on the other side of the Krgunca Fault. A wide fracture zone also runs across the Bukove Doline and joins in the SW with the fracture zone along which the abyssal entrance of the Kačna jama occurs. Fracture zones oriented generally in the E–W direction occur sporadically and terminate at previously described structures. All over the mapped area, beds dip at low angles towards the S, SSE, or SSW.

DISCUSSION

The discussion is divided into three sections. Firstly, we introduce a geostructural model of the wider area that explains the mapped structure. Secondly, we discuss the role of the structure on the development of the cave network. In the third section, we propose a hydrogeological model for the Kačna jama system.

GEOSTRUCTURAL MODEL OF DIVAČA AREA

The Kras Plateau is located in the External Dinarides, characterised by dextral strike-slip neotectonic activity with major faults in the NW–SE (Dinaric) direction (Placer 1999; Vrabec & Fodor 2006). In the mapped area, the regional Divača Fault is paralleled by several, previously undetected faults linked by fracture zones and smaller faults. Similar structural conditions and diverse kinematic models were determined for the comparable karst terrains of Postojnska gmajna (Čar & Šebela 1997) and Črnovška planota (Čar & Zagoda 2005). The same authors noted that the areas of tectonic tension are directly morphologically reflected as topographic depressions. Furthermore, in these areas, vertical entrances (shafts) into cave systems occur.

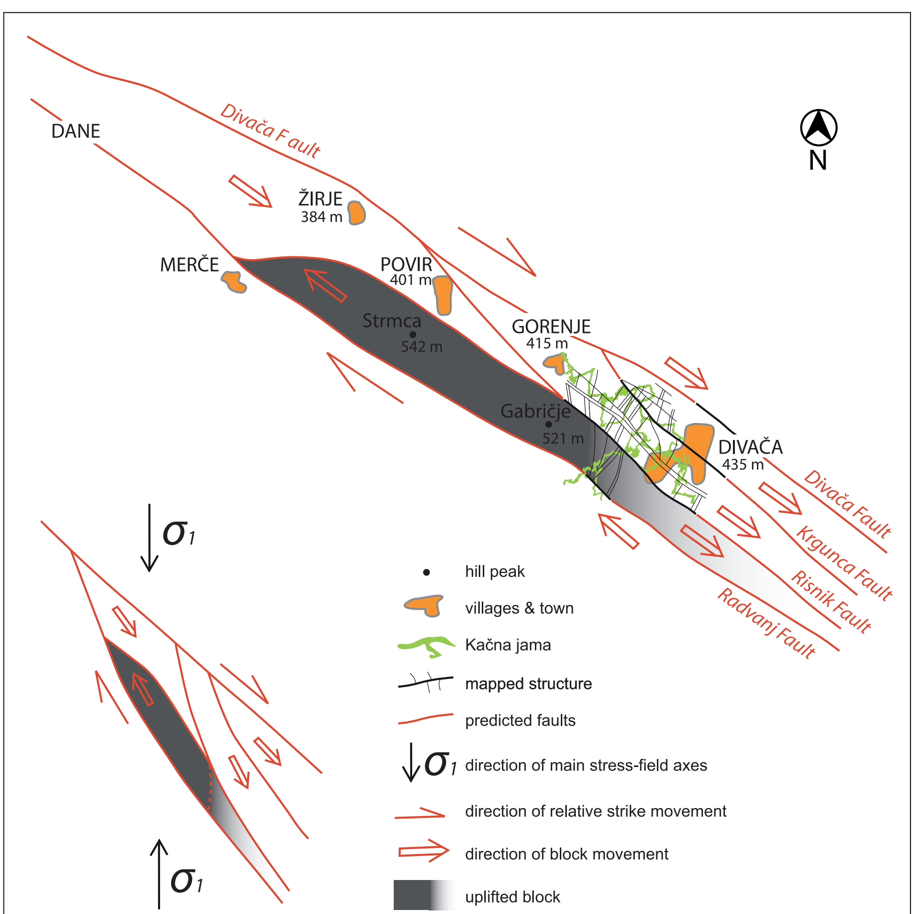

Fig. 6: Geological structure explained as a consequence of single tectonic deformation. The model predicts a wedge-shaped, divergent-convergent, dextral strike-slip fault zone.

A strike-slip duplex can be applied as a single model explaining the observed structure in the Kačna jama area (Fig. 6), whereas the position of faults and fracture zones mostly indicates the releasing bend (McClay & Bonora 2001). A similar transtension regime in the divergent fault system producing the pull-apart basins (cf. Christie-Blick & Biddle 1985) was proposed for the origin of the karst poljes (Vrabec 1994). However, the morphology of the Divača wider area shows a well-expressed double character and hence a more complex structure (Fig. 6). The area between Divača and the Risnik Fault lies at an altitude of between 342 and 475 m (near Dane), this altitude gradually decreases towards the NW. The wedge-shaped terrain between the hills of Strmec and Gabričje, west of the mapped terrain, is distinctly morphologically elevated up to 100 m. The highest part is at the NW, but the topography decreases towards the SW and finally reaches the mapped area between the Risnik and Radvanj Faults at similar heights as the rest of the mapped territory.

Taking into account that the maximum stress is in the N-S direction, the described tectonic and structural situation can be explained by the characteristic wedge-shaped divergent-convergent kinematic model. The tectonic block of the Strmec and Gabričje Hills is "dragged" by the rock mass SW of the Radvanj Fault and is typically wedge-shaped. On its NW edge, i.e. the area of the greatest pressure, it is widened. Towards the SW, the terrain within the wedge gradually loses altitude and may have already passed to the transtensional conditions in the mapped area. The latter is also indicated by the location of the entrance shaft of the Kačna jama, which tend to form in tensional conditions (Čar & Šebela 1997).

The terrain between Divača and the Risnik Fault is considerably lowered due to tension conditions and descends even further towards the NW. For confirming the proposed model, a map should be extended to a much greater area in the NW direction. Fracture zones in the E–W direction terminate at dominant structures and presumably originated during an older tectonic phase. A similar intersection relationship was recognised in the study of structural elements in the nearby Škocjanske jame (Šebela 2009).

INFLUENCE OF GEOLOGICAL STRUCTURE ON THE DEVELOPMENT OF KARST FEATURES

We generally distinguish between surface and underground karst features. The surface objects within the mapped area are numerous dolines that occur in the forested area W, SW and S of the Divača town, whereas the topography of the town is completely altered. It has been shown that it is possible to distinguish between series of typically shaped dolines that have formed in particular geological predispositions (Čar 2001). On the mapped area, the majority of dolines are located directly on the structural elements, which indicates their clear dependence from the structure. With the exception of wide fracture zones, structures in the mapped area exhibit linear character. Our field observations show that along fracture zones, dolines are often elongated and show variable slope inclinations which is in accordance with previous findings (Čar 2001). The described dependency can be recognised on the existing basemaps (the shapes of dolines in Fig. 2 are drawn on the topographical basemap with a scale of 1:5000), but the shape analysis of the dolines with the currently developing method for analysing altitude variably based on LIDAR data with a dense resolution (1x1 m) has great potential for supplementary fieldwork research. Its use in the remote sensing interpretation of geomorphological and geological data was already shown in the Vipava Valley, located north of the investigated area (Popit & Verbovšek 2013; Popit *et al.* 2014).

The main underground object beneath the mapped area is Kačna jama which consists of more than 15 km of so-far discovered channels and is the longest cave system of the entire Kras Plateau. Its entrance is located in the SW part of the mapped area and is represented by a spectacular, 186 m deep shaft that opens at 435 m above sea level. The cave has three levels (Fig. 7); the lower level

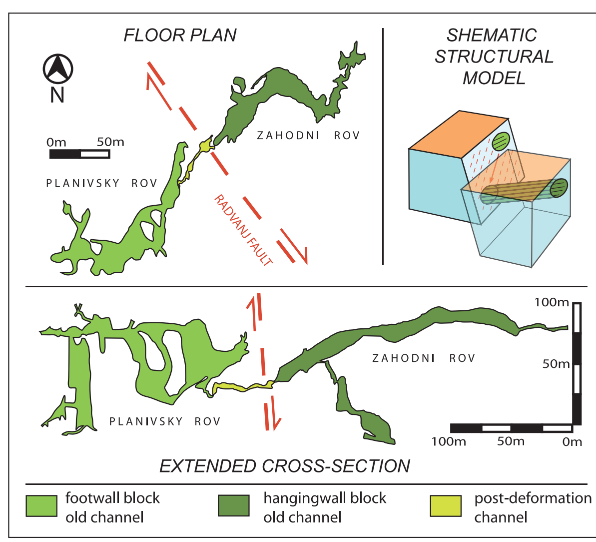

Fig. 7: Floor plan and extended cross-section of the Planivsky rov and Zahodni rov (modified from Kravanja, 2008) with proposed speleological and structural evolution of the Kačna jama SW part. The position and orientation of the Radvanj Fault is predicted from the surface structural map. In the upper right is the schematic structural model showing displacement of the old channel along the transtensional fault.

which is between 154 and 195 m above sea level and has active flow from the Reka River, the middle level is located at an altitude of 220-240 m, and the upper level is at an altitude above 250 m (Mihevc 2001). The first two levels extend NE of the Risnik Fault, while the highest level is present mainly SW of the same fault. Some other, mostly small, underground objects occur in the mapped area, among which is the recently discovered Brezno Treh Generacij which represents a second entrance to the Kačna jama (Kravanja 2008).

The development of such cave systems is a complex process, where the groundwater widens the initial network of penetrable discontinuities within the karst rock. The two types of basic discontinuities are tectonical joints and faults, and stratigraphical bedding planes (Kiraly 1975; Lowe 1992, 2000; Klimchouk & Ford 2000; Ford & Williams 2007; Filipponi 2009). Several case studies have been made in the Kras region in which the role of bedding planes on speleogenesis was outlined (Knez 1996, 1998; Verbovšek 2003). Numerous studies also indicate a clear connection between cave channel formation and structural setting (Gospodarič 1970; Čar 1982; Čar & Gospodarič 1984; Čar & Šebela 1997; Šebela 1998, 2009; Šebela & Čar 1991; Šušteršič 2006; Šušteršič *et al.* 2001; Verbovšek 2007). For the development of channels in folded and fractured rocks, "moved bedding planes" (interbedded slips) and connective fissures between bedding planes are also important (Čar & Šebela 1998, Knez 1998). So far no study on the relationship between the structure and development of Kačna jama has been presented.

The degree of fracturing of individual tectonic zones on the surface cannot be directly compared with the orientation and shape of Kačna jama channels 200 to 300 m below the surface, as it is necessary to consider the variation of fracturing in each fault zone in the horizontal and vertical directions, even at very short distances. Such lateral changes have been previously documented and explained with variable (paleo-)stress fields (Čar 1986; Čar & Šebela 1997). In addition, the spatial shifting of individual structures downwards the rock-mass is also caused by various dips of tectonic zones. Our structural map (Fig. 2) indicates that the complex pattern of the Kačna jama generally mimics the structure mapped on the surface, however, direct overlapping is not expected due to the previously described factors. Three main directions of the channels predominate, where the first two were clearly dictated by the orientation of structural elements (Fig. 3).

NW-SE oriented channels correspond to Dinaric faults and the three best representatives are outlined. First is the Škocjanski Kanal which runs along the Krgunca Fault. Second is the channel that starts at the Logaški rov and runs SE along the fracture zone detected below the railway station. Third is Rov za zrcalom, which represents the recently discovered NW continuation of the Kačna jama and occurs outside the mapped area. At the Risnik Fault, no longer channels are developed, this is discussed in the next section.

A second group of channels is N–S to NE–SW oriented and corresponds to fracture zones which connect the main Dinaric faults. Typical representatives in the long known portion of the cave (Fig. 3) are listed from W to E as follows: Petkovškov rov, Peščeni rov, a large portion of Ozki rov, Spodnji rov, Vzhodni, Zahodni rov, and some channels in the Logaški rov. In more recently discovered parts of the cave, east of the Logaški rov, the channels are Kačja sled, Romania, Miranovo jezero, and channels between Slap and Žabje jezero. In a study of Kačna jama spelogenesis (Mihevc 2001), two distinct channel shapes were distinguished, these can be directly connected with the mapped structure on the surface. The NW-SE (Dinaric) oriented channels, which originated along or within fault zones, are typically larger and rectangle shaped in the cross-section. Conversely, channels developed along the NE–SW to N-S oriented fracture zones are lens-shaped i.e. narrow and high with smoother walls (Mihevc, 2001).

A third group of channels are E–W to ENE–WSE oriented with typical representatives being Cimermanov rov, Rov Desetih jezer, and part of Ozki rov. The relationship between these channels and the structure is not univocal. They could originate along the old E–W oriented fracture zones, which were detected on the surface, or more likely they follow the strike of bedding planes.

Collapse dolines are herein also regarded as underground objects as they originate with the destruction of cave ceilings, where intersection of tectonic fractures and erosive/corrosive groundwater flow are considered as the main influential factors (Šušteršič 1998, 2000; Mihevc, 2009; Gabrovšek & Stepišnik 2011; Hiller *et al.* 2014). In the mapped area, two typical collapse dolines occur, the first being the Risnik Doline and the second being the Bukovnik Doline. They are located at the Risnik Fault, especially on its SW side. According to the herein presented tectonic model (Fig. 6), they are located in a less-subsided block. We can speculate that in this block, potential cave channels (similar to Vzhodni rov) are located closer to the surface, which contributes to the formation of collapse dolines. The Kurgunce Doline is probably also an old collapse doline and is as such considered as "inherited" object (Čar in prep.).

From the existing data, we were not able to link potentially old, pre-displacement channels across the Risnik fault. However, interesting data came from Planivsky rov that was recently discovered SW of the Zahodni rov and structurally lies across the Radvanj Fault. Kravanja (2008) stated that "By laic estimate, the (newly discovered main) channel could represent the continuation of tectonically displaced Zahodni rov". In the floor-plan, a dextral displacement is evident, whereas the side-plan shows the downward move of the NE-lying Zahodni rov (Fig. 7), which is in accordance with the dextral transtension recognised in the entire mapped area. The large channels are therefore old features, whereas the channel that links them is younger and smaller. Its relative narrowness could have been also enhanced by rock deformation introduced by faulting.

INFLUENCE OF GEOLOGICAL STRUCTURE ON THE HYDROGEOLOGY OF THE KAČNA JAMA SYSTEM

In this section, we present a hypothetical hydrogeological model of the Kačna jama based on: (A) the geological structure of the Divača area that was elaborated from detailed surface mapping represented in this paper, (B) previous studies which recognise the influence of the structure on the hydrology of the Postonjska jama, Karlovice, and Logaršček cave systems (Šušteršič *et al.* 2001; Šušteršič 2006), and (C) hydrological behaviour and spelological features of the Kačna jama that were described in great detail by Mihevc (2001) and subsequent hydrological, speleological, and geomorphological data (Gabrovšek and Peric 2006; Kravanja 2008; Mihevc 2009).

During low flow, the Reka River enters the Kačna jama at the south-easternmost part (Fig. 3), flows towards the Žabje jezero, where it disappears into a sump. Afterwards, it flows for approximately 200 m through permanently flooded channels and enters the Škocjanski kanal, then flows further to the Slepič, where it goes into a second sump. After a short distance, it reappears in the Ozki rov, flows through it and finally leaves the Kačna jama at the end of the Ozki rov. The elevation of the terminal sump is 154 m above sea level, which is the lowest point of the cave (Mihevc 2001).

During floods, the level of the underground river raises drastically and the cave hydrogeology completely alters (Figs. 3 and 8). Gabrovšek and Peric (2006) state that the prominent rise of the water level in the Kačna jama happens even at medium flood events, where the critical inflow is 15 m^3/s. They attribute this to the constrictions downstream from their P2 measuring point, which was located in Škocjanski kanal. Herein, we propose that this constriction is the high flow resistance of the terminal sump. Mihevc (2001) reported that during floods, the NW–SE (Dinaric) channels transmit major water quantities towards the NW parts of the cave. In cave sections where the NW–SE channels are not present, floodwater meanders through existing channel networks, but the general direction of the flow towards the NW remains the same. Simultaneously, water flow through NE–SW to N–S fracture-zone oriented channels stays weak. We suggest that during floods, the Reka River remains temporarily trapped in the tectonic block, which is limited to the SW with the Risnik Fault and to the NE, partly with the Kurgunca Fault, and finally with the Divača Fault.

The described groundwater behaviour combined with the mapped structure provides an important analogy with the hydrogeological model proposed by Šušteršič *et al.* (2001). These authors evidenced that in karst areas with prominent surface water inflow, namely at the margins of karst poljes (Pivka Basin, Cerkniško polje, and Planinsko polje), specific hydrogeological conditions develop. Sinkholes are usually numerous and contribute water through small-scale channels into a main large channel, which runs parallel to the polje margins. Such a cave system was first noticed by Gams (1965) and the main channel was named a collector channel. Šušteršič *et al.* (2001) pointed out that these large-scale channels further distribute collected water along regional faults, which with strongly deformed inner fault zones form a partial barrier to groundwater. Consequently, the development of collector channels is directly influenced by such faults, which were termed deflector faults (Šušteršič *et al.* 2001, Šušteršič 2006). The hydrogeological role of deflector faults arises from the finding that in the inner fault zone, the degree of tectonic fracturing alternates in the horizontal direction as well as the vertical direction (Čar 1986, 2001). Where the crushed zones are developed, the faults practically act as barriers and large-scale (collector) channels distribute groundwater along them. Whereas laterally, in areas of dominant broken zones, faults become more transmissive, which enables groundwater to penetrate across these faults. Therefore, deflector faults should not be considered as complete hydrological barriers, but they solely hinder streaming through them and redirect water in the main channels along the faults in the direction of "less-problematic" flow towards the subsequent transmissive areas (Čar in prep.). For this reason, deflector faults locally deviate groundwater flow from a regional gradient. Šušteršič *et al.* (2001) also showed that on the surface, collapse dolines tend to form along deflector faults, whereas in caves, rock-fall accumulations determine the points where main channels pass through the faults. From the Karlovice system at the margin of Cerkniško polje, the same authors report that smaller channels, which branch from the main (collector) channel towards the deflector fault prior to main penetration point, terminate by frontal collapses.

Direct correlation between the hydrogeological model from the polje margins of Šušteršič *et al.* (2001)

with the Kačna jama system is not possible due to the absence of a typical collector channel (sensu Gams 1965) that gathers water from numerous sinkholes along the polje margins. However, the Kačna jama system shares other important characteristics with aforementioned hydrogeological model, such as prominent inflow of allogenic waters and their redirection from the regional gradient. The Kačna jama regional gradient is towards the W, whereas the main groundwater flow is towards the NW, which is parallel to faults documented by our geological mapping. The latter is especially evident during flood events, but can be recognised also during low flow. We believe that the hydrogeological role of the deflector fault can be adopted also for the Kačna jama system.

Considering the described characteristics of deflector faults, in the Kačna jama, we suggest the Risnik Fault is a main deflector (Fig. 8). On the surface, its deflector nature is directly indicated by the Bukovnik and Risnik collapse dolines. Inside the Kačna jama, the prominent crushed zone of the Risnik Fault is manifested in the presence of large rock-fall accumulations, which appear at Kalvarija, where the Risnik Fault crosses the Vzhodni rov (upper cave level), and at the end of the Spodnji rov (lower cave level), located directly below the Kalvarija (Mihevc 2001). The second location is at the terminations of the Ozki rov and Peščeni rov channels. This location is situated NW of the previous two locations (along the fault) and at the same time NE of the Bukovnik collapse doline (across the fault). Near the Risnik collapse doline, no rock-fall deposits are reported from the Kačna jama (Mihevc 2001), presumably due to the larger distance between the accessible channels and the fault.

As mentioned above, the terminal sump of the Reka River is located at the end of the Ozki rov channel. The described features illustrate this location as one of the prominent transmissive zones where the groundwater breaks through the Risnik Fault. This particular area is therefore marked by a coinciding groundwater stream and intensively fractured rock, which enhances the formation of the Bukovnik collapse doline (sensu Šušteršič 1998, 2000; Gabrovšek & Stepišnik 2011; Hiller *et al.* 2014). Simultaneously, continuous collapsing of highly unstable broken fault zone inhibits the creation of a large underground channel and reduces the conductive effectiveness of the transmissive zone. We propose that an additional obstacle to the water is represented by fissured rock from the lifted Strmec and Gabričje tectonic block on the other side of the Risnik Fault, which is related to the compressive conditions within this block (Fig. 6). Consequently, in low flow conditions, the terminal sump is able to transmiss sufficient quantities of groundwater, whereas the Kačna jama hydrological behaviour changes during floods events.

During floods, the Ozki rov terminal sump can no longer effectively conduct excessive water through the Risnik Fault. For this reason, the main Kačna jama network between the Risnik and Krgunca (and/or Divača) faults activates and turns into a large channel that distributes the water NW along the Risnik fault, which is in accordance with the second role of collector channels i.e. distribution of groundwater along the deflector faults (Šušteršič *et al.* 2001). Based on the behaviour of floodwater flow (Mihevc 2001), we can speculate that in flood conditions, higher (abandoned or minor) transmissive zones within the Kačna jama reactivate. Their potential locations are at the terminations of the Peščeni rov, Spodnji rov, and along the Okretnica. As the main flow during floods is towards the NW, additional, not accessible transmissive zones in the NW portion of the cave are possible.

The main channel network, which distributes floodwater towards the NW, could represent an old Reka River pathway that developed between the major faults in different hydrological conditions. If this prediction is correct, channels that distribute water towards (and across) the Risnik Fault from this old channel network are younger and developed after lowering of the regional water gradient in the SE direction, which can be attributed to the neotectonic activity along the Čičarija imbricated structure (Placer 2007; Placer *et al.* 2010). Such cave evolution is indicated also by dating of speleothems in the Kačna jama (Mihevc 2001).

The role of the Risnik Fault as an important hydrogeological element within Kačna jama is indicated also by the somewhat independent hydrological conditions in the channels located SW of the fault including the Vzhodni rov, Zahodni rov (until the Kalvarija), Južna dvorana, and the recently discovered Planivsky rov and Rov Tomota Vrhovca. In the lowest parts, such as Južna Dvorana (see Mihevc 2001) and Rov Tomota Vrhovca, the groundwater enters, flows generally towards the north and disappears again (Figs. 3 and 7). During floods, the near-entrance part of the cave fills mainly with water from Južna dvorana (Mihevc 2001). Whereas during extreme floods, water percolates through the rock-fall at Kalvarija from the highly flooded central part of Kačna jama (NE side of the Risnik Fault) towards the less flooded part of the cave entrance (SW side of the Risnik Fault). In extreme flood events, the previously mentioned transmissive zones of the Kačna jama are therefore joined also by the Vzhodni rov, which at the same time represents the highest level of the cave.

Whereas the Risnik Fault acts as a deflector due to its strong tectonic rock-fracturing, other NW-SE (Dinaric) structures have no such character and serve mostly as fractures and faults along which spacious dis-

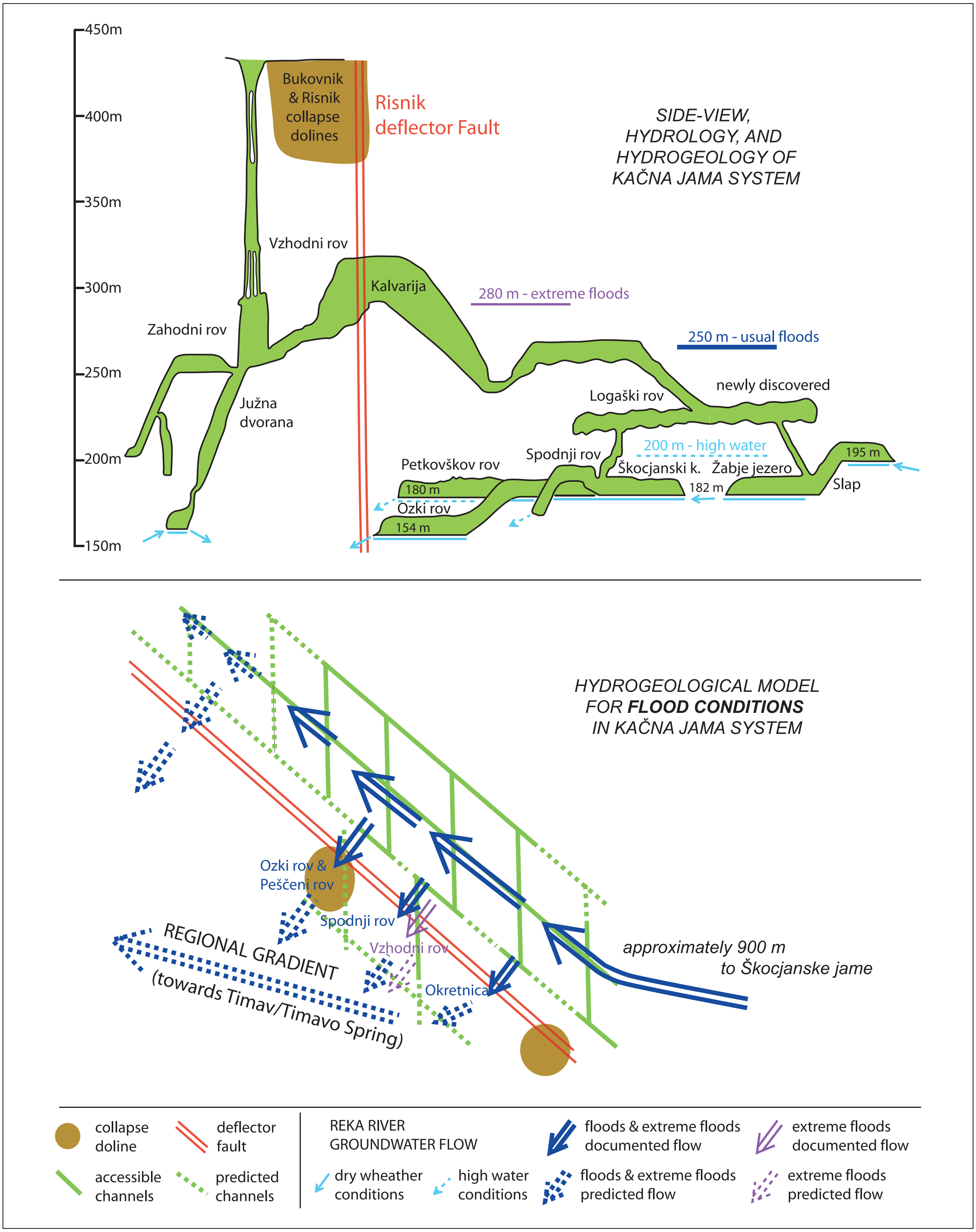

Fig. 8: Vertical distribution of the channels within the Kačna jama with the main hydrological characteristics of the cave (modified from Mihevc 2001) indicating the deflector role of the Risnik Fault (above). Hydrogeological model for flood conditions elaborated on the basis of our structural map combined with the floodwater behaviour within the cave (Fig. 3), which is dominated by NW-directed water flow (below).

tributary channels developed within the well-developed channel network of the central cave system (see above). Rather weak deformation in the Kačna jama can be attributed also to the Kurgunca Fault, although it is well expressed on the surface. Its partial deflector role can be (together with the NW-SE fracture zone passing under the railway station) assessed in the NW part of the mapped area where cave channels became caught between the two structures. Such a change in hydrogeological characteristics is attributed to the previously mentioned lateral variations within fault zones (Čar 1986; Čar & Šebela 1997). However, the main deflector role of the NE within the whole system is certainly attributed to the Divača Fault.

The hydrogeological role of the Radvanj Fault cannot be assessed solely from the existing map. Although attempts have already been made (Rijavec 2008), this problem requires further detailed structural mapping in the area between the Kačna jama and the structurally well-studied Škocjanske jame (Gospodarič 1983; Šebela 2009) with the goal of understanding the hydrogeological characteristics of the complex Divača karst.

CONCLUSIONS

On the basis of surface structural mapping above the Kačna jama combined with speleological and hydrological data from the Kačna jama (mainly from Mihevc 2001), we conclude that:

- The structure of the Divača Area is characterised by NW-SE oriented (Dinaric) faults that are parallel to the regional Divača Fault. Three of them exhibit prominent deformation on the surface and were named the Radvanj, Risnik, and Krgunca faults after the largest dolines that they cross. These faults are connected to NE-SW to N-S oriented fracture zones. The structure is characteristic for wedge-shaped, dextral, predominantly transtensional strike-slip tectonic setting.

- The complex channel pattern of the Kačna jama network mimics and locally overlaps structures observed on the surface and reveals the crucial role of the structure on the spelogenesis of the Kačna jama. The shape of the channels is related to specific types of structures. Fault zones produce wider, rectangle shaped channels, whereas along fracture zones, narrow, vertically elongated channels originate.

- The hydrological behaviour of the Kačna jama, combined with the locations of rock-fall accumulation in the cave and the microlocations of collapse dolines on the surface, shows that the Risnik Fault is the main groundwater deflector.

- The terminal sump at the end of the Ozki rov is the active transmissive zone of the Risnik deflector fault within Kačna jama. In high flow conditions, the terminal sump can no longer support sufficient quantities of water and the Kačna jama becomes flooded. During floods, other transmissive zones within the accessible cave presumably activate. As a result of floodwaters being distributed in the main channel network towards NW (along the Risnik deflector fault), the existence of subsequent transmissive zones in this direction is possible.

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