



Geostructural mapping of karstified limestones

Strukturno-geološko kartiranje zakraselih apnencev

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Abstract

The goal of the present paper is presentation of the structural mapping of the karstified limestones, and the relations between the surface and the underground karstification. When mapping on the large scale the frequency of the dip and strike must be increased. Possible interbeds of alien rock must be registered. Measurements of the dip make it possible to ascertain possible plicative deformations. Intercalations of non-carbonate rocks influence the underground water flow and affect the formation, shaping and location of the karst voids as well as the surface karst features. For the understanding of the karstification processes exhaustive collection of structural data, and recognition of broken, crushed and fractured zones within and parallel to fault zones, plus thrust–shear–zones are essential. As spatial organization and dimensions of the underground karst voids, as the surface karst shaping are guided by thrust parallel and fault induced deflection structures. All structural elements, which include tectonic elements as well as bedding planes, lithological changes, lithological partings, less permeable or impermeable interbeds, plus structural elements contribute to the structural framework. It directs both vertical percolation and horizontal streaming within the limestone and influence the frequency, size, spatial distribution, and shape of interconnected karst voids. The later form the speleogenetic network. Due to the permanent denudation the intersection of the Earth surface and the structural framework and speleogenetic network permanently moves downwards. New structural elements emerge while speleological structures change to less recognizable succession objects. The surface of the karst may be characterized as a dynamic, spatial, hydrogeological and speleological succession system permanently affected by the current tectonic activity.

Izvleček

Pri strukturnem kartiranju zakraselih apnencev moramo povečati pogostnost merjenja vpadov in slemenitve plasti in izrisati vse vključke drugih kamnin v apnencih. Meritve plasti nam omogočajo ugotoviti plikativne deformacije, vključki kamnin usmerjajo pretakanje vode in vplivajo na nastanek, oblikovanje in potek podzemskih prostorov in na oblikovanje kraškega površja. Pri kartiranju obnarivno in obtektosko pretrtih apnencev, je za razumevanje procesov zakrasevanja, potrebno ločiti zdrobljene porušene in razpoklinske cone. Velik vpliv na razpored in velikost podzemskih prostorov in površinsko oblikovanje kras imajo tudi litološke, obnarivne in prelomne hidrološke zadrževalno-zaporne strukture. Vsi strukturni elementi, med katere poleg tektonskih elementov štejemo tudi lezike, litološke spremembe, vložki drugih kamnin in zadrževalno-zaporne strukture gradijo strukturno rešetko. Ti vplivajo na nastanek speleogenetske mreže, ki zajema vse podzemskie prostore. Zaradi denudacije se presek kraškega površja pomika navzdol po strukturni in speleogenetski mreži. Odpirajo se novi strukturni elementi, speleološki elementi pa postopno izginjajo in na površini ostajajo le bolj ali manj spoznavni nasledstveni objekti. Kraški teren lahko opredelimo kot dinamičen prostorsko hidrogeološki in speleološki-nasledstveni sistem, ki je pod stalnim vplivom aktualnih tektonskih premikanj.

Introduction

Physical karstology research has primarily been focussed upon "... *speleogenesis, hydrogeology, sedimentology, geochemistry, mineralogy, cave biology and unusual landforms. Only a smaller number of papers focus on karst surface landforms and among these only a few attempt organic and comprehensive studies of the entire assemblage of relief forms in a karst morpho-unit. In reality, it is evident that the surface landform complex in a karst morpho-unit has to be considered in its entirety and that only such an integrated approach to this complex entity may bring significant progress in understanding.*" (Sauro, 2013, 5). There is no doubt that fundamental knowledge about the surface forms stems from an understanding of the geological background.

Geological investigation generally focusses upon the study of large limestone-covered areas, in lithostratigraphical as well as structural contexts. Nevertheless, on the local level, studies of limestone terrains that contribute significantly to the understanding of the organization of the karst surface are relatively scarce (Čar, 2015).

The following text presents a general discussion about the results of detailed *lithological, structural, and geomorphological* mapping, supported by examples of recent outcomes. The results of the mapping make it easier to understand the determination of the relationships between the structure and various structural-lithological settings of karst surface phenomena, the interpretation of the areal location and distribution of surface karst phenomena, and interpretation of their sizes and shapes, as well as their inter-relationships (Čar, 1986, 2001). Further considerations lead to deeper understanding of the dynamics of karst surface development, the links with the subsurface, and relationships to remnants of former speleological objects that are now exposed at the surface.

Karst is a complex geological, hydrological, speleological, and geomorphic system. Consequently, mapping of karstified terrains is a challenging task. In order to ensure a reliable interpretation of the actual karst surface shaping a detailed knowledge of the local geological situation (lithology and structure, not forgetting details of the regional tectonic development) is vital. Knowledge of the local speleological situation is necessary to help explain any denudational artefacts comprising the remains of previous cave objects that are important elements of the present karst surface (Čar, 2015).

Development of a methodology for mapping karstified limestones, and the most relevant outcomes

These procedures for detailed structural mapping originate from the author's long-term experience gained in the Idrija (Slovenia) mercury mine, where all of the mine workings were mapped at scales of 1: 500 or 1: 1000. Added to this experience was the insight provided by a longstanding interest in the karst. There was an inevitable curiosity to investigate whether the techniques applied in the mine could be applied to the mapping of karstified limestones. Hence, step by step, a methodology for structural mapping of karstified limestone was developed, as synthesized the present paper.

The approach described for the structural mapping of karstified limestone evolved predominantly in the karst close to Idrija and the Karst of Notranjska (basin of the Ljubljanica river), in western and central Slovenia. Most of the information provided in the present text stems from these terrains; nevertheless an identical approach has also tested and implemented successfully in several other areas of Slovenia.

To the author's knowledge there is no description of a comparably detailed approach to the structural mapping of karstified limestones that is documented within the karstological literature.

The genetic relationships between karst phenomena and the thrust-front in the Idrija region were first recognized in 1974 (Čar, 1974). Specific geological and hydrogeological conditions appear along the thrust margin, thus inducing the formation of vertical shafts beneath the dolomite block where it is thrust over limestone - *subthrust karst*. The "subthrust karst" phenomenon I first described (Čar, 1974) under the term "covered karst" (zakriti kras).

It transpired that a profound knowledge of the structural-lithological setting, which can be revealed only by detailed geological mapping, is required for a reliable interpretation of the surface to be produced.

Further, a methodology for the detailed lithological and structural mapping, including registration of all surface karst objects and phenomena, as well as of other outstanding geomorphic entities, has been evolving during the mapping of the wider fringes of Planinsko polje (Čar, 1982). The outflow border of the Planinsko polje is located in a wide, shattered, area of the Idrija fault. Consequently, various carbonate rocks have undergone significant tectonic alteration. Three

different intensities of tectonic change of the rock were distinguished by Čar (1982): *crushed zone*, *broken zone*, and *fissured zone*, whereas the more general term *fractured zone* was used to label zones of tectonically injured rocks without implying more-precise detail. Placer (1982) described crushed zone characteristics in detail. The other two categories, together with the general term *fractured rock*, were introduced by the present author (Čar, 1982). Later, the concept presented above was extended slightly (Čar & Pišljarič, 1993).

The main finding of extensive, detailed, structural, lithological and geomorphological mapping in the areas between Grčarevec, Unec, Postojna, Strmica/Planina, and the Banjšce plateau, Grgar basin, and the Črni Vrh–Zadlog plateau is the fact that different *fractured zone* properties may change from one pattern to another in horizontal as well as vertical directions (Čar, 1986). The hydrological conditions having remained constant, changes of the fractured zones in the horizontal direction result in the formation of different surface karst depressions and linear-but-sinuous elevations between them that are aligned parallel to the zones. Due to the steady denudational lowering of the terrain and changes in the fracture zones in a vertical direction different types of karst depressions may appear, guided by the same vertical structures during some longer time span (Čar, 1986). On the basis of the statements above and the mapping of approximately 4000 solution dolines, 8 different doline types, occurring in a variety of lithological and structural situations have been distinguished (Čar, 2001).

The methodology of mapping limestone terrains has gradually been complemented by establishing the dynamic and kinematic properties of the Postojna and Idrija areas. Such models permit a deeper insight into the formation of various types of karstic depressions and reveal the relationships between the location of cave entrances and specific types of local faulting and other structures (Čar & Šebela, 1997; Čar & Zagoda, 2005). Specifics of the karst surface shaping and the hydrological conditions along the overthrust fronts of dolomite upon limestone have been studied in the Idrija area (Čar, 1974; Zagoda, 2004; Čar & Zagoda, 2005) and in the vicinity of Predjama (Čar & Šebela, 2001).

Structural mapping was carried out in the hinterland of the Lijak spring in the Vipava valley (Čar & Gospodarič, 1988), at Kajža in the Avšček valley (Janež & Čar, 1990), at Možnica (Čar & Janež, 1992) and at the Divje jezero spring

(Čar, 1996). The structural conditions of the karst hinterland of large springs at the foot of the Trnovski gozd plateau and adjacent areas of elevated relief were discussed in 1997 (Janež et al., 1997).

The mapping procedure that was developed on the surface of the limestone massifs has also been implemented successfully when mapping underground karst (Šebela & Čar, 1991; Šebela, 1991). It has revealed a fair degree of inter-relationship between the location and shaping of the cave passages, lithology, and structural elements distinguishable underground. Positive correlation was established between the better expressed surface features, structural elements and the locations of certain types of cave passages. On the other hand, it is generally seen that direct inter-relationships between the surface-distinguishable structural elements and the location of cave tunnels is relatively weak (Šebela & Čar, 1991; Šebela, 1991, 1992, 1994, 1998). Important roles played by *bedding planes*, *zones of bedding-plane slip* and any *connecting fissures*, generating an effective porosity during the early period of speleogenesis, have been identified (Čar & Šebela, 1998). Mihevc (2001) discussed the complex processes of speleogenesis in the Divača karst, and the great impact of the former epiphreatic underground karst upon the arrangement of the recent karst surface in terms of the detailed study of unroofed caves. Šušteršič (1998) studied a similar topic in the context of the completely phreatic, denuded, cave system at Logaški Ravnik.

Alternating sets of physical properties related to fracture patterns within deflector fault zones impose a strong influence upon speleogenesis, producing effective hydrological barriers deep in the interior of the karst. Poorly permeable or impermeable fault-zones guide the general direction of groundwater flow and influence the arrangement of complex active cave systems. On the overlying karst surface, strings of collapse dolines of different ages commonly indicate their subjacent locations (Šušteršič et al., 2001; Šušteršič, 2006; Žvab Rožič, et al., 2015).

So far, the published results of the detailed lithological and structural mapping mentioned above have been based on mapping the karstified limestone, mainly of Jurassic–Cretaceous age, at the scale of 1: 5000; partly in the Idrija region, on the border of the Trnovski gozd plateau, and partly in the area between Logatec, Postojna and Cerknica. On the regional scale, the tectonic structure of the areas of western Slovenia referred to has been studied in depth (Mlakar, 1969; Placer, 1973, 1981, 1999, 2008, 2015; Gospodarič,

1986; Poljak, 2007; Vrabc et al., 2009; Mlakar & Čar, 2009; Jurkovšek, 2010). Local structural conditions in the limestone, which directly affect surface shaping and the arrangement of the hydrological background have been studied by Gams (1966), Čar (1982), Habič (1984); Čar & Gospodarič (1984, 1988); Janež & Čar (1990), Janež et al. (1997) and Čar & Šebela, (1997).

Mapping karstified limestone areas

The method of mapping limestone areas stems essentially from more-generally applied geological mapping procedures, upgraded by making more measurements of dip and strike, and including more abundant, exact, registration of the structural elements. In parallel, geomorphological examination of the characteristic karst elevations and depressions, and recording of other, possibly recent, geomorphic details must be performed (Čar, 1982, 1986). All identified geological information and other karstological data are recorded. Annotation of base maps at scales of 1: 10000 and 1: 5000 (exceptionally, at larger scales) is carried out "on the spot".

During field work in limestone terrains two main problems may arise. On nearly completely bare limestone the "abundance" of exposed rock commonly threatens to obscure the distinction between relevant and irrelevant information, especially when mapping highly variable fissure

systems. Of course, one should record as much information as the base maps allow. After the field work has been done, facing of the adjacent terrains reveals repetitive, important, structural trends, and changes in the fracture density. Elsewhere, opposed or contrasting difficulties may arise. Due to the soil layer, such as covers arable land and extensive meadows, original bare rock exposures may have been covered, or even eliminated intentionally, and original information is not accessible directly. In such cases, mapping of all available exposures is the only possible approach. Information acquired from adjacent areas, beyond the borders of the covered terrain, generally suffices as the basis for a reliable interpolation and interpretation of the situation in the unexposed or poorly exposed area.

Karstologists have identified a number of more or less characteristic geomorphic features on bare karst surfaces (Gams, 1973; Habič, 1986).

Suitably dense (1 m × 1 m grid, presently available) LIDAR-derived surface elevation data have facilitated efficient interpretation of the spatial distribution of solution dolines and other surface features of the same order of size (fig. 1, A1-the result of terrestrial mapping). Additionally, these data have facilitated a significantly more accurate interpretation of the geological conditions. If the recording is not based upon LIDAR-generated data one must make use of pre-existing data

Figs. 1. A and B: Interpretation of the geostructural mapping of the Magdalena gora near Postojna

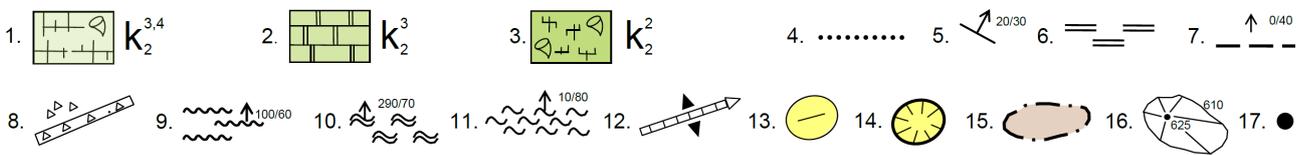
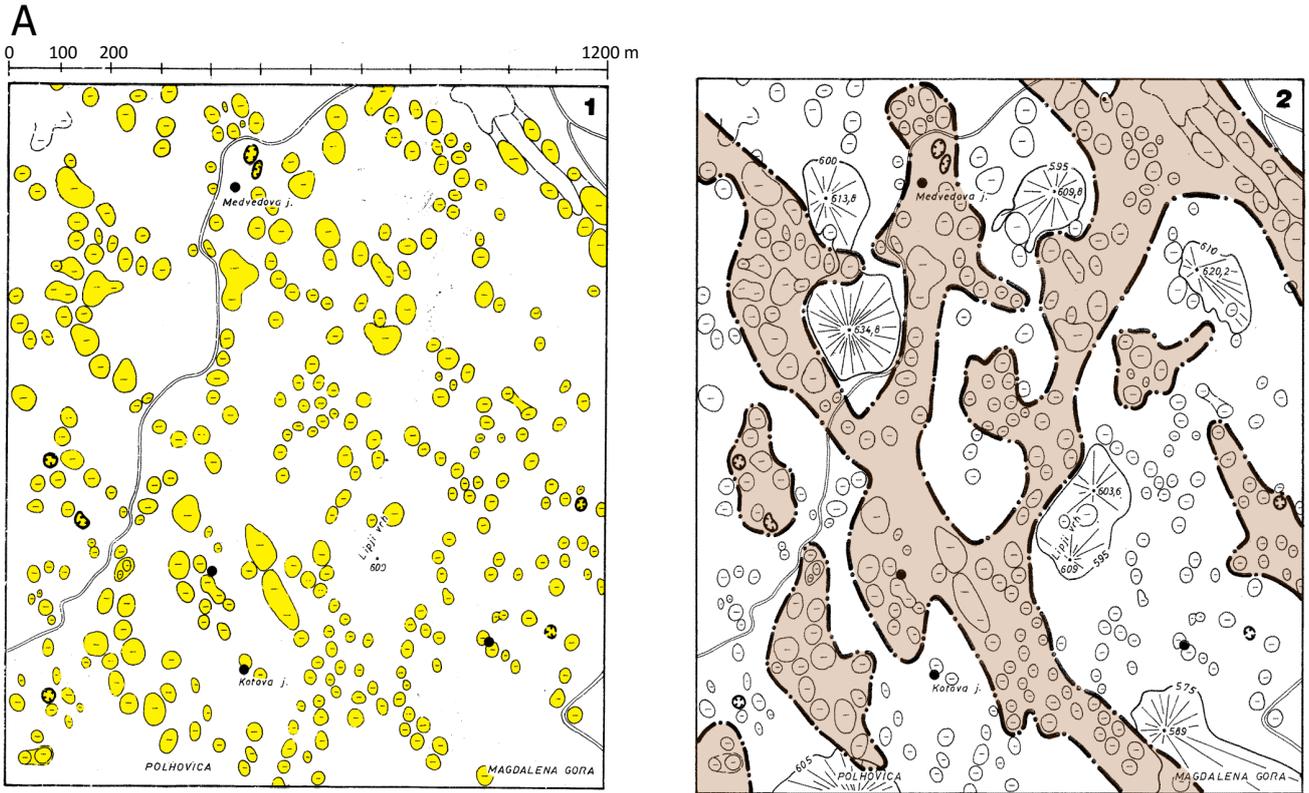
A1 - Areal distribution of (solution) dolines – the result of terrestrial mapping

A2 - Outstanding elevations and general terrain lowerings

B3 - Lithological and stratigraphical information, including the dip angles, plus records of fold axes and stronger faults

B4 - Structural map of the terrain: dip angles and fold axe, faults and fractured zones plus terrain lowerings are superimposed on the rudimentary terrain shaping. The map reveals an important accordance with medium scale karst surface entities and general relief lowerings.

1. Light grey, bedded or unbedded organogenic limestone with transitions to organogenic breccia
2. Grey to light-grey, thinly bedded limestone with rudistacea shells sections.
3. Grey to dark-grey, bedded or unbedded, organogenic limestone with inclusions of organogenic breccia
4. Gradual change in lithology
5. Dip and strike of the strata
6. Tensional fissured system
7. Fault, and dip of the fault plane
8. Crushed zone, tectonic breccia
9. Broken zone and the dip
10. Very dense fissured zone and the dip
11. Dense and less closely laminated fissured zone and the dip
12. The anticlinale axis with the direction of setting
13. (Solution) doline.
14. (Solution) doline with close-to-perpendicular slopes
15. General terrain depression
16. Elevation with height code
17. Entrance to a cave or pothole



Figs. 1. A and B

(usually large-scale topographical maps). Especially in forested areas most such basic information is insufficiently detailed. At some stage, surface karst entities, and essential structural elements, must be recorded during the general mapping procedure.

Solution dolines are ubiquitous and characteristic karst surface features (Ford & Williams, 2007). As was stated many years ago (Čar, 2001), their spatial distribution, interrelationships, shape and depth are related intimately to the geo-structural setting; therefore it is self-evident that particular attention should be paid to them. With dolines it is intuitive to outline the planar form of their perimeters on the map, and to measure the direction of the regolith-filled central part of the doline floor (the direction of the longer axis), which generally reveal trends of different fracture zones (Čar, 2001). In the case of adjacent dolines the interconnections (relatively lowered surfaces in the contact areas) must be recorded, if they exist. In most cases it is desirable to sketch two approximately mutually perpendicular profiles across the doline. These reveal fundamental types of slopes (*catenae*) and relationships to the geological succession and structure. At the same time, the doline depth should be estimated (Čar, 2001).

As well as solution dolines, other relevant karst features must also be recorded, especially collapse dolines and ponors, including cave and pothole entrances. If appropriate, local high points, linear depressions, fault-zone side walls and general terrain lowerings, plus other prominent closed depressions, may also be recorded (fig. 1, A2). Attention should be paid to the remains of various denuded, earlier, speleological objects, such as unroofed caves and phantoms of collapse dolines (Šušteršič, 2000), etc. "Unclear or equivocal" cases must be noted, ideally to be studied in greater detail later.

Bedding and lithology

Intra-stratal structural and textural peculiarities of limestone, which can be commonly studied only under a microscope, are particularly critical to gaining an understanding of the earliest stages of karstification. Much has been published about this topic all around the world. In Slovenia, only a few publications, directly influencing the present paper, can be mentioned (Šušteršič, 1994b, 1999; Brenčič, 1996; Knez, 1996; Lowe & Gunn, 1997; Čar & Šebela, 1998).

Stratification bedding and lithological changes in the limestone are of primary importance to the understanding of surface and underground karstification, on local and regional levels (Knez, 1996; Čar & Šebela, 1998). Different lithological partings and bedding planes provide notable influences upon the general permeability of the limestone and the orientation and morphology of karst phenomena. Clearly, one must trace and record various partings and lithological changes in the limestone during structural geological mapping, as well as making numerous measurements of dip and strike.

Stratification

As with surface karstification the role of stratigraphical bedding (bedding planes) is important for speleogenesis, i.e. the organization of cave passages was recognized and appreciated quite early (see literature in Knez, 1996). With respect to speleogenesis in the phreatic zone, master (leading) bedding planes (inception horizons) are particularly important (Knez, 1996; Šušteršič, 1998; Mihevc, 2001).

Stratification (bedding) planes are usually highly permeable and have a significant influence upon the organization of karst channel patterns. For the purposes of karstological studies in limestone Čar (2001) distinguished: A: *thinly bedded* (from 1 to 10 cm); B: *medium bedded* (10 cm and

Fig. 2. Interbeds of early-diagenetic dolomites within Lower-Cretaceous limestone, and position of Najdena jama close to northwestern border of Planinsko polje. Lithologically complex dolomite beds guided the general directions of groundwater flow. They guided the speleogenesis and spatial distribution of the Najdena jama passages (see text!).

1. Light grey to grey bedded organogenic limestone
2. Coarse to block grained limestone conglomerate
3. Bedded, bituminous, dark-grey limestone with interbeds of early-diagenetic dolomites
4. Erosional surface
5. Fault, and dip of the fault plane
6. Dip and strike of the strata
7. The Najdena jama ground plan
8. Larger collapse dolines

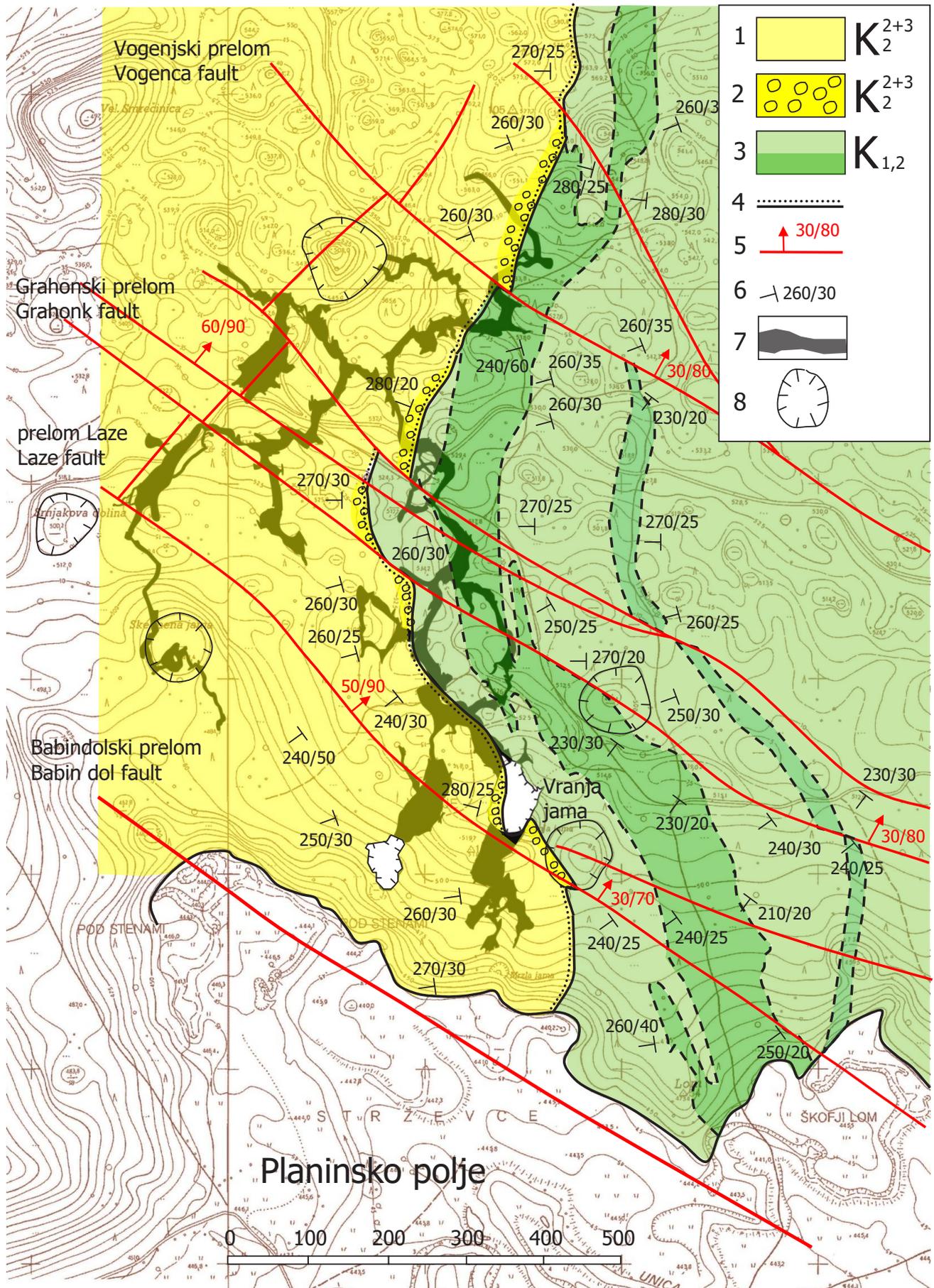


Fig. 2.

more); and C: *unbedded (massive)* limestones. To a great extent the thickness of the strata determines the mechanical properties of the limestone; however, the spatial orientation of the layers is equally important. Both of these factors also affect the arrangement of the surface. Regardless of the potential subjective feeling that both spatial elements either do not change or change only insignificantly, measuring the dip and strike wherever possible is indispensable. This is the only way to ensure a solid starting point that will help to determine the impact of the bedding planes upon the course of karstification and also to obtain an insight into the potential fold deformations, which might be expressed in the form of large and barely detectible open folds. Folded strata may influence the formation and the shaping of the surface significantly.

Lithology

In the presence of appropriate hydrological and climatic conditions changes in lithology help to direct underground water streaming, and also guide the shape and positioning of minute surface karst phenomena; in some cases the areal position of larger karst depressions, such as solution dolines, can also be affected. Two types of lithological changes in limestone influence the development of surface karstification and speleogenesis on local, possibly even regional, levels. The first type are linked to the stratification and comprise less permeable or impermeable interbeds in the form of thin stratified or laminar bodies of clay-enriched limestones, marlstones or claystones. Specific lithological changes generally encompass extensive, possibly-ancient, erosional surfaces, and unconformities with paleosols accompanied by other paleokarstic features. Most such interbeds are of local importance. Exceptionally their influence extends to greater distances and they act as hydrological barriers, guiding the arrangement and direction of the system drains. Mineral composition of interbeds can also affect the chemical composition of the karst water and, consequently, enhance karstification processes (Pezdič et al., 1998).

The other group of changes encompasses all other modifications anywhere in the limestone. It includes the presence of various, generally less-permeable, non-fractured biostromes, lumachelles, and calcirudites or limestone breccias with micritic or clayey cement within the otherwise uniform limestone sequence. Commonly they stand proud of the surrounding rocks. Unmodified biostromes and lumachelles are basi-

cally brittle. If cut by intense laminations they disintegrate into blocks and produce a relatively subdued surface topography (fig. 1, B3).

Due to their faster rate of mechanical disintegration, dolomite terrains set into broader limestone surroundings are relatively smooth with virtually no larger blocks protruding from the ground. In the case of early-diagenetic dolomites the relatively flattened surfaces extend along strike, whereas late-diagenetic ones tend to be irregular. Considering that, compared to most limestones, the permeability of dolomites is relative low, the downward washing of insoluble weathering products is impeded. Consequently, the dolomite "oases" are covered by layers of soil or loam of different thicknesses.

Interbeds of early-diagenetic dolomites can be of local or regional importance, depending upon their thickness and areal extents. From the hydrological viewpoint they are less permeable and therefore they represent potential hydrological barriers within the limestone. They can guide the general directions of groundwater flow and influence the spatial distribution of speleological objects (fig. 2). Late-diagenetic dolomites play a similar role, and other late-diagenetic changes of local or regional dimensions can be imposed. Hydrologically and geomechanically, even limestones that are only partially dolomitized may behave quite differently from purer limestones. On the surface, dolomitic interbeds and beds of dolomitized limestone weather faster than do pure limestones, and thus influence the shaping of the landscape (Šušteršič, 1998, 2013).

When poorly permeable or impermeable rocks lie at the base of, or on top of, the karstified limestone they induce specific hydrological conditions at the contact. Distinctive karst phenomena, bound to the contact zones, and their interrelationships, can be deciphered only with the help of detailed mapping.

Structural mapping

Since the early days of karst studies the role of faulting has been appreciated as an important influence upon karstification and the development of a number of specific phenomena, both on the surface and in the underground. This applies in the Dinaric karst of Slovenia as well as in other karst areas throughout the world. The most prolific authors are Cvijić (1924), Bahun (1969), Gams (1974, 2003), Čar (1974, 1982), Gospodarič (1976), Habič (1982, 1986), Šebela (1991, 1994), Čar & Šebela (1997, 2001), Čalić, (2009). Earlier researchers took faults into account mainly as a

general phenomenon, considered simply as individual discontinuities in the rock, or as undifferentiated fracture zones. Such an approach (Placer, 1972; Šebela & Čar, 1991; Šebela, 1992, 1998) is perhaps adequate for the study of regional situations on the karst surface and in the underground karst. Nevertheless, it is inadequate for a full understanding of individual local relationships. Only a detailed consideration of different degrees of fracturing (Čar, 1982, 2001; Bauer et al., 2016) can yield sufficient information to enable interpretations of the dimensions and shaping of particular phenomena, their dependence upon structural controls (especially the degree of fracturing) and the history of their genesis.

Thus far, it is clear from the literature that, when interpreting the development of karst phenomena, faulting (in its widest sense) has been considered seriously, whereas relationships due to fold-related deformations have been studied more rarely (Davies, 1960; Aubert, 1966; Cucchi, et al., 1976; Čar & Zagoda, 2005). Overthrusting, which also imposes special conditions for the karstification of limestone and impacts significantly upon the formation of surface karst, has been tackled only in exceptional cases (Čar, 1974, 1982, 2001; Herak, 1986; Čar & Šebela, 2001; Zagoda, 2004).

Deformation along folds overthrusts and a variety of faults in limestone does not differ essentially from the general pattern of deformation related to plicative and disjunctive tectonic processes (Twiss & Moores, 1992; Woodcock & Schubert, 1994). Nevertheless, common deviations from the theoretical geometrical distribution of structural elements are not negligible. Predominantly they can be explained by changes in lithology along the fault zones, by varying lengths of slips along individual faults, or by movement and changing related to multi-stage fracturing along tectonized zones. When describing and interpreting the actual situation observed on the terrain, it is necessary to take into account the impact of all the stages of tectonic movement that have so far been recognized (Gospodarič, 1976; Habič, 1982; Šebela, 1998; Placer, 2008, 2015).

Folds and related deformations

Initial folds (i.e. structures imposed by the effects of early compression before the development of any subsequent overthrust units) can encompass extensive structural blocks that were created during the pre-thrusting period (Mlakar, 1969; Placer, 1973; Čar, 2010). At the time of thrusting, less-pronounced folded deformations

with gently inclined limbs form within the underthrust block, whereas deformations are far more pronounced in the overthrust blocks. Particularly well-marked folds are formed parallel to the thrust fronts (Čar & Gospodarič, 1988). Tightly folded strata and minor folds are observed predominantly along strike-slips and normal faults (Twiss & Moores, 1992). Their impact upon karst morphology and the resultant karst objects can be both important and specific (Davies, 1960; Aubert, 1966; Cucchi, et al., 1976; Čar & Zagoda, 2005). *Zones of bedding-plane slip* and any *connecting fissures* are characteristic features (Čar & Šebela, 1998).

Generally, major regional folds are not readily recognizable directly in limestone successions. Nevertheless, such folds may be revealed by taking abundant measurements of the dip and strike (fig. 1 B3). Fold deformations and their – possibly strong – impact upon the geomorphic and karstic shaping of the limestone surface are easier to detect at locations where they have not suffered secondary distortion by later tectonic effects. *Fissure systems* with a fan-like distribution of more or less well-pronounced tension cracks in anticlinal structures, and pressure fractures in synclinal folds, which are generally sub-parallel to their axial planes, are of crucial importance to karst-surface shaping (Aubert, 1966; Cucchi, et al., 1976; Čar & Zagoda, 2005), (figs. 1 B3 and B4).

Thrust-shear-zone karst

Fracture deformations related to compression, and with dip angles less than 45°, are generally termed thrust structures. Dip angles of thrust planes commonly vary between 15° and 35°, yet some may be closer to horizontal (Mlakar, 1969; Placer, 1973; Herak, 1977, 1986, Twiss & Moores, 1992). In most cases, more or less distinctive, secondary, thrust planes of various dimensions are observed within the over-thrust and under-thrust blocks (fig. 3, A1, A2).

Dependent upon the local lithologies and the mechanical properties of the rocks that are in contact along the thrust planes, and also upon the energy released during thrusting, complicated zones of thrust-shear-zone karst can appear. In consequence these zones are sub-horizontal and more or less parallel to the main thrust plane (fig. 3, A1, A2). In cases of the thrust contact of two mechanically different rocks, for instance dolomite and limestone, the thrust-shear-zones are well expressed, and readily identified, whereas some contacts between two limestone blocks remain hardly visible and thus barely recognizable.

Crushed, broken and fissured rocks, similar to the tectonically fractured zones (Čar, 1982), also appear along thrust planes. They develop in the under-thrust as well as in the over-thrust blocks.

Thrust-generated crushed zones consist of cataclastic rocks, possibly secondarily re-cemented to various degrees. Their thickness varies widely. Generally they are significantly more extensive in over-thrust limestone blocks than

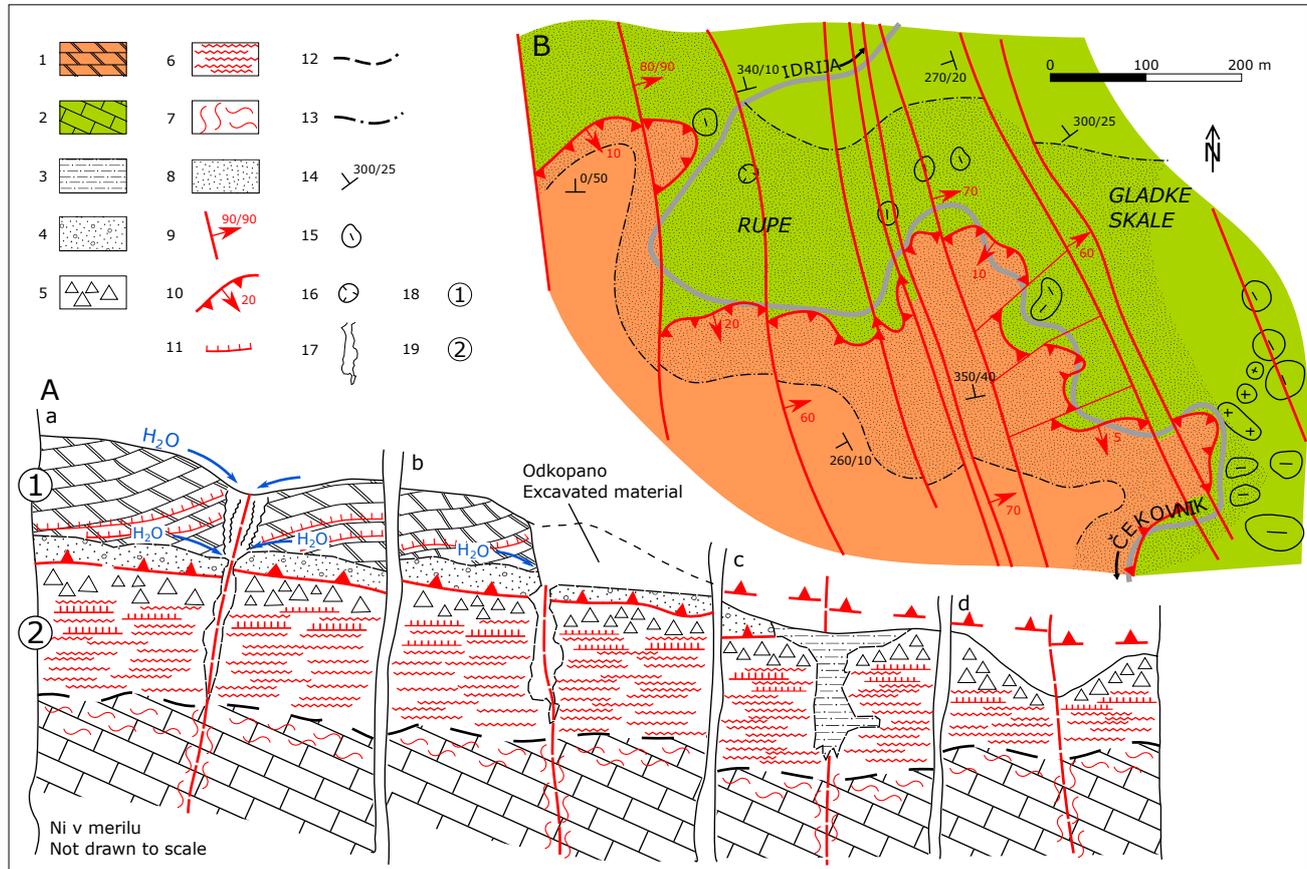


Fig. 3. Parallel to thrust structural and karst features.

A Section of parallel-to-thrust generated fractured zone. Being far less permeable than the adjacent intact rock they function as hydrological barriers. It resulted in the formation of reproduced dolines (A-a) and covered karst (A-b). Succession objects appear on the thrust border area (A-c and A-d). Explanation in the text.

B Position of the thrust-shear-plane between the Lower-Cretaceous limestone and Upper-Triassic dolomite at Rupe (by Idrija). Delineated are broken to crushed zones.

1. Grey, thinly bedded, Norian –Rhaetian dolomite (Hauptdolomit) fractured close to the thrust plane
2. Bedded, bituminous, dark-grey, bituminous, bedded Lower-Cretaceous limestone fractured in the thrust plane vicinity
3. Clayey weathering products
4. Crushed zone in dolomite (overthrust block); clay-rich tectonic rock-flour and breccia
5. Broken to crushed zone in limestone; chaotically arranged limestone blocks
6. Broken zones
7. Fissured zone
8. Groundplane of the crushed to broken zone in the thrust-shear-zone vicinity
9. Dip and strike of the fault plane
10. Thrust border and dip of the thrust plane
11. Secondary, more or less distinctive, thrust planes of different dimensions within the over-thrusted and under-thrusted blocks
12. A section of the border between thrust-shear zone and fractured rocks in the base (A).
13. A groundplane of the border between thrust-shear zone and fractured rocks in the base(B).
14. Dip and strike of the strata
15. Solution doline and the direction of the central part dip
16. Collapse doline
17. Covered karst – a vertical shaft generated beneath the over-thrusted dolomite
18. The over-thrusted block
19. The under-thrusted block

Fig. 4. Characteristically chaotic arranged limestone boulders and cobbles in the broken zone.

a. Close to thrust-plane broken zone at Kodrov rovt near Idrija.



b. Close to thrust-plane broken zone at Za Pšenkom near Idrija.



in the under-thrust blocks (fig. 3, A1, A2). In the latter case compact tectonic breccias just a few metres thick appear. As a rule they are cemented by clay-rich tectonic rock-flour. Eventually, they become far less permeable than the adjacent intact rock and they function as hydrological barriers. In cases where such zones are dissected by

younger faults, specific hydrological conditions develop, bringing about the formation of thrust-shear-zone karst (fig. 3A).

Thrust-shear-zones can develop to a wide variety of thicknesses, depending upon the general conditions at the time of thrusting. Most of them are several tens of metres thick; in the Idrija region this might reach 100 or more metres. In the *broken zones* more-brittle limestones are disintegrated into boulders and cobbles (block tectonites), (fig. 4 a, b), with the largest clasts several tens of metres in diameter. Primary bedding and dip can be preserved in the larger blocks, but such blocks were rotated, and the apparent dip differs from the true dip in the adjacent undeformed rocks.

Thrust-shear-zones comprise rock that is traversed by numerous, closely spaced, less well-expressed thrust planes. Generally they are cut by sets of connecting fault planes that may penetrate far into the under-thrust and over-thrust blocks (fig. 3A). As distance from the main thrust plane increases, related deformations become scarcer and less extensive in both blocks.

The previously discussed zones of bedding-plane slip (Čar & Šebela, 1998) have a genetic connection with the thrust-plane-parallel slip zones. Bedding-plane slip zones appear within susceptible strata, approximately parallel to the main thrust plane or splaying from it at shallow angles. Their degree of expression and frequency depend upon the position of the affected stratum within the over-thrust or under-thrust blocks. Bedding-plane slip structures might have an im-

portant role in speleogenesis, as they also do in surface shaping (Čar, 1974, 1982; Knez, 1996; Čar & Šebela, 1998, 2001; Mihevc, 2001).

Thrust zones have been researched only poorly in the structural-karstological context. Thus far, the existing studies have revealed that zones of minor or severe shearing can play an important role in karst surface shaping (Čar, 1974, 1982, 2001; Čar & Gospodarič, 1984; Herak, 1986; Čar & Šebela, 2001; Zagoda, 2004; Čalić, 2009).

Fault-related deformations

In Slovenian literature the concepts of *fissure* and *fault* are defined only with a short general tag (Pavšič, 2006, 225, 236). Thus, it is necessary to reference foreign literature (Twiss & Moores, 1992). The distinction between fissures and faults is necessarily consensual because, in Nature, the transition from one to the other is continuous. By definition, fissures are mechanical discontinuities in the rocks where cracking has occurred. Small displacements may have occurred, perpendicular to the fissure surfaces, or along them; they might, however, be completely absent. For the reasons mentioned above they do not affect the over-riding tectonic grain of the territory. In practice this means that the strike remains essentially continuous, and the dip doesn't change. Where the stratification has been displaced along mechanical discontinuities and the dip and strike angles are at least partially changed, minor faulting must be suspected. For the purposes of karst-surface studies it is perfectly reasonable to consider rock discontinuities that can be traced for at least some tens of metres as *faults*. All the rest, i.e. the shorter discontinuities, are *fissures (joints)*.

According to the nature of the prevailing stress field, normal and reverse faults occur, as well as strike-slips. As mentioned above in the context of thrust zones, sub-horizontal deformations appear along reverse faults. With normal faults, tension fissures and fault zones of tensional character develop, whereas closed fissures are characteristic of compression zones. Internal structures differ between the two types of fault zone. To a great extent the different internal structures influence the general geomorphic situation, the course of weathering, and the extent of karstification along the zones. Therefore it is important to scrutinize whether the fault zone is of compressional or tensional character.

Initially Gladkov (1967) and Placer (1982) differentiated an *internal zone* and an *external zone*. Based on a case study in the Idrija Mine

he (Placer, 1982) progressed the then knowledge about the structure and composition of the respective zones in dolomitic rocks.

In limestone the internal structure of strike-slip faults is generally well-defined and readily observable (fig. 5a). At their outer margins they are delimited by *boundary fault planes*, whereas shear-planes mainly occur within the zones themselves (Placer, 1982) (fig. 5a, present text). The *internal zones* are filled with a variety of cataclastic rock material. Usually they comprise different-sized rock lenses mutually separated by *internal fault planes*. There are normally two *external zones*. They are built up differently according to the way the rock has fractured. As is to be expected, their thicknesses are also variable. In some cases an outer zone is developed just on one side. On the other side only a zone of weak, parallel, fissuring is observable (fig. 5a, right). Generally the external zones pass gradually into unaffected rock (figs. 5, a, b) or into an adjacent fault zone. Only exceptionally they might be delimited from the outside by shorter fault planes. The width of the fault zones depends upon the properties of the rocks that they cut and the extent of the strike-slip movement.

Tectonically affected rocks within fault zones are generally termed *fractured rocks*. As in thrust zones, *crushed, broken* and *fissured zones* are identified, depending upon the severity of fracturing (Čar, 1982, 1986, 2001) (fig. 5b, present text). In the case of an idealized fault zone the crushed zone passes longitudinally into the broken zone, and then into the narrow but closely laminated fissured zone, beyond where it either vanishes or reverts to a wide or narrow crushed zone (fig. 5b). Similar transitions are also possible laterally across the fault zone, except that the fractured zones are significantly narrower (fig. 5a). Sequences of the different broken zones along stronger and longer faults can change repeatedly across relatively short distances, according to local conditions. Some systems of fissures can also remain isolated, without passing into adjacent fractured zones. These represent the initial state in the formation of a fault zone.

Given the general hydrological conditions, throughput of drainage along the fault zones changes in horizontal and vertical directions in parallel with the alternating properties of the fractured zones (Čar, 1986) (fig. 6, present text). For this reason different surface karst phenomena can arise along just one single fault (Čar, 2001). It transpires that a general knowledge of fault lines is insufficient. Instead, the degree of

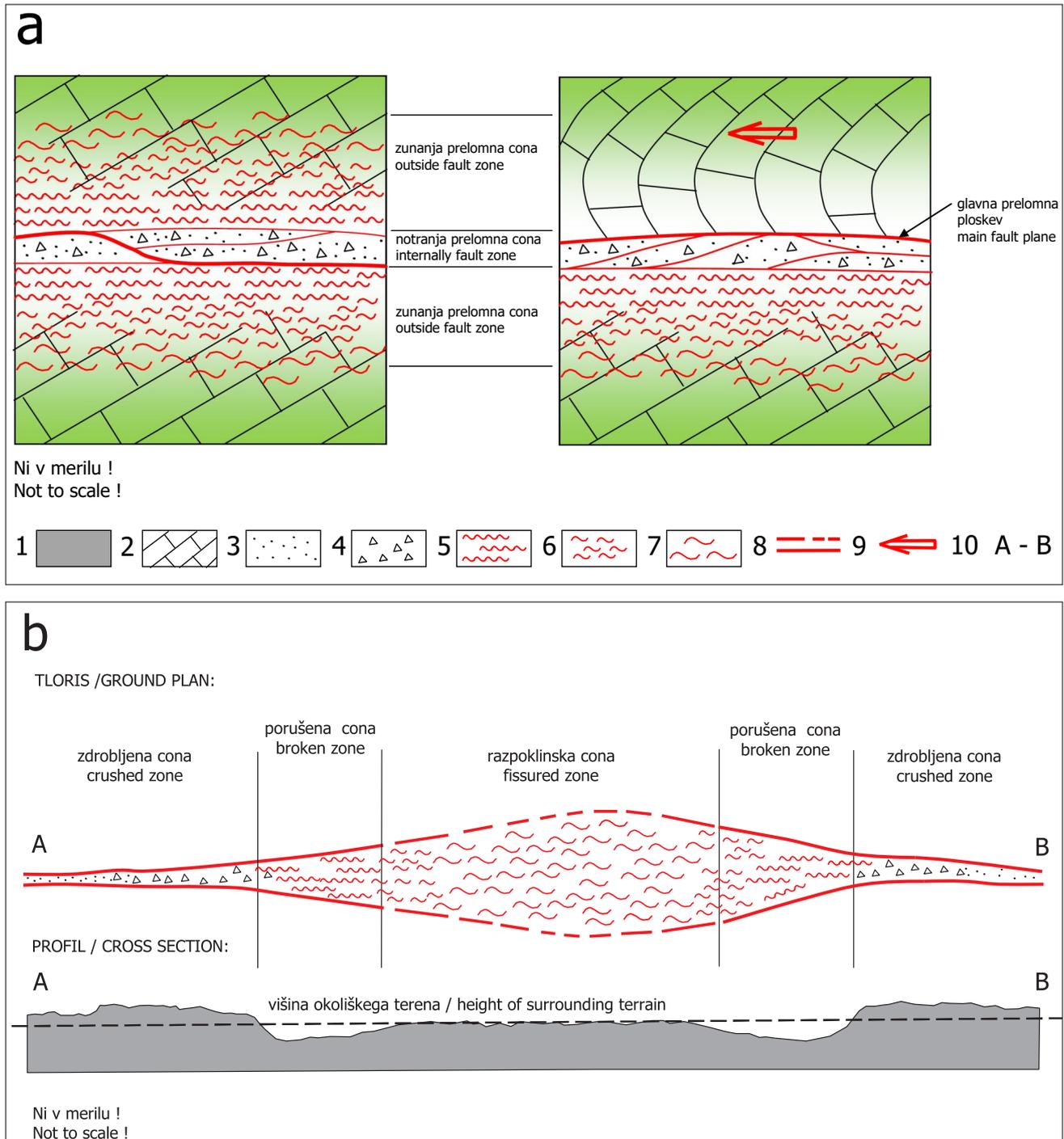


Fig. 5. Drawings a and b: Characteristics of fault zones.

a. Drawing of two characteristic horizontal sections of the faults with the fault zones, main fault planes and characteristic arrangement of the fractured zones.

b. Ground plane and section of a fault; indicated are changes of the fractured zones along the fault direction

1. Section of tectonically fractured rocks
2. Bedded limestone
3. Tectonic silt
4. Tectonic breccia
5. Broken zone
6. Dense fissured zone
7. Infrequently fissured zone
8. Fault
9. Direction of a block displacement
10. Transect A-B (drawing b)

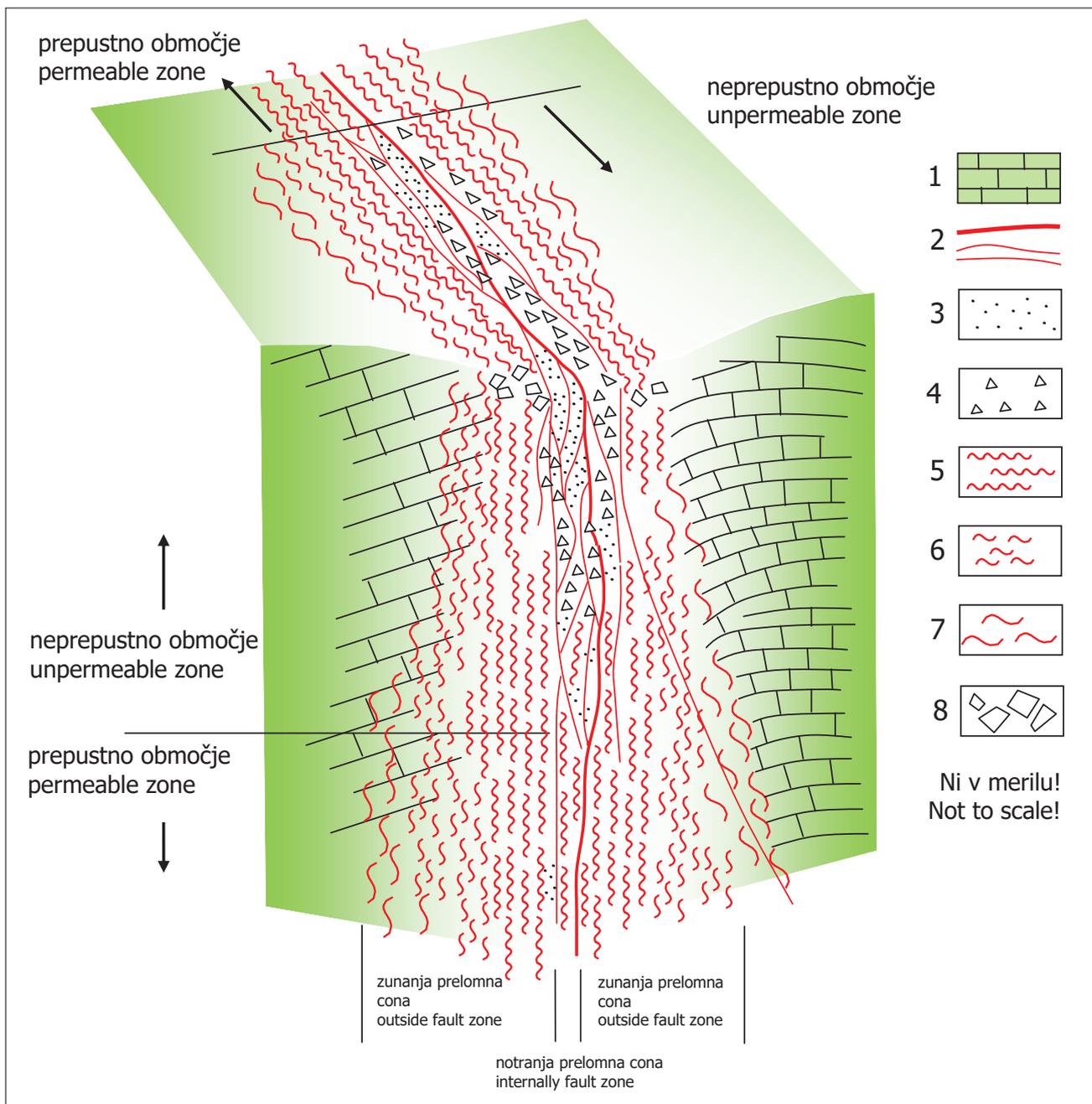


Fig. 6. Changes of the rock fracturation in the fault zone, in the vertical and horizontal direction.

- | | |
|----------------------------------|---|
| 1. Bedded limestone | 5. Broken zone |
| 2. Intersection of a fault-plane | 6. Dense fissured zone |
| 3. Tectonic silt | 7. Infrequently fissured zone |
| 4. Tectonic breccia | 8. Individual limestone blocks within the broken zone |

fracturation of the rock must be sub-divided and recorded in detail, with special regard to recognizing and recording specific details of the *crushed*, *broken* and *fissured* zones (figs 5a, b).

Crushed zones

Placer (1982) investigated the structure of crushed zones, specifically in dolomitic rocks. He noted that the internal zone can be filled with *tectonic clay (fault gouge)*, *mylonitic (cataclastic) rock-flour*, *mylonitic (cataclastic) silt*, *tec-*

tonic breccia (fault breccia), and also “floating” blocks of rock of different sizes. On the basis of general estimates Bauer et al. (2016, 1152-1153) ranged the degree of tectonic fracturing of carbonate rocks into 4 classes: *weakly fractured* rock, *moderately fractured* rock, *intensely fractured* rock, and *very intensely fractured* rock.

They (Bauer et al., 2016) noted that the zones in question are filled with four types of cataclastic breccias that can range from highly permeable to impermeable. The two aspects of faults in

limestones are generally better defined than in dolomites, and the inner zones are more simply built up (Čar, 1982). Individual mechanical properties of the infilling material vary from case to case, but they change within a smaller range. The relatively thin tectonic clay coating and more- or less-well-cemented zones of tectonic silt and rock-flour are restricted predominantly to the inner fault-zone (Placer, 1982; Čar, 1982; Bauer et al., 2016) (figs. 6 and 7, present text). In most cases tectonic breccias of different grain-size prevail (fig. 7). Properties of the crushed rocks within the 'left' and 'right' external fault zones pass gradually from one to the other, in either direction; they appear in the form of differently-sized lenses separated by minor, internal, fractures (fig. 5a).

Depending upon the petrology of the parent rocks and the physico-chemical conditions during and after formation, the crushed rocks are more or less indurated, with a predominantly reddish, clayey, cement (fig. 7). As well as the thicknesses of the crushed zones themselves varying, the dimensions of clasts of different crushed rocks within the zones (figs. 5 and 6) also vary. Locally, in the more-extensive crushed zones and in fracture inflection zones, plastic deformation occurs, leading to the development of folded cataclastic rocks.

In cases where the cataclastic rocks of the internal fault-zones are well cemented, especially within the pressure zones of strike-slip faults, they may protrude at the surface as long, narrow, crests. Where cementation is weak or otherwise poorly developed, the surface is marked by elongated, trench-like depressions (*bogazes*) (fig. 5b). Underground in the karst, primarily crushed, subsequently well-cemented rocks within the internal zones of strike-slip faults function as impermeable, or weakly permeable, hydrological barriers.

Broken zones

The fundamental characteristic of *broken zones* in limestone sequences is the disintegration of the intact bedrock into angular blocks of various sizes that may be more or less rotated. Generally the original bedding becomes no longer detectible (Čar, 1982) or can barely be deduced (fig. 8).

The size of blocks ranges between comminuted rock debris, held within a matrix of finely ground rock flour, and large cobbles, depending upon the lithological and sedimentological characteristics of the original limestone and the stress conditions. Broken zone thickness varies within a



Fig. 7. Tectonic breccia cemented with terra rossa. Crushed zone of the Laze fault internal zone (Laze at Planinsko polje).

broad range, possibly even reaching several tens of metres. Within the tensional stress-field linking broken zones between two strike-slip faults they can exceed several tens of metres or even more. Mostly they are developed on both sides of the inner fault zones, filled with broken rocks. Broken zones occur commonly on the external sides of fault zones. With less well-defined faults, they appear as lateral transitions on one or both sides of the internal fault zones. In many cases they are developed within the continuation of the crushed zones. However, they may also appear as isolated broken zones (figs. 5 a, b; fig. 6).

Fissured zones

Fissures (= joints; Čar, 1982) are the most common mechanical deformations of limestones, but they are the most difficult to deal with using standard geological mapping techniques. Fissures of various trends are commonly interwoven. They impose a grid-like structure, and they can influence the form of the surface terrain strongly (figs. 9 and 10). The terminology of joints is complex and as yet it has not been unified (Twiss & Moores, 1992). Researchers must adapt appropriate terminology to match the actual field



Fig. 8. Section of the fault broken zone (Kacjanovec by Idrija).

conditions. Most commonly joints are classified according to their dominant mode of genesis (dynamic-kinematic classification) and according to their spatial geometry.

A number of faults of different intensity, accompanied by swarms of secondary fissure systems, cut through western Slovenia in a north-west–southeast direction (the Dinaric trend). Related to the fault strike direction, shear joints may appear more or less parallel to the north-west–southeast master faults. Conjugate joints on the Dinaric trend are normally absent. However, if they do occur it is hard to detect them due to the extreme fracturing of the parent rock. Depending upon the degree of stratification and lithological variations, fissure directions may readily adapt and change their direction, thus curving according to micro-local conditions. According to the present author's field experience, the maximum angle of deviation from the master direction varies up to 35° . If observed deviation angles exceed this value the fissures in question belong to a different fault system. A number of minor, tensional, accommodation faults may appear between two better-expressed faults. In most cases they form wide swarms of tension joints (longitudinal splitting), in the north–south direction, mainly with some degree of sinistral strike-slip. Adjacent to the two major faults the fissures are commonly contorted due to the primarily dextral strike-slip of individual blocks. Closed pressure-joints with small horizontal/longitudinal displacements of blocks, possibly with a minor vertical component, can appear along strike-slip faults. Tension (relaxation) con-

ditions give rise to joints with small horizontal displacements, and minor differential lowering of blocks between individual joints.

In the context of individual swarms of fissures within any specific fissured zone (compressional or tensional) the types of fissures mentioned above can join into *strings*, and subsequently into *clusters*. They may be several tens or several hundred metres in length. If the fractures belong to differently directed fault-sets they may combine or intersect at different angles. Such dissected areas are designated as *fissure zones* (Twiss & Moores, 1992). Most of them are clearly delimited laterally. They either pass over into areas of macroscopically unfractured rock or they are delimited by short, poorly expressed fault planes. Longitudinally they may pass into a more-fractured, crushed, zone or gradually become less numerous and eventually vanish (figs. 5a, b and 6). To help understand the course of karstification and the formation of karst phenomena at the local level, identification of *fissured* zones is sufficient.

Distinguishing individual swarms of joint-fissures within the fissured zones is less important for the interpretation and understanding of karst surface shaping. However, because the degree of jointing influences the intensity of karstification and the nature of terrain shaping, the density of jointing within crushed zones is virtually crucial. Depending upon the type of problem to be solved and the accuracy required, in some cases it becomes desirable to subdivide fissured zones into *rare*, *dense*, and *very dense* categories (fig. 9 and 10). There are no clear-cut and widely useful criteria for helping to distinguish joint density

and specific details of fracturing with certainty. Simply counting the fissures in a particular area does not produce useful results. Only comparative estimates of fracture density are reliable. Within each individual fracture cluster the joint density may change significantly across relatively small distances. One must also consider the lithological and sedimentological changes of rocks, which can bring about insurmountable complications. So far, it is best to estimate the relative density on the basis of a comparison of adjacent fissured zones. Bauer and colleagues (2016) came to similar conclusions. On the basis of subjective estimates, they have suggested “fracture class 1 (FC1) and fracture class 2 (FC2)”. In general these correspond to the present author’s classification of *fissured* zones (Čar, 1982). If fissured systems of different intensities are mutually interrelated in either a longitudinal or a lateral way they can readily be distinguished on the spot by simply assessing the density of fracturing within the zones. Extremely closely fissured systems consist of dense, short, fractures of decimetre to metre lengths that are approximately mutually parallel. Fractures that are several metres long are rare in this context (fig. 9).



Fig. 9. Dense fissured zone (Suha grapa by Idrija).



Fig. 10. Dense fissured zone; bedding is still recognizable (Pringl by Idrija).

Extremely dense fissure systems commonly represent intermediate, longitudinal, continuations of crushed zones. Alternatively, they may extend in narrow stripes parallel to them. Transitions are generally continuous and gradual (fig. 5b). In such cases, the logical boundary between the fissured and the crushed zones can be set where stratification becomes observable (fig. 10). If the rock is not stratified attention must be paid to sedimentological and other early, structural, phenomena. Detailed mapping always confirms that one fracture direction is dominant. Obviously this one must be recorded.

Deflecting structures (temporary hydrological barriers)

Temporary hydrological barriers are important structural elements in the karst. According to their relationships to various structural elements one may distinguish *lithologically conditioned hydrological barriers*, *thrust-parallel hydrological barriers*, and *deflector faults* (Šušteršič et al., 2001; Šušteršič, 2006). Bahun (1979) pointed out the importance of the guiding role of

types of rupture that induce essential changes in karst water-table levels. Unfortunately, he did not characterize such ruptures in more-general geological terms. Bauer et al. (2016) tackled the hydrological role of faults with poorly permeable cataclastic cores. Deflecting structures are not only paramount factors in determining the arrangement of the karst surface, but they have an important, in many cases even decisive, influence on the underground hydrological situation, and on the course of speleogenesis. They can be detected by more-precise, conventional, geological, mapping of both the karst surface and of cave systems. In general they do not present absolute hydrological barriers. Rather than being absolutely impermeable “dam-barrages”, they manifest as less permeable tracts within the otherwise highly permeable limestone mass. At times of lower discharge they (normally) do not impede underground flow at all. Under conditions of higher discharge, however, their transmission capability is restricted and they limit the maximum through-flow to a specific volume (Šušteršič et al., 2001; Bauer et al., 2016). Their hydrological role is not constant and varies depending upon the internal structures of the barriers, as well as upon the amount of water being transmitted.

During times of extreme inflow they deflect any excess water flow and direct the surplus along more-permeable fissured zones and other high-conductivity structures, predominantly along broken zones, fissured zones, and bedding-plane partings. Such a role of the deflector structures induces conditions that are appropriate for the development of cave sub-systems parallel to the master fault (Šušteršič et al., 2001; Žvab Rožič, Čar & Rožič, 2015).

Lithological barrier strata

Less permeable intercalations within highly permeable limestones behave as lithological, hydrological, barriers (fig. 2). In most cases they are intra-formational lenses of early-diagenetic or late-diagenetic dolomite, or beds of marly limestone. Less common are disconformity or unconformity planes characterized by crusts of palaeo-regolith (palaeosols) or basal carbonate sand-conglomerate bedrock. Each of these rocks can exert an effective influence upon the underground karst and act as water-tight or poorly-permeable lithological, mineralogical barriers.

Due to the effects of diagenetic processes most of the dolomite beds in otherwise limestone-dominated lithological sequences are not completely uniform (Zogović, 1966). Within early-diagenetic

dolomite developments, lenses of limestone, dolomitized limestone, and transitional lithologies can appear where late-stage dissolution of primary gypsum creates a honeycomb-like texture within early-diagenetic dolomite intervals. Similar rocks may also appear in late-diagenetic dolomite. Rocks of the lithologies listed above, occurring on the margins of dolomite lenses are significantly more permeable than the pure dolomite or “standard limestone” occurring in the wider area around the lenses. This is why the lithologically heterogeneous dolomite lenses – so called because the dolomite predominates – play such a markedly dual role hydrologically. On the one hand “pure” dolomite blocks interfere with and deflect the water flow. However, the highly permeable intercalations within dolomite lenses enhance the through-flow and guide the outflow. In this way cave channels can form along and within dolomite lenses (Šušteršič, 1994b; fig. 2, present text).

An example of such a composite lithological sequence and its influence upon the local karst phenomena, is the approximately 30 m-thick dolomite layer within the Early Cretaceous limestone at the northeastern margin of the Planinsko polje (Čar, 1982; Gospodarič, 1982; Šušteršič, 1982; fig. 2, present text). The dolomite surface is relatively smooth and free of karren. Solution dolines are less abundant (Šušteršič, 1987) and less pronounced than on the limestone in the neighbouring terrain. Most of the presently known passages in Najdena jama have been formed on its upper and lower contacts, and partly within this lens (Šušteršič, 1994b). Cave passages developed even in the more transmissive layers within the dolomite lenses (Gospodarič, 1982; Šušteršič, 2002).

The main barrier is the transition zone between the syn-sedimentary erosion surface overlain by a coarse, basal, partly dolomitic conglomerate with clayey cement (Gospodarič, 1982).

Thrust-parallel hydrological barriers

The process of karstification and its intermediate geomorphic effects upon the impermeable or poorly permeable, sub-horizontal, crushed zones along thrust planes have brought about the formation of a specific type of limestone karst along the thrust front. Each combination of underthrust and overthrust rocks brings about particular hydrological conditions. They induce a specific development of karstification and specific shaping of the karst surface. So far such cases have been examined only along the zone where Norian–Rhaetian dolomite (Ček-

ovnik thrust slice - Mlakar, 1969) is thrust over limestones of the Koševnik thrust slice (Mlakar, 1969) in west-central Slovenia (the Idrija region and in the wider area of Planinsko and Cerknjsko poljes) (Čar, 1974; Čar, 2001; Čar & Šebela, 2001; Zagoda, 2004; fig. 3, present text). Any anticipated comparable effects of such a style of karstification on other locations of similar type have not yet been studied in adequate detail.

Within the range of the thrust contact between two limestone blocks the crushed zones in both the overthrust and the underthrust blocks are characterized by the occurrence of compact, tectonic, re-cemented limestone breccias, which assume the appearance of solid limestone. Generally a barely noticeable thrust plane, which may readily be overlooked, is present in the middle of the brecciated mass. Compact breccias are significantly less permeable than the adjacent unbrecciated rock, and generally they function as barriers. Meteoric water can penetrate the breccia layers only via various fault structures and joints, bringing about the formation of corrosional excavations, overhangs and minor caves. Details of how thrust planes between limestone-upon-limestone appear underground are yet to be studied.

Comparable contacts between limestones and mechanically weaker rocks (figs. 3 A and B) are essentially better expressed (Čar, 1974, 1982; Herak, 1986; Mihevc, 1994; Čar & Zagoda, 2005; Mlakar & Čar, 2009). Extensive planation surfaces appear on the overthrust contacts of Late Triassic, Norian–Rhaetian, dolomite upon limestones of various ages (Čar, 1982; Čar & Šebela, 2001; Zagoda, 2004). Thick crushed zones within the overthrust dolomite are permeable only along younger, post-thrusting faults cutting through the zone (fig. 3 A). Numerous poorly developed dolines (Čar, 1974; Čar, 2001; Zagoda, 2004) and proto-dolines (Sauro, 1995) appear next to the faults. Generally a crushed zone is absent in the underthrust limestone block. Along a narrow band in the immediate vicinity of the thrust contact the surface topography is relative flat and subdued, covered with dolomite weathering debris that extends into the thrust-parallel broken zone (figs. 3 A,B and 4 a and b). At a greater distance from the thrust front the land surface takes on a characteristically karstic appearance, with solution dolines and minor potholes (Zagoda, 2004; Čar & Zagoda, 2005; fig. 3 B, present text).

In cases where relatively more compact limestone is thrust over dolomite or flysch, watertight crushed zones form within the less-resistant

underthrust rock. In appropriate hydrological conditions overhangs and minor caves will develop along the thrust plane. The thrust-parallel crushed zones are exceptionally transmissive. Fissured zones increase the permeability of the limestone significantly, and influence the direction of the drainage (Zagoda, 2004).

Deflector faults

Early ideas about the hydrological aspects of deflecting fault structures in the karst were put forward by Jenko (1959). He felt that karst water-streaming simply crosses the main faults and predominantly follows “...all kinds of parallel fractures (*viz. to the main fault*) in order to avoid the master faults where there is a greater possibility of ongoing blockages caused by the breakdown and collapse of the tectonically damaged rock...” (Jenko, 1959, 158). Gams (1966) noted the presence of collector channels in the outflow system of Cerknjsko polje. Important ideas about the role of neotectonic displacements in the karst were advanced by Bahun (1979). He felt that zones of reduced permeability related to the active faults are the reason that local step-like disruptions of the upper surface of the water table are present. The issue of deflecting structures and thus the concept of *deflector faults* were considered in greater detail by Šušteršič and co-workers (2001) based upon study of the sample cases of the underground Pivka river (Postojnska jama), the outflow system of Cerknjsko polje (Karlova Cave), and Logarček Cave (one of the Planinsko polje drains). The latter authors clarified the hydrological significance of the deflecting structures, and pointed out their role in the development of cave systems. Related ideas were developed further by Šušteršič (2002, 2006). More recently the hydrological role of the Risnik deflector fault (Kačna jama – extension of the Škocjanske jame system) guiding the flow direction of the underground Reka river was discussed by Žvab Rožič et al., (2015). The permeability of specific cataclastic rocks was established by Bauer and co-workers (2016), who presented meticulous descriptions of various cataclastic rocks within the central parts of selected fault zones in the Northern Limestone Alps (Austria).

Generally, deflector faults are better-expressed fractures or sections of sub-regional faults with well-developed internal ruptures i.e. crushed zones (Šušteršič et al., 2001; Žvab Rožič et al., 2015; figs 5a and 6, present text). The latter are filled with re-cemented cataclastic rocks in the form of compact tectonic breccias of various

grain sizes. The cement may comprise tectonic clay or silt (fig. 6). Strongly cemented crushed zones take on the role of sub-vertical barrier zones, which may be totally impermeable, or nearly so (fig. 6). Just as with other lithological barriers they might leak small quantities of water during periods of low discharge. In cases of increased discharge, however, they partly deflect and redirect the surplus water flow parallel to the fault, along the crushed and fissured zones. Intricate cave channel systems, winding all along the fault zone, form within the feeder block (Šušteršič et al., 2001; Žvab Rožič et al., 2015). As a reflection of the varying severity of fracturing within the fault zone, the underground water eventually encounters more permeable locations within the zone (fig. 6) and it turns squarely across the fault in the direction of the gradient into whichever adjacent block has a lower watertable. Just as in the karst of Slovenia, deflector faults are common and important structures within the entire Dinaric Karst (Bahun, 1979).

The fundamental characteristic of deflector faults is their variability. Highly permeable, mechanically unstable locally, and totally re-cemented segments alternate, both horizontally and vertically, at an approximate scale of several tens of metres or more (fig. 6). Considering that the fault planes are vertical or sub-vertical they may be recognized on the surface either as shallow bogazes, as linear ridges, or as small scarps due to minor vertical component of movement, protruding above general ground-level, but differing from the general “karren crest” morphology. Their role can be observed fully only where hydrological conditions are favourable.

A large-scale example is provided by the (surface) intersection of the deflecting structure of the Idrija fault zone and the flat floor of Planinsko polje (figs. 11 A and B). At times of low water-level the Unica river disappears almost entirely into numerous swallow-holes in the extreme southeastern corner of the Planinsko polje basin, in the areas known as Milavčevi ključi and Ribce (Čar, 1982). Swallow holes have formed within intensive broken and fissured zones in the southeastern marginal area of the Idrija fault zone (figs. 11 A and B). At higher water-levels, because the capacity of the ponors is limited due to the wide inner crushed zone of the Idrija fault, the main water body rebounds along the fault, heading northwestwards (figs. 11 A and B). The Unica River meanders across the flat floor of the Planinsko polje between the Idrija and Zala faults and

sinks into a number of swallow holes within the wider area of the fracture-zone of the Idrija fault (Čar, 1982). On the northwestern side of the polje the Idrija fault zone becomes wider. The Unica crosses it and finally sinks at Podstene and Škofji Lom. The deflecting role of the Idrija fault offers a convincing explanation of the hydrological situation in the Planinsko polje, as revealed by water-tracing experiments (Gospodarič & Habič, 1976). Hydrological development in the polje is, thus, comparable to situations encountered in the karst underground, such as in Kačna jama (Žvab Rožič et al., 2015).

Structural framework and speleogenetic network

Ignoring the properties of the rock itself, the basic structural elements, distributed in 3-D space, remain time stable. In the case of karstified limestone they are bedding planes, lithological changes and partings of other rocks, plus structural elements, including deflecting structures. The listed structural elements pervade the limestone and extend through it continuously, yet they gradually change their properties. In order to explain karstological issues it suffices to focus research upon a specified, well-defined block with a uniform structure that is large enough to enable recognition and understanding of all relevant structural elements. The structure revealed by such a spatially-limited limestone research-block is termed the *structural framework* (defined in the present paper). Variations of the structural elements in horizontal and vertical directions induce specific hydrological conditions within different parts of the structural framework and thus establish different conditions for karstification.

Speleogenesis is permanently in progress within limestone massifs, conditioned by the general hydrological conditions, especially the base level and hydraulic gradient. Depending upon the actual structural conditions locally various initial corrosional widenings can develop into a plethora of different cavities, active and abandoned water channels, and other accessible or inaccessible speleological objects (Gams, 2003). All speleological objects and other karst phenomena of all types and sizes within a studied block (*speleogenetic space* - Šušteršič, 1991, 1999) form the (spatial) *speleogenetic network* (defined in the present paper). Development within it is also influenced by aspects of locally and regionally active tectonics. During the course of karstological research it is necessary

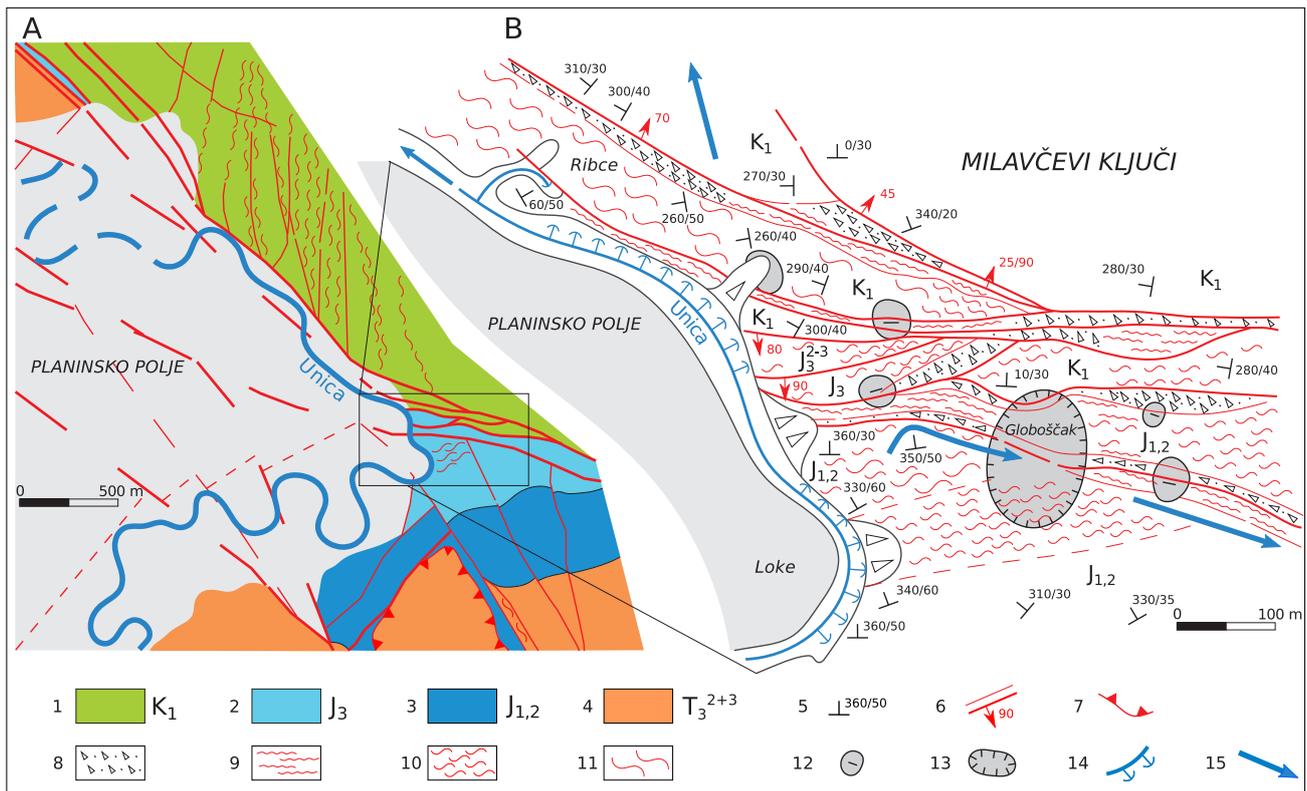


Fig. 11. Drawings A and B: General geological and hydrological situation in the area of Milavčevi ključiči at Planinsko polje. Drawing A: Geological situation at the Milavčevi ključiči ponor zone.

Drawing B: Tectostratigraphical and structural situation; indicated are bedrock fracturation and hydrological relations.

1. Dark-grey, bedded, limestone
2. Coarse grained, white, dolomite and limestone; micritic and oolitic limestone.
3. Different limestones and bituminous, coarse grained, dolomites
4. Grey grained and stromatolitic dolomite
5. Dip and strike of the dolomite beds
6. Fault and dip and strike of the fault plane
7. Thrust border
8. Crushed zone; tectonic silt and breccia
9. Broken zone
10. Densely fissured zone
11. Infrequently fissured zone
12. Solution doline and the direction of the central part dip
13. Collapse doline
14. Swallow-hole area
15. Underground stream direction

to take into account the constantly changing structural conditions within the framework that result from ongoing geological evolution, especially neotectonics.

For the establishment of karst in general, and particularly for the development of karst phenomena in any limestone block, the *structural framework* is of fundamental importance. Structural elements, encompassed within the *structural framework*, direct both vertical percolation and horizontal streaming within the limestone, and influence the spatial distribution and frequency, as well as the size and shape of karst voids.

Fundamentals of the karst surface arrangement

Certainly, the most studied and the most discussed aspect of the karst phenomenon, worldwide as well as in Slovenian publications, is the karst surface itself. Gams (2003) presented a wide-ranging and thorough review (with extensive comments) of the earlier literature about different surface karst forms and phenomena, as well as various aspects of the surface karstification in Slovenia. Progress in understanding the role of remnants of speleological objects on the karst surface (Mihevc, 1996; Šušteršič, 1999), and its implications for the formation of specific landforms was far slower (Gospodarič, 1976;

Habič, 1982; Čar, 1982; 1986; Čar & Šebela, 1997; Čar & Zagoda, 2005). Whereas it appears obvious that ongoing denudation must have brought “inherited” speleological objects to the karst surface, it was not until 1996 that Mihevc published his ground-breaking paper (Mihevc, 1996). Later, Šušteršič (1998, 1999), Šebela & Čar (2000), and Mihevc (2001, 2007) expanded the ideas in several ways, thus casting more light upon the significance of unroofed caves in the architecture of the karst surface.

Habič (1986) was the first to draw attention to the complexity of the limestone karst surface in Slovenia, and he proposed the first, non-fluvial classification of karst surface entities. In addition to the more obvious, larger-scale karst phenomena he identified and named a number of specific, small-scale geomorphic features. Unfortunately, he did not pursue their possible relationships to particular aspects of the background geology. By considering the roles of geological elements, subsequent studies of the karst relief (Šušteršič, 1987, 1994a, 1998, 2006; Mihevc, 1996, 2001, 2007; Čar, 2001) extended and enriched Habič's ideas. Recognition of the effects of continuously-ongoing surface denudation led to the inclusion and adaptation of unroofed caves and other relict karst voids within the accepted scope of surface relief entities. Consequently, in parallel with the general geological approach, detailed study of inherited underground features became unavoidable (Mihevc, 1996, 2001; Šušteršič, 1998). As a result of the steady mass-removal the karst surface migrates steadily downwards, thus intersecting elements of both the structural framework and the speleogenetic network.

Gams (1966) estimated an overall lowering rate of 65 metres per million years for the karst surface in the hinterland of the Ljubljana river. Northern Mediterranean limestone lowering rates measured in the Classical Karst (18 m/Ma) and

Istrian Karst (9 m/Ma (Furlani et al., 2009). Detailed research in the region between the Idrija and Vipava rivers (Habič, 1964) and the present author's direct observations in the Idrija region suggest even greater surface lowering rates. Subsequent geological mapping (Janež, et al., 1997) revealed similar figures. In this context, new genetic and functional connections were revealed between the structural framework and various karst phenomena, in both longitudinal and vertical directions. Providing other influences (hydrological and climatic conditions) remain constant, lateral and vertical changes of the fractured zones properties are the essential cause of the variability of surface karst phenomena (Čar, 1986, 2001).

Along with the fractured and thrust-parallel-zones, the main influences upon karstification are stratification and changes in lithology, especially interbeds or partings of other rock types. Surface karst structures associated with elements of the structural framework are generally related to different evolutionary phases (Čar, 1986). Denudational lowering of the karst surface induces changes to the speleogenetic network itself. Šušteršič (1999) noted that ongoing denudation brings underground karst features to the surface. Eventually, speleological objects forming integral parts of the speleogenetic network are simply destroyed. New surface karst features related to the structural framework are constantly evolving in parallel with the annihilation of the earlier ones. Or, in other words, cave voids constantly appear to migrate upwards within speleogenetic space (Šušteršič, 1999). The same author (Šušteršič, 1998, 1999) characterized the disintegration of speleological objects close to, or at, the karst surface as the ultimate stage of speleogenesis (*speleothanatosi*). The same topic has also been tackled by several other Slovene researchers (Knez & Šebela, 1994; Geršl et al.,

Fig. 12. A section of the manuscript lithological and structural map of the area north of Laze at Planinsko polje.

1. Bedded, bituminous, limestone with thinly bedded, grained, dolomite inlays
2. Dip and strike of the dolomite beds
3. Fault and dip and strike of the fault plane
4. Crushed zone and tectonic breccia
5. Broken zone
6. Fissured zone
7. Solution doline
8. Solution doline and the direction of the central part dip
9. Recognized succession objects: U, V – collapse doline, j – unroofed cave
10. Individual limestone blocks in the broken zone
11. Weak spring in the weathered rock

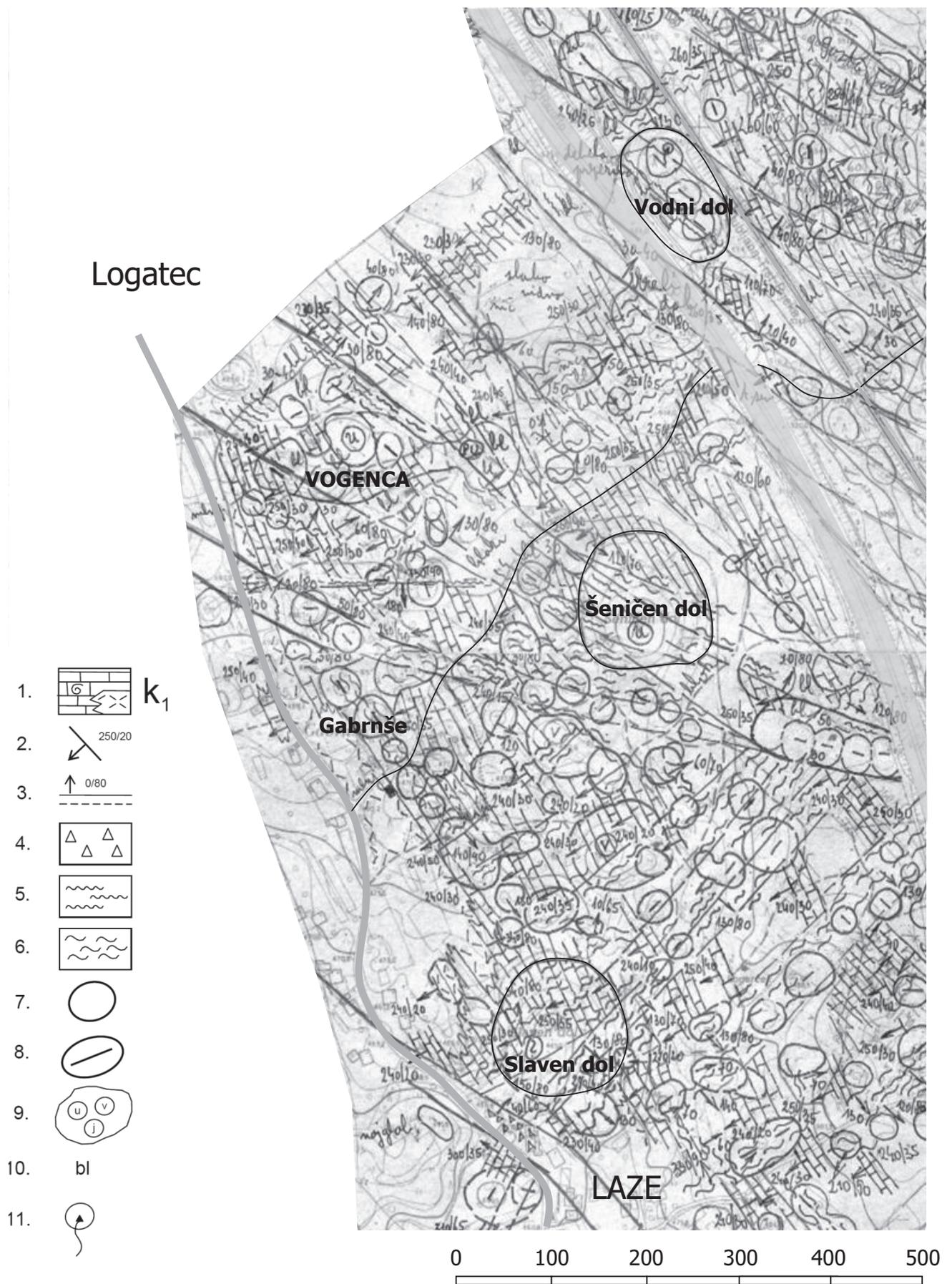


Fig. 12.

1999; Šebela, 1999; Knez & Slabe, 1999). In his 1996 paper Mihevc concluded that the remains of former caverns (*unroofed caves*) are no longer speleological objects but have become surface entities. Many former speleological objects have been removed completely, others remain identifiable and it is possible to deduce “what they used to be” (Šušteršič, 1999). All speleological relics are important contributors to the actual surface shaping (Šušteršič, 1999; Knez & Slabe, 1999; Mihevc, 2001). These were referred to as *succession objects* by Čar (2015; fig. 12, present text). Generally, *succession objects* are the still-identifiable remains of unroofed caves exhibiting various degrees of disintegration, *filled-in potholes* (Šušteršič, 1978, 1999; Knez & Slabe, 1999; Šebela, 1999; Mihevc, 2001, 2007), *collapse dolines* (Šebela & Čar, 2000), *steep-slope (originally: broken) dolines* (Čar, 2001), and other indicators of former speleological objects, including remnant speleothem and clastic cave-sediment deposits (Mihevc, 2001, 2007; Šušteršič, 2004, 2017; Stepišnik & Mihevc, 2008).

At present the criteria for determining different types of genuine surface karst phenomena, either in the formative phase, or in the phase of decay (Summerfield, 1991), remain vague. In contrast, the consecutive phases of unroofed cave disintegration, and their immediate consequences, were studied, at least in general terms, by Šušteršič (1998, 2004). Essentially the underground and surface karst objects are geological structures that have been reworked in a “karstic” way. Considering that they can be observed in different stages of (de-)formation it is of great importance to record as much field data as possible according to the methods presented in the initial paragraphs of the present paper (fig. 12). General recognition of consequent stages of surface karst phenomena development and unambiguous identification of the succession objects is of course also important. It yields an insight into the “fourth dimension” of the karst surface, i.e. into the part of the structural framework and speleogenetic network that has disappeared. It is also important to consider that the guidance of particular morphological objects may switch between different (sub-) vertical features as they follow the most advantageous combinations of structures (Čar, 1985). On the same essentially vertical route it might have come across a fissured zone and formed a characteristic *fissure doline* (Čar, 2001, fig. 1B). At a lower level it might have encountered a local fault and its volume adopted the shape of a *near-fault doline* (Čar, 2001). Or, virtually the

opposite, if the crushed zone was re-cemented, a crushed-zone ridge could appear. Of course, during longer periods, different karst voids (elements of the *speleogenetic network*) might have appeared along the same vertical trend, adapting on the way to different elements of the pre-existing *structural framework*. Great skill and experience are needed to decipher details of the various object(s) that may possibly accumulate (emerge) in succession at the surface.

Topographically-closed depressions of different dimensions, and their complementary, stand-alone, mounds or hillocks that exist in karst terrains, cannot be explained simply as a result of the intersection of the structural framework with the speleogenetic network, followed by the effects of surface mass removal. Such geomorphic features are generally tied to the effects of neotectonics, which are studied with the help of dynamic-kinematic models based upon the results of detailed structural mapping (Čar, 1982; Čar & Šebela, 1997; Čar & Zagoda, 2005; Žvab-Rožič, Čar & Rožič, 2015).

Conclusions

1. Lithological and structural mapping can help to unravel details of the interaction between geological and speleogenetic features, including the effects of denudation. Regard must be paid to: (1) mass is being removed in solution; (2) the transport of denuded material is gravity-driven and ultimately vertical; and (3) accumulation of residual sediment is negligible (Šušteršič, 1982).
2. When mapping karstified limestones special attention must be paid to making numerous measurements of dip and strike angles, determination of the spatial position of interbeds and partings of different lithologies, and other more subtle changes in the rock properties. Exhaustive collection of structural data and recognition of broken, crushed and fractured zones within and parallel to fault zones is essential.
3. Details of fracturing within fault zones vary both horizontally and vertically. For this reason the same degree (or style) of tectonic injury cannot be assumed to persist at points horizontally or vertically distant from a sample location.
4. Hydrological deflecting structures in the limestone karst – lithological barriers, thrust barriers and deflector faults – are of crucial importance to the underground hydrological situation and, consequently, also to speleogenesis.
5. All structural elements within any specific limestone block contribute to a *structural framework* that is the starting point for the creation

of the *speleogenetic network*. Speleogenetic networks include all existent karst channels, whether voids or sediment-filled. They are dynamic, constantly changing systems.

6. Taking into account climatic and hydrological influences, the karst surface is defined as the current intersection of the structural framework and the speleogenetic network, reworked and modified by present-day surface karstification and (possible) ongoing tectonic activity.

7. Karst terrain can be regarded as a dynamic, spatial, geological-hydrological and speleological-succession system, which is under the constant influence of ongoing tectonic movements.

8. Lithological and structural mapping of the karstified surface have proved to be highly productive and useful tools in deciphering both hydrogeological and engineering-geological problems in the karst.

Strukturno - geološko kartiranje zakraselih apnencev

Povzetek

V prispevku pregledno razpravljam o dopolnjeni metodologiji in rezultatih podrobnega litološkega, strukturnega in geomorfološkega kartiranja zakraselih apnenčevih terenov. Rezultati kartiranja omogočajo ugotavljanje povezav med litološko-strukturno zgradbo in različnimi kraškimi površinskimi pojavi, interpretacijo lege in razporeditve kraških površinskih pojavov v prostoru, razlago njihovih dimenzij in oblik ter medsebojnih povezav. Nadaljnji premisleki pripeljejo do globljega razumevanja dinamike razvoja kraškega površja, spoznavanja povezav s podzemljem in razlago ostankov nekdanjih speleoloških objektov na površju.

Metodika kartiranja zakraselih apnencev slo ni v osnovi na splošno uveljavljenih postopkih geološkega kartiranja dopolnjena s pogostejšim merjenjem vpadov in slemenitev plasti. Poleg različnih parametrov vrtač izrišemo tudi druge izstopajoče kraške pojave, predvsem udornice, požiralnike in vhode v jame in brezna. Po presoji izrišemo še vzpetine, tektonske brazde, prelomne stene, obliko znižanj in druge izstopajoče globeli. Prav tako moramo biti pozorni na ostanke in sledove različnih nekdanjih speleoloških objektov. Beležimo tudi "nejasne primere", ki jim lahko kasneje posvetimo večjo pozornost. Pri tem so nam v veliko pomoč LIDAR-ski posnetki. Vse ug-

otovljene geološke in druge podatke vpišemo in rišemo na terenu neposredno na karte v merilu 1: 10 000 in 1: 5000, izjemoma v večjih merilih.

Za zakrasevanja na lokalnem in regionalnem nivoju so temeljnega pomena lezike; oziroma stratifikacijska plastnatost; in litološke spremembe v apnencih. Različni litološki vložki in lezike vplivajo v prvi vrsti na splošno prepustnost apnencev ter usmerjenost in oblikovanost kraških pojavov.

Ob primernih hidroloških in klimatskih pogojih različne litološke spremembe v apnencih usmerjajo pretakanje vode in vplivajo na razpored in obliko manjših površinskih kraških pojavov, včasih tudi na velikost, obliko in prostorski razpored večjih kraških globeli. Različni vložki neapnenčastih kamnin, posebno še zgodnje in poznodiagenetskih dolomitov, so glede na debelino in razprostranjenost lahko lokalnega ali regionalnega pomena. Znotraj dobro prepustnih apnencev predstavljajo hidrološke prepreke in so zato pomembni usmerjevalci pretakanja podzemne vode in tako vplivajo na razpored speleoloških objektov. Tudi samo delno dolomitizirani apnenci se hidrološko in geomehansko precej drugače "obnašajo" kot čisti apnenci. Na površju dolomitni vložki in dolomitizirani apnenci hitreje razpadajo kot apnenci in vplivajo na oblikovanost površja.

Deformacije ob gubah, narivih in različnih prelomih so tudi v apnencih soglasne s splošnimi teorijami deformacij ob plikativnih in disjunktivnih tektonskih deformacijah. Številne odklone od teoretične geometrijske razporeditve tektonskih elementov; razložimo z litološkimi spremembami vzdolž prelomnih con, z različnimi dolžinami premikov ob prelomnih conah, večfaznim premikanjem in spreminjanjem pretrnosti vzdolž tektonskih con; oziroma energijo, ki se je ob posameznih prelomih sprostila. Pri opisu in razlagi današnjih razmer na kraških terenih je potrebno upoštevati tudi vpliv aktualnih tektonskih premikanj.

Za pravilno razlago strukture je potrebno čim pogostnejše merjenje vpadov in slemenitev plasti, kljub morebitnemu subjektivnemu občutku, da se oba elementa v prostoru ne spreminjata ali neznatno spreminjata. Tako dobimo osnove za ugotavljanje njihovega vpliva na potek zakrasevanja in vpogled v morebitne plikativne deformacije v obliki včasih tudi zelo velikih in blagih antiklinalnih ali sinklinalnih upognitev plasti. Pri gubanju se dogajajo medplastni zdrsi, pri tem nastajajo *zdrse lezike*, ki predstavljajo prednostne smeri za pretakanje vode in zakrasevanje.

Ločitev med razpoko in prelomom je dogovor-na, prehodi med njima so zvezni. Za preučevanje kraškega površja povsem zadostuje, če s prelomom označimo nezveznost v kamnini, ki ji lahko sledimo vsaj nekaj deset metrov, ostale krajše nezveznosti pa štejemo med razpoke. V okviru prelomne cone, tlačne ali natezne, se isti tipi razpok združujejo v nize, ti pa v snope, ki so dolgi od nekaj deset do več sto metrov. Razpoklinski sno-pi, ki pripadajo več prelomnim smerem, se lahko na nekem omejenem terenu med seboj združujejo ali pod različnimi koti križajo. Tako razpokano območje označimo kot *razpoklinsko cono*.

Pri razlagi velikosti in oblikovanosti kraških pojavov ter navezanost posameznih kraških objektov na strukturne elemente in njihove gene-ske posebnosti; je potrebno upoštevati različne stopnje pretrtosti apnencev. V prelomnih conah spremenjene (tektonsko prizadete) kam-nine v splošnem označimo kot *pretrte kamnine*. Glede na stopnjo pretrtosti ločimo *zdrobljene, porušene in razpoklinske cone*.

V odvisnosti od litologije in mehanskih last-nosti ob narivnicah stikajočih kamnin ter ener-gije, ki se je pri narivanju sprostila, so nastale zapleteno zgrajene obnarivne pretrte cone. So subhorizontalne in bolj ali manj vzporedne z glavno narivno ploskvijo. Razvite so tako v podrinjenem kot tudi narinjenem bloku. V gene-ski povezavi z razpoklinskimi obnarivnimi conami so *obnarivne zdrsne lezike*, ki imajo pomembno vlogo v speleogenezi in pri oblikovanju kraškega površja. Njihova izrazitost in pogost-nost je odvisna tudi od lege plasti v narinjenem kot tudi podrinjenem bloku.

V zakraselih apnencih ponavadi opazujemo ob različnih prelomih dobro definirane prelomne cone. Posebno izrazite so ob zmičnih prelomih, kjer ločimo notranjo in običajno dve zunanji prelomni coni. Notranje prelomne cone so zapolnjene z različnimi kataklastičnimi kamninami v obliko različno velikih leč, ki so med seboj ločene z notranjimi prelomnimi ploskvami. Po notranji prelomni coni, ki je navzven največkrat omejena z mejnimi prelomnimi ploskvami, poteka tudi glavna prelomna ploskev. Soglasno s spreminjanjem pretrtih con v vzdolžni in ver-tikalni smeri se ob danih hidroloških pogojih spreminja tudi prepustnost ob prelomih v vertikalni in horizontalni smeri. Zaradi tega nastanejo na površju vzdolž istega preloma različni kraški pojavi.

Pomembni strukturni elementi na krasu so *hidrološke zadrževalno-zaporne strukture*. Glede na njihovo navezanost na različne litološke in

tektonske elemente ločimo *litološke, obnarivne in prelomne hidrološke zadrževalno-zaporne strukture*. Naštete strukture niso neprepustne pregrade, pač pa slabše prepustna območja sredi dobro prepustnih apnencev, ki vodi ob določenih vodostajih le zapirajo pot in otežujejo pretok skozi strukturno območje. Njihova hidrološka vloga je dinamična in se spreminja v odvisnosti od notranje zgradbe zapor in količine vode. Zadrževalno-zaporne strukture ob nizkih vodostajih vodo ponavadi v celoti prepuščajo, ob visokih in poplavnih razmerah jo zaradi premajhne prepustnosti zadržujejo in ‚odbijajo‘. Usmerjajo jo po prepustnejših conah vzdolž struktur in sicer po porušeni in razpoklinskih conah, lezikah ter poroznih-satastih kamninah. Opisana vloga zadrževalno-zapornih struktur ustvarja pogoje za usmerjeni potek speleogeneze in nastajanje tudi velikih zapletenih jamskih sistemov.

Če v zakraselih apnencih odmislimo ap-nenčevo kamnino, ostanejo le prostorsko raz-porejani strukturni elementi in sicer lezike, litološke spremembe, vložki drugih kamnin, tektonske deformacije in hidrološko zadrževalne strukture. Našteti strukturni elementi prepredajo apnenčeve kamnine in gradijo prežemajočo prostorsko mrežo. Ker se strukturni elementi spreminjajo in razprostirajo »v neskončnost«, ponavadi reševanje krasoslovnih problemov omejimo le na določen raziskovalni blok, ki mora biti tako velik, da lahko določimo in razumemo vse strukturne elemente, ki v njem nastopajo. V takem, prostorsko omejenem raziskovalnem apnenčevem bloku, govorimo o *strukturni rešetki*. Spreminjanje strukturnih elementov v horizontali in vertikali ustvarja v različnih delih strukturne rešetke svojske hidrološke pogoje in s tem spreminjajoče pogoje zakrasevanja.

Podzemne speleološke objekte in pojave vseh oblik in velikosti v nekem raziskovanem bloku (speleogenetski prostor) združimo v prostorsko *speleogenetsko mrežo*. Na dogajanje v njej vplivata tudi aktivna lokalna in regionalna tektonika.

Z zniževanjem kraškega površja se dogajajo spremembe v strukturni in speleogenetski rešetki. Medtem, ko v okviru strukturne rešetke zaradi zniževanja terena poleg izginjanja starejših nastajajo ob sočasem zakrasevanju tudi novi površinski kraški objekti, se odvija v okviru speleogenetske rešetke le postopno izginjanje speleoloških objektov. Ostanki nekdanjih podzemskih jam seveda niso več speleološki objekt pač pa površinski objekti. Veliko nekdanjih speleoloških objektov je že povsem izginilo, drugi

so še razpoznavni in lahko ugotovimo, kaj so nekoč bili. Vsi speleološki relikti, ali bolje rečeno speleološki objekti v zadnji fazi speleogeneze, pomembno sooblikujejo kraško površje. Imenujemo jih *nasledstveni objekti*. K njim prištevamo različno spoznavne ostanke brezstropih jam in zasutih brezen, udornic in porušnih vrtač in druge sledove nekdanjih speleoloških objektov ter tudi ostanke jamskih sedimentov.

Na podlagi povedanega lahko kraški teren opredelimo kot aktualen presek strukturne rešetke in speleogenetske mreže. V pogledu procesov pa je kraško površje dinamičen prostorsko hidrogeološki in speleološki-nasledstveni sistem, ki se spreminja pod stalnim vplivom aktualnih tektonskih premikanj in klimatskih razmer.

Za zaključek naj omenim, da smo idrijski geologi metodiko podrobnega strukturnega kartiranja uspešno uporabljali tudi pri reševanju hidrogeoloških in inženirsko-geoloških problemov v najrazličnejših kamninah na številnih lokacijah po Sloveniji.

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References

- Auber, D. 1966: Phénomènes et formes du Karst jurassien. *Eclogae Geol. Helv.*, 62/2: 325-399.
- Bahun, S. 1969: On the formation of karst dolinas. *Geološki vjesnik*, 22: 25-32.
- Bahun, S. 1979: Model razvoja hidrogeologije nekih polja u dinarskom kršu. In: Čičić, S. (ed.): *Zbornik radova, IX kongres geolog Jugoslavije*, Sarajevo: 855-861.
- Bauer, H. Schröckenfuchs, T.C. & Decker, K. 2016: Hydrogeological properties of fault zones in a karstified carbonate aquifer (Northern Calcareous Alps, Austria). *Hydrogeology Journal*, 24/5: 1147-1170. <https://doi.org/10.1007/s10040-016-1388-9>
- Brenčič, M. 1996: Konceptualni model razvoja krasa = Conceptual approach to modeling karst development. *Geologija*, 37/38 (1994/95): 391-414. <https://doi.org/10.5474/geologija.1995.015>
- Cvijić, J. 1924: *Geomorfologija*. Knjiga prva, Državna štamparija, Beograd.
- Cucchi, F., Forti, F. & Ulcigrai, F. 1976: Relazioni tra tettonica e morfogenesi di doline del carso Triestino e Monfalconese. *Istituto di Geologia e Paleontologia dell'Università di Trieste*. Trieste.
- Čalić, J. 2009: Uvala-contribution to the study of karst depressions, with selected examples from Dinarides and Carpatho-Balkanides. *Dissertation*. Univerza v Novi Gorici, Nova Gorica: 213 p.
- Čar, J. 1974: Zakriti kras v bližnji okolici Idrije. *The covered karst in the near Idrija vicinity*. *Naše jame*, 16: 51-62.
- Čar, J. 1982: Geološka zgradba požiralnega obrobja Planinskega polja = Geologic setting of the Planina polje ponor area. *Acta carsologica*, 10 (1981): 75-105.
- Čar, J. 1986: Geološke osnove oblikovanja kraškega površja = Geological bases of karst surface formation. *Acta carsologica*, 24/25 (1985-86): 31-38.
- Čar, J. 1996: Geološka zgradba Divjega jezera. V: *Kulturni in naravni spomeniki Slovenije: zbirka vodnikov*. Ljubljana, Ministrstvo za kulturo, Uprava Republike Slovenije za kulturno dediščino, 26-37, Ljubljana.
- Čar, J. 2001: Structural Bases for Shaping of Dolines = Strukturne osnove oblikovanja vrtač. *Acta carsologica* 30/2, 239-256, Ljubljana.
- Čar, J. 2010: Geološka zgradba idrijsko - cerkljanskega hribovja = Tolmač h geološki karti idrijsko - cerkljanskega hribovja med Stopnikom in Rovtami 1: 25 000 = Geological structure of the Idrija - Cerklno hills. *Explanatory Book to the Geological map of the Idrija - Cerkljansko hills*. Geological Survey of Slovenija, Ljubljana: 127 p.
- Čar, J. 2015: Geološko kartiranje zakraselih apnencev. *Geološki zbornik*, 23: 22-27.
- Čar, J. & Gospodarič, R. 1984: O geologiji krasa med Postojno, Planino in Cerknico = About geology of karst among Postojna, Planina and Cerknica. *Acta carsologica*, 12 (1983): 91-106.
- Čar, J. & Gospodarič, R. 1988: Geološka zgradba in nekatere hidrološke značilnosti bruhalnika Lijaka = Geological Setting and some Hydrological Properties of Lijak Effluent. *Acta carsologica*, 17/1: 13-32.

- Čar, J. & Janež, J. 1992: Strukturno-geološke in hidrogeološke razmere izvirov Možnice = Structural-geological and hydrogeological conditions at the Možnica springs. *Acta carsologica*, 21 (1992): 77-96.
- Čar, J. & Pišljari, M. 1993: Presek Idrijskega preloma in potek doline Učje glede na prelomne strukture = Cross section of the Idrija fault and the course of the Učja valley regarding the fault structures. *Rudarsko-metalurški zbornik*, 40: 79-91.
- Čar, J. & Šebela, S. 1997: Structural position of vertical karst objects on Postojnska Gmajna = Strukturna lega vertikalnih kraških objektov na Postojnski gmajni. *Acta carsologica*, 26/2, 295-314.
- Čar, J. & Šebela, S. 1998: Bedding planes, moved bedding planes, connective fissures and horizontal cave passages (Examples from Postojna jama cave) = Lezike, zdrzne lezike, vezne razpoke in horizontalni rovi (Primeri iz Postojnske jame). *Acta carsologica*, 27/2: 75-95.
- Čar, J. & Šebela, S. 2001: Kraške značilnosti naravnega stika apnenec-dolomit pri Predjami – Karst characteristics of thrust contact limestone-dolomite near Predjama. *Acta carsologica*, 30/2: 141-156.
- Čar, J. & Zagoda, B. 2005: Strukturna lega Habečkovega brezna (Idrijsko, Slovenija) Structural position of the shaft Habečkovo Brezno (Idrijsko, Slovenia). *Acta carsologica*, 34/1: 113-133.
- Davies, W.E. 1960: Origin of Caves in Folded Limestone. *Bulletin of the National Speleological Society*, 22/1: 5-18.
- Ford, D.C., & Williams, P.W. 2007: Karst geomorphology and hydrology. 2nd ed. John Wiley & Sons, Chichester, U.K.
- Furlani, S., Cucchi, F., Forti, F. & Rossi, A. 2009: Comparison between coastal and inland Karst limestone lowering rates in the northeastern Adriatic Region (Italy and Croatia). *Geomorphology*, 104:73-81. <https://doi.org/10.1016/j.geomorph.2008.05.015>
- Gams, I. 1966: K hidrologiji ozemlja med Postojnskim, Planinskim in Cerkljanskim poljem. *Acta carsologica*, 4: 5-54.
- Gams, I. 1973: Slovenska kraška terminologija, Ljubljana.
- Gams, I. 1974: Kras. Zgodovinski, naravoslovni in geografski oris. Slovenska matica. Ljubljana: 358 p.
- Gams, I. 2003: Kras v Sloveniji v prostoru in času. ZRC SAZU, Ljubljana: 516 p.
- Geršl, M., Stepišnik. U. & Šušteršič, S. 1999: The »unroofed cave« near the bunker (laški Ravnik – Brezstropa jama pri bunkerju (Logaški Ravnik). *Acta carsologica*, 28/2: 77-90.
- Gladkov, V. G. 1967: O strukturnih formah pojavljanja razryvnyh narušenj. *Dok. Akad. nauk SSSR*, 172, 5, Moskva.
- Gospodarič, R. 1976: Razvoj jam med Pivško kotlino in Planinskim poljem v kvartarju = The quaternary caves development between Pivka basin and Polje of Planina. *Acta carsologica*, 7: 8-135.
- Gospodarič, R. 1982: Morfološki in geološki položaj kraških votlin v ponornem obrobju Planinskega polja = Morphologic and Geologic Situation of Caves at the Planina Polje Ponor Boundary. *Acta carsologica*, 10: 156-171.
- Gospodarič, R. 1986: O geološkem razvoju klasičnega krasa = About the geological development of classical Karst. *Acta carsologica*, 14/15 (1985-86): 19-29.
- Gospodarič, R. & Habič, P. (ur.) 1976: Underground Water Tracing. Investigations in Slovenia 1972-1975. Institute for Karst Research, SAZU, Postojna. Ljubljana: 309 p.
- Habič, P. 1982: Kraški relief in tektonika = Karst Relief and Tectonics. *Acta carsologica*, 10: 23-42.
- Habič, P. 1984: Novo vrednotenje tektonske oblikovanosti reliefa v zahodni Sloveniji = New evaluation of tectonic relief forming in the Western Slovenia. *Geografski vestnik*, 56: 3-12.
- Habič, P. 1986: Površinska razčlenjenost dinarskega krasa = Surface dissection of Dinaric karst. *Acta carsologica*, 14/15: 39-58.
- Herak, M. 1977: Tecto-genetic Approach to the Classification of Karst Terrains. *Krš Jugoslavije*, 9/4: 227-238.
- Herak, M. 1986: Geotektonski okvir zaravni u kršu = Geotectonic frame of karst plains. *Acta carsologica*, 14/15 (1985-86): 11-18.
- Janež, J. & Čar, J. 1990: Kraški izvir Kajža in njegovo zaledje = Karst spring Kajža and its hydrological background. *Acta carsologica*, 19: 101-138.
- Janež, J., Čar, J., Habič, P. & Podobnik, R. 1997: Vodno bogastvo Visokega krasa. Ranljivost kraške podzemne vode Bajnsic, Trnovskega gozda, Nanosa in Hrušice. *Geologija d.o.o. Idrija, Idrija*: 167 p.
- Jenko, F. 1959: Hidrologija in vodno gospodarstvo krasa. Ljubljana.
- Jurkovšek, B. 2010: Geološka karta severnega dela Tržaško-komenske planote 1: 25 000

- Geological Map of the Northern part of the Trieste-Komen Plateau 1: 25 000, Explanatory Book. Geološki zavod Slovenije, Ljubljana: 72 p.
- Knez, M. 1996: Vpliv lezik na razvoj kraških jam. Primer Velike doline, Škocjanske jame. ZRC SAZU, Ljubljana.
- Knez, M. & Šebela, S. 1994: Novo odkriti kraški pojavi na trasi avtoceste pri Divači. Naše jame, 36: 102.
- Knez, M. & Slabe, T. 1999: Unroofed caves and recognising them in karst relief (discoveries during motorway construction at Kozina, South Slovenia) = Jame brez stropa in njihovo razpoznavanje na kraškem površju (odkrite pri gradnji avtoceste pri Kozini, južna Slovenija). Acta carsologica, 28/2: 103-112.
- Lowe, D. & Gunn, J. 1997: Carbonate Speleogenesis: An Inception Horizon Hypothesis. Acta carsologica, 26/2: 38, 457-488.
- Mihevc, A. 1994: Contact karst of Brkini Hills = Brkinski kontaktni kras. Acta carsologica, 23: 100-109.
- Mihevc, A. 1996: Brezstropa jama pri Povirju = The cave Brezstropa jama near Povir. Naše jame, 38: 65-76.
- Mihevc, A. 2001: Speleogeneza Divaškega krasa. Založba ZRC, ZRC SAZU: 5-180.
- Mihevc, A. 2007: The age of Karst relief in west Slovenia = Starost kraškega reliefa v zahodni Sloveniji. Acta carsologica, 36/1: 35-44. <https://doi.org/10.3986/ac.v36i1.206>
- Mlakar, I. 1969: Krovna zgradba idrijsko žirovskega ozemlja = Nappe Structure of the Idrija-Žiri Region. Geologija, 12: 5-72.
- Mlakar, I. & Čar, J. 2009: Geološka karta idrijsko – cerkljanskega hribovja med Stopnikom in Rovtami 1 : 25. 000. Geološki zavod Ljubljana.
- Pavšič, J. (ur.) 2006: Geološki terminološki slovar. Založba ZRC, Ljubljana: 331 p.
- Pezdič, J., Šušteršič, F. & Mišič, M. 1998: On the role of clay-carbonate reactions in speleoinception: a contribution on undestending of the earliest atage of karst channel formation. Acta carsologica, 27/1: 187-200.
- Placer, L. 1972: Usmerjenost kraških jam na Idrijskem = The orientation of karstic caves in the region of Idrija. Naše jame, 13 (1971): 71-76.
- Placer, L. 1973: Rekonstrukcija krovne zgradbe idrijsko žirovskega ozemlja = Reconstruction of the Nappe Structure of the Idrija-Žiri Region = Rekonstruktion des Deckenbaus des Idrija-Žiri gebietes. Geologija, 16: 317-334.
- Placer, L. 1981: Geološka zgradba jugozahodne Slovenije = Geologic structure of southwestern Slovenia. Geologija, 24/1: 27-60.
- Placer, L. 1982: Tektonski razvoj idrijskega rudišča = Geologic history of the Idrija mercury deposit. Geologija, 25/1: 7-94.
- Placer, L. 1999: Contribution to the macrotectonic subdivision of the border region between Southern Alps and External Dinarides = Prispevek k makrotektonski rajonizaciji mejnega ozemlja med Južnimi Alpami in Zunanji Dinaridi. Geologija, 41 (1998): 223-255. <https://doi.org/10.5474/geologija.1998.013>
- Placer, L. 2008: Principles of the tectonic subdivision of Slovenia = Osnove tektonske razčlenitve Slovenije. Geologija, 51/2: 205-217. <https://doi.org/10.5474/geologija.2008.021>
- Placer, L. 2015: Poenostavljena strukturno-geološka karta Krasa. Geološki zbornik, 23: 151-152.
- Poljak, M. 2007: Strukturno-tektonska karta Slovenija 1: 250 000 = Structural-Tectonic Map of Slovenia 1: 250 000. Geološki zavod Slovenije, Ljubljana.
- Sauro, U. 1995: Highlights on doline evolution. In: Barany-Kevei L. (ed.): Environmental effects on Karst Terrains (homage to Laszlo Jackucs). Acta Geographica, Scegedinsis, 34:107-121.
- Sauro, U. 2013: Landforms of mountainous karst in the middle latitudes: reflections, trends and research problems = Relijefne oblike gorskega krasa srednjih geografskih širin: razmišljanja, trendi in raziskovalni problemi. Acta carsologica, 42/1: 5-16. <https://doi.org/10.3986/ac.v42i1.629>
- Stepišnik, U. & Mihevc, A. 2008: Investigation of structure of various surface karst formations in limestone and dolomite bedrock with application of the Electrical resistivity imaging = Proučevanje zgradbe različnih kraških oblik v apnencih in dolomitih z uporabo metode električne upornosti tal. Acta carsologica, 37/1, 133-140. <https://doi.org/10.3986/ac.v37i1.165>
- Summerfield, M. A. 1991: Global Geomorphology. Longman, Singapore: 537 p.
- Šebela, S. 1991: Vpliv površinskih geoloških struktur na oblikovanje Predjame. Magistrsko delo. Inštitut za raziskovanje krasa ZRC SAZU, Postojna: 115 p.
- Šebela, S. 1992: Geološke značilnosti Pisanega rova Postojnske jame = Geological characteristic of Pisani rov in Postojna cave. Acta carsologica, 21: 97-116.
- Šebela, S. 1994: Vloga tektonskih struktur pri nastajanju jamskih rovov in kraških površinskih oblik. Doktorska disertacija. Univerza v Ljubljani, FNT, Ljubljana: 129 p.

- Šebela, S. 1998: Tektonska zgradba sistema Postojnskih jam = Tectonic Structure of Postojnska jama Cave System. Zbirka ZRC, 18: 112 p.
- Šebela, S. 1999: Morphological and Geological Characteristics of two denuded caves in SW Slovenia = Morfološke in geološke značilnosti dveh denudiranih jam v JZ Sloveniji. *Acta carsologica*, 28/2: 175-185.
- Šebela, S. & Čar, J. 1991: Geološke razmere v podornih dvorinah Vzhodnega rova Predjame = Geological setting of collapse chambers in Vzhodni rov in Predjama cave. *Acta carsologica*, 20: 205-222.
- Šebela, S. & Čar, J. 2000: Velika Jeršanova dolina - a former collapse doline = Velika Jeršanova dolina - nekdanja udornica. *Acta carsologica*, 29/2: 201-212. <https://doi.org/10.3986/ac.v29i2.460>
- Šušteršič, F. 1978: Some considerations about the infilled potholes and their filling (in Slovenian, English summary). *Naše jame*, 19: 7-14.
- Šušteršič, F. 1982: Morfologija in hidrografija Najdene jame = Morphology and Hydrography of Najdena jama, *Acta carsologica*, X: 127-153.
- Šušteršič, F. 1987: Drobno kraško površje ob severovzhodnem obrobju Planinskega polja = The small-scale surface karst and solution dolines at the north-eastern border of Planinsko polje. *Acta carsologica*, 16/3: 51-82.
- Šušteršič, F. 1994a: Jama Kloka in začetje = The cave Kloka and the speleo-inception. *Naše jame*, 36: 9-30.
- Šušteršič, F. 1994b: Classic dolines of classical site = Klasične vrtače klasičnega krasa. *Acta carsologica*, 23/10 (1994): 123-154.
- Šušteršič, F. 1986: The pure karst model and the speleo-inception. *Acta carsologica*, 14/15 (1985/86): 59-70.
- Šušteršič, F. 1998: Interaction between a cave system and the lowering karst surface; Case study: Laški ravnik = Jamski sistemi in nižajoče se površje krasa; vzorčni primer: Laški ravnik. *Acta carsologica*, 27/2: 115-138.
- Šušteršič, F. 1999a: Is the karst becoming more predictable? = Ali je kras bolj predvidljiv? *RMZ*, 46/3: 583-599.
- Šušteršič, F. 1999b: Vertical zonation of the speleogenetic space = Vertikalna conacija speleogenetskega prostora, *Acta carsologica*, 28/2: 187-201.
- Šušteršič, F. 2000: Are collapse dolines formed only by collapse? *Acta carsologica*, 29/2: 213-230.
- Šušteršič, F. 2002: Collapse dolines and deflector faults as indicators of karst flow corridors. *Int. Journal of Speleology*, 31: 115-127. <https://doi.org/10.5038/1827-806X.31.1.6>
- Šušteršič, F. 2004: Cave sediments and denuded caverns. In: Sasowsky, I.D. & Mylroie, J. (eds.): *Studies of Cave Sediments*. Kluwer Academic/Plenum, New York: 129 p.
- Šušteršič, F. 2006: Relationships between deflector faults, collapse dolines and collector channel formation: some examples from Slovenia. *International Journal of Speleology*, 35/1: 1-12. <https://doi.org/10.5038/1827-806X.35.1.1>
- Šušteršič, F. (gost. ur.) 2013: Glas podzemlja: jubilejna izdaja ob 50-letnici preboja v Radeščkovi pasaži. Društvo za raziskovanje jam, Ljubljana: 64 p.
- Šušteršič, F. 2017: A conceptual model of Dinaric Solution Doline dynamics. *Cave and Karst Science*, 44/2: 66-75.
- Šušteršič, F. & Čar, J. & Šebela, S. 2001: Zbirni kanali in zaporni prelomi = Collector channels and deflector faults. *Naše jame*, 43: 8-21.
- Twiss, R. J. & Moores, E. M. 1992: *Structural geology*. Ereeman and Company, New York: 532 p.
- Vrabec, M., Šmuc, A., Pleničar, M. & Buser, S. 2009: Geološki razvoj Slovenije = Geological evolution of Slovenia – an overview. In: Pleničar, M., Ogorelec, B. & Novak, M. (eds.): *Geologija Slovenije = Geology of Slovenia*. Geološki zavod Slovenije, 23-40.
- Woodcock, N. H. & Schubert, C. 1994: Continental Strike-Slip Tectonics. In: Hancock P. L. (ed.): *Continental Deformation*, Pergamon Press, Oxford.
- Zagoda, B. 2004: Karstification along the thrust contact between the dilomite and limestone in Idrijski Log and Koševnik = Zakrasevanje ob narivnem stiku dolomit in apnenca v Idrijskem Logu in Koševniku. *Acta carsologica*, 33/2: 55-74. <https://doi.org/10.3986/ac.v33i2.291>
- Zogovič, D. 1966: Hidrogeološka uloga dolomitita u dinarskom karstu. *Vesnik, inženirska geologija i hidrogeologija*. Zavod za geološka i geofizička istraživanje, Ser. B: 5-112.
- Žvab Rožič, P., Čar, J. & Rožič, B. 2015: Geological Structure of the Divača Area and its Influence on Kačna Cave Speleogenesis and Hydrogeology = Geološka struktura na območju Divače in njen vpliv na speleogenezo ter hidrološke značilnosti Kačne jame. *Acta carsologica*, 44/2: 153-168. <https://doi.org/10.3986/ac.v44i2.1958>