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Cover page: The Gaberke canyon. The torrent stream of Velunja has carved a deep canyon above the mining tunnels. 1st prize at the photo contest Geoscience for Society in the scope of this year's 5th Slovenian Geological Congress. (photo: A. Kavčnik)

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Manj sivine

(uvodnik)

Jasna, neposredna in merljiva dobrobit, ki jo ustvarjajo geoznanosti in predvsem koristi, ki jih ima in bi jih lahko imela od njih družba, so nam, bralcem Geologije, dobro znane. Ob vrhunskem raziskovanju je vsaj enako pomembno ali še pomembnejše vračanje rezultatov družbi v obliki neposredno uporabnih rezultatov. Tega se zavedamo in v tej smeri tudi delujemo, kar je dokazala tudi izjemna raznolikost znanstvenih in strokovnih prispevkov na petem slovenskem geološkem kongresu, ki sta ga Slovensko geološko društvo in Geološki zavod Slovenije s partnerji organizirala med 3. in 5. oktobrom 2018 v Velenju.

Vprašanje pa je, ali se tudi okolje oziroma družba, v kateri delujemo, v zadostni meri zaveda, da je znanje o lastnostih našega planeta temelj za sonaravni razvoj, da se brez temeljnega geološkega znanja ne bi mogli, ali se ne bi smeli izvesti nobeni večji infrastrukturni, energetski in okoljski projekti? Se, pa ne dovolj. Zato smo si kot enega od ključnih ciljev petega kongresa zastavili, da jasno povemo širšemu družbenemu okolju, naj vendar več in bolje uporablja naše znanje.

Med vrsto vrhunskih predavanj in posterjev smo tako na kongresni program uvrstili tudi okroglo mizo z uglednimi razpravljavci z naslovom: Je Slovenija pripravljena na uporabo geološkega znanja pri svojem razvoju? Cilj okrogle mize je bil odpreti razpravo o tem, ali sta zbiranje in dostopnost geoloških podatkov v Slovenji primerno urejeni. Ali so ti podatki sistematično zbrani, interpretirani in razpoložljivi vsem, ki vstopajo v procese kakršnihkoli posegov v prostor. V kontekstu razprave o vlogi in pomenu geoznanosti za družbo smo povabili tudi plenarna predavatelja iz dveh največjih geoloških združenj v Evropi in vodilno svetovno povezovalko znanosti in strokovnega dela. Vsi trije so predavanja posvetili povezovanju znanosti s strokovnim delom, pomenu in izjemnim koristim našega znanja za sodobno družbo. Spregovorili pa so o še eni, še kako pomembni temi, o geoetiki.

Večina geoznanstvenikov se tudi izven strogo strokovnega okolja trudi približati geoznanost našim deležnikom in graditi zavedanje o njenem pomenu. Odziv se izboljšuje in upam si trditi, da so časi za našo stroko dobri, in da se znamo vse bolje sporazumevati z uporabniki našega znanja.

Črni časi za našo stroko so torej za nami. So, ampak še dlje za nami so ostali tudi zlati časi za geologijo, ki so bili, ne naključno, tudi zlati časi za družbo in za njen ekonomski razvoj. Zato moramo vztrajati pri povezovanju in prebujanju geološke stroke in prebudili bomo tudi družbo, da se bo ta začela še bolj zavedati njenega pomena.

Če kje, se ravno v naši stroki zavedamo, da v naravi ni nič končnega. Zavedamo se, da se vse spreminja in zato bi bilo napačno razmišljati, da bi lahko z enim velikim dokončnim korakom spremenili percepcijo naše stroke v okolju. Potrebna je množica malih korakov proti cilju. Z malimi koraki lažje obvladujemo in tudi usmerjamo spremembe na tej poti. In kaj nas na njej čaka? Ob upoštevanju najnovejših smernic stroke in znanosti je treba strniti vse znanje in izkušnje pri nikoli končanem posodabljanju programa izobraževanja geologov. Z vsemi močmi moramo podpreti prizadevanja naših kolegov za uvajanje geoloških vsebin v šolski sistem. Naši otroci nas morajo bolje razumeti kot naši sodobniki. Predvsem pa nas čaka ureditev geološke zakonodaje, ki mora postaviti stroko in državo nazaj na zemljevid držav, ki svoj trajnostni razvoj temeljijo na odkrivanju in ne skrivanju dognanj o zgradbi in lastnostih svojega podpovršja. Brez tega ne bo šlo. Ob posodabljanju geološke zakonodaje ne smemo pozabiti na široko sodelovanje pri prizadevanjih inženirskega dela naše stroke, da si s kakovostnim delom in stalnim izobraževanjem zagotavlja svoje mesto na zahtevnih in visoko konkurenčnih področjih svojega dela.

Peti geološki kongres je pokazal enotnost stroke, da ribarjenja v kalnem in ustvarjanja sivin zaradi nedosegljivosti geoloških podatkov ne koristi nikomur. Potrebujemo urejenost in jasno določena sedišča na vlaku, ki potuje v eno smer, v smer urejenosti in dostopnosti sodobno interpretiranih geoloških podatkov.

Trenutek je torej pravi. Nenazadnje o tem govori tudi udeležba visokih gostov na kongresu in za organizatorje presenetljivo pozitiven odziv raznovrstnih uglednih podjetij in drugih deležnikov, ki so pristopili k partnerstvu ali sponzorstvu kongresa. Tudi to je dokaz, da se dojemanje potrebe po sodelovanju z geološko stroko izboljšuje.

Simbolično ali ne, naključno ali ne, z velikim veseljem izpostavljam, da tokratna tiskana izdaja Geologije spet prihaja med nas v barvah, ki zamenjujejo sivino. Čestitam avtorjem, ki s kvalitetnimi prispevki hitro dvigujete raven naše stanovske znanstvene revije in čestitam uredništvu, ki s svojimi prizadevanji to uspešno podpira.

dr. Miloš Bavec, direktor GeoZS

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Geostructural mapping of karstified limestones

Strukturno-geološko kartiranje zakraselih apnencev

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Key words: geostructural mapping of karstified limestones, plicative deformations, thrust– shear–deformations, fault induced deformations, structural framework, speleogenetic network, karst surface shaping

Ključne besede: strukturno-geološko kartiranje zakraselih apnencev, deformacije pri gubanju, obnarivne deformacije, prelomne in obprelomne deformacije apnencev, strukturna rešetka, speleogenetska mreža, oblikovanje kraškega površja

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 intebeds 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 kraškga površja. Pri kartiranju obnarivno in obtektonsko 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 podzemske 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 desceibed for the structural mapping of karstified limestone evolved predominantly in the karst close to Idrja 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 "subthrast 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 & Pišljar, 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; Vrabec 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

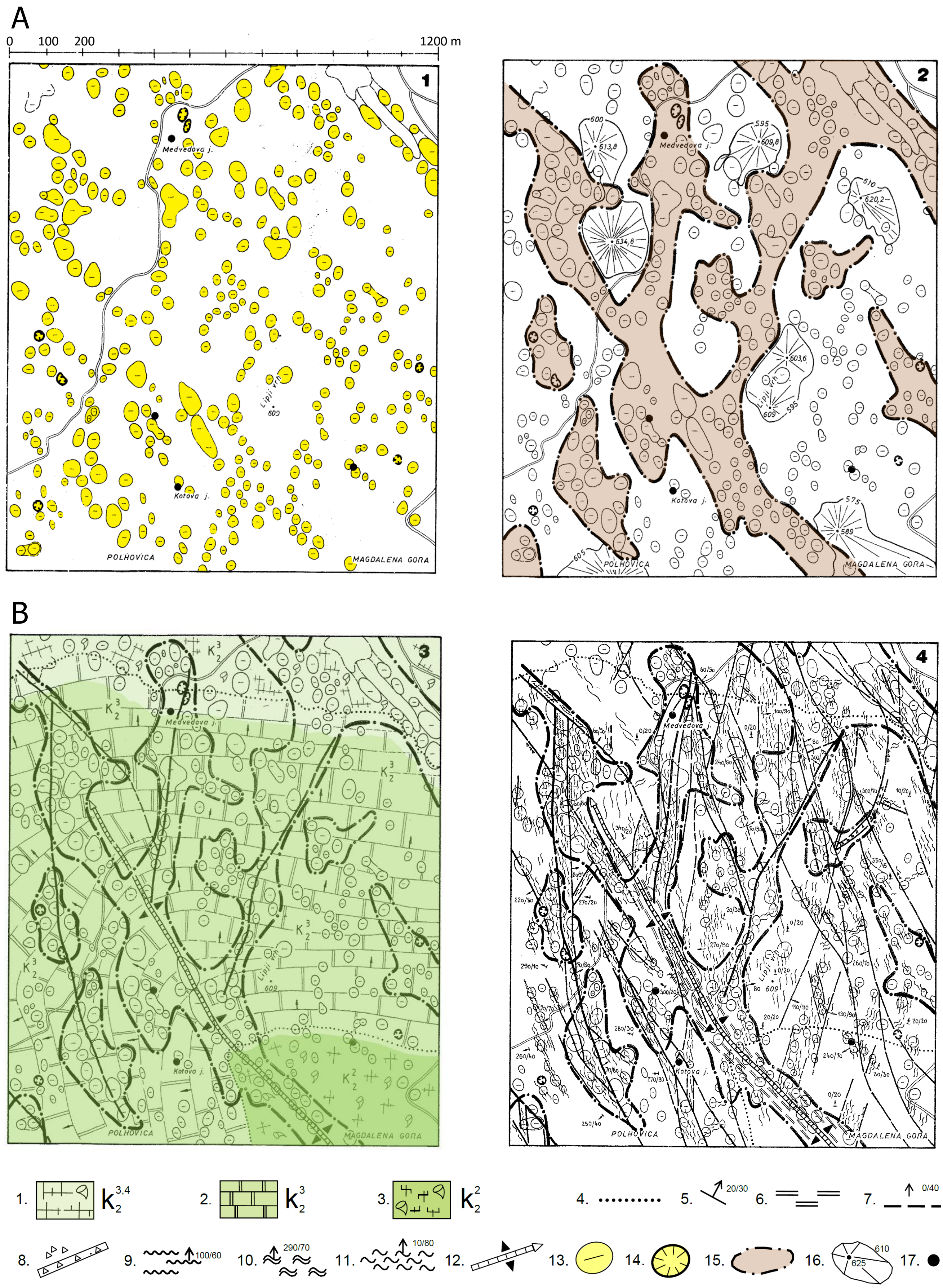
A1 - Areal distribution of (solution) dolines – the result of terrestrial mapping

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


A
0 100 200 1200 m
1
2
Medvedova j.
Kotova j.
POLHOVICA
MAGDALENA GORA
600
613,8
634,8
595
609,8
610
620,2
603,6
575
589
605
B
3
4
K$_2^3$
K$_2^2$
1. K$_2^{3,4}$
2. K$_2^3$
3. K$_2^2$
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9. 100/60
10. 290/70
11. 10/80
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16. 610 625
17.

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, is 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.

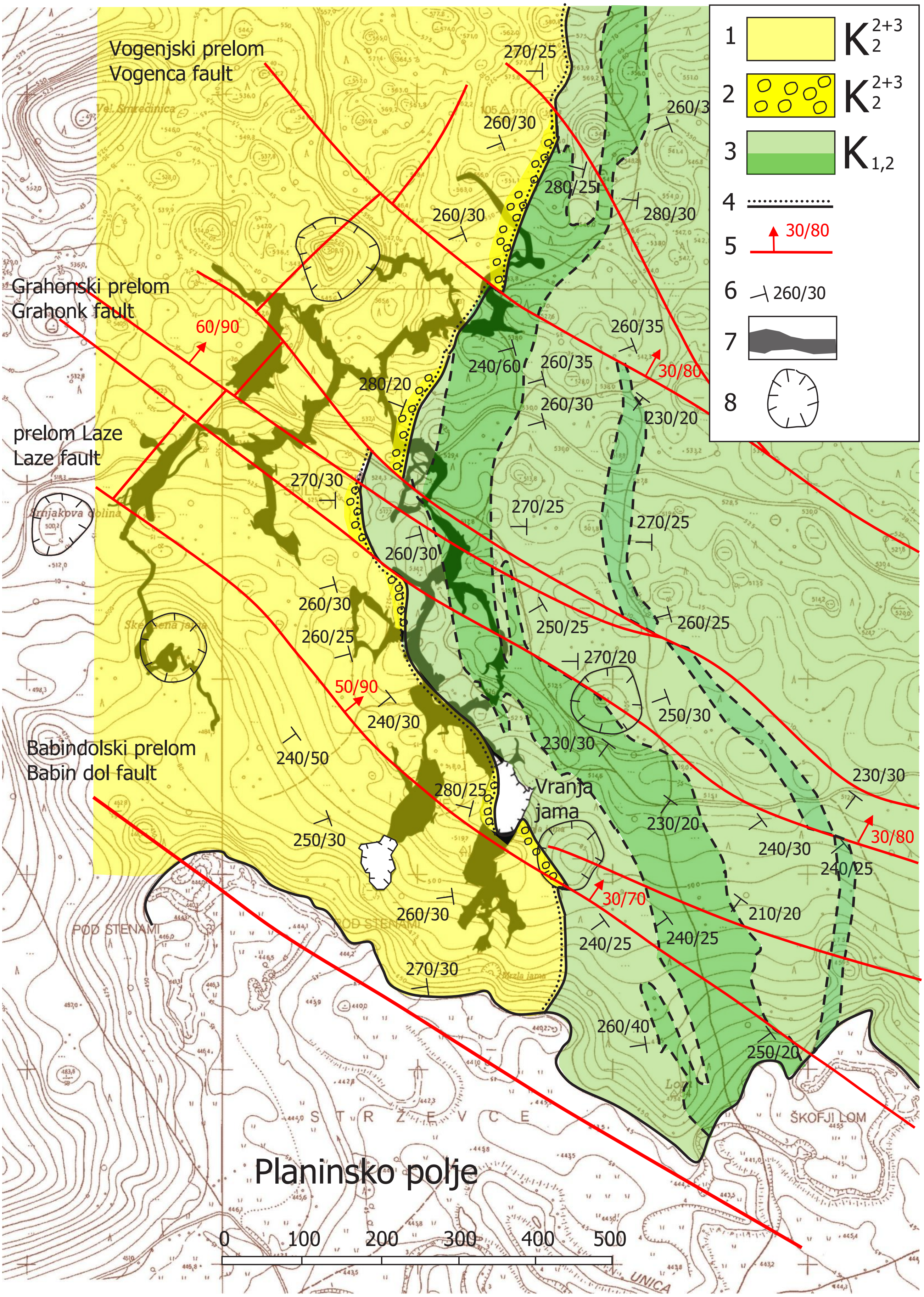
Stratification

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-Createcous 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


Vogenjski prelom
Vogenca fault
Grahonski prelom
Grahonk fault
prelom Laze
Laze fault
Babindolski prelom
Babin dol fault
Vranja jama
Planinsko polje
0 100 200 300 400 500
1 K 2+3 2
2 K 2+3 2
3 K 1,2
4
5 30/80
6 260/30
7
8
60/90
50/90
30/80
30/70
270/25
260/30
280/25
280/30
240/60
260/35
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PO D STENAMI
S T R Ž E V C E
ŠKOFJI LOM
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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 kartstification 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 basically 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), Ćalić, (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 deformatios

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

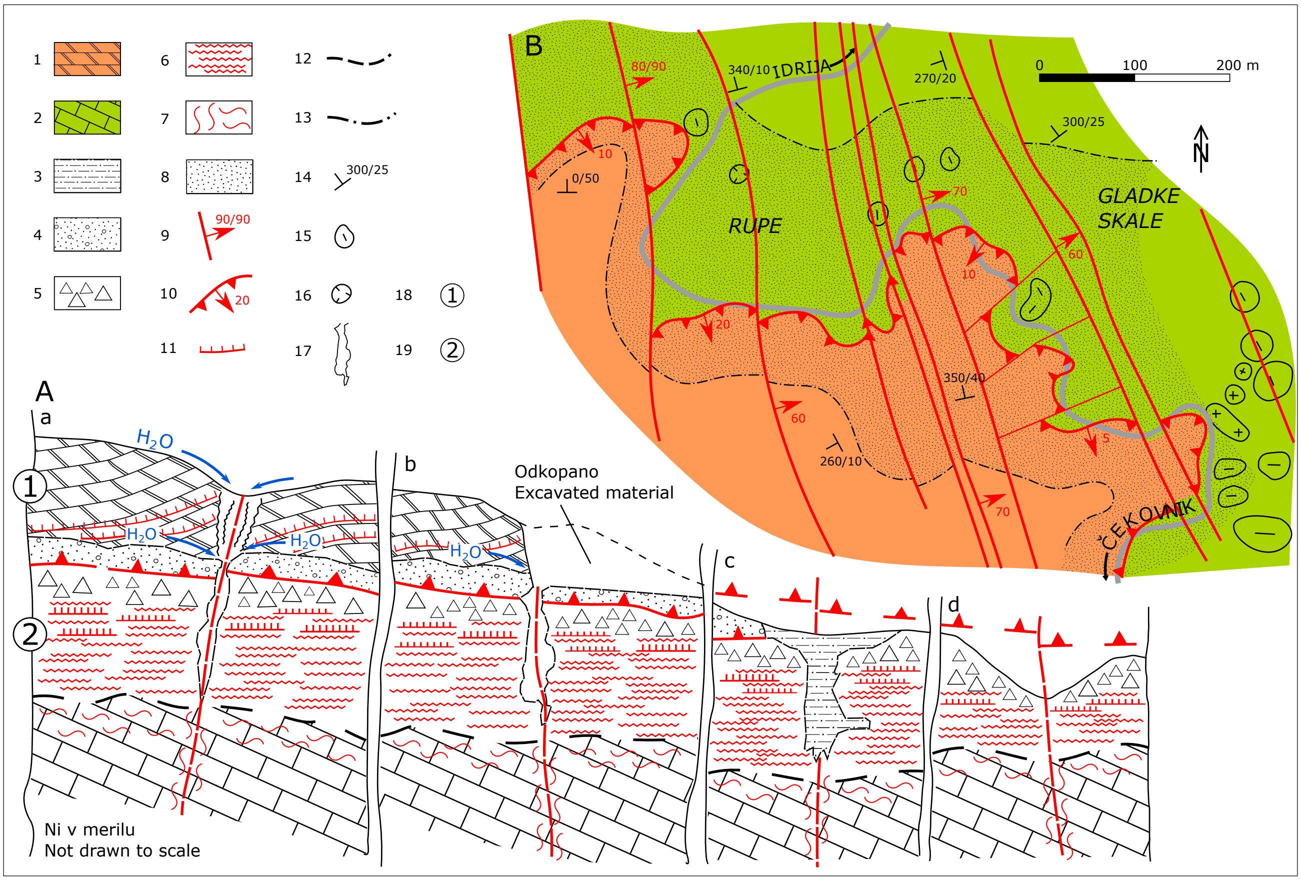


Fig. 3. Parallel to thrust structural and karst features.

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-Createaceous limestone fractured in the thrust plane vicinity
3. Clayey weathering products
4. Crushed zone in dolomite (overthrusted 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 important 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; Ćalić, 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)*.

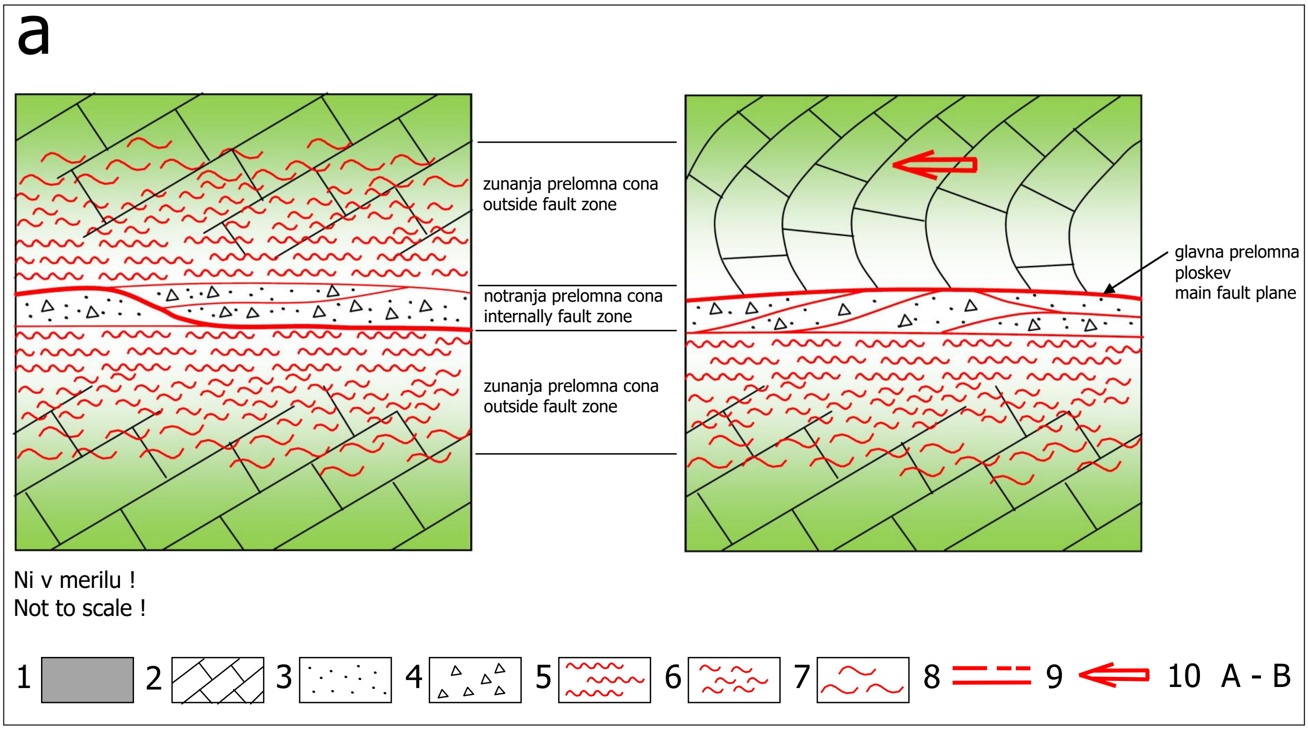
According to the nature of the prevailing stress field, normal and reverse faults occur, as well as strike-slips. As mentioned above in the context of thrust zones, sub-horizontal deformations appear along reverse faults. With normal faults, tension fissures and fault zones of tensional character develop, 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



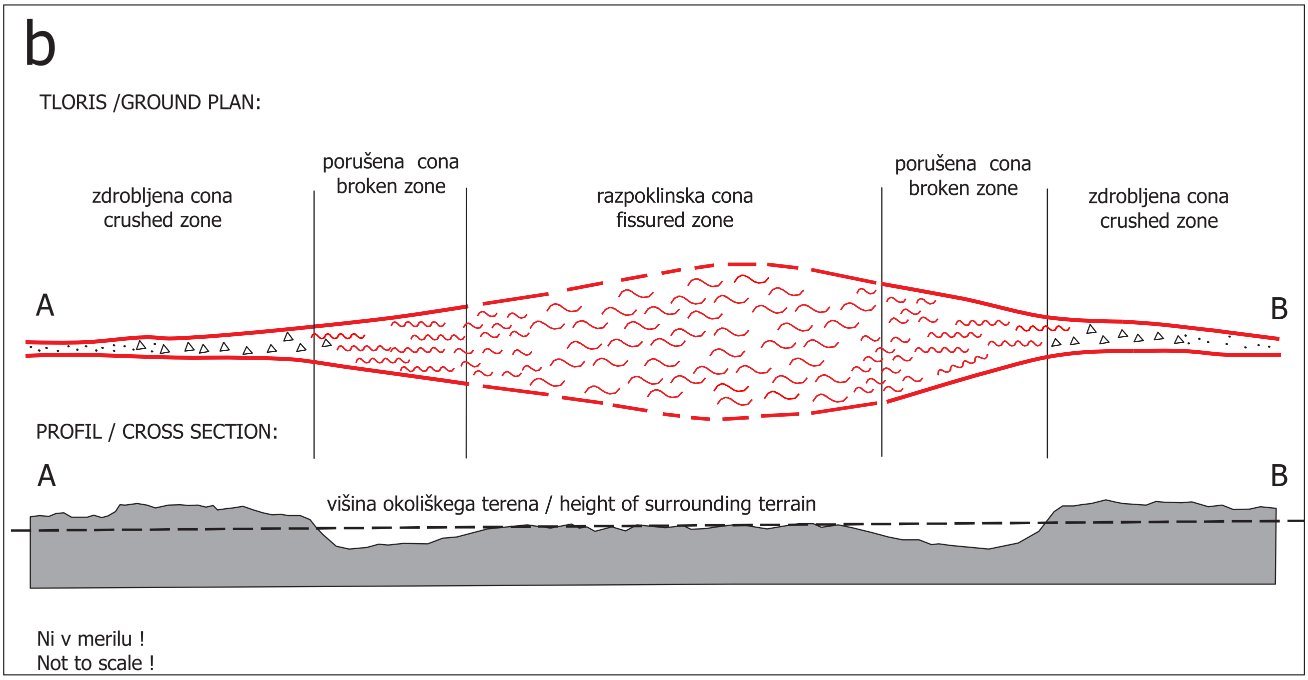


Fig. 5. Drawings a and b: Characteristics of fault zones.

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)

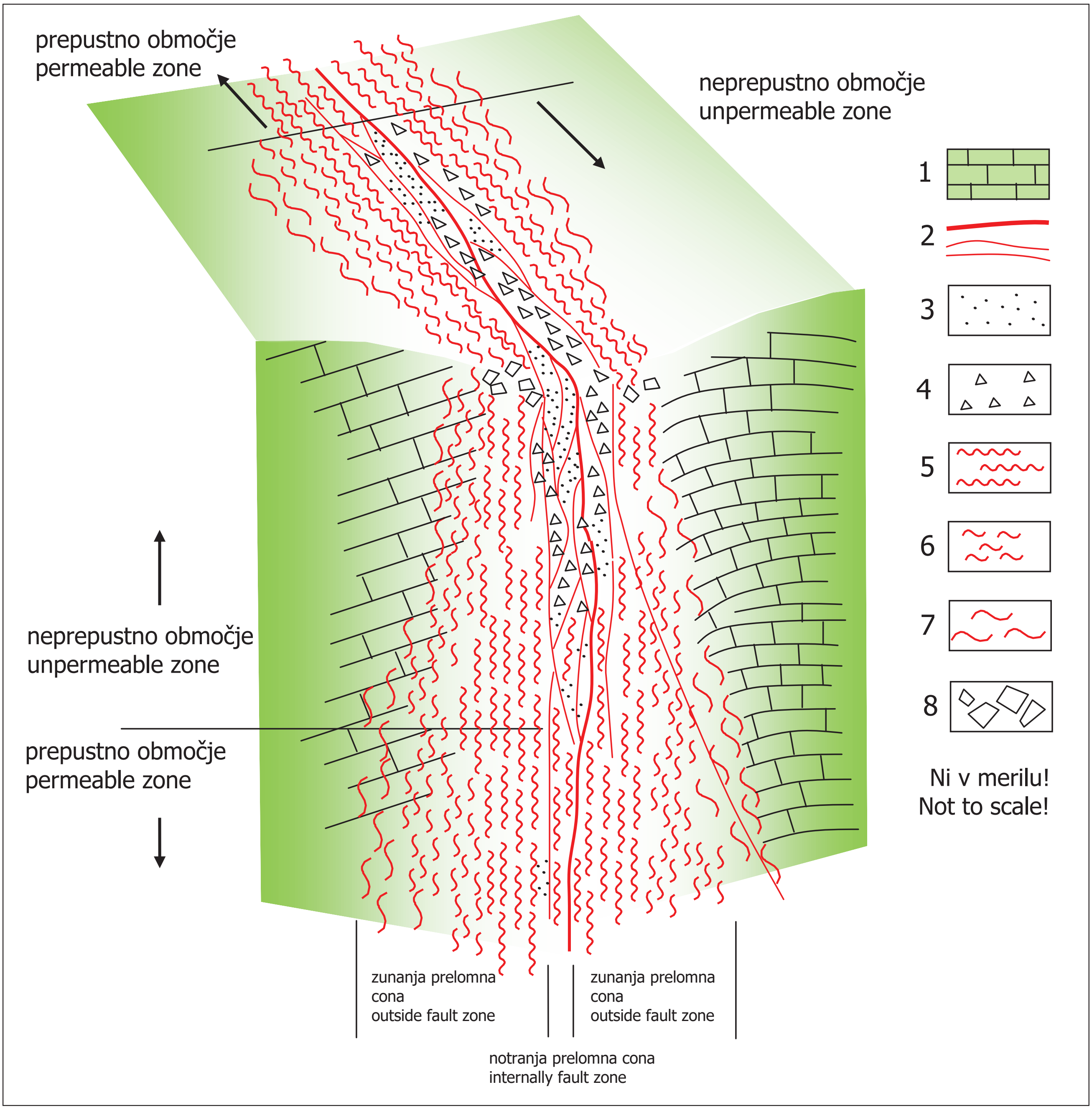


Fig. 6. Changes of the rock fracturation in the fault zone, in the vertical and horizontal direction.

1. Bedded limestone
2. Intersection of a fault-plane
3. Tectonic silt
4. Tectonic breccia
5. Broken zone
6. Dense fissured zone
7. Infrequently fissured zone
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, tectonic 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.

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

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 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 northwest–southeast direction (the Dinaric trend). Related to the fault strike direction, shear joints may appear more or less parallel to the northwest–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) conditions 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 (Čekovnik 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 Cerkniško 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 Cerkniško 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 Cerkniško polje (Karlovica 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

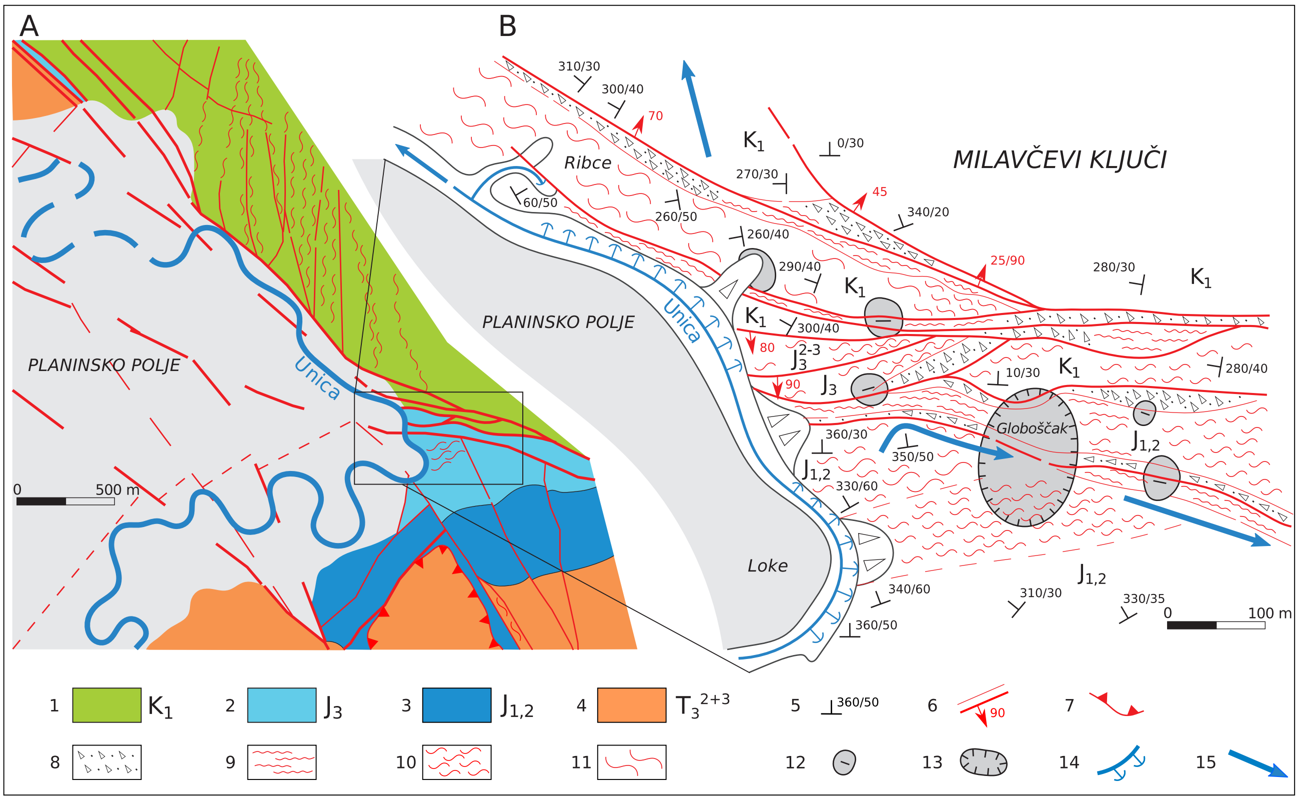


Fig. 11. Drawings A and B: General geological and hydrological situation in the area of Milavčevi ključi at Planinsko polje.
Drawing A: Geological situation at the Milavčevi ključi ponor zone.
Drawing B: Tectostratigraphical and structural situation; indicated are bedrock fracturation and hydrological 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 Ljubljanica river. Northen 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 Idrijca 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 speleogentic 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 (*speleothanatosis*). 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

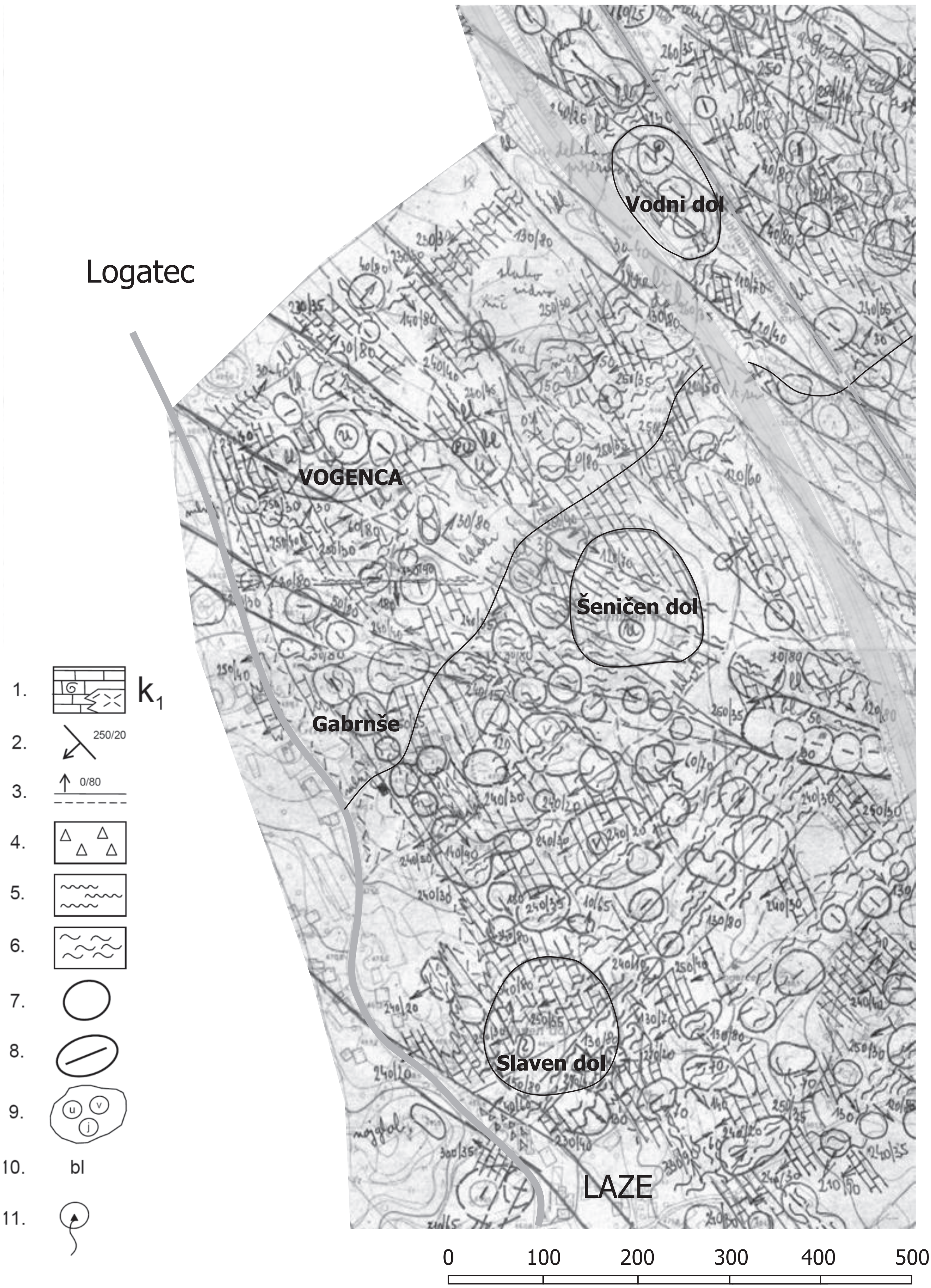

Logatec
Vodni dol
VOGENCA
Šeničen dol
Gabrnše
Slaven dol
LAZE
1.
k1
2.
250/20
3.
0/80
4.
5.
6.
7.
8.
9.
u
v
j
10.
bl
11.
0
100
200
300
400
500

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, standalone, 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 sloni 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 ugotovljene 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 usmerjevalce 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 pretrtosti 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 slemenitve 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 *zdrsne lezike*, ki predstavljajo prednostne smeri za pretakanje vode in zakrasevanje.

Ločitev med razpoko in prelomom je dogovorna, 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 snopi, 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 genetske posebnosti; je potrebno upoštevati različne stopnje pretrtosti apnencev. V prelomnih conah spremenjene (tektonsko prizadete) kamnine v splošnem označimo kot *pretrte kamnine*. Glede na stopnjo pretrtosti ločimo *zdrobljene, porušene in razpoklinske cone* .

V odvisnosti od litologije in mehanskih lastnosti ob narivnicah stikajočih kamnin ter energije, 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 genetski povezavi z razpoklinskimi obnarivnimi conami so *obnarivne zdrsne lezike*, ki imajo pomembno vlogo v speleogenezi in pri oblikovanju kraškega površja. Njihova izrazitost in pogostnost 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 vertikalni 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 porušenih 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 apnenčevo kamnino, ostanejo le prostorsko razporejeni 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 sočasnem 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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Nahajališča zemeljskega plina na naftno-plinskem polju Petišovci

Natural gas reservoirs on the oil-gas field Petišovci

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Key words: hydrocarbons, oil-gas field Petišovci, reservoir development

Izvleček

Za nastanek nahajališč z ogljikovodiki so potrebni trije pogoji in sicer; matična kamnina, v kateri ogljikovodiki nastanejo (podlaga ali talnina), kolektorska porozna kamnina, v katero se ogljikovodiki ujamejo in zgornja neprepustna kamnina (krovnina). Poleg geološke strukture so potrebni še primerna temperatura, tlak in čas, da organska snov pri redukcijskih pogojih preide faze diageneze in generira ogljikovodike, kot jih poznamo danes. Vsako nahajališče ogljikovodikov, ki se odkrije in ima ekonomsko pomembne zaloge za proizvodnjo, gre skozi pet stopenj razvoja polja. Najprej se izvedejo geološke, geofizikalne, petrofizikalne, rezervoarske raziskave, katerih rezultati se nato razložijo in ovrednotijo z 2-D in predvsem s sodobnimi 3-D geološkimi modeli. Sledi razvoj celotnega polja, v okviru katerega se ovrednotijo geološke in bilančne zaloge vseh nahajališč. Sledi faza proizvodnje in na koncu faza sanacije polja. V Sloveniji smo največ zemeljskega plina proizvedli iz nahajališč »Petišovci globoko« in sicer od leta 1963 do leta 2017 skupaj več kot 341 milijonov Sm3. V zadnjih letih se polje dodatno razvija z obdelavo perspektivnih nahajališč zemeljskega plina v tako imenovani seriji 'K' (»Petišovci globoko«). Od leta 2017 poteka proizvodnja plina iz vrtin Pg-10 in Pg-11A.

Abstract

Three conditions are required for the existence of hydrocarbon reservoirs: source rock (usually basement or footwall), collector (porous rock in which the hydrocarbons are caught), and upper impermeable rock (hanging wall). In addition to a geological structure, temperature, pressure and time are needed for the organic matter to pass through the diagenesis phase into hydrocarbons, as we know them today. Every hydrocarbon deposit found and having economical reserves for production passes five stages of the life cycle of the reservoir. First, geological, geophysical, petrophysical and reservoir exploration is carried out, and then results of these explorations are evaluated by 2D and 3D geological models. Next stage is evaluation of entire field potential (in-place) and proved reserves of all hydrocarbons-bearing reservoir strata (reservoirs). Afterwards, the most important stage is production and the end phase with the remediation of the field. In Slovenia, most of the natural gas was produced from the "Petišovci globoko" reservoirs in the years between 1963 and 2017, totaling to more than 341 million Sm3. In recent years, the field has been further developed by processing prospective natural gas reservoirs in so-called 'K' series ("Petišovci globoko"). Since 2017, the production of gas from two new wells, Pg-10 and Pg-11A, takes place.

Uvod

Eden izmed kriterijev stabilnega gospodarstva vsake države je čim manjša energetska odvisnost. Kljub temu, da se svet vse bolj usmerja v iskanje in razvoj alternativnih in obnovljivih virov energije, je trenutno še vedno najcenejša in najčistejša fosilna energija zemeljski plin. V preskrbi s primarno energijo razvitih dežel zavzema zemeljski plin okoli 25 odstotni delež (za nafto in pred premogom), pri nas pa razmeroma nizkega, le okoli 12 % (Nerad, 2012).

S pojmom ogljikovodiki opredeljujemo fosilne energetske vire, kot so surova nafta, zemeljski plin in plinski kondenzat. V nadaljevanju jih skrajšano imenujemo nafta, plin in kondenzat. Prvotno so nastali v matični kamnini, v kateri je bila organska snov rastlinskega in živalskega porekla odložena v redukcijskih pogojih, ohranjena v sedimentih, šla skozi procese diageneze in zorenja ter nastanka naftnih in/ali plinastih snovi. Tem procesom je sledila manjša ali večja migracija ogljikovodikov v zbirne ali kolektorske plasti.

V Sloveniji imamo v Panonskem bazenu znano le eno gospodarsko pomembno območje nahajališč nafte in zemeljskega plina. To je območje Doline in Petišovcev nekoliko jugovzhodno od Lendave, znano tudi kot naftno-plinsko polje Dolina-Petišovci, obratujoče od leta 1943 dalje. Nahajališča omenjenega polja, ki so neogenske starosti, delimo na plitka nahajališča v globinah od 1000 m do 2000 m in na globoka nahajališča v globinah od 2000 m navzdol do predterciarne podlage. Slednja so danes ekonomsko bolj perspektivna kot plitka.

Nosilec rudarske pravice za izkoriščanje mineralnih surovin – ogljikovodikov na področju Murske depresije je družba Geoenergo d.o.o. Angleška družba z registrirano podružnico v Sloveniji Ascent Slovenia Limited, je glavna investitorka na področju pridobivanja zemeljskega plina na naftno-plinskem polju Petišovci-Dolina, upravljavec rudarske infrastrukture za pridobivanje ogljikovodikov je Petrol Geo, proizvodnja ogljikovodikov d.o.o. Ker je proizvodnja nafte danes praktično zanemarljiva, bo tematika tega članka poudarjeno obravnavala le plinska nahajališča.

Razvoj nahajališča in proizvodnja zemeljskega plina

Ko zaslišimo besedi nafta ali pa zemeljski plin, pogosto pomislimo na pokrajino, posejano z vrtalnimi stolpi in prepredeno z naftovodi in plinovodi. Kot na vseh področjih je tudi na naftnem področju tehnologija zelo napredovala, saj nam ta omogoča manjšo degradacijo okolja tako v času vrtanja kot tudi v času proizvodnje. Po končani proizvodnji je treba vrtine sanirati, urediti okolje v primerno stanje, čim bolj podobno prvotnemu, in vzpostaviti državni monitoring naftno-plinskega polja (opazovalne vrtine).

Osnovni pojmi

Za lažje razumevanje spodnjega besedila bomo na kratko opisali nekaj osnovnih pojmov, ki se nanašajo na naftno in plinsko industrijo (Čikeš, 2013):

- Ogljikovodik (angl. *hydrocarbon*) je organska spojina, ki jo sestavljata izključno ogljik in vodik. Večino ogljikovodikov na Zemlji najdemo v surovi nafti in zemeljskem plinu.
- Surova nafta (angl. *crude oil*) je tekočina, ki jo najdemo v Zemlji in je sestavljena iz ogljikovodikov, organskih spojin in majhnih (slednih) količin kovinskih elementov.
- Plin v plinski kapi (angl. *gas cap*) je plin v strukturni pasti in se nahaja nad nafto.
- Naftni plin (angl. *associated gas*) je zemeljski plin, ki je v zgornjem delu nahajališča in je v kontaktu z nafto (plin v plinski kapi) imenovan kot prosti zemeljski plin (angl. *gas cap*) ali raztopljen zemeljski plin (angl. *solution gas*) v nafti.
- Zemeljski plin (angl. natural gas) je plin, sestavljen predvsem iz metana, ki pa lahko vsebuje tudi majhne količine drugih ogljikovodikov: etana, propana, butana, pentana in heksana, ki jih imenujemo s kratico "C_1-C_6" plini.
- Plinski kondenzat (angl. *condensate*) je zemeljski plin, ki je v nahajališčnih pogojih v plinastem agregatnem stanju, pri proizvodnji pa se plin kondenzira in se ga pridobi v tekočem stanju.
- Nahajališče (angl. reservoir), imenovano tudi kolektor, kolektorska plast ali kolektorski sloj je kamnina, v kateri so v porah (medzrnskih ali razpoklinskih) ujeti akumulirani ogljikovodiki. Najpogostejša nahajališča so v klastičnih in karbonatnih kamninah, lahko pa tudi v magmatskih in metamorfnih. Ime za nahajališče je tudi ležišče, ki pa se v novejšem času opušča (Pavšič, 2013).
- Naftno in/ali plinsko polje (angl. *oil and/or gas field*) je določeno območje na površini, kjer poteka pridobivanje ogljikovodikov in je po naši rudarski zakonodaji omejeno kot pridobivalni prostor.

- Naftna geologija (angl. *oil geology*) je veja geologije, ki temeljno in uporabno raziskuje nahajališča ogljikovodikov in ocenjuje ter vrednoti njihove vire in zaloge. Pri tem upošteva izsledke sorodnih in dopolnjujočih ved: stratigrafije, geofizike, petrologije in petrofizike, rezervoarskega inženirstva, kemije in fizike ogljikovodikov itd.

Proces od raziskovanja do proizvodnje ogljikovodikov zajema pet razvojnih stopenj, od odkrivanja ogljikovodikov do sanacije naftnega in/ali plinskega polja ter monitoringa. V nadaljevanju je opisana vsaka stopnja glede na dejavnosti, delovna mesta, stroške in časovne okvire.

Stopnje razvoja polja

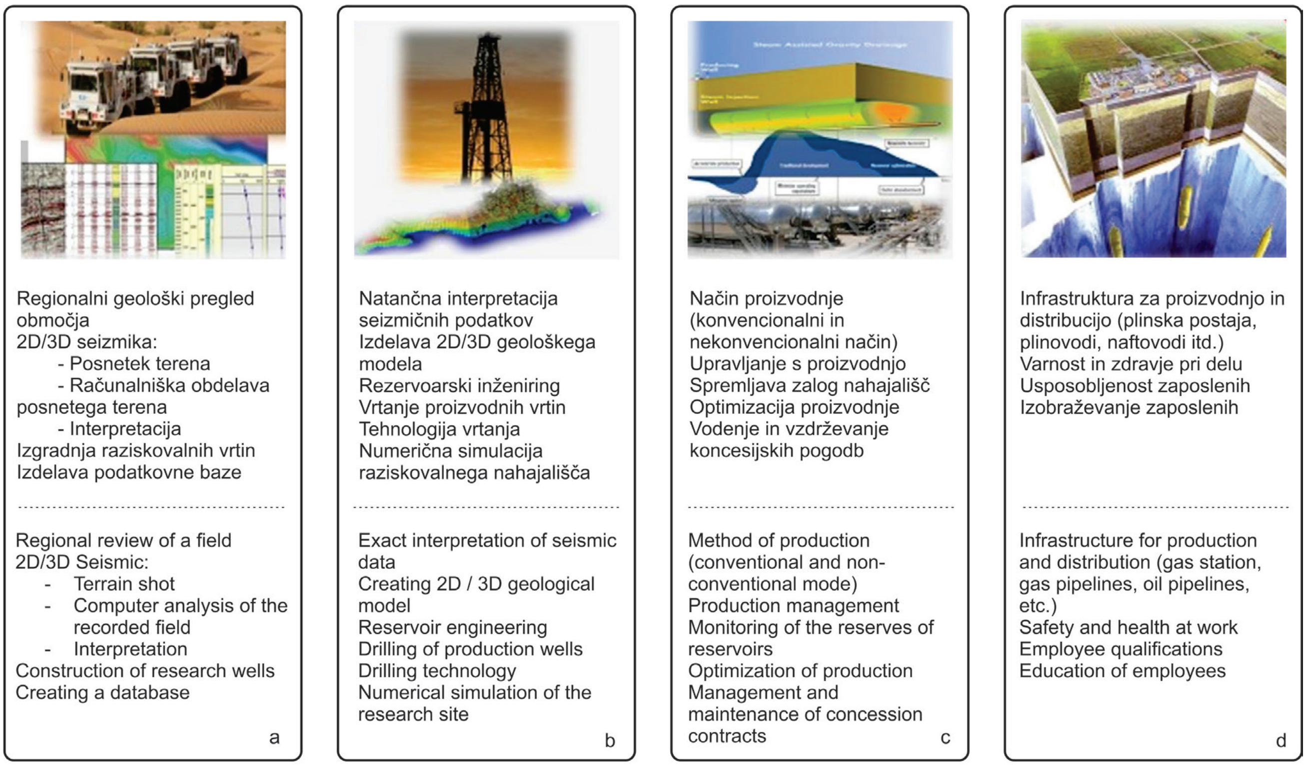
Raziskovanje

Raziskovanje nafte in plina je metoda, ki jo uporabljajo naftni geologi in geofiziki za iskanje ogljikovodikov na območjih celin (angl. *on-shore*), ali izven njih (angl. *off-shore*) – v morjih. Sestavljena je iz iskanja virov in zalog nafte in/ali plina z uporabo primarnih tehnologij, zlasti geofizikalnih globokih seizmičnih raziskav in raziskovalnih vrtin (sl. 1a). Raziskovanje je draga in tvegana operacija, ker se z njim povezani odhodki običajno vrednotijo v milijonih evrov in pri tem v povprečju saka druga vrtina od treh (Čikeš, 2013) ne vsebuje sledi ogljikovodikov. Zato je na potencialnem območju potrebno izvrtati večje število vrtin, preden se lahko ugotovi pravo velikost naftnega in/ali plinskega nahajališča, kar pa lahko traja več let ali celo desetletij.

Med raziskovalnim vrtanjem se pridobivajo pomembni podatki na podlagi vzorcev kamnin (izpirkov navrtanega materiala), vzorcev fluidov (nafta in plinski kondenzat), vzorcev plina (zemeljski plin) in karotažnih meritev (določitev lastnosti kamnin – tip kamnine, poroznost, nasičenost z ogljikovodiki itd.) z namenom, da se lahko določijo (Jahn et al., 2003):

- perspektivnost nahajališča,
- tipi surove nafte in zemeljskega plina v nahajališču,
- prostornina nahajališča (korelacija več vrtin).

Za vsako delo, ki zahteva fizični napor (seizmične raziskave, vrtanje, vzorčenje itd.), se morajo upoštevati visoki standardi glede varnosti in zdravja ljudi pri delu, ki ga narekujejo zakonodaja in pravilniki.



Sl. 1. Stopnje razvoja naftno-plinskega polja (Tanoh, 2016), a - raziskovanje in pridobivanje podatkov, b - obdelava podatkov in izdelava 3D geoloških modelov, c - upravljanje proizvodnje naftno-plinskega polja, d - vzdrževanje proizvodnje na naftno-plinskem polju.

Fig. 1. Stages of oil and gas field development, a - Research and data acquisition, b - Data processing and preparation of 3D geological models, c - Oil and gas field production, d - Maintenance of production on oil and gas field.

Ocenjevanje

Ko podjetje uspešno opravi raziskovalno vrtanje in odkrije nafto ali plin, je naslednja stopnja ocenjevanje razvojnega cikla nahajališča. Glavni namen te faze je zmanjšati negotovost ali možnost izgube začetnih investicij glede perspektivnosti in velikosti naftnega in/ali plinskega polja. Med ocenjevanjem se poleg vrtin za raziskovanje izvrta tudi več vrtin za zbiranje informacij, kot so na primer jedra v določenih intervalih nahajališč in podrobnejše raziskave na njih (geomehanske značilnosti, struktura in tekstura kamnin, poroznost itd). Druga seizmična raziskava se ponovi, če je potrebno, da bi z njo dobili boljšo podobo nahajališča. Te dejavnosti trajajo še nekaj let in stanejo desetine do stotine milijonov evrov, kar zavisi od velikosti polja (Jahn et al., 2003). Več seizmičnih raziskav in raziskovalnih vrtin pomaga naftnim geologom, geofizikom in rezervoarskim inženirjem razumeti nahajališča (sl. 1b). Na primer, kako se spreminjajo lastnosti kolektorskih kamnin in s tem posledično razporejenost nafte in plina v prostoru, koliko nafte ali plina je v nahajališču in kako hitro se bosta nafta in/ali plin gibala (migrirala) skozi nahajališče v času proizvodnje. Po uspešni stopnji ocenjevanja se podjetje odloči, ali se naftno ali plinsko polje lahko dejansko razvije ali ne.

Nastanek polja

Faza nastanka naftno-plinskega polja se pojavi ob uspešni oceni in pred začetno proizvodnjo. Glavne dejavnosti so (Saridja, 1985):

- Oblikovanje načrta za razvoj naftnega ali plinskega polja z vključitvijo zadostnega števila vrtin, potrebnih za proizvodnjo nafte in/ali plina. Načrt pripravijo geologi, geofiziki in rezervoarski inženirji.
- Odločitev o uporabi tehnologije vrtanja za proizvodne vrtine, ki jo utemeljijo geotehnologi, strokovnjaki za vrtanje, rudarski strojniki.
- Odločitev o velikosti proizvodne zmogljivosti polja (ocena proizvodne zmogljivosti polja skozi časovno obdobje) narekuje potrebe po objektih za obdelavo nafte ali plina (rafinerije, plinske postaje itd.), ki jo utemeljijo inženirji za procesno tehniko.
- Odločitev glede transporta nafte in plina, ki jo opredelijo inženirji logistike.

Razvojni načrt se zaključi z v prvi fazi izvrtanimi proizvodnimi vrtinami in zgrajenimi vsemi potrebnimi objekti za procesiranje ogljikovodikov. V razvojni načrt so vključeni inženirji s področja geotehnologije, logistike in procesne tehnike, ki ustvarijo pogoje za proizvodnjo ogljikovodikov iz nahajališč (sl. 1c). Pri tem se ustvarjajo številne možnosti zaposlovanja, kjer ljudje lahko sodelujejo pri izgradnji proizvodnih objektov. Najpomembnejša prednostna naloga pri tem je varnost. Tveganje za nesrečo je v tej fazi najvišje zaradi števila ljudi, ki se ukvarjajo s pripravo delovišča in samim vrtanjem (Jahn et al., 2003).

Razvoj naftnega polja lahko stane več milijard evrov in običajno traja 5-10 let, odvisno od lokacije, velikosti in kompleksnosti objektov ter števila potrebnih vrtin. Razvoj na kopnem je razmeroma veliko cenejši od razvoja na morju.

Naftna in plinska podjetja naredijo na tej stopnji razvoja polja dokumentacijo o racionalnih pričakovanjih uspešnosti pridobivanja ogljikovodikov z analizo stroškov raziskovanja, stroškov razvoja ter dobička pri prodaji ogljikovodikov. Razvojni cikel se izvede, če so izpolnjeni vsi pogoji po ustrezni rudarski in okoljevarstveni zakonodaji.

Sl. 2. Vrtalni stolp na plinski vrtini Pg-3 in površinska črpalka na naftni vrtini Pt-1 (vir: Petrol Geo, 2018).
Fig. 2. Drilling rig on the gas well Pg-3 and surface pump on the oil well Pt-1 (source: Petrol Geo, 2018).

Proizvodnja

Proizvodnja je zadnja faza, v kateri se pridobivajo ogljikovodiki iz naftnega in/ali plinskega polja ter prvi prihodek iz prodaje nafte in/ali plina. Po tem, ko prihodki presežejo začetno naložbo in fiksne stroške podjetja, se začne ustvarjati dobiček. Proizvodnja na naftno-plinskem polju lahko traja več let, do okoli 40 let, odvisno od velikosti, oblike in tipa kamnin (peščenjaki, skrilavci, karbonati in druge kamnine) v nahajališču (sl. 1d).

Operaterji delajo v izmenah za nemoteno proizvodnjo. Inženirji skrbijo za pravilno delovanje proizvodnega procesa (nadgrajevanje, izboljševanje), rezervoarski inženirji pa spremljajo stanje zalog v nahajališčih in iščejo nova perspektivna nahajališča (Jahn et al., 2003).

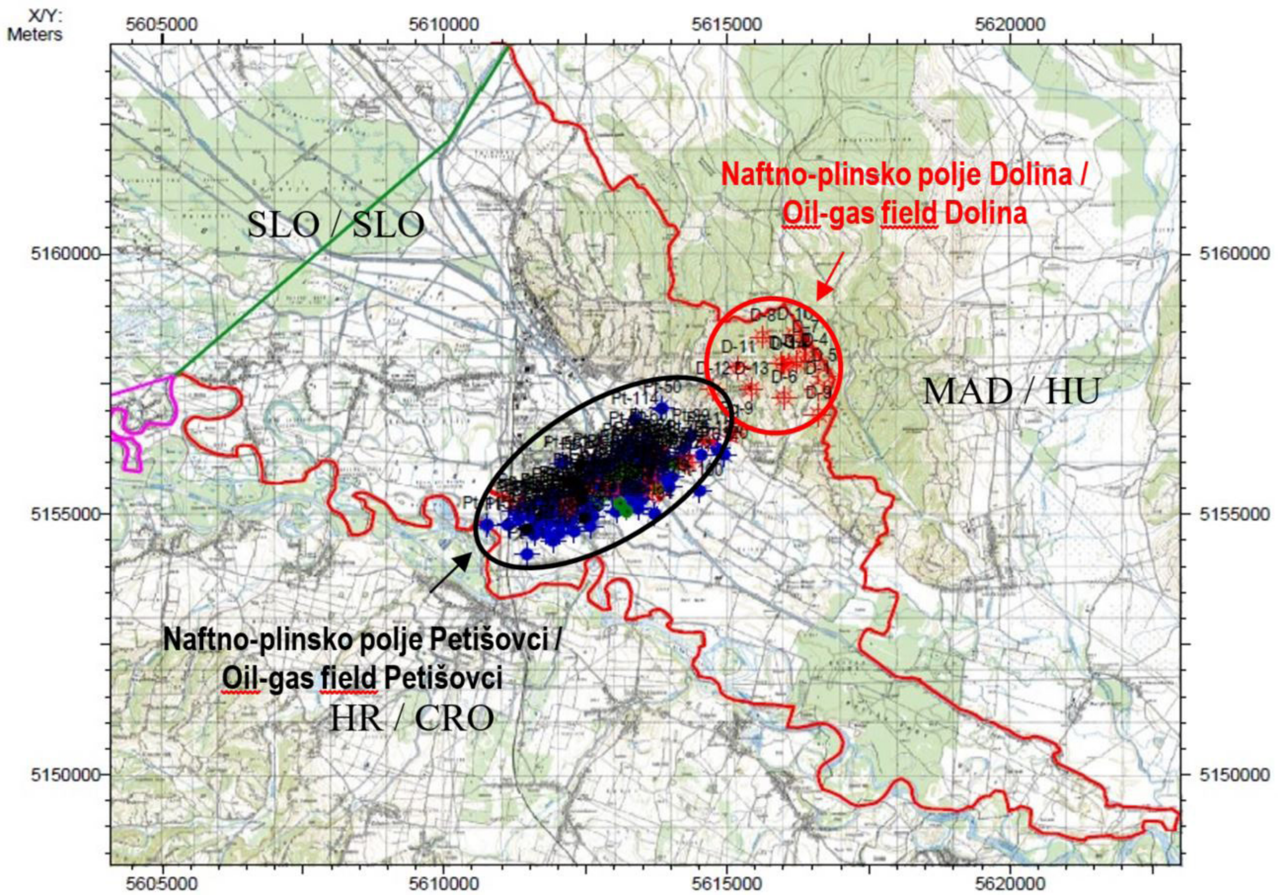
Sanacija

Sanacija je izraz, ki se uporablja za opis vzpostavitve degradiranega okolja zaradi izkoriščanja nafte in/ali plina v stanje, ki bo čim podrobnejše prvotnemu stanju in prijazno okolju brez škodljivih vplivov na zdravje ljudi in živali. Prvotnega stanja sicer ni mogoče nikoli povsem povrniti, zato pa se upoštevajo najvišji standardi za izvedbo sanacije, in sicer (Jahn et al., 2003):

- cementiranje proizvodnih intervalov v vrtinah,
- postavitev cementacijskih čepov v vrtinah,
- odstranitev ustij vrtin in pritrditev slepih prirobnic,
- odstranitev naftovodov in plinovodov,
- odstranitev vseh ostalih objektov (plinskih postaj, rafinerij itd.),
- nekaj vrtin se preuredi za monitoring nahajališč, ki ga izvaja državni monitoring.

Odkritje naftno-plinskega polja Petišovci-Dolina

Naftno-plinsko polje Petišovci sodi po naftno-geološki prostorski opredelitvi v Mursko depresijo (Pleničar, 1954; Mioč & Marković, 1998). Začetki raziskav nahajališč ogljikovodikov na območju Murske depresije segajo v sredino 19. stoletja, ko so na Hrvaškem v neposredni bližini meje s Slovenijo v vaseh Peklenica in Selnica začeli pridobivati nafto na površinskih izvirih. Raziskave nahajališč ogljikovodikov so se od tod postopno razširile tudi proti severu v Prekmurje oziroma slovenski del Murske depresije. Na začetku 2. svetovne vojne so bile po obsežnih površinskih geoloških raziskavah širšega območja



Sl. 3. Prikaz lokacije naftno-plinskega polja Petišovci-Dolina v pridobivalnem prostoru Murske depresije (vir: Petrol Geo, 2018).
Fig. 3. Location map of the oil and gas fields Petišovci-Dolina within the exploitation area of the Mura depression (source: Petrol Geo, 2018).

Murske depresije izvedene gravimetrične meritve (Pleničar, 1954). Na osnovi pridobljenih podatkov je bila leta 1942 najprej določena lokacija in nato izvrtana vrtina Dolina 1 (D1) do globine okrog 1460 m in leta 1943 vrtina Petišovci-1 (Pt-1) do globine okrog 1750 m. Črpalko na naftni vrtini Pt-1 kaže slika 2.

Tako sta bili odkriti naftno-plinski polji Dolina in Petišovci (sl. 3). Kmalu je bilo ugotovljeno, da je naftno-plinsko polje Dolina sestavni del velikega madžarskega polja Lovászi in da je naftno-plinsko polje Petišovci samostojna antiklinalna struktura, ki se nahaja na severnem delu Ormoško-selniške antiklinale (antiforme).

Po odkritju naftno-plinskega polja Petišovci z raziskovalno vrtino Pt-1 se je še v času 2. svetovne vojne nadaljevalo z izgradnjo razdelovalnih vrtin Pt-2 in Pt-3 in po 2. svetovni vojni do leta 1958 z izgradnjo še 107-ih proizvodno-razdelovalnih vrtin. Z dodatnimi seizmičnimi meritvami v letu 1960 je bilo ugotovljeno, da se na območju naftno-plinskega polja Petišovci, pod zgornjemiocenskimi sedimenti, nahaja perspektivna struktura srednje in spodnjemiocenskih sedimentov (Bokor, 1986). Leta 1961 je sledila izgradnja prve globoke raziskovalne vrtine Pg-1 do globine približno 2970 m, s katero so bila odkrita globoka plinska nahajališča, tako imenovana nahajališča »Petišovci globoko«. V obdobju od leta 1961 do leta 1990 je bilo skupno izvrtanih 9 vrtin, ki so vse razen ene (ki ni bila dokončana) navrtale slabo prepustna plinska nahajališča »Petišovci globoko« (sl. 2 - primer plinske vrtine Pg-3). Po izvedbi in interpretaciji 3D seizmičnih meritev sta bili leta 2011 izdelani še dve globoki vrtini (Pg-10 in Pg-11A), ki sta bili leta 2017 vključeni v proizvodnjo.

Geološka zgradba naftno-plinskega polja Petišovci

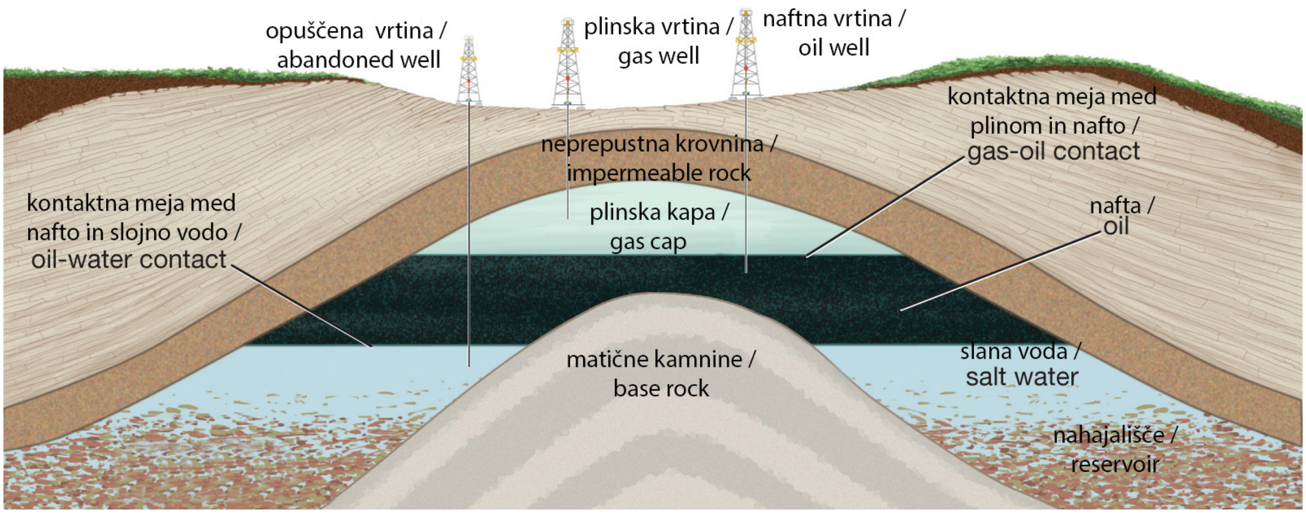
Za nastanek nahajališč ogljikovodikov morajo biti izpolnjeni trije pogoji (sl. 4). Obstajati morajo (Nedeljković, 1963):

- matične kamnine,
- porozne in prepustne rezervoarske kamnine, v katerih se ogljikovodiki akumulirajo,
- neprepustna krovnina nahajališča (angl. *cap rock*) ali drugi mehanizmi, ki preprečujejo uhajanje ogljikovodikov.

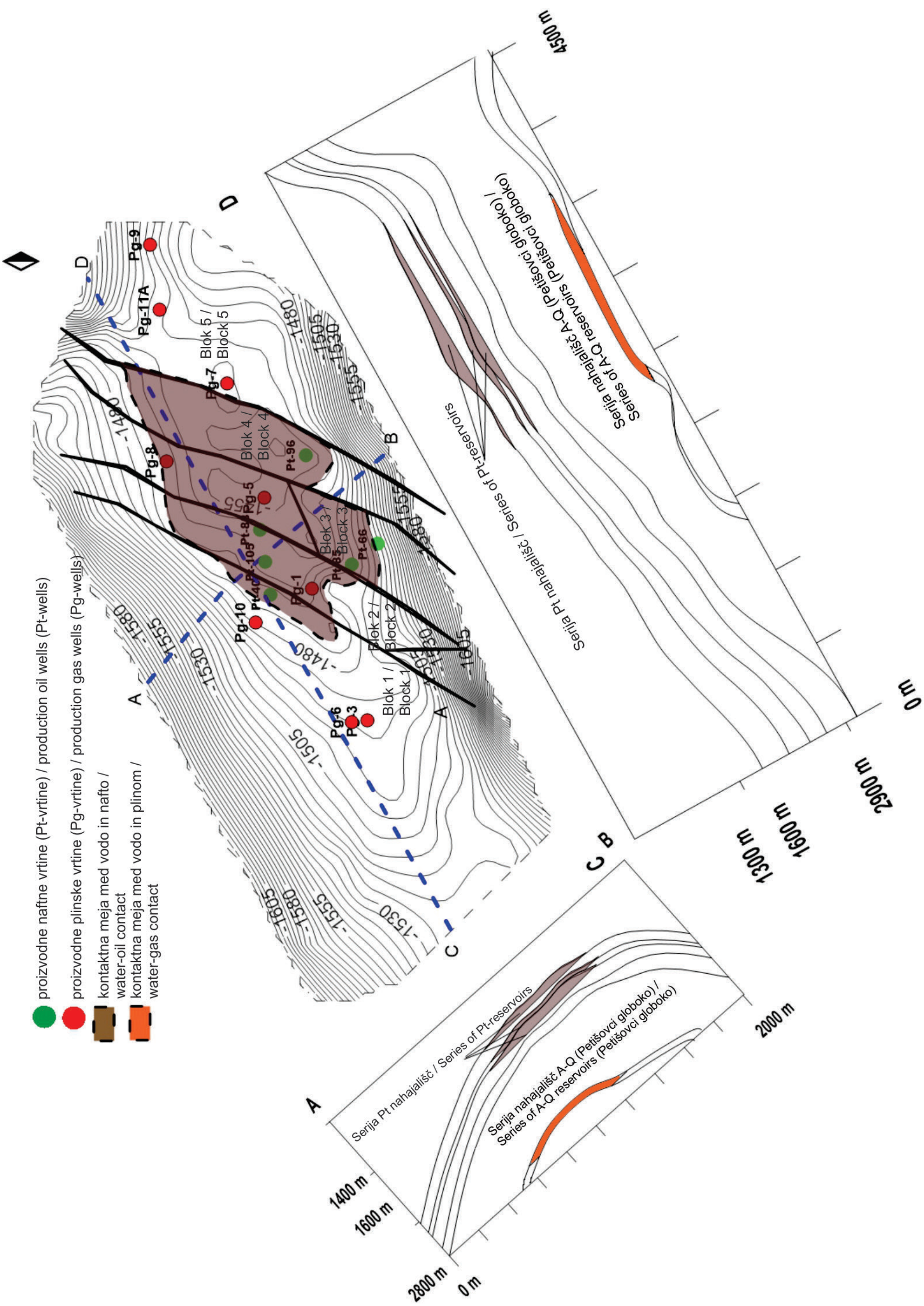
Naftno-plinsko polje Petišovci delimo v osnovi po vertikali v 5 glavnih nahajališč ogljikovodikov, ki si sledijo od vrha navzdol po naslednjem vrstnem redu (od površine terena):

- Paka, serija naftnih nahajališč (1080-1200 m),
- Ratka, serija naftnih nahajališč (1300-1400 m),
- Lovaszi, serija plinskih nahajališč (1550-1600 m),
- Petišovci, serija naftnih nahajališč (1650-1700 m),
- »Petišovci globoko«, serija plinskih nahajališč (od 2000 m navzdol – terciarna podlaga).

V primeru Petišovcev so mnogoštevilni plinonosni in/ali naftonosni sloji bolj ali manj porozni miocenski neogenski peščenjaki z vmesnimi tankimi plastmi laporjev. Naftonosne in/ali plinonosne plasti so debele od nekaj metrov do nekaj deset metrov in približno enako debele so tudi vmesne neprepustne (izolacijske) plasti laporovcev.



Sl. 4. Poenostavljen geološki prerez skozi antiformno nahajališče ogljikovodikov (Internet 1).
Fig. 4. Generalized geological cross-section through an antiform hydrocarbon reservoir (Internet 1).



Sl. 5. Struktura naftnih nahajališč Petišovci in plinskih nahajališč "Petišovci globoko" (Kerčmar, 2014).
Fig. 5. Structure of oil reservoirs Petišovci and gas reservoirs "Petišovci globoko" (Kerčmar, 2014).

Znotraj naftno-plinskega polja Petišovci je trenutno najbolj perspektivno plinsko nahajališče »Petišovci globoko«, ki je predmet natančnejše razlage v nadaljevanju članka.

Nahajališča »Petišovci globoko«

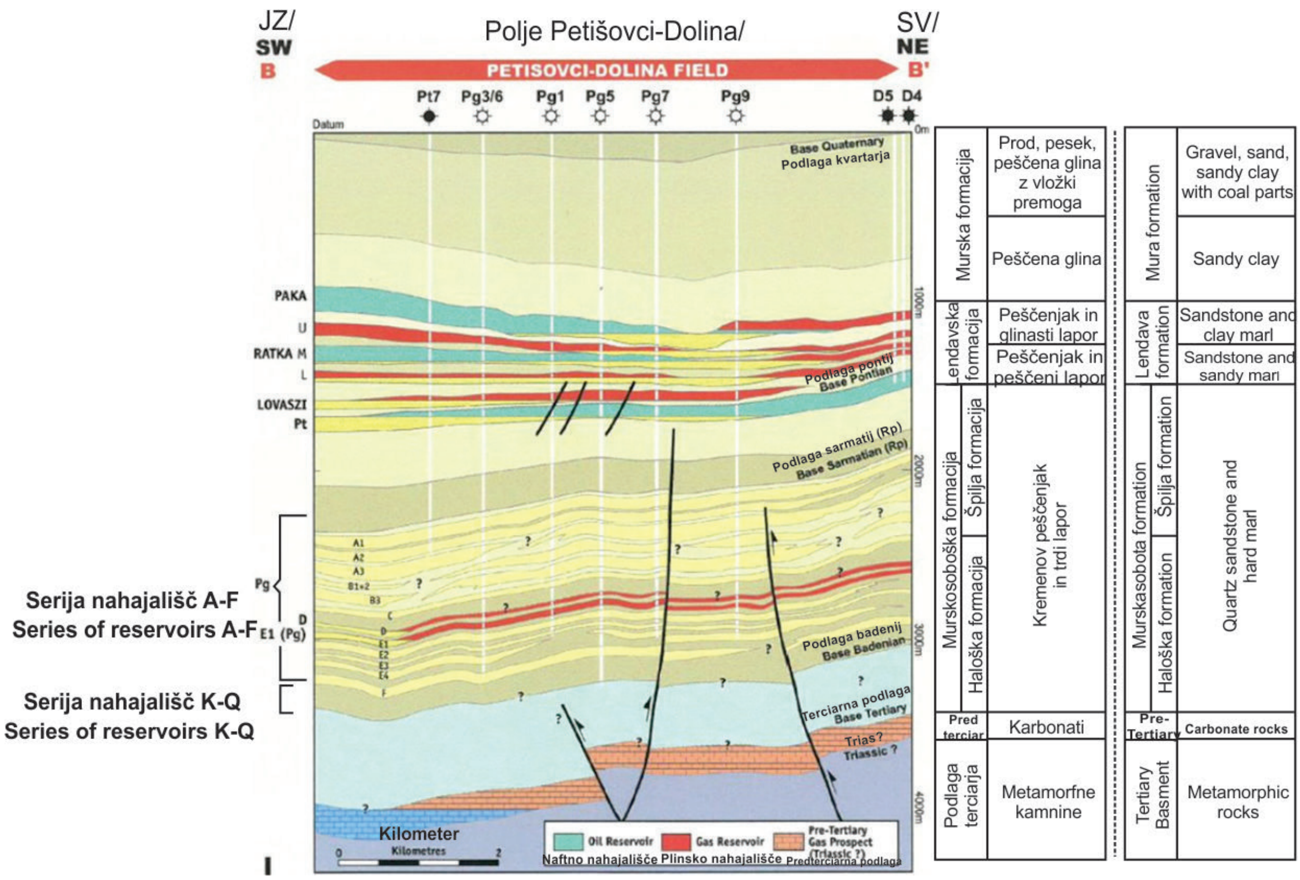
Strukturno-tektonska zgradba

Najstarejše ogljikovodikonosne karpatijske in badenijske plasti tvorijo na obravnavanem območju kompleksno antiformno strukturo z nekaj maksimumi, ki predstavljajo »strukturne pasti« za akumulacijo oziroma »ujetje« ogljikovodikov v njih. Omenjena antiforma (sl. 5) v prečnodinarski smeri SW-NE je v geološki literaturi (Mioč & Marković, 1998) imenovana kot Ormoško-selniška antiklinala. Interpretacije v 1980-ih letih (Djurasek, 1988) so pokazale, da je omenjena antiforma dvignjena (iztisnjena) ob dveh reverznih prelomih, Ljutomerskem in Donačkem prelomu. Antiformo sekajo prečni prelomi, ki jo delijo v več blokov (Mioč & Marković, 1998). Gre za pet glavnih blokov z značilno strukturo horstov in vmesnih grabnov. Vsak blok zase predstavlja posebno hidrodinamsko enoto.

Litostratigrafske razmere

Stratigrafija plasti polja Petišovci je na osnovi velikega števila litoloških in paleontoloških preiskav vzorcev izvrtanih kamnin ter korelacij z geofizikalnimi elektrokarotažnimi (EK) diagrami potrjena kot kronostratigrafska in litostratigrafska zgornjeterciarna (neogenska) starost plasti, značilna za Mursko depresijo. Terciarni sedimenti so razvrščeni v tri formacije. Najstarejša je Mursko-soboška formacija, ki se po novem deli na Haloško in Špiljsko formacijo (Jelen & Rifelj, 2011), nad njo je v normalnem zaporedju Lendavska formacija in nato najmlajša Murska formacija (sl. 6).

Murskosoboška formacija (Špiljska in Haloška formacija) zajema v stratigrafskem zaporedju obdobja karpatija, badenija, sarmatija in spodnjega panonija. Karpatijske, badenijske in sarmatijske plasti sestavljajo trdo vezani drobno- do srednjezrnati kremenovi peščenjaki s sljudo, meljevci in trdi do srednje trdi meljasti laporji. Spodnjepanonijske plasti pa sestavljajo srednje vezani drobno- do srednjezrnati kremenovi peščenjaki s sljudo, lapornati peščenjaki, meljevci in srednje trdi laporji (Bokor, 1986; Lisjak, 1988).



Sl. 6. Presek naftno-plinskega polja Petišovci-Dolina z litološkim stolpcem (vir: Ascent Resources, Geomega, 2012).

Fig. 6. Cross-section through the Petisovci-Dolina oil and gas field with lithological column (source: Ascent Resources, Geomega 2012).

Lendavska formacija je zgornjepanonijske do spodnjepontijske starosti. Zgornjepanonijske plasti sestavljajo srednje vezani drobno- do srednjezrnati kremenovi peščenjaki s sljudo in srednje trdi laporji, spodnjepontijske plasti pa sestavljajo slabo do srednje vezani kremenovi peščenjaki s sljudo in srednje trdi laporji.

Murska formacija je zgornjepontijske starosti in jo sestavljajo slabo vezani peščenjaki, peski in prod ter peščene in lapornate gline z vložki lignitnega do rjavega premoga (Markič et al., 2011).

Kvartar sestavljajo gline, peski, prod in humus.

Serija peščenjakov »Petišovci globoko« na naftno-plinskem polju Petišovci je s podrobno korelacijo EK-diagramov, jeder in podatkov, dobljenih z geološko spremljavo vrtin, izdvojena v badenijskih in karpatijskih plasteh in sicer (od spodaj navzgor): serija F, serija E z nahajališči E_4, E_3, E_2 in E_1, serija D z nahajališči D_2 in D_1, serija C, serija B z nahajališči B_3, B_2 in B_1 ter serija A z nahajališči A_4, A_3, A_2 in A_1.

Na osnovi korelacije EK-diagramov je ugotovljeno, da so serije F, C, B in A nasičene z vodo, oziroma vsebujejo le manjše količine plina. Serija E z nahajališči E_4, E_3, E_2 in E_1 je ugotovljena na celotnem polju. Nahajališči E_3 in E_2 sta zavodnjeni oziroma nasičeni z manjšimi količinami plina. Dotok plina iz nahajališča E_4 je bil ugotovljen samo v jugozahodnem delu polja v bloku 1 iz vrtin Pg-3 in Pg-6. Glavno nahajališče plina je E_1, ki je najproduktivnejše v bloku 1 in v bloku 2. Serija D z nahajališči D_1 in D_2 se nahaja nad serijo E. Dotok plina iz nahajališča D_1 je potrjen na vseh vrtinah. Največje količine plina iz nahajališča D so dobljene iz 2. bloka. Z dvema novima vrtinama, Pg-10 in Pg-11A pa se je izkazalo, da so perspektivna nahajališča še globlja od serije nahajališč F, to je vse do nahajališč Q.

Nahajališča K, L, M, N, O, P in Q (sl. 6) so vključena v proizvodnjo z vrtinama Pg-10 in Pg-11A. V vrtini Pg-10 sta bili razkriti in mehansko obdelani nahajališči F in L, v vrtini Pg-11A pa M/N, O in P. Vsa naštete nahajališča so bila vključena v testno proizvodnjo leta 2011, v redno proizvodnjo pa so stopila leta 2017.

Vsa nahajališča plina "Petišovci globoko" so slabo prepustni peščenjaki miocenske starosti. Zaradi majhne primarne prepustnosti oziroma nizke permeabilnosti so bili omenjeni peščenjaki v fazi proizvodne razdelave polja obdelani z mehansko stimulacijo, ki je za polje Petišovci standardni postopek za spodbujeno pridobivanje plina že več kot šest desetletij (vir: Arhiv Petrol Geo).

Fizikalne lastnosti kolektorskih kamnin nahajališč

Izračun fizikalnih lastnosti kolektorskih kamnin nahajališč je bil narejen na podlagi podatkov o poroznostih posameznih nahajališč (ogljikovodikonosnih slojev), pridobljenih z analizo EK diagramov s programom EPILOG. Vrednosti glede nasičenja z vodo (Sw) zaradi vrste in lastnosti kamnin niso povsem zanesljive, kajti dobljene vrednosti so večje od realnih.

Laboratorijske vrednosti poroznosti in prepustnosti so bile izmerjene na sedmih odvzetih jedrih (Lisjak, 1988), na podlagi katerih se lahko poda verodostojno oceno kolektorskih parametrov. V tabeli 1 so prikazane vrednosti (povprečje med laboratorijskimi meritvami in vrednostmi, pridobljenimi iz EK diagramov) za poroznost, prepustnost in zasičenost s fluidi za nahajališča od D_1 do E_4. Fizikalne lastnosti za trenutno nova proizvodna nahajališča serije, 'K' (K-Q) navrtane na vrtini Pg-10 in Pg-11A niso podane zaradi zaupnosti podatkov, ki si jih pridržuje investitor.

Klasifikacija in kategorizacija plinskega nahajališča

Raziskovanje in izkoriščanje mineralnih surovin v R Sloveniji opredeljuje Zakon o rudarstvu (Uradni list RS, št. 14/2014). Po Pravilniku o klasifikaciji in kategorizaciji zalog in virov nafte, kondenzata in naravnih plinov (Uradni list RS, št. 61/10), ki ga določa Rudarski zakon, se morajo nahajališča v času testiranja oziroma na začetku redne proizvodnje ovrednotiti z elaboratom o zalogah. Šele na podlagi izdelanega elaborata se skupaj z rudarskim projektom za izkoriščanje mineralnih surovin na določenem pridobivalnem prostoru za določeno obdobje dodeli koncesija s strani države Republike Slovenije.

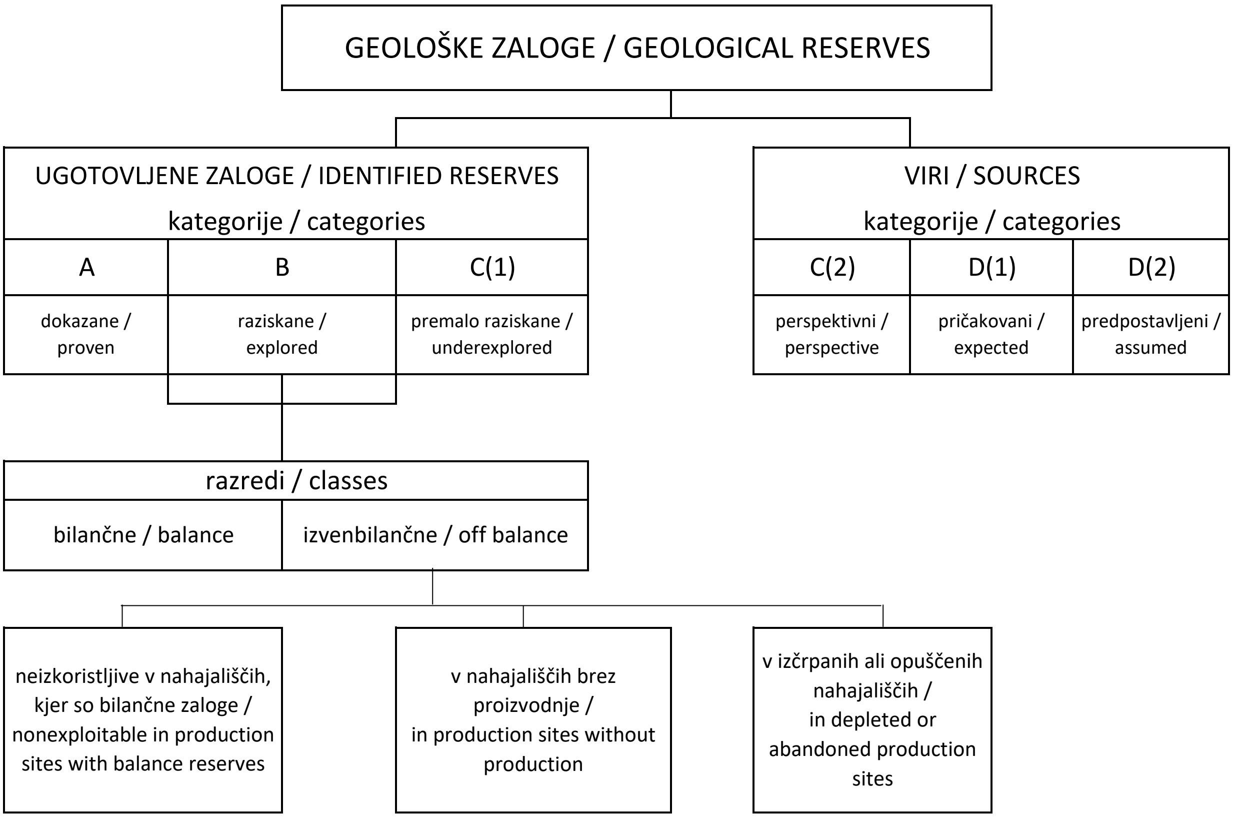
S klasifikacijo nahajališč opredelimo, ali gre za vire ali za zaloge, s stopnjo raziskanosti pa jih ovrednotimo v kategorije. Glede na ekonomsko terminologijo se zaloge nafte in plina delijo v tri skupine in sicer (Internet 2):

- Geološke zaloge: so skupne ugotovljene ali ocenjene zaloge mineralnih surovin znotraj nahajališča ali rudnega telesa brez upoštevanja odkopnih in industrijskih izgub.
- Bilančne zaloge: so zaloge, ki se lahko pri obstoječi stopnji znanosti, tehnike, tehnologije in ekonomike gospodarno izkoriščajo.
- Izvenbilančne zaloge: so zaloge, ki se ne morejo po obstoječi stopnji znanosti in tehnike ekonomično izkoriščati.

Tabela 1. Povprečne vrednosti za poroznost, prepustnost in nasičenost s fluidi v nahajališčih "Petišovci globoko" (po Lisjak, 1988).

Table 1. Average values for porosity (ϕ) water saturation (Sw), gas saturation (Sg) and permeability (k) of the »Petišovci globoko« D and E reservoirs as analysed in the Pg wells (after Lisjak, 1988).

Nahajališče / Reservoir	**POROZNOST / POROSITY**		**NASIČENOST S FLUIDI / FLUID SATURATION**			**PREPUSTNOST / PERMEABILITY**	
	Vrtina / Well	**ϕ**	**Vrtina / Well**	**Sw (voda) / Sw (water)**	**Sg (plin) / Sg (gas)**	**Vrtina / Well**	**k (10^{-3} μm^2)**
D1	Pg-2,5,6	0,081	Pg-5,6	0,40	0,60	Pg-5	0,38
D2	Pg-5,6	0,079	Pg-5,6	0,35	0,65		
E1	Pg-2,3,5,6	0,091	Pg-5,6	0,35	0,65	Pg-3	8,6
E2	Pg-5,6	0,054	Pg-5,6	0,45	0,55		
E3	Pg-3,5,6	0,065	Pg-5,6	0,45	0,55	Pg-5	0,27
E4	Pg-5,6	0,048	Pg-5,6	0,38	0,62		



Sl. 7. Klasifikacija in kategorizacija zalog in virov nafte, kondenzatov in naravnih plinov v Sloveniji (vir: Internet 3).

Fig. 7. Classification and categorisation of reserves and resources of oil, condensates and natural gas as in use Slovenia (source: Internet 3).

Računsko se bilančne zaloge ovrednotijo po naslednji enačbi:

BILANČNE ZALOGE = GEOLOŠKE ZALOGE -IZVENBILANČNE ZALOGE

Razvrščanje zalog in virov mineralnih surovin v ustrezne kategorije je pogojeno s stopnjo poznavanja (Internet 2):

- prostorska razporejenost kolektorja,
- fizikalne lastnosti kolektorja,
- fizikalne in kemične lastnosti fluidov,
- razmerja PVT fluidov,
- proizvodne značilnosti kolektorja.

Ugotovljene in razvrščene zaloge ter viri mineralnih surovin (sl. 7) izražajo stopnjo njihove raziskanosti in pripravljenosti za nadaljnje izkoriščanje. Delijo se v (Internet 2):

- A zaloge, ki se razvrščajo v nahajališču ali delu nahajališča, ugotovljene z vrtinami z dotokom fluidov, dobljenim z osvajanjem vrtin, ki so predvidene za proizvodnjo. Pri tem se ugotovi tudi: geološka sestava, oblika in velikost nahajališča ali njegovega dela, kolektorske lastnosti, položaj nahajališča ter fizikalno-kemične značilnosti fluidov.

- B zaloge, ki se razvrščajo v nahajališču ali delu nahajališča, ugotovljene z nekaj vrtinami, iz katerih je dobljen dotok fluidov z osvajanjem in potrjen s hidrodinamičnimi meritvami ali s poskusno proizvodnjo. V drugih vrtinah je prisotnost fluidov ugotovljena s karotažnimi meritvami, jemanjem vzorcev jedra ali testiranjem med vrtinami. Ugotovljena mora biti geološka sestava, oblika in velikost nahajališča ali njegovega dela, kolektorske lastnosti, razmerja ter fizikalne in kemijske značilnosti fluidov.
- C(1) zaloge, ki se razvrščajo v nahajališču ali delu nahajališča, ki so odkrite z raziskovalnimi vrtinami. Dotok fluidov se doseže z osvajanjem in hidrodinamičnimi raziskavami najmanj na eni raziskovalni vrtini. Meje nahajališča so določene na podlagi podatkov geološko-geofizikalnih raziskav in vrtanja.
- C(2) vire, katerih prisotnost se predpostavlja na podlagi podrobnih geološko-geofizikalnih raziskav (razvoj strukturno-tektonske enote nahajališča).
- D(1) vire, ki jih je mogoče pričakovati na podlagi rezultatov regionalnih geoloških in geofizikalnih raziskav (prisotnost naravnega rezervoarja, njegova strukturna oblika, prisotnost ogljikovodikov).
- D(2) vire, ki jih je mogoče oceniti na podlagi temeljnih geoloških in geofizikalnih raziskav.

Za izračun zalog mineralnih surovin kategorij A, B in C(1) se uporabljajo naslednje metode:

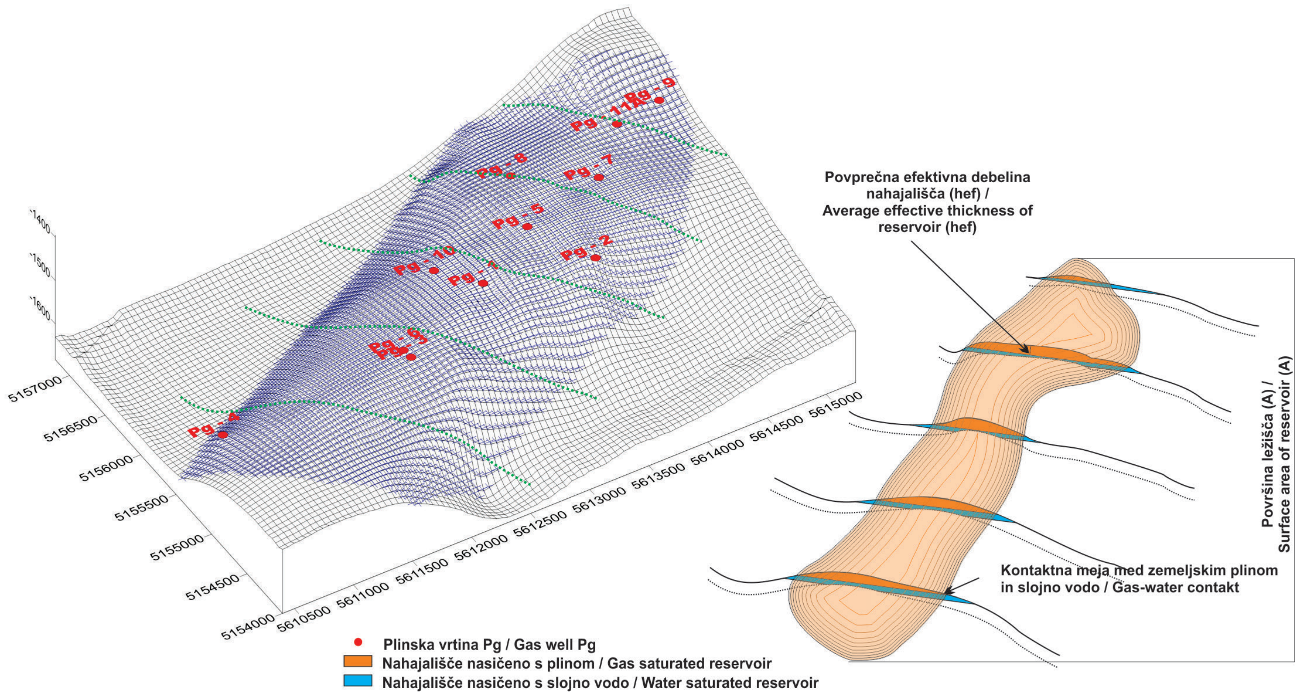
1. prostorninska metoda,
2. metoda materialnega ravnovesja,
3. statistična metoda,
4. metoda matematičnega modeliranja.

Viri mineralnih surovin kategorije C(2) in D(1) se izračunavajo s prostorninsko metodo, viri kategorije D(2) se izračunavajo po metodi geološke analogije.

Pri elaboratu iz leta 1986 (Bokor et al, 1986) in leta 1988 (Lisjak et al., 1988) za izračun začetnih geološki zalog in virov nafte, plina in kondenzata na območju naftno-plinskega polja Petišovci-Dolina se je uporabila prostorninska metoda. Zaloge in viri so bili izračunani po naslednji enačbi (sl. 8):

$$G_i = \frac{A * h_{ef} * \emptyset * S_{gi}}{B_{gi}}$$

- G_i - začetne geološke rezerve (Sm^3) / initial geological reserves (Sm^3),
- A - površina nahajališča (m^2) / reservoir area (m^2),
- h_{ef} - povprečna efektivna debelina nahajališča (m) / average effective thickness of a reservoir (m),



Sl. 8. Primer volumenskega preseka posameznega nahajališča „Petišovci globoko“ (Kerčmar, 2014).
Fig. 8. An example of a volumetric cross-section of a reservoir from “Petišovci globoko” (Kerčmar, 2014).

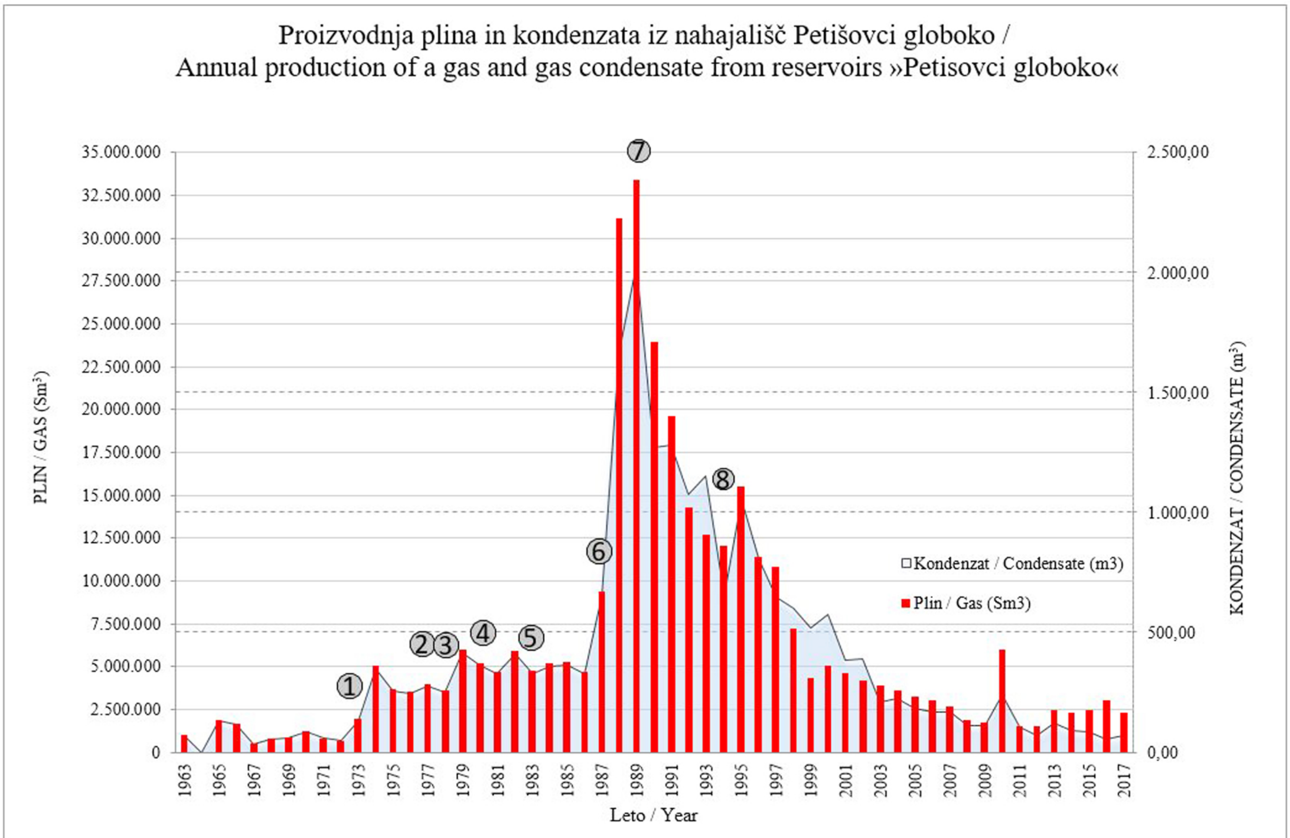
- $\o$ - povprečna poroznost (v delih enote, ne %) / average porosity (in parts of the unit, not %),
- S_{gi} - povprečno začetno nasičenje s plinom (1-S_{wi}) (v delih enote, ne %) / average initial gas saturation (1-S_{wi}) (in parts of the unit, not %),
- B_{gi} - začetni prostorninski koeficient plina (m^3/m^3) / initial gas volume factor (m^3/m^3).

Stopnja izkoriščenosti geoloških zalog (mednarodno znanih kot *in-situ* zalog) znaša za plinska nahajališča serije A-F »Petišovci globoko« 45–60 % (Bokor, 1986).

Trenutno se v svetu za izračun zalog uporablja statistična metoda, imenovana metoda Monte Carlo. Z omenjeno metodo se uporabijo vrednosti velikega števila meritev posameznih parametrov (debelina plasti, poroznost, nasičenost z ogljikovodiki itd.), ki se nato prikažejo v verjetnostni porazdelitveni frekvenčni krivulji. Te se nato prevedejo v kumulativno krivuljo in nato odčitajo vrednosti P90, P50, P10 in mediana. Te vrednosti verjetnosti se potem uporabijo za izračun zalog s pomočjo površinske metode. V primeru ocene virov in zalog plina na območju Petišovcev z Monte-Carlo metodo je v smisel našega pravilnika o zalogah prevedel Markič (2014), kar je bilo predstavljeno tudi komisiji Komisiji za ugotavljanje zalog in virov mineralnih surovin januarja 2014.

Proizvodnja plina iz nahajališč »Petišovci globoko«

S Pg-vrtinami so bila raziskana plinska nahajališč »Petišovci globoko«, iz katerih se črpata zemeljski plin in plinski kondenzat vse od leta 1963 do danes. V času raziskav in poizkusne proizvodnje je bilo ugotovljeno, da so plinska nahajališča



1. Mehanska stimulacija (število stimulacij: 1, nahajališče E_4) / Mechanical stimulation (number of stimulations: 1; reservoir: E_4)
2. Mehanska stimulacija (število stimulacij: 3, nahajališče E_1, E_3, E_4) / Mechanical stimulation (number of stimulations: 3; reservoir: E_1, E_3, E_4)
3. Mehanska stimulacija (število stimulacij: 1, nahajališče E_1) / Mechanical stimulation (number of stimulations: 1; reservoir: E_1)
4. Mehanska stimulacija (število stimulacij: 2, nahajališče B_2, D_2) / Mechanical stimulation (number of stimulations: 2; reservoir: B_2, D_2)
5. Mehanska stimulacija (število stimulacij: 2, nahajališče E_1) / Mechanical stimulation (number of stimulations: 2; reservoir: E_1)
6. Mehanska stimulacija (število stimulacij: 2, nahajališče E_4) / Mechanical stimulation (number of stimulations: 2; reservoir: E_4)
7. Mehanska stimulacija (število stimulacij: 3, nahajališče E_1, E_3) / Mechanical stimulation (number of stimulations: 3; reservoir: E_1, E_3)
8. Mehanska stimulacija (število stimulacij: 1, nahajališče D_1) / Mechanical stimulation (number of stimulations: 1; reservoir: D_1)

Sl. 9. Proizvodnja plina in plinskega kondenzata po letih iz nahajališč »Petišovci globoko« serije A-F (vir: Petrol Geo, 2018).
Fig. 9. Annual production of a gas and gas condensate from reservoirs »Petišovci globoko« series A-F (source: Petrol Geo, 2018).

D_1, D_2, E_1, E_3, E_4 in F proizvodna pod pogojem, da se poveča naravna propustnost z mehansko stimulacijo. Po izvedbi mehanske stimulacije je bila daleč najboljša proizvodnja dosežena iz nahajališča E_1.

Takoj po stimulaciji nahajališč se vidi trend povečanja proizvodnje in sicer največja letna proizvodnja se je zgodila leta 1989, kjer so količine presegale 33 milijonov Sm^3 in 2.000 m^3 kondenzata. Skozi proizvodno obdobje nahajališča serije A-F je bilo narejenih 17 mehanski stimulacij od leta 1973 do 1994. Pet stimulacij je bilo narejeni leta 2011 na vrtini Pg-10 in Pg-11A za nahajališča serije, 'K' (K-Q).

Skupno je bilo na naftno-plinskem polju Petišovci iz plinskih nahajališč od začetka proizvodnje leta 1963 do konca leta 2017 pridobljeno 341.754.115 Sm^3 zemeljskega plina in 21.803 m^3 kondenzata (Kraljič, 2015).

Letne proizvodnje zemeljskega plina in kondenzata od leta 1963 do 2017 iz nahajališč »Petišovci globoko« serije A-F (D_1, D_2, E_1, E_3, E_4 in F) so prikazane na sliki 9. Proizvodnja iz novih nahajališč serije K-Q na tej sliki še ni prikazana.

Zaključek

Kljub temu, da se zdi proizvodnja zemeljskega plina pogosto samoumevna in enostavna, gre za celovit razvoj naftno-plinskega polja, se pravi vse od raziskav, nastanka, proizvodnje in na koncu tudi sanacije polja, kjer je vključena cela vrsta strokovnjakov, ki pokrivajo različne stroke za to dejavnost. V zadnjih letih so v Sloveniji dela potekala na perspektivnih nahajališčih zemeljskega plina (»Petišovci-globoko«) na podlagi najnovejših 3-D seizmičnih meritev. Uspešni rezultati se kažejo v proizvodnji plina iz serije,'K' iz vrtin Pg-10 in Pg-11A. Pospešeno pa se proučujejo tudi možnosti pridobivanja ogljikovodikov, predvsem plina tudi v območjih drugih vrtin z možnostjo njihove poglobitve in iskanja naknadnih perspektivnih globokih nahajališčih. Dejstvo namreč je, da se z večanjem globin raziskovanja in morebitnega pridobivanja plina vse bolj približujemo območju matičnih kamnin. S tem je pričakovati tudi večjo vsebnost ogljikovodikov, predvsem plinonosnost kolektorskih kamnin obravnavanega območja.

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Engineering-geological conditions of landslides above the settlement of Koroška Bela (NW Slovenia)

Inženirskogeološke značilnosti plazov v zaledju naselja Koroška Bela (SZ Slovenija)

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Key words: landslide, debris flow, engineering-geological mapping, geotechnical monitoring, Urbas, Čikla, Bela stream, Koroška Bela

Ključne besede: plaz, drobirski tok, inženirskogeološko kartiranje, geotehnični sistem za opazovanje, Urbas, Čikla, potok Bela, Koroška Bela

Abstract

This paper focuses on the studying of landslides in the hinterland area of the Koroška Bela settlement, NW Slovenia. Research has shown that these landslides have the potential to mobilize the material into a debris flow. The area of interest is located on the Karavanke mountain ridge, above the settlement of Koroška Bela, which lies on the outskirts of the town of Jesenice. In order to recognize and understand the kinematics of landslides and their triggering mechanisms, a multidisciplinary approach using engineering-geological and geotechnical investigations was applied. Thus, landslide source areas were determined based on engineering-geological mapping. Furthermore, landslide boundaries, types of landslides and sediments that are involved in processes of sliding were mapped in detail. Geotechnical monitoring is beneficial in evaluating rates of movement and failures in the ground under real conditions in the field. Current investigations as well as historical evidence and previous research prove that the hinterland of Koroška Bela is prone to various types of landslides that together form a source area that has the potential to mobilize into larger debris flow.

Izvleček

Članek se osredotoča na proučevanje plazov v zaledju naselja Koroška Bela v severozahodni Sloveniji, ki na podlagi dosedanjih raziskav predstavlja potencialno izvorno območje za nastanek drobirskih tokov. Obravnavano območje se nahaja v Zahodnih Karavankah nad vasjo Koroška Bela v bližini Jesenic. Za prepoznavanje in razumevanje kinematike plazov in njihovih sprožilnih dejavnikov smo aplicirali interdisciplinarni pristop, ki je obsegal inženirskogeološke in geotehnične raziskave. Na podlagi inženirskogeološkega kartiranja smo določili izvorna območja plazov in njihov obseg, vrsto plazov in vrsto sedimenta, ki sestavlja plazeči material. Geotehnični sistem za opazovanje je pripomogel k oceni velikosti premikov v samem telesu plazov pri realnih pogojih. Obsežne raziskave zaledja potoka Bela nad Koroško Belo so poleg zgodovinskih virov in preteklih raziskav potrdile domneve o dovzetnosti tega območja za nastajanje mastnih (drobirskih) tokov, kakor tudi zemeljskih plazov in skalnih podorov.

Introduction

The fact that Slovenia is highly susceptible to landslides underlines the need for the intensive study and monitoring of landslides in Slovenia, with the aim of defining prevention measures and mitigation measures in order to reduce the hazards associated with landslides. The past decade has seen four large landslides (Stože, Slano Blato, Strug and Koseč) with volumes of approximately 1x10^6 m^3 (Jemec Auflič et al., 2017). In the case of the Stože landslide that occurred in November 2000 above the village of Log pod Mangartom in NW Slovenia and caused seven casualties and destroyed farm and residential buildings, the monitoring system consisted of 13 geodetic object points, 8 inclinometers for monitoring absolute displacements and streamflow measurements (Majes, 2001; Mikoš et al., 2006a; Četina et al., 2006; Mikoš, 2011). In the same period, reactivation of the Slano Blato landslide occurred above the village of Lokavec. The landslide was investigated using geophysical methods, geomechanical boreholes and engineering-geological mapping of the wider area (Majes et al., 2002; Ribičič & Kočevar, 2002; Logar et al., 2005; Fifer Bizjak & Zupančič, 2009; Mikoš et al., 2009; Maček et al., 2016). One year later, in 2001, the Strug landslide occurred above the village of Koseč. In that instance, the monitoring system consisted of periodical engineering-geological mapping, precipitation measurements, terrestrial laser scanning, geotechnical (inclinometers) and hydrological (piezometers) monitoring (Mikoš et al., 2005; Mikoš et al., 2006b; Mikoš et al., 2006c).

This paper summarizes observation of the landslides above the settlement of Koroška Bela (NW Slovenia) using engineering-geological and geotechnical monitoring. Based on the previous investigation and given geological conditions and field surveys, the area of interest reflects number of source areas that have the potential to mobilize the material there into a debris flow. The most active and characteristic are the Urbas and Čikla landslides (Jež et al., 2008; Peternel, 2017; Sodnik et al., 2017; Peternel et al., 2017a).

Historical sources describe the broader area of Koroška Bela as known to have experienced several debris-flow events in the recent geological past. The most recent of these events occurred back in the 18th century and caused the partial or total destruction of more than 40 buildings and cultivated areas in a Koroška Bela village located in the area of the debris fan deposits (Lavtižar, 1897; Zupan, 1937).

The first investigation and research of the Koroška Bela alluvial fan and its hinterland began in 2006 within the Target Research Project (TRP): “Debris flow risk assessment in Slovenia”. Within the TRP project, the following activities were applied: geological mapping of the hinterland of Koroška Bela (at scale 1: 5,000); and an investigation of alluvial fan deposits and debris flow modelling using the Flo-2D model. The thrust of the investigations indicated that the alluvial fan is composed of a sequence of diamicton layers and related subaeric sediments that had been deposited by several debris flow events in the past (Mikoš et al., 2008; Jež et al., 2008).

The first monitoring was established at the Urbas landslide using InSAR and GNSS technologies. InSAR and GNSS results showed relatively large (up to 32 mm horizontal and up to 15 mm vertical) displacements over the course of the monitoring period of six months (feb.–aug./2011), indicating a displacement of the central-upper and south-eastern parts of the landslide body (Komac et al., 2012a; Komac et al., 2012b; Komac et al., 2014).

In order to evaluate the kinematics of Urbas landslide and also to understand the specifics of a sliding processes, to assess the surficial displacement rates and changes in the surface topography a periodical monitoring using tachymetric measurements, UAV photogrammetry, and terrestrial laser scanning (TLS) was applied (Peternel et al., 2017b; Peternel, 2017).

Presently, some 2,200 inhabitants live in the area of the alluvial fan of past debris flows. With this risk potential in mind, monitoring the sliding mass and assessing the displaced material volumes is crucial, and more important than the purely scientific value of any assessment efforts (Peternel et al., 2017b).

In this regard, the Koroška Bela hinterland was investigated using a combination of detailed engineering-geological mapping, together with geotechnical, geophysical and geodetic methods. With this paper we present the results obtained from the engineering-geological mapping and the geotechnical monitoring system using inclinometer measurements for the Urbas and Čikla landslides.

Site-specific geotechnical data is essential in evaluating movements and failures in the ground under real field conditions, and for the design and implementation of a monitoring system and early warning system for this large landslide. That data provides important information related to the characterization and strength of the geological structures involved and the kinematics of the unstable areas there.

The most common geotechnical instrumentation installed to monitor landslides consists in piezometers to measure groundwater levels and instruments like inclinometers to measure displacements.

Slope inclinometers have been used to determine the magnitude, rate, direction, depth, and type of landslide movement (Stark & Choi, 2008). This information is essential to understanding the cause and behaviour of landslides (Stark & Choi, 2008).

Geological settings

The broad area of the hinterland of Koroška Bela exhibits fairly complex geological and tectonic conditions (fig. 1). Geological units of the study site are mainly represented by Upper Carboniferous and Permian sedimentary clastic rocks – Permian carbonates and Triassic to Lower Jurassic carbonate rocks (Jež et al. 2008). The main slope instabilities are related to tectonic contacts between the Upper Carboniferous to

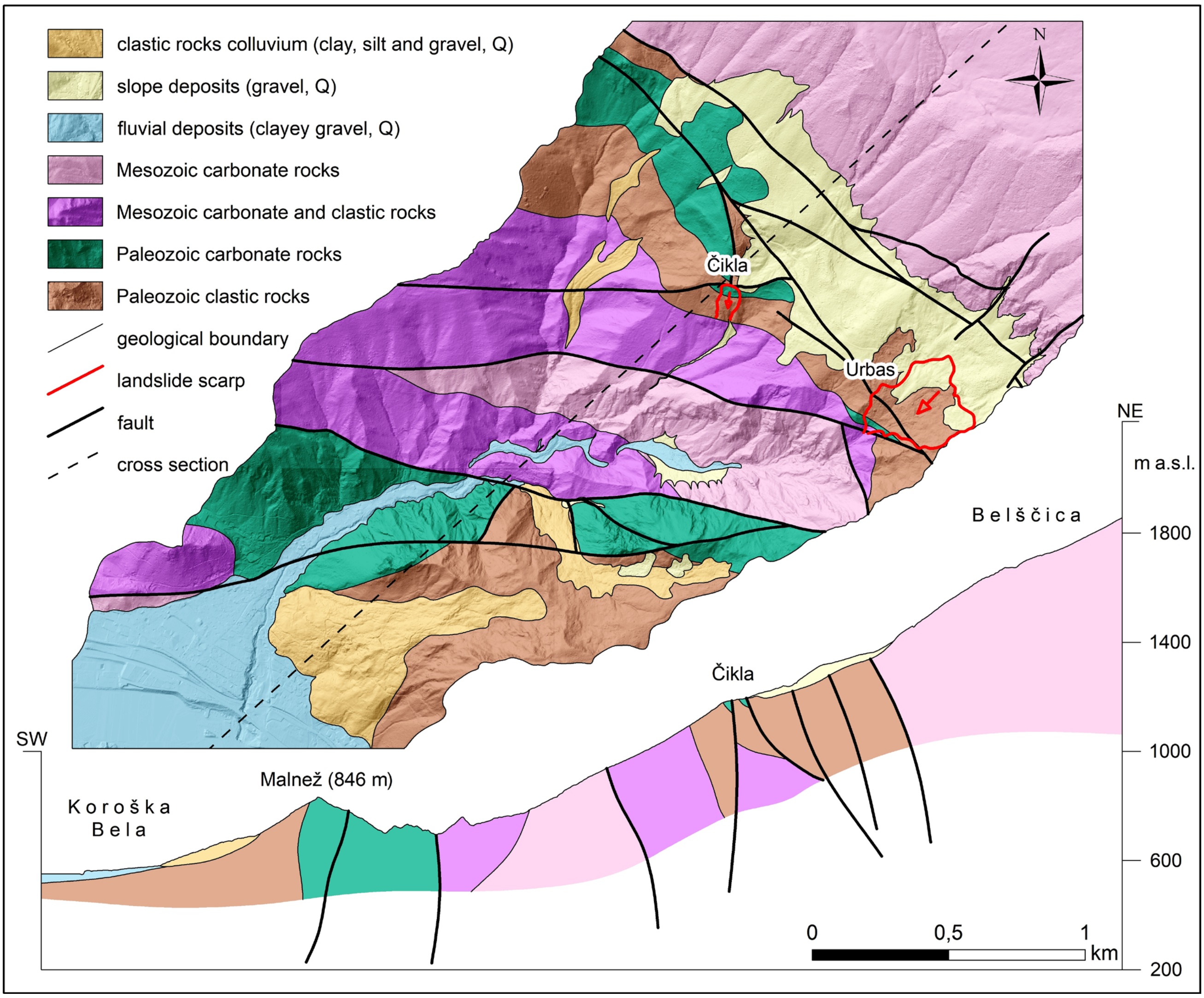

Fig. 1. Geological map and cross section of the hinterland of Koroška Bela.

Permian clastic rocks (claystone, siltstone, sandstone and conglomerate) and different Permian and Triassic carbonate and clastic rocks. The contact is represented by several reverse faults dipping approximately 70° to the NE (Jež et al., 2008).

In terms of tectonics, the area is part of the Košuta fault zone and is dissected by numerous NW-SE faults linking two major fault zones (the Sava and Periadriatic fault zones) (Jež et al., 2008). Due to active tectonics the Upper Carboniferous and Permian clastic rocks are heavily deformed, and, consequently, very prone to fast and deep weathering. Carbonate rocks in the uppermost parts of the Karavanke ridge are also subject to physical and chemical weathering, resulting in large quantities of talus and scree material covering the part lying below the clastic rocks.

These landslide events are largely related to soft fine-grained and tectonically deformed clastic rocks, most of which are covered with large quantities of carbonate scree material.

Landslides descriptions

The territory of interest is located in the Karavanke mountain ridge in north-western Slovenia (46.26° N, 14.8° W), above the settlement of Koroška Bela that lies on the outskirts of the town Jesenice. The study area extends between an elevation of 600 m at the surface of the alluvial fan and 2100 m at the summit of peak Belščica. The area is characterized by medium- to high-slope gradients ranging from 30° to 70°. It covers an area of approximately 6 km^2.

The Karavanke mountain ridge is characterised by an annual average precipitation of about 2600–3200 mm, distributed over 70–100 days. The study area has two precipitation peaks, with the main peak falling in autumn, and the second precipitation peak in spring. The lowest precipitation rate is recorded in summer (Internet).

Due to its lithological and structural conditions and precipitation rates the area of the Koroška Bela hinterland is highly prone to land-

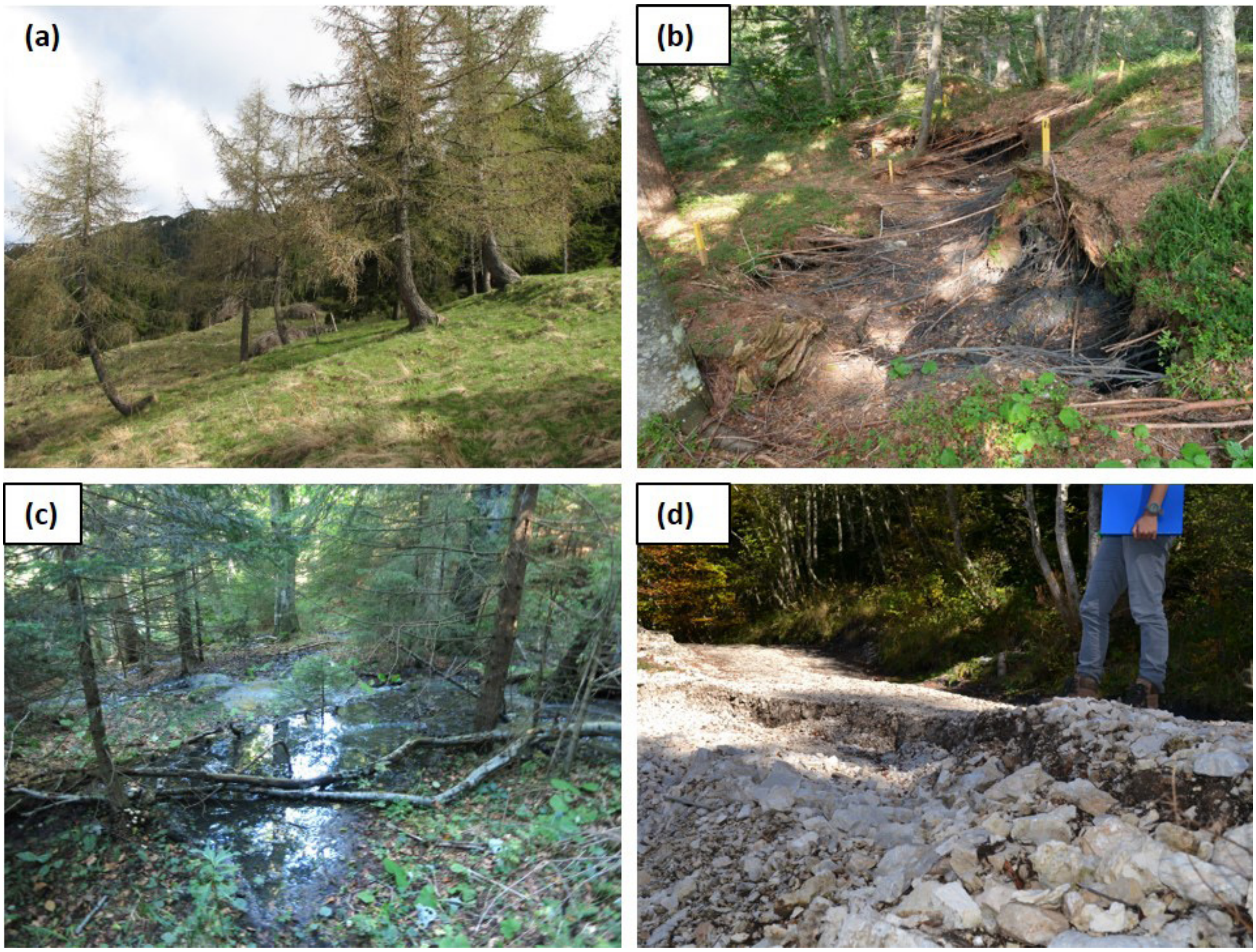

Fig. 2. Failure features on the surface: (a) Hummocky terrain with curved trees (b) Longitudinal tension cracks (c) Ponds on the surface (d) Subsidence of road

slides. The upper part of the Urbas landslide at the main scarp and the part below are dominated by rockslides and runoff of the scree material. The main body of both landslides is formed by heavily deformed and weathered clastic rocks and is presumed to be a rotational deep-seated slow-motion slide that has accelerated predominately with the percolation of surface and ground water (Jež et al. 2008; Komac et al. 2012). At the main body of the Čikla landslide a vast structure of carbonate rocks is also included, which locally disintegrate into a form of rockfall.

The morphology of the entire hinterland of Koroška Bela is characterized by irregular and hummocky terrain comprised of protrusions and depressions of various sizes. Such activity is evidenced by "pistol butt" trees (fig. 2a), longitudinal tension cracks (fig. 2b), erosion slumps and ponds on the surface (fig. 2c), as well as the common deformation of local roads (fig. 2d).

A greater spatial density of springs and wetlands is evident at the contact between scree and clastic rocks, partly supplied from the infiltration. Two of the most significant of these are the Urbas (1275 m.a.s.l) and Čikla springs (1190 m.a.s.l.).

The monitoring sites are located at the Urbas and Čikla landslides, which are currently considered to be the most active parts of the Bela stream hinterland based on previous investigations and field observations. The Urbas landslide is crossed by the Bela stream; meanwhile, the Čikla landslide is crossed by the Čikla torrent, which is a tributary of the Bela stream. Both landslides have a gully-type morphology. The sliding mass is composed of tectonically deformed and weathered Upper Carboniferous and Permian clastic rocks covered with a large amount of talus material, which is prone to slope instability. Additionally, the Bela stream and its Čikla tributary cause significant erosion and increase the possibility of the sliding mass mobilizing downstream. The active parts of the Urbas and Čikla landslides are characterized by bare ground with fallen trees, rugged surfaces, strong gully erosion and flank ridges.

Methods

In order to recognize and understand the landslides and their dynamics it is crucial to apply an engineering-geological approach. It is also essential to set up a flexible and reliable monitoring system to monitor changes through time and space. Changes on the surface and observation of absolute displacements can be monitored using various surveying techniques.

The Koroška Bela hinterland has been investigated by combining detailed engineering-geological mapping, geotechnical, geophysical and geodetic methods. This paper reports the results of engineering-geological mapping and geotechnical monitoring using inclinometer measurements. Hydrogeological investigations are represented in Janža et al., 2018. The spatial distribution of all applied methods is shown in fig. 3.

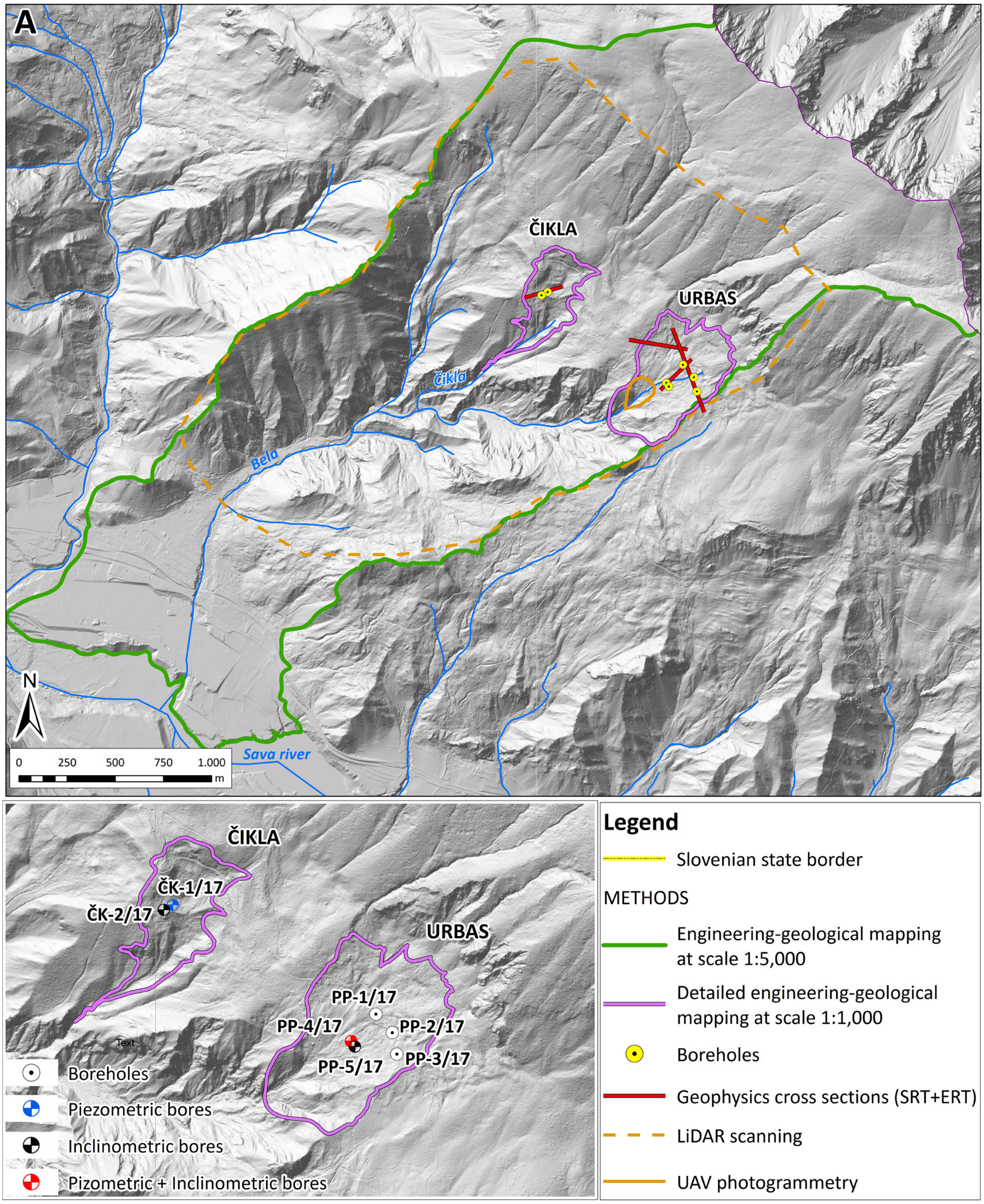

Fig. 3. Spatial distribution of applied methods (Peternel et al., 2017a).

Landslide identification and mapping

The field survey and the analyses of a 1-m grid digital elevation model (DEM) derived from lidar data were used for engineering-geological and geomorphological mapping.

The entire hinterland of the Bela stream was geologically mapped at scale 1: 5,000, while selected important landslides were mapped at scale 1: 1,000.

In the frame of detailed engineering-geological mapping the following features were determined: landslide boundaries at the ground surface and landslide failure features on the surface (main and secondary scarps, shear zones, tension cracks, ponds, curved trees, deformation of local roads). Additionally, monitoring locations and related techniques (type of monitoring, data acquisition and locations) and geomechanical boreholes were also defined.

Geotechnical investigation

An important part of the investigation of the Urbas and Čikla landslides involved the core drilling and core logging of 7 boreholes that was undertaken in September 2017. The locations for the boreholes were determined based on a field survey and logistical factors (accessibility of area) (fig. 3).

Using the information provided by core logging allowed us to identify the main lithological units in the study area. Subsurface conditions, absolute displacement rates and measurements of ground water levels were interpreted on the basis of 4 boreholes equipped with inclinometers or piezometers (Table 1).

Boreholes PP-4/17, PP-5/17 and ČK-2/17 were equipped with inclinometers. Inclinometer measurements at PP-4/17 and PP-5/17 were taken using a Digitilt inclinometer probe with a measurement interval of 0.5 m. The full equipment consisted of the probe, a heavy-duty control cable wound on a slip-ring reel, the DataMate II readout and DigiPro2 software. The PVC inclinometer casings have longitudinal grooves in two perpendicular directions A and B (in which case direction A has to be determined southward) to ensure the probe remains oriented in the desired direction. The grooves of the guide casings were oriented in the expected direction of movement of the Urbas and Čikla landslides.

The main purpose of employing inclinometer measurements was to determine absolute and displacement rates. The results are presented as displacement profiles (fig. 8), which are used to determine magnitude, depth, direction and rate of ground movement.

Results

Engineering-geological maps

Based on engineering-geological mapping of the Bela stream hinterland at scale 1: 5,000, the most extensive and active landslides are the Urbas and Čikla landslides. In order to reconstruct the extension and kinematics, detailed mapping at scale 1: 1,000 was applied for both landslides.

As a result, the Urbas and Čikla landslides were divided according to landslide prone areas (figs. 4, 5):

Table 1. List of boreholes.

	Borehole	Location	GKX	GKY	Depth (m)	Groundwater level * (m)	Type of observation wall
1	PP-1/17	Urbas	433762	143830	40,0	7,80	none
2	PP-2/17	Urbas	433818	143766	29,0	11,2	none
3	PP-3/17	Urbas	433834	143692	31,0	21,30	none
4	PP-4/17	Urbas	433675	143735	33,0	3,70	Inclinometer
	PP-4 -Ppl/17	Urbas	433676	143737	15,0	3,1	Piezometer
	PP-4-Pgl/17	Urbas	433675	143736	6,0	3,2	Piezometer
5	PP-5/17	Urbas	433689	143717	40,0	8,8	Inclinometer (13 m) - destroyed
6	ČK-1/17	Čikla	433059	144207	40,0	31,1	Piezometer
7	ČK-2/17	Čikla	433027	144191	39,0	8,5	Inclinometer

**groundwater level data were set after the drilling.*

Table 1 also shows data about groundwater level for each borehole. Groundwater level measurements were taken manually after the drilling. All information about hydrogeological investigations and groundwater dynamics are represented in Janža et al., 2018.

- stable areas without clear landslide features,
- potentially unstable areas with some landslide and geomorphological features that indicate persisting sliding in the past or consist of soft sediments,
- active areas that are characterized by numerous features that are the result of active landslide (e.g. bare ground, open cracks, tilted trees, etc.).

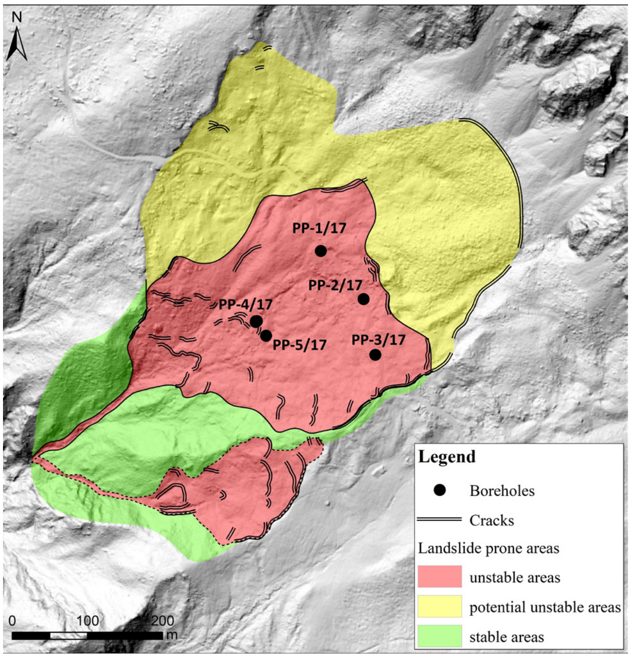

Fig. 4. Map of Urbas landslide-prone areas with contribution landslide.

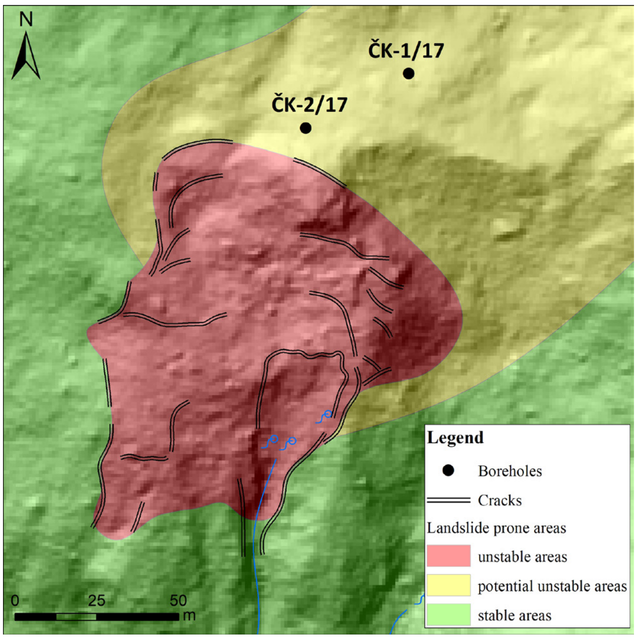

Fig. 5. Map of Čikla landslide-prone areas.

The active part of the Urbas landslide (fig. 4) extends over an area measuring some 320 × 420 m and covers an area of approximately 85,320 m^2. The entire landslide including potentially unstable areas measures up to 460 × 560 m.

In the case of the Čikla landslide (fig. 5), the active area covers an area of 105 × 130 m, and is actively progressing toward NE, with a surface area extending over an area of approximately 8,000 m^2.

Core logging

The results of the core logging for the Urbas landslide are shown in figure 6.

In borehole PP-1/17 a core was drilled up to 40.0 m. According to the detailed core logging of PP- 1/17 three main lithological units were recognized. The uppermost layer (0 –7.8 m) is represented by Quaternary Unit (Q) debris deposits that are composed of scree material (GW) and scree material with clayey or/and silty binder (GC/GM). A lower depth (7.8–13.2 m), the silty and clay debris (ML, CL) prevail over talus debris. At a depth of 13.2 m the bedrock appears as grey, heavily deformed Upper Carboniferous and Permian clastic rock. Three slip surfaces are presented in boreholes PP-1/17 at depths of 11.2, 13.2 and 15.0 m. The determined slip surfaces are related to wet segments, to contacts between soil and soft rock, and to a segment inside highly tectonized PC-siltstone.

In borehole PP-2/17, the core was drilled down to 29.0 m. The upper layer (0–2.7 m) of PP-2/17 is represented by scree material containing silt and clay particles (GW/(CL/(GC)). This layer gradually becomes a silt section with individual layers of silty gravel and silty sand (2.7–8.3 m). At a depth of 8.3 m, the section of grey, heavily-deformed Upper Carboniferous and Permian carbonate and clastic rock appears. Between 8.3 and 13.0 m the section is represented by limestone, sandstone and sandy marlstone. Further down (13.0–19.0 m) PP-2/17 is represented by a section of limestone that at a depth of 19 m becomes limestone breccia. In borehole PP-2/17 two slip surfaces were recognized at depths of 3.5 and 8.3 m. The first is related to a wet core segment, while the second represent the contact between soil and soft rock immediately above the bedrock.

In the third borehole of PP-3/17, the total length of the core is 31.0 m. In the upper part it starts with a 3.9 m layer of Quaternary Unit (Q) debris deposits (GW). At a depth of 3.9 m the grey, completely weathered Upper Carboniferous and Permian clastic rock appears. From engineering-geological point of view this layer can be classified as the residual soil (silt) of weathered PC siltstone without any recognizable structure.

Three slip surfaces are presented at depths of 7.7, 12.5 and 15.7 m. The determined slip surfaces are related to segments inside completely weathered PC siltstone.

In borehole PP-4/17, the core was drilled down to 33.0 m and was equipped with an inclinometer. The uppermost layer (0–3.80 m) is represented by Quaternary Unit (Q) debris deposits that are composed of scree material (GW) and scree material with clay matrix. From 3.8 to 13.75 m

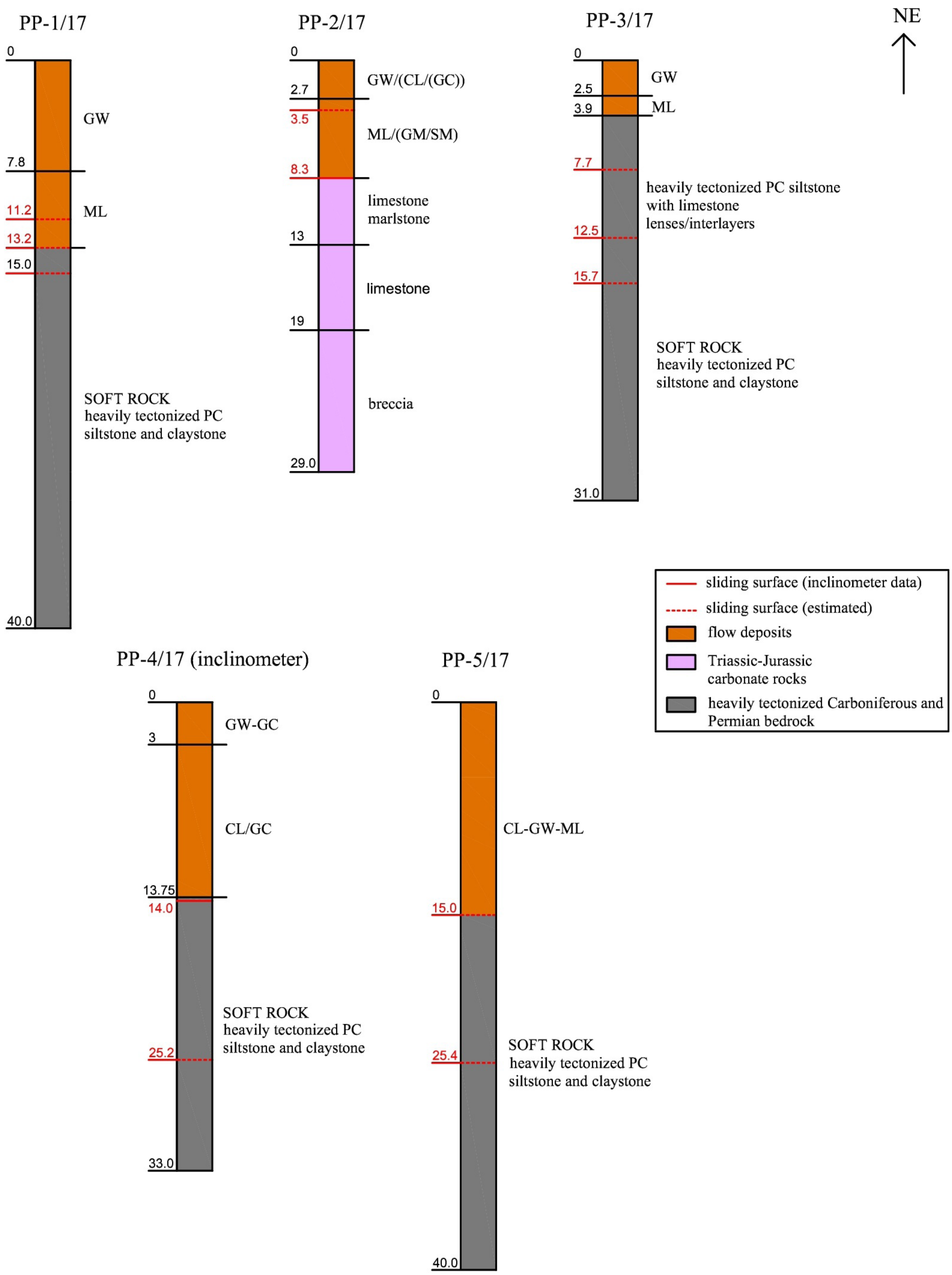

Fig.6. Geotechnical borehole logs of the Urbas landslide. The locations of the boreholes are shown in fig. 3.

the carbonate scree is mixed with clay debris (CL). At a depth of 13.75 m the bedrock appears as grey, heavily-deformed Upper Carboniferous and Permian clastic rock. In borehole PP-4/17 two slip surfaces were recognized at depths of 14.0 and 25.2 m. The first was recognized based on inclinometer measurements, while the second is related to a segment inside well-weathered PC-siltstone and a wet zone.

In the fifth borehole of PP-5/17, the core was drilled to 40.0 m. The upper layer (0–16.0 m) of PP-5/17 is represented by alternating scree material (GW), scree material with silty binder (GM) and sand (SM), clay (CL) or silty (ML) debris. The bedrock appears at a depth of 16.0 m as a grey, heavily-deformed Upper Carboniferous and Permian clastic rock. Two slip surfaces are presented in PP-5/17 at depths of 15.0 and 25.4 m. The determined slip surfaces are related to wet segments, to contacts between soil and soft rock, and to a segment inside highly-weathered PC-siltstone.

The area of the Čikla landslide was investigated through 2 boreholes. Borehole ČK-1/17 was equipped with a piezometer, while ČK-2/17 was equipped with an inclinometer. Both boreholes were drilled in area that was considered as potentially unstable areas in the immediate hinterland of the currently active landslide (fig. 5). The results of core logging for the Čikla landslide are shown in figure 7.

In borehole ČK-1/17, the core was drilled down to 40.0 m and was equipped with a piezometer. Hydraulic conductivity of borehole sections and groundwater level fluctuations in ČK-1/17 are presented in Janža et al., 2018. According to detailed core logging of ČK-1/17, three main lithological units were recognized. The uppermost layer (0–29.5 m) is represented by Quaternary Unit (Q) debris deposits that are the consequence of fossil alluvial events. Deposits are composed of scree material (GW) with limestone blocks and scree material with silty binder. At a depth of 29.5 m the residual soil is composed of completely tectonized and weathered Upper Carboniferous and Lower Permian siltstone, with lenses of marlstone that gradually transit into massive siltstone.

In the second borehole of ČK-2/17, the total length of the core is 39.0 m. The uppermost layer (0–4.9 m) some 4.9 m thick is composed of silty

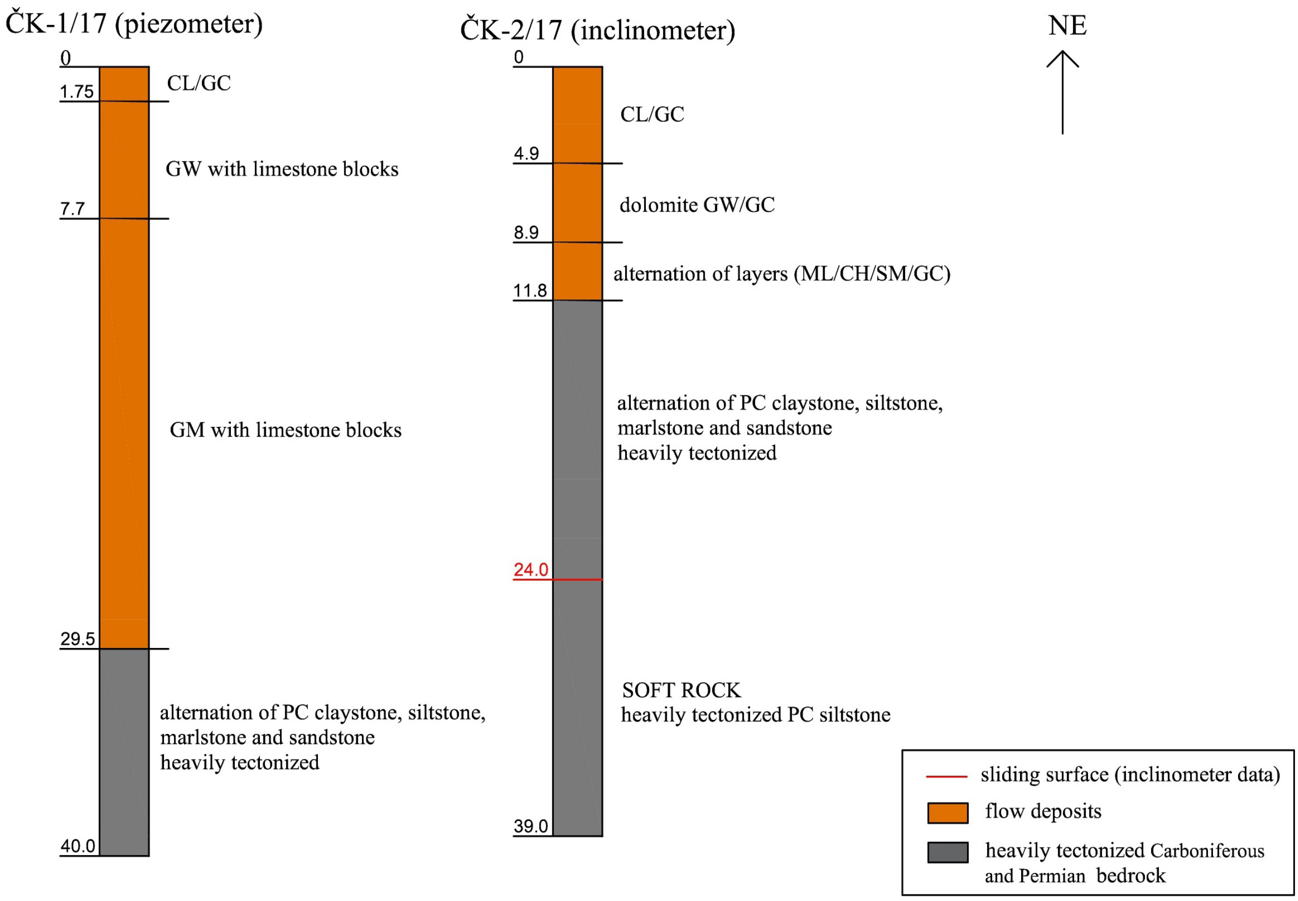

Fig. 7. Geotechnical borehole logs of the Čikla landslide. The locations of the boreholes are shown in fig. 3.

clay (CL) and clayey gravel (GC) with a transition into silty sand (SM) and clay (CH). At a depth of 4.9 m to 8.9 m a layer of dolomite gravel and gravel with clay matrix appears, followed by a section (8.9–11.8 m) of alternating layers (ML, CH, SM, GC). At a depth of 11.8 m a section (11.8–24.0 m) of completely tectonized and weathered Upper Carboniferous and Permian clastic rock appears. This layer is composed of alternation of gravel and clayey gravel with alternating layers (SM, CH, ML) followed by silty sand with gravel. At a depth of 24.0 m a grey, completely deformed Upper Carboniferous and Lower Permian siltstone appears. Due to drilling, primary sedimentary structures of the rocks are largely unrecognizable in the core.

Inclinometer measurements

PP-4/17 and ČK-2/17 were equipped with two inclinometers that reached down to significant depths (between 39 and 40 m) beyond the expected slip surface (Table 1). The grooves of the inclinometer (Aos, Bos) were oriented in the direction of the expected movement. Inclinometer monitoring was performed between September 2017 and May 2018. Until now, data has been collected for 3 observation periods for inclinometer PP-4/17, and for 2 observation periods for ČK-2/17 (Table 2).

The zero measurement at the inclinometer borehole PP-4/17 was taken on 28 September 2017. The zero measurement (for borehole ČK-2/17) and the first reading (for borehole PP-4/17)

Table 2. Observation periods of inclinometer monitoring.

Observation period	Date	Length of observation period	Inclinometer
1st	28 September – 12 October 2017	2 weeks	PP-4/17
2nd	12 October – 27 October 2017	2 weeks	PP-4 /17 +ČK-2/17
3rd	27 October 2018 – 23 May 2018	7 months	PP-4 /17 +ČK-2/17

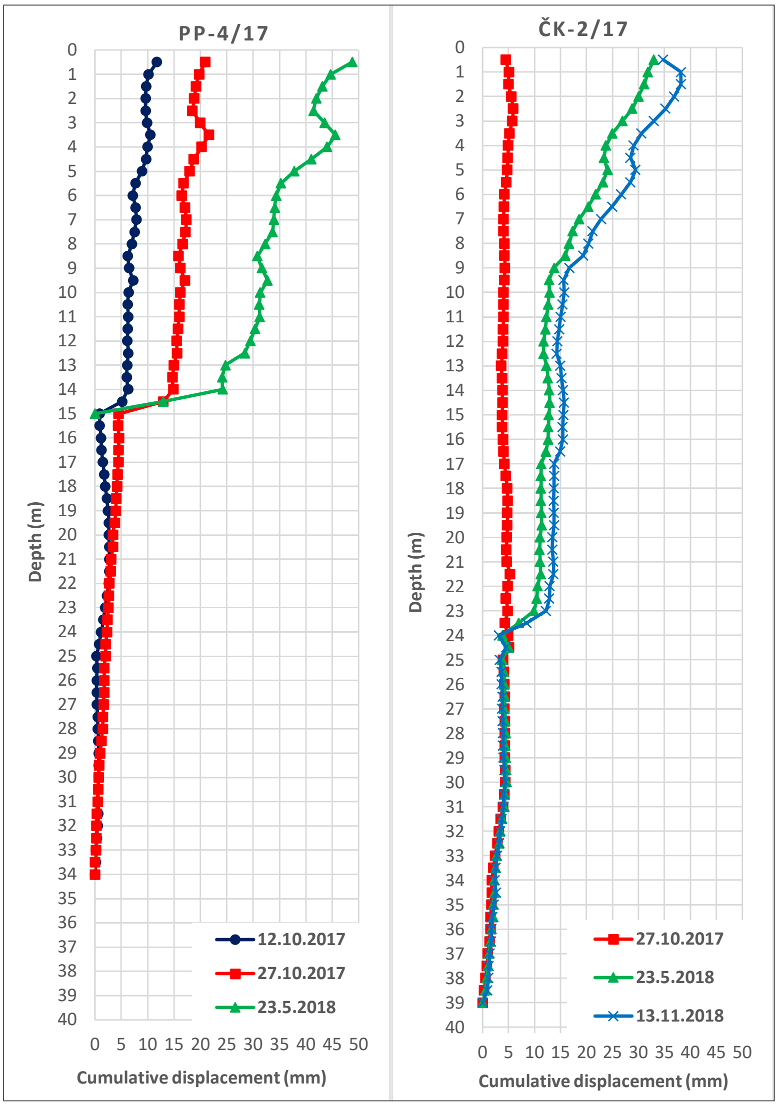

Fig. 8. Displacement measured by the inclinometers installed at PP-4/17 (Urbas landslide) and ČK-2/17 (Čikla landslide).

were performed on 12 October 2017. Follow-up measurements were performed on 27 October 2017, with the last on 24 May 2018 (Table 2). As the dates indicate, monitoring covered a period of 8 months.

The displacement vertical profiles of the 2 inclinometer measurements at PP-4/17 and ČK-2/17 are shown in figure 8. The inclinometer installed in borehole PP-4/17 shows cumulative absolute displacements in the slope face direction of some 24 mm between October 2017 and May 2018 down to a depth of 14 m. Based on core logging the slip surface is related to heavily deformed Upper Carboniferous and Permian clastic rocks. The last measurement showed that the inclinometer installed in borehole PP-4/17 was cut at a depth of 14 m (fig. 8).

Although that borehole ČK-2/17 was located in the area that was considered as potential unstable area (approx. 15 m behind the crown crack of active landslide), inclinometer installed in borehole ČK-2/17 showed significant displacements at a depth of 24 m. The measurements detect absolute cumulative displacements near 12 m over a period of 1 year (fig. 8). As in PP-4/17, the slip surface is related to heavily deformed Upper Carboniferous and Permian clastic rocks.

Discussion

This research focuses on the observation of large landslides that represent a direct risk to the settlement of Koroška Bela below. With this risk in mind a multidisciplinary monitoring approach was applied – specifically, slope mass instabilities were identified and investigated through detailed field investigations, including engineering-geological mapping, geophysical investigations and core logging of 7 boreholes (figs. 3, 6, 7). Applied surveys show that spatial distribution of the slope material and the relationships between lithological units are closely related to mass movement processes that have occurred in the past. The sliding mass is composed of tectonically deformed and weathered Upper Carboniferous and Permian clastic rocks covered with a large amount of talus material that is prone to slope instability.

The Urbas landslide spreads out over an area of nearly 90,000 m^2 and was estimated to include up to 1 million m^3 of sliding material. Sliding is expected to progress towards the north. The Čikla landslide, however, covers a significantly smaller area, but inclinometers indicate the sliding surface near the 25 m point. Additionally, in April 2017 a part of the Čikla landslide was transformed to debris-flow, which came to a halt about 500 m down from the Čikla stream. Additionally, the Bela and Čikla streams causes significant erosion and contributes significantly to the mobilization of the sliding mass downstream. After Varnes (1978) classification and based on the determined depth of slip surfaces, both landslides are understood to be deep-seated rotational slides.

Additionally, two boreholes were equipped with pressure probes with recorders to observe fluctuations in groundwater levels. These observations, which involved hydraulic tests, show complex and heterogeneous hydrogeological conditions predisposed by geological and tectonic settings and active mass movements that cannot be uniformly described (Janža et al., 2018).

Conclusions

In this study, the landslides above the settlement of Koroška Bela (NW Slovenia) were observed using engineering-geological mapping and through geotechnical investigations. By combining inclinometer data with core logging and engineering-geological surveys, the extension and kinematics of relevant active movements were reconstructed. The presented study reveals that the Urbas and Čikla landslides are deep-seated landslides such as Macesnik landslide (Pulko et al., 2014) and Rebernice landslide (Popit et al., 2017). Based on engineering-geological mapping and previous investigations the Urbas and Čikla landslides represent the most active landslides of the Bela stream hinterland. The Urbas landslide covers an area of approximately 85,320 m^2, while the Čikla landslide extends over an area of approximately 8,000 m^2. Due to the geological and tectonic conditions of the study area, both landslides are prone to different landslides: rockslides and runoff of scree material, deep-seated landsliding at the main body, and debris flow. Based on inclinometer readings, the Urbas landslide is moving at a maximum rate of down to a maximum depth of 14 m, while at the Čikla landslide significant displacements were registered at a depth of 22.5 m.

This research finds and proves that mechanisms of landslides in the hinterland of the Koroška Bela settlement are related to: (1) geological and tectonic conditions affecting rocks that are heavily deformed, and, consequently, very prone to fast and deep weathering, (2) surface and underground water circulation in the wider landslides area and weak geomechanical properties of the lithological units of the study area.

In the future, integration of the geomorphological, geotechnical and geophysical information obtained, together with the monitoring data provided by the inclinometers installed there will provide particularly relevant information for a better understanding of the behaviour and kinematics of the studied instabilities. Furthermore, this data represents input data that can be used in the 3D modelling of sliding surfaces and volume assessment, and in the planning of mitigation measures and risk management strategies.

In order to estimate the real effect of the tectonic, geological and meteorological conditions (e.g. amount of precipitation, snow melt, etc.) on the kinematics of landslides further, upgraded application of established monitoring (e.g. rain gauges, geotechnical sensors, etc.) is recommended. Similarly, future additional research on the relationship between precipitation, groundwater levels and landslide dynamics site is required (and planned), in order to determine correlations between displacement rates and long-term rainy periods and/or snowmelt.

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Hydrogeological investigation of landslides Urbas and Čikla above the settlement of Koroška Bela (NW Slovenia)

Hidrogeološke raziskave plazov Urbas in Čikla nad naseljem Koroška Bela (SZ Slovenija)

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Ključne besede: plaz, podzemna voda, infiltrometrski preizkus, nalivalni preizkus, opazovalna vrtina, Koroška Bela

Abstract

The area above the settlement of Koroška Bela is highly prone to slope mass movements and poses a high risk for the safety of the settlement. To get an insight into the hydrogeological conditions and processes which can affect mass movements in this area, hydrogeological investigations, including hydrogeological mapping, discharge measurements of springs, performance of infiltrometer and slug tests were performed. The results of these investigations show complex and heterogeneous hydrogeological conditions, predisposed by geological and tectonic setting and active mass movements which cannot be uniformly described. Observed large fluctuations in the rate of discharge of springs and groundwater level in observation wells are highly dependent on meteorological conditions. Estimated hydraulic conductivity of the soil is relatively high (2×10^{-4} m/s) and reflects the loose structure and high content of organic matter in the upper part of the forest soil. Hydraulic conductivity of more permeable sections of boreholes is in general higher in the upper parts, in predominantly gravel layers (in range from 2×10^{-3} to 1×10^{-5} m/s), than in the deeper clayey gravel parts (3×10^{-5} to 1×10^{-7} m/s). In the area of the Čikla landslide the average hydraulic conductivity is estimated at 8.99×10^{-4} m/s and is higher than in the area of the Urbas landslide (3.05×10^{-4} m/s).

Izvleček

Na območju nad naseljem Koroška Bela je velika nevarnost nastanka pobočnih masnih premikov, kar predstavlja tveganje za varnost naselja. Za razumevanje hidrogeoloških pogojev in procesov, ki lahko vplivajo na masne premike na tem območju, so bile izvedene hidrogeološke raziskave, ki so vključevale hidrogeološko kartiranje, meritve pretokov izvirov ter izvedbo infiltrometrskih in nalivalnih preizkusov. Rezultati raziskav kažejo zapletene in heterogene hidrogeološke razmere, pogojene z geološkimi in tektonskimi značilnostmi širšega območja ter aktivnimi masnimi premiki, ki jih ni mogoče enoznačno opisati. Opazovana velika nihanja pretokov izvirov in gladine podzemne vode v opazovalnih vrtinah so močno odvisna od meteoroloških razmer. Ocenjeni koeficient prepustnosti tal je relativno visok (2×10^{-4} m/s) in odraža rahla tla z visoko vsebnostjo organske snovi, ki so značilna za gozd. Koeficient prepustnosti bolje prepustnih odsekov vrtin je v splošnem višji v zgornjih delih, v plasteh s prevladujočim gruščem (v razponu med 2×10^{-3} in 1×10^{-5} m/s), kot v globljih delih vrtin, v zaglinjenih plasteh (med 3×10^{-5} in 1×10^{-7} m/s). Na območju plazu Čikla je ocenjen povprečni koeficient prepustnosti 8.99×10^{-4} m/s in je višji kot na območju plazu Urbas (3.05×10^{-4} m/s).

Nomenclature

v	infiltration velocity (m/s)
ΔV	volume of infiltrated water during measuring phase when flow is close to steady-state condition (m^3)
A_i	area of inner infiltrometer ring (m^2)
t	time (s)
K	hydraulic conductivity (m/s)
i	hydraulic gradient (-)
z_w	saturated thickness trough which flow occurs (underground depth of infiltrated water reach) (m)
h	hydraulic head (m)
V	total volume infiltrated over the entire duration of the infiltration test (m^3)
θ	volumetric water content - ratio of water volume to total soil volume (-)
θ_s	saturated soil volumetric water content (-)
θ_i	initial soil volumetric water content (-)
$\Delta\theta$	difference between θ_s and θ_i (-)
A	effective area of casing or excavation (m^2)
F	shape factor (-)
L	length of effective intake or filtering zone (m)
D	diameter of effective intake or well point (m)
Q	injection rate (m^3/s)
m	shape factor (-)
r	well screen radius (m)

Introduction

Hydrogeological conditions have an important role in the stability of slopes. Part of the rainfall that infiltrates into the ground can contribute to the increase of pore pressures and saturation (decrease of suction) of the ground or even to the rise of the groundwater table, all of which may initiate mass movements on slopes. The changes of hydraulic conditions propagate from the ground surface into the subsoil and slope failures are more likely to take place a certain time after a rainfall event (Jemec Auflič et al., 2016; Nilsen et al., 1976). The time rate of propagation depends on the hydrogeological properties of the ground. The response of the slope material relies primarily on the ground material; granular soils are more sensitive to short-duration intense rainfall events, whereas fine sediment (clay-like) materials are sensitive to long-duration and moderate intensity precipitation (Casagli et al., 2006).

Beside the in-situ infiltration, the occurrence of groundwater that affects landslides can result from lateral flow, or exfiltration from the bedrock. Due to the unique groundwater flow pattern in every landslide, triggering mechanisms related to hydrogeology are complex (Brönnimann, 2011). The local hydraulic field is related to the structure of the landslide mass, which is a result of landslide activity, the formation of cracks, and increased hydraulic conductivity due to soil saturation. Therefore, the hydraulic conductivity of the landslide mass, which controls the groundwater flow, may be very heterogeneous (Guglielmi et al., 2002).

The area of Koroška Bela settlement in NW Slovenia has experienced severe debris-flow events in the past and a big part of the settlement is even built on an alluvial fan of past debris flows (Jež et al., 2008). Due to the geological, tectonic and hydrogeological conditions, the area above the settlement is highly prone to different slope mass movements, posing a high risk for the safety of the settlement (Peternel et al., 2016). To assess the risk of mass movements and provide supportive information for the planning of safety measures for the protection of the settlement, various series of geological (Jež et al., 2008), engineering (Peternel et al., 2018), geophysical, geomechanical, geomorphological, geodetic, and hydrogeological investigations were performed (Peternel et al., 2017).

In this paper, hydrogeological investigations, which include hydrogeological mapping, discharge measurements of springs, performance of infiltrometer and slug tests in the period from 29 August to 26 October 2017 are presented. The aim of these investigations was to get an insight into the hydrogeological conditions and processes which can affect mass movements in the area above Koroška Bela settlement.

Study area

The areas of the Urbas (85000 m^2) and Čikla (8000 m^2) landslides lie in the NW part of Slovenia in the hinterland of the settlement Koroška Bela (figs. 1a, 1b). The areas of landslides extend from an elevation of 1150 m to 1300 m on the south to southwest oriented slope with gradient ranging generally from 30° to 70°. Average annual precipitation and temperature in this area range from 2000 mm to 2600 mm and from 3 °C to 5 °C respectively (ARSO, 2018a).

The area is a part of the high east-west extended mountainous ridge of Karavanke, a mountain range of the Eastern Alps. The terrain of the Karavanke Mountains consists of long and prominent ridges, whose slopes fall steeply to the northern and southern side. The ridges are interrupted by long, deep and narrow valleys streams, exhibiting properties typical for high-mountain watercourses: irregular and uneven channels with rapid flows (Brenčič & Poltnig, 2008).

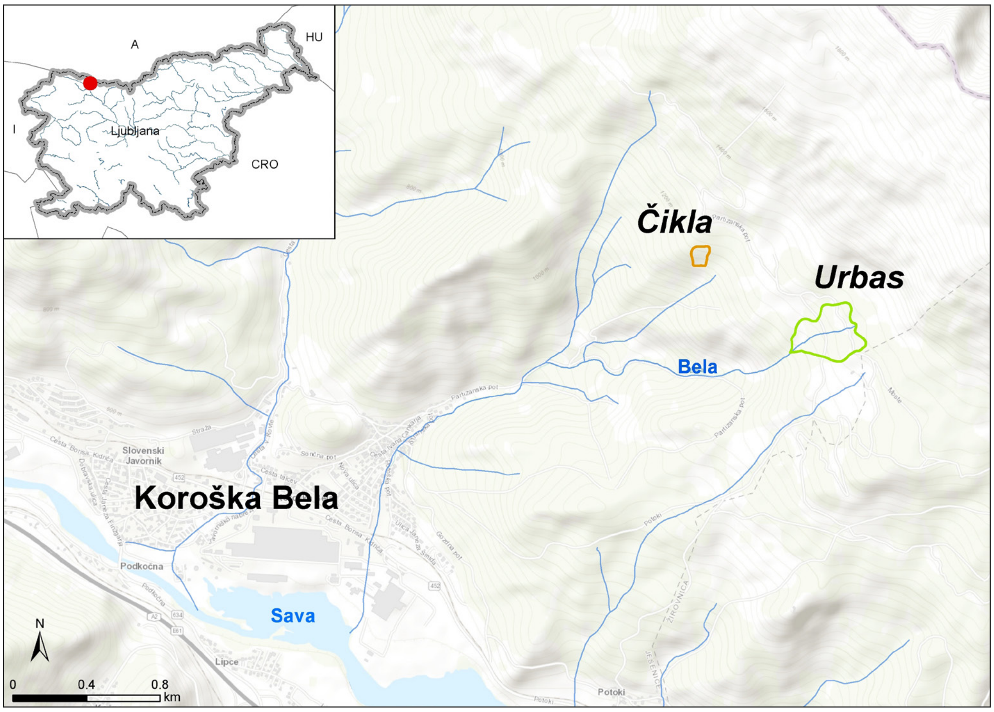

Fig. 1a. Location of study areas.

Regional hydrogeological setting

In general, two types of aquifers characterize regional hydrogeological settings, intergranular and karst-fissured aquifers. Intergranular aquifers are presented by sediments formed as a consequence of intense slope processes typical for steeper mountain regions (slope sediments). In these sediments, groundwater may be retained, but their spatial extension is limited, and such aquifers mostly represent negligible groundwater sources (Prestor et al., 2008). In some areas, groundwater can be found in sediments which were created by slowly slipping material formed by landslides, such as considered at the study area. In these cases, groundwater occurs at the contact between the above lying sloping sediment and the underlying lower permeable bed-

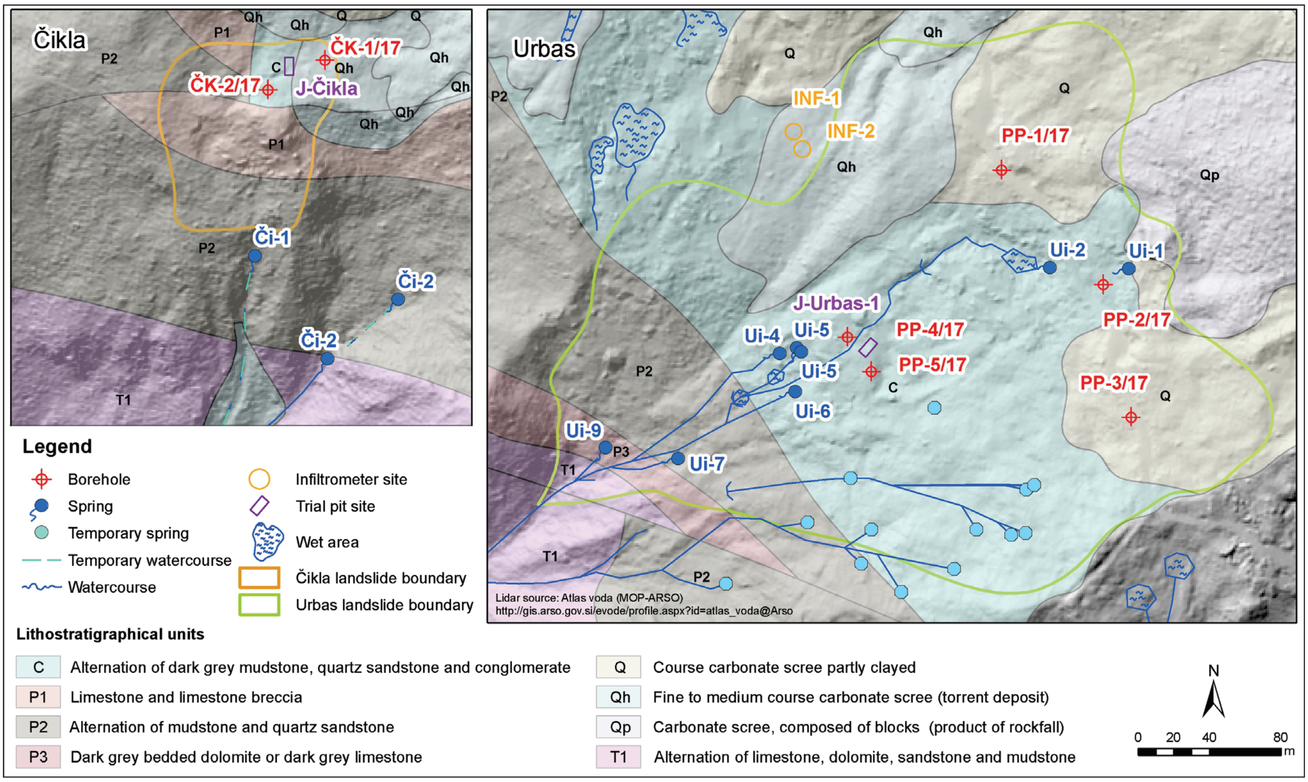

Fig. 1b. The areas of the Čikla and Urbas landslides with the locations of measurements and identified springs.

rock. Within those layers, the groundwater flow is often interrupted by the presence of low permeable clay or mud material (Brenčič & Poltnig, 2008).

The karst-fissured aquifers are represented by carbonate rocks, which also form the drainage area of the investigated landslides. They are characterized by numerous karst springs of very diverse outflow regime. When considering karst-fissured aquifers in the Karavanke Mts. area, it is necessary to also note the differences in the hydrogeological characteristics of limestones and dolomites, which also influence the development of karst phenomena. The permeability of dolomites comparing to limestone is usually lower. The hydrogeological properties of dolomites depend also on the type of diagenesis, or whether dolomites were formed as a result of primary or secondary dolomitization. Most karst-fissured aquifers in the Karavanke Mts. are unconfined, characterized by direct recharge of infiltrated precipitation. In the South Karavanke Mts., springs occur at the (tectonic) contact of extensive aquifer with low permeable layers and represent the high-water overflow from this aquifer. The groundwater level within the karst-fissured aquifer is strongly related to precipitation and is highly variable. This is also reflected in the high discharge fluctuations of springs. In dry periods in summer, some springs can almost dry out, while in periods of intense rainfall they can reach discharges of a few 100 l/s (Brenčič & Poltnig, 2008).

Methods

The field investigation in the two months period (29. 8. 2017 – 26. 10. 2017) started with the mapping of springs and other hydrogeological phenomena in the study area. Based on hydrogeological mapping locations of discharge measurements, new observation wells and in situ measurements of hydraulic conductivity were defined (fig. 1b).

Discharges of Ui-1 and Či-2 springs were estimated with using bucket and a stopwatch. The flows of other springs could not be collected in a bucket; therefore discharges were only visually estimated. Field measurements of pH value, electrical conductivity and temperature (Table 1) were carried out with measuring instrument pH/Cond 340i, and measurements of ORP (Oxydation Reduction Potential) and dissolved oxygen with instrument Multi 3410 SET C, both products of the WTW company.

In situ measurements of hydraulic conductivity

Infiltrometer tests

Infiltrometer tests enable the estimation of infiltration rate (infiltration capacity) as the maximum rate at which soil will absorb water impounded on the surface at a shallow depth, when adequate precautions are taken regarding boundary effects (Richards, 1952; Johnson, 1963). In the study area, a double ring infiltrometer was used which creates vertical (one-dimensional) flow of water beneath the inner ring and simplifies interpretation of measurements (Köhne et al. 2011) (fig. 2a). The method is based on the Darcy law of groundwater flow through intergranular porous material at steady state conditions (constant-head and constant infiltration velocity). The volume of water used during each measured time interval was converted into the incremental infiltration velocity using the equation (EN ISO 22282-5-2012, 2012):

$$v = \frac{\Delta V}{A_i \Delta t}$$

from Darcy law follows:

$$v = Ki$$

hydraulic gradient can be approximated as:

$$i = \frac{z_w + h_i}{z_w}$$

saturated thickness (z_w) through which flow occurs can be determined as:

$$z_w = \frac{V}{A_i \Delta \theta}$$

where $\Delta\theta$ is difference between the saturated soil volumetric water content (θs) and the initial soil volumetric water content (θi).

To assure horizontal surface and avoid surface cracks and fissures, typical for landslide mass, infiltrometer tests were performed at two locations close to the boundary of the Urbas landslide (fig. 1b), which could be accessed by car and supplied with the required amount of water. At these locations is present a soil typical for coniferous forest which covers a large part of the study area (fig. 2b). The rings were inserted into the ground to a penetration depth of 0.05 m and a constant-head was maintained in both rings (h_i=0.05 m) with the supply of water with Mariotte's bottle (fig. 2a). The tests were performed on 26. 10. 2017, three days after a moderate rainfall event.

Fig. 2a. Double ring infiltrometer with Mariotte's bottle (photo: Zmago Bole).

Fig. 2b. The top soil at location INF-1 (photo: Zmago Bole).

Falling and constant-head tests

The constant and falling-head tests in the cased boreholes or trial pits are commonly-used field methods for estimating the hydraulic conductivity of porous material. The review of existing practical engineering procedures for the performance of constant and falling-head tests was presented by Brenčič (2011), while the theoretical background can be found in literature on hydraulic tests (e.g., Batu, 1998; Butler, 1998; Bouwer & Rice, 1976; Cedergren, 1989; Kruseman & De Ridder, 1990).

Falling-head tests

The widely used interpretation of falling-head tests is the Hvorslev method (Hvorslev, 1951), because it provides a quick and inexpensive procedure for obtaining a relatively reliable estimation of hydraulic conductivity from a single well. This method is based on the interpretation of hydraulic head changes in time and is suitable for wells that are open in a short section at their base. Hvorslev (1951) found out that the return of the hydraulic head to the original, static hydraulic head occurs at an exponential rate with the time and is dependent on the hydraulic conductivity of the porous material. The Hvorslev method is valid for confined aquifers. However, Bouwer (1989) observed that the water table boundary in an unconfined aquifer has little effect on test performance results, unless the top of the well screen is positioned close to the water table. Therefore, in many cases, we may apply the Hvorslev solution for confined aquifers to approximate unconfined conditions. The basic equation for unsteady conditions is as follows (Hvorslev, 1951):

$$K = \frac{A}{\Delta t \times F} \times \ln \frac{h_1}{h_2}$$

where the shape factor F is expressed as:

$$F = \frac{2\pi \times L}{\ln\left(\frac{2L}{D}\right)}$$

or when the water flow is limited only through well walls:

$$F = \frac{2\pi L}{\ln\left(\frac{2L}{D}\right)} 2.75D$$

or when the water flow is limited only on the bottom of tube:

$$F = 2.75D$$

Hvorslev method (Hvorslev, 1951) is valid only if the length of the well screen is more than 8 times larger than its radius (L/r >8). The transient solution omits storativity of the formation and assumes a quasi-steady-state flow between the control well and the tested formation. The following assumptions should be applied to the use of the Hvorslev method: the aquifer has infinite areal extent; the aquifer is homogeneous and of uniform thickness; the aquifer potentiometric surface is initially horizontal; a volume of water is injected or discharged instantaneously (Hvorslev, 1951).

The second method used in this investigation was proposed by Schneebeli (1987). This method shows the same results as the Hvorslev method, if small diameter wells (negligible well storage) are used. In the case of large diameter wells or objects (i.e., excavated trail pit), the results of the methods differ, since the way that the geometric shape factor in Schneebeli's equation is determined is more robust and its value is proportional to the geometry of the tested object. The shape factor suits the recharge with semiellipsoidal shape (Dachler, 1936; Hvorslev, 1951). Schneebeli (1987) suggested the equation as follows:

$$K = m \cdot A \cdot 2.3 \cdot \frac{\log\left(\frac{h_1}{h_2}\right)}{t_1 - t_2}$$

where m represents a geometric shape factor:

$$m = \frac{\alpha}{D}$$

and α is expressed as:

$$\alpha = \frac{\ln\left(\frac{L}{D} + \sqrt{\left(\frac{L}{D}\right)^2 + 1}\right)}{2 \cdot \pi \cdot \left(\frac{L}{D}\right)}$$

However, it should be noted that there are some other limitations that affect the reliability of falling-head tests in large diameter wells or objects. For example, the hydraulic conductivity of the material should not be high, or the changes of hydraulic head should be fast, and in large diameter wells the capacity effect can greatly slow down the reduction of hydraulic head (Mace, 1999).

Constant-head test

The constant-head test is based on steady state conditions, where the hydraulic head in the borehole is stabilized with a constant water injection. The stabilized hydraulic head reached in a borehole or other tested object in which a constant injection is given by the following expression (Custodio & Llamas, 1983):

$$h = \frac{Q}{FK}$$

where F is a shape factor of tested object and is expressed as:

$$F = \frac{2\pi L}{\ln \frac{L}{r}}$$

From the test conditions and the injection rate to stabilize water level, the application directly obtains the hydraulic conductivity as follows:

$$K = \frac{Q}{2\pi L h} \ln \frac{L}{r}$$

Application of hydraulic conductivity measurements in the field

Falling-head and constant-head test were performed in three different types of hydrogeological objects: trial pits, open-bottom tubes, and boreholes. In all objects, the water level was measured with a pressure probe (PPI 200) with data

Fig. 3. Trial pit for performing falling-head test (photo: Zmago Bole).

Fig. 4. Open-bottom tubes for performing falling-head test (photo: Zmago Bole).

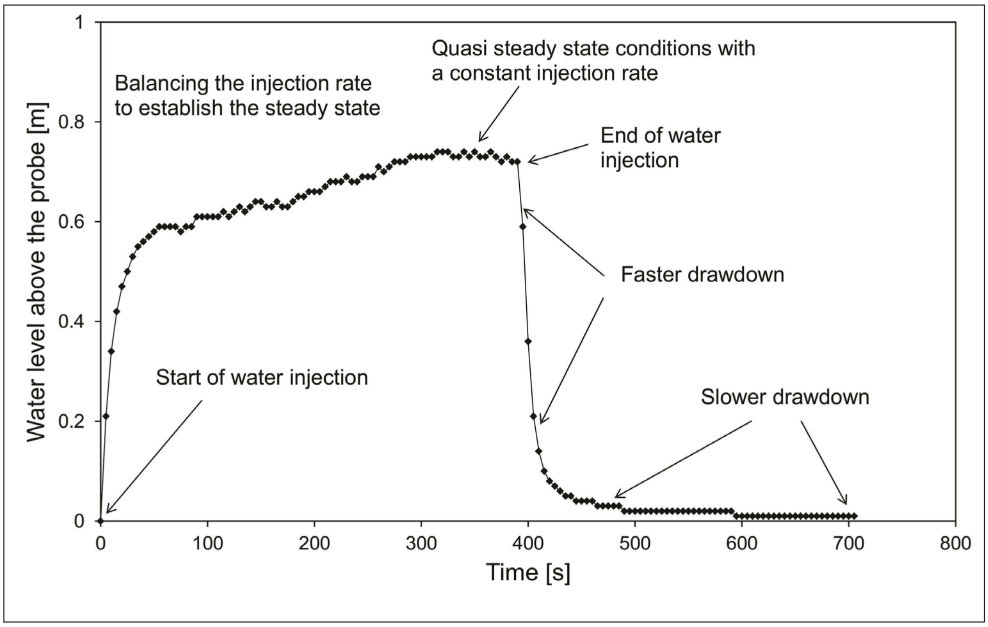

Fig. 5. An example of falling-head test performed in the well (PP-4/17).

logger (GSR 120NTG), produced by the Eltratec company. The pressure probe measures to an accuracy of 1 to 10 mm and in a range from 0 to 30 m of water column. Each test was carried out within specific field conditions; therefore the injection rate and duration were different for each individual tested object. Water level measurements were recorded at 5 to 10 s intervals.

Falling-head tests in trial pits were carried out in rectangular-shaped excavations made with a digger (fig. 3). Falling-head tests in open-bottom tubes were carried out with a tube (internal diameter of 100 mm), inserted into the ground surface or bottom of trial pit. The J-Urbas trial pit was 2.7 m deep. In the deepest part, it was 1.5 m long and 0.6 m wide (fig. 3). In its upper part, two shelfs were made, at the depths 2.0 and 0.6 m. On the upper shelf, an open-bottom tube test was performed (fig. 4). Tests at this location were made on 8. 9. 2017. The J-Čikla trial pit was 2.4 m deep, 1.6 m long and 0.6 m wide. Near the trial pit, two open-bottom tube tests were performed (Table 3). In both locations, the upper soil was removed, in the first location down to 0.4 m (Tube-1) and in the second location down to 0.2 m (Tube-2). Tests at this location were made on 18. 9. 2017.

The borehole falling-head test was performed on more permeable sections of boreholes, which were determined on the basis of lithological borehole logs (Peternel et al., 2017). On these sections, drilling with a core drill was carried out after the completion of the technical column. Measurements were performed in 1 – 2 m open hole sections. Before the test started, the occurrence of groundwater was checked.

At locations where we could provide enough water, the performance of falling-head test was carried out in two steps. The second step or second injection was performed after the stabilization of the water level in previous step. Moreover, at suitable borehole sections we also performed a constant-head test. In the study area, the most permeable layers are presented in the form of several-metre-thick coarse (gravel) sediments. In most cases, the tested borehole section included different types of lithology. The common example of the falling-head test performance is shown in the fig.5. The example shows that in the upper 0.7 m of the borehole, in the gravel layers, the drawdown is rapid, while in the lower part, in clayey material, drawdown is significantly slower. In such cases, two different lines were used to interpret the slope of the curve, for the purposes of the processing and estimation of the coefficient of hydraulic conductivity.

Results

In the area of Urbas landslide, seven permanent springs were identified and one in the broader area of Čikla landslide, beside permanent springs several temporal springs were observed (fig. 1b). Spring Urbas (Ui-1) is captured for the water supply of nearby mountain huts Potoška planina and Valvasorjev dom pod Stolom. Discharge measurements during the field campaign show a large fluctuation of discharge, from up to 25 l/s shortly after rainfall, to very low or even no discharge in dry conditions (figs. 6a and 6b). Basic water parameters measured at permanent springs on 29. 8. 2018 are presented in Table 1.

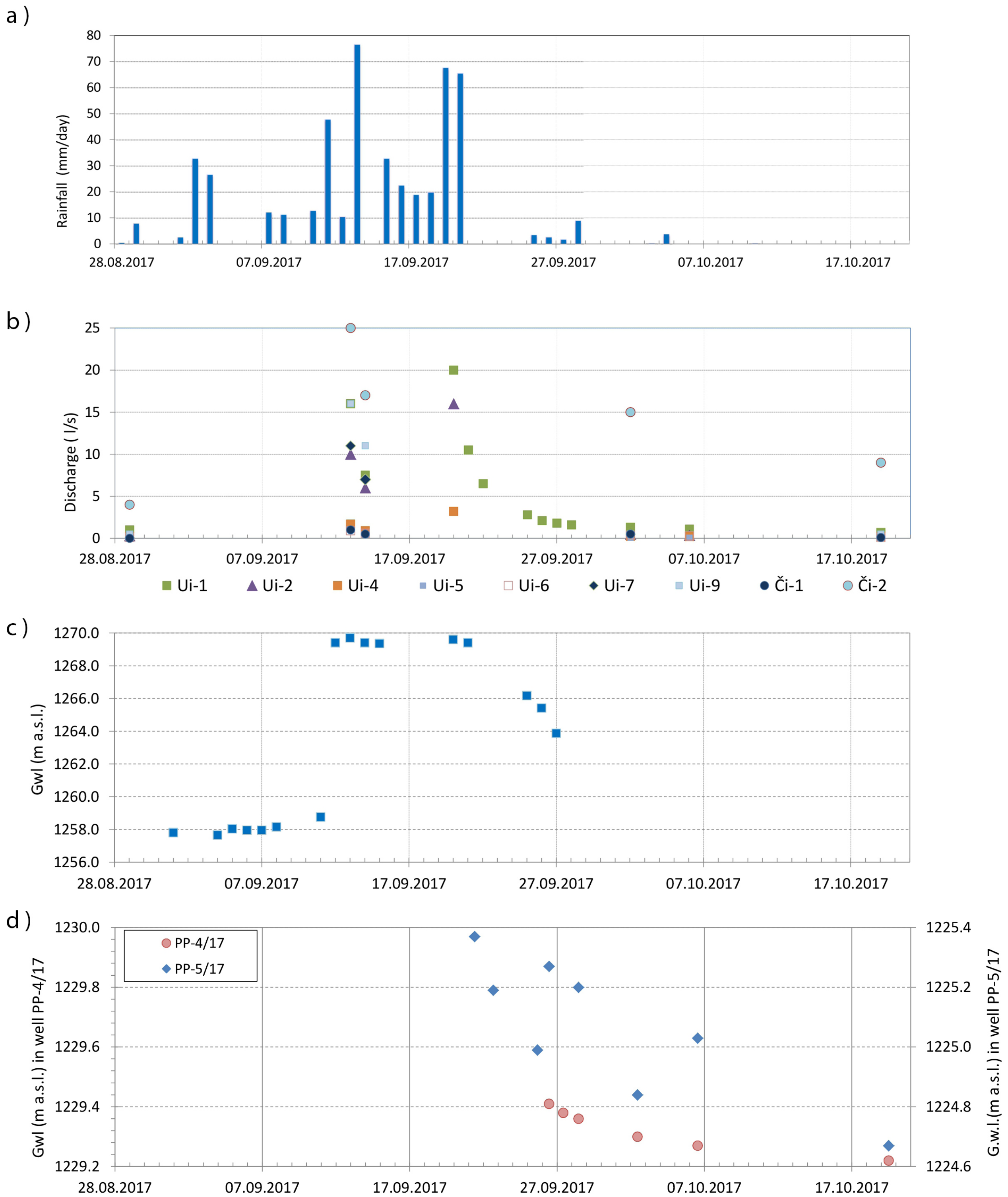

Fig. 6. a) Precipitation measured at meteorological station Planina pod Golico (ARSO, 2018b), b) Observed discharge at springs, c) Groundwater levels in well PP-2/17, d) Groundwater levels in wells PP-4/17 (circles) and PP-5/17 (squars).

Occasional manual measurements of groundwater level during the field campaign were performed in 7 boreholes (Peternel et al., 2017, fig. 6c). After the field campaign, continuous measurements with a pressure probe were recorded in wells PP-4/17 and ČK-1/17 (fig. 7).

Results of two infiltrometer tests performed in the study area (fig. 1b) are summarized in Table 2.

Hydraulic conductivity of upper ground, estimated with falling-head tests in trial pit and open-bottom tube is presented in Table 3. In the area of landslide Urbas hydraulic conductivity of upper silted gravel layers is in the range between 1.65×10^{-5} m/s and 1.96×10^{-5} m/s (avg. 1.8×10^{-5} m/s). Similar values with an average of 3.24×10^{-5} m/s were estimated for upper clayey sandy layers with gravel at Čikla location.

Table 1. Basic water parameters: pH, electrical conductivity (EC), temperature (T), dissolved oxygen (DO), redox potential (Eh), and discharge (Q), measured at permanent springs on 29.8.2018.

Spring	Elevation (m a.s.l.)	pH	EC (µS/cm)	T (oC)	DO (mg/l)	Eh (mV)	Q (l/s)
Ui-1	1267	8.3	186	4.0	11.9	434	1.0
Ui-2	1260	8.5	240	11.1	10.1	417	0.3
Ui-4	1233	7.7	226	5.9	10.4	506	0.2
Ui-5	1242	7.8	228	6.8	10.6	469	0.1
Ui-6	1237	7.7	234	6.1	10.6	515	0.1
Ui-7	1199	7.8	255	8.0	10.4	435	0.1
Ui-9	1176	8.0	228	5.7	11.1	441	0.5
Či-2	1027	8.2	290	6.8	11.3	393	4.0
Mean	1205	8.0	236	6.8	10.8	451	0.3
Range	240	0.8	104	7.1	1.8	122	3.9

Table 2. Results of infiltrometer tests.

Parameter	INF-1	INF-2
Δt (s)	1007	664
ΔV (m^3)	0.017	0.015
Δ (-)	0.2	0.2
V (m^3)	0.022	0.026
z_w (m)	1.43	1.40
***K* (m/s)**	**2.10×10^{-4}**	**2.81×10^{-4}**

Table 3. Hydraulic conductivity of upper ground, estimated with falling-head tests in trial pit and open-bottom tube.

Location	Soil type	Classification symbol	Testing object	Pouring water step	Unsteady K [m/s] - Hvorslev	Unsteady K [m/s] - Schneebeli
J-Urbas	Silted gravel	GM	Trial pit		/	1.96×10^{-05}
			Tube		1.65×10^{-05}	/
J-Čikla	Clayey sandy silt with gravel	ML/GC	Trial pit		/	2.91×10^{-05}
Near J-Čikla			Tube-1	1.	2.55×10^{-05}	/
				2.	5.74×10^{-05}	/
			Tube-2	1.	2.72×10^{-05}	/
				2.	2.30×10^{-05}	/

Hydraulic conductivities of more permeable sections of boreholes ČK-1/17 and PP-4/17 (fig. 8), estimated with performance of falling-head and constant-head tests in boreholes are presented in Table 4 and Table 5.

Estimated hydraulic conductivities in well ČK-1/17 range between 2.64×10^{-3} and 7.78×10^{-6} m/s. The Hvorslev and Schneebeli methods give practically identical results. The average value calculated for all three tested depth using only results of Hvorslev (or Schneebeli) and steady state method is 8.99×10^{-4}. In well PP-4/17 values of hydraulic conductivities ranges between 1.67×10^{-3} and 1.02×10^{-7} m/s. The average value calculated for all five tested depth intervals using results of Hvorslev (or Schneebeli) and steady state method is 3.05×10^{-4} m/s.

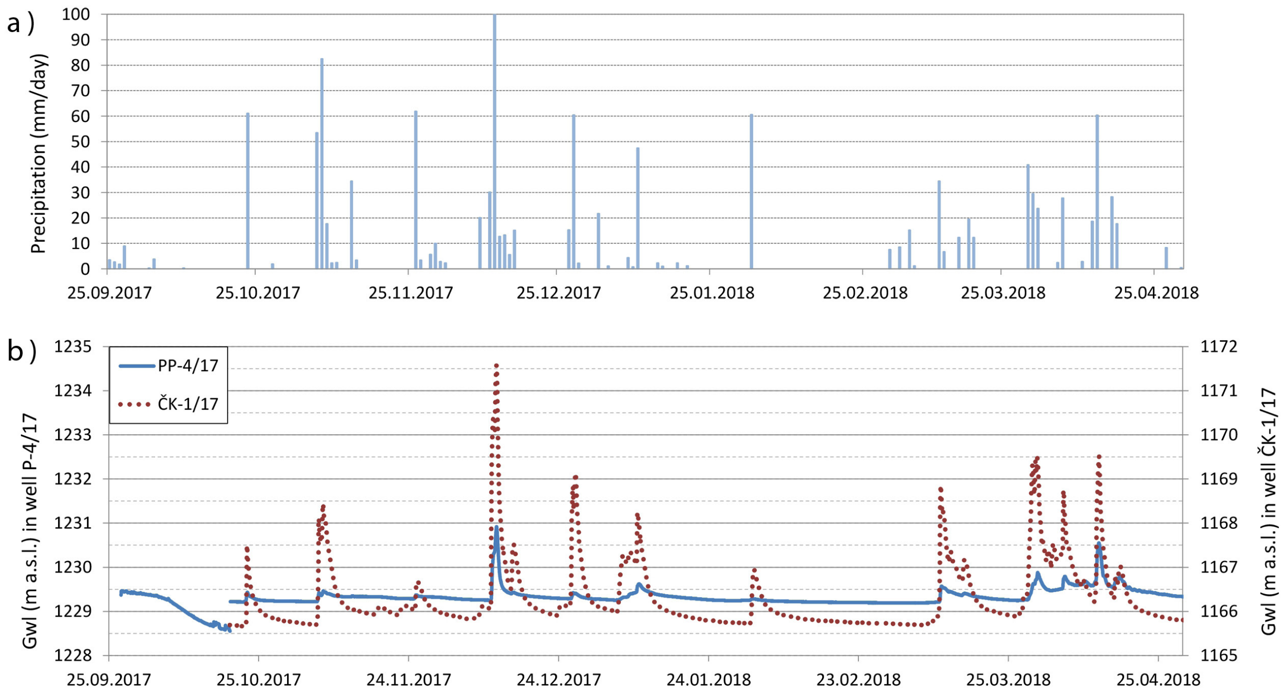

Fig. 7. a) Precipitation measured at meteorological station Planina pod Golico (ARSO, 2018b) in comparison with b) Groundwater level fluctuation in wells PP-4/17 (solid line) and ČK-1/17 (dotted line).

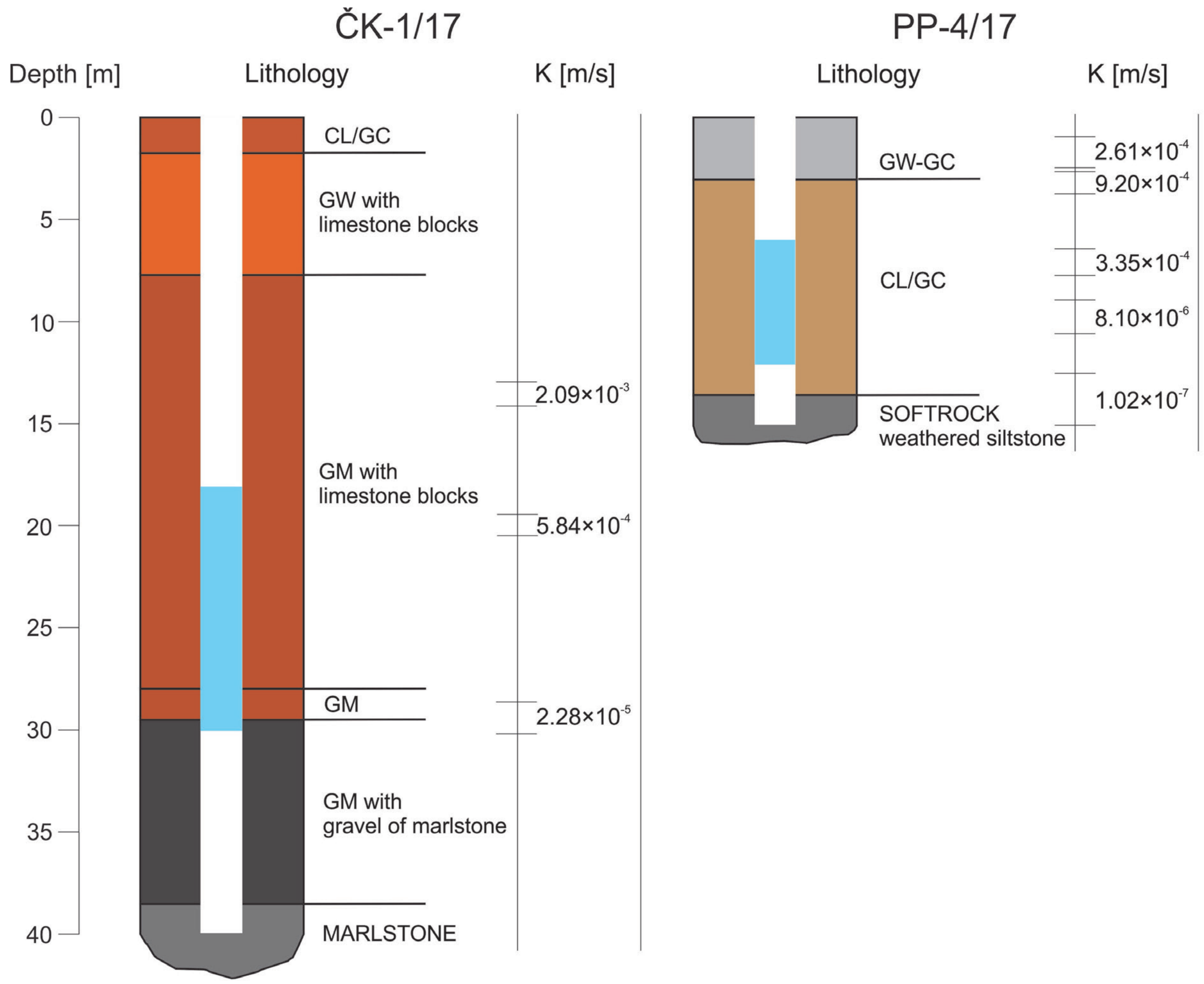

Fig. 8. Simplified lithological profiles of piezometers ČK-1/17 and PP-4/17 (segment with blue colour represents the perforated area).

Table 4. Estimated hydraulic conductivity of three sections in well ČK-1/17.

Tested section [m]	Soil type	Classification symbol	Injection step	Interpreted line slope	Unsteady *K* [m/s] - Hvorslev	Unsteady *K* [m/s] - Schneebeli	Steady *K* [m/s]
13.00 – 14.12	Silted gravel	GW – GM	1.		2.17×10^{-3}	2.17×10^{-3}	9.14×10^{-4}
			2.		2.64×10^{-3}	2.64×10^{-3}	/
19.50 – 20.28	Clayey sandy silt with gravel	GM - GW	1.	1.	7.83×10^{-4}	7.83×10^{-4}	/
				2.	2.39×10^{-4}	2.39×10^{-4}	/
			2.	1.	1.25×10^{-3}	1.25×10^{-3}	/
				2.	6.20×10^{-5}	6.21×10^{-5}	/
28.70 – 30.25	Silted gravel	GM	1.	1.	3.23×10^{-5}	3.23×10^{-5}	/
				2.	7.47×10^{-6}	7.46×10^{-6}	/
			2.		2.57×10^{-5}	2.56×10^{-5}	/

Table 5. Estimated hydraulic conductivity of four sections of borehole PP-4/17.

Tested section [m]	Soil type	Classification symbol	Injection step	Interpreted line slope	Unsteady *K* [m/s] - Hvorslev	Unsteady *K* [m/s] - Schneebeli	Steady *K* [m/s]
1.07 - 2.52	Gravel with clay and sand in lower part	GW-GC	1.	1.	3.36×10^{-4}	3.36×10^{-4}	5.40×10^{-4}
				2.	1.15×10^{-5}	1.15×10^{-5}	
			2.	1.	4.46×10^{-4}	4.46×10^{-4}	/
				2.	6.68×10^{-6}	6.68×10^{-6}	/
2.70 - 3.87	Gravel with sand and silt	CL/GC	1.	1.	1.67×10^{-3}	1.67×10^{-3}	5.72×10^{-4}
				2.	5.18×10^{-4}	5.18×10^{-4}	/
6.55 - 7.88	Gravel with gravel clay	CL/GW	1.		/	/	3.32×10^{-4}
			2.		/	/	3.37×10^{-4}
9.00 - 10.70	Clayey gravel with sand	CL/GW	1.		8.10×10^{-6}	8.09×10^{-6}	/
12.6 - 15.17	Weathered siltstone	SOFTROCK	1.		1.02×10^{-7}	1.02×10^{-7}	/

Discussion

The observed large fluctuation of discharge of springs and occasional dry outs are highly dependent on meteorological conditions, which reflects the low storage capacity of aquifers or locally limited recharge areas of the springs. A strong relation between meteorological and groundwater conditions is reflected also in the groundwater level fluctuation, observed in the wells. The fast rise of groundwater level after rainfall is observed in all wells, however, the amplitudes of fluctuation differ (figs. 6 and 7). The largest amplitude (12 m) was observed in the well PP-2/17. At this location, low permeable permo-carboniferous layer overlay the aquifer which consists of marly limestone and breccia. It seems that the aquifer is a part of an aquifer system that has a large catchment and is partly drained out at the Urbas spring. Due to the low permeable upper layer, semi confined conditions are created.

Also continuous measurements of groundwater level fluctuation in wells ČK-1/17 and PP-4/17 show fast changes of groundwater level which are strongly related to precipitation (fig. 7). Amplitudes are higher, up to 6 m, in well ČK-1/17 than in well PP-4/17, where the maximum amplitude of groundwater level is below 2 m. These differences could be attributed to the higher hydraulic conductivity, larger thickness (Table 4 and Table 5), and probably also larger spatial extent of more permeable layers at location of well ČK-1/17.

The results of infiltrometer tests show relatively high hydraulic conductivity of the soil. Presumably, this reflects the loose structure and high content of organic matter in the top soil found in the forest which covers a big part of the study area (fig. 2b). The tests were performed at locations where the ground has not been deformed by mass movement. Due to the presence of cracks and fissures, locally higher infiltration could be expected in the landslide body.

The planning of the falling-head test in wells assumed that significant groundwater flow can be established only through more permeable layers. Consequently, falling-head test were performed in more permeable gravel sections of boreholes. Therefore, calculated hydraulic conductivities reflect properties of more permeable parts of the ground in the study area. In general, higher hydraulic conductivity is observed in the upper parts of the boreholes. Those layers are predominantly represented by gravel and have a medium hydraulic conductivity, while the lower clayey gravel parts have a low hydraulic conductivity. In the area of Čikla landslide, values of hydraulic conductivities were estimated approximately half order of magnitude higher than in the Urbas landslide. The differences in hydraulic conductivities could be attributed to the lithological composition of the ground, which, in general, shows a larger share of course material in upper parts of the ground and in the area of Čikla landslide. The groundwater occurrence was identified in the last tested interval (28.70–30.25 m), while the first two tested intervals were in an unsaturated zone. In borehole PP-4/17 all tested intervals were in a saturated zone.

Conclusions

The observations and hydraulic tests performed in the area above Koroška Bela settlement have shown complex and heterogeneous hydrogeological conditions, predisposed by geological and tectonic setting and active mass movements. Therefore, the observed hydrogeological environment cannot be uniformly defined. To adequately address such conditions, an approach is required which combines various hydrogeological methods, partly already performed in the presented study.

The performed investigations enabled a very rough insight into the landslide hydrogeological mechanism and provided the first data on the hydraulic conductivity of the material in the landslide masses, the groundwater level, the infiltration capacity of the ground, the occurrences of the springs and their discharges. However, still many uncertainties exist about the hydrological processes occurring in observed landslides. In order to evaluate the role of groundwater and hydrogeological processes on landslides movements continuation of hydrogeological monitoring (groundwater level and temperature measurements) and additional investigations (e.g., hydrogeochemical and isotope analysis) for better defining recharge mechanism and groundwater flow patterns in the landslide bodies and their catchment areas are proposed.

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Comparison of the fully penetrating well drawdown in leaky aquifers between finite and infinite radius of influence under steady-state pumping conditions

Primerjava znižanja gladine podzemne vode v hidravlično popolnem vodnjaku v polzaprtem vodonosniku med končnim in neskončnim radijem vpliva pri stacionarnem črpanju

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Key words: leaky aquifer, groundwater drawdown, relative difference, absolute difference, modified Bessel functions of zero order, Hantush integral

Ključne besede: polzaprt vodonosnik, znižanje podzemne vode, relativna razlika, absolutna razlika, modificirana Besselova funkcija ničelnega reda, Hantushev integral

Abstract

In the paper theoretical derivation of steady state groundwater well pumping from leaky aquifers with infinite and finite radius of influence are presented. Based on the extensive literature review following mainly Jacob and Hantush work equations were derived from the cylindrical Bessel partial differential equation and results expressed in the combination of modified Bessel functions of zero order of the first and the second kind (I_0, K_0). We have shown that equation for steady state well pumping in the infinite aquifer is infinite limit of Hantush integral. Mathematical characteristics of solutions for infinite and finite radius of well influence were combined in the way that they can be represented as relative and absolute differences of drawdowns of each model. In the case when available data do not allow us to make a decision on the type of the radius of influence of the pumping well, they can help us in the interpretation of various errors due to application of different analytical models of pumping test.

Izvleček

V članku je prikazana izpeljava enačb črpanja podzemne vode iz vodnjaka v polzaprtem vodonosniku pri stacionarnih pogojih za primer končnega in neskončnega radija vpliva. Na podlagi obsežnega pregleda literature, ki izhaja predvsem iz del Jacoba in Hantusha, smo iz cilindrične Besselove parcialne differencialne enačbe izpeljali izraze za znižanje podzemne vode, ki predstavljajo kombinacijo modificiranih Besselovih funkcij ničelnega reda prve in druge vrste (I_0, K_0). Pokazali smo, da je enačba stacionarnega črpanja iz neskončnega vodonosnika neskončna limita Hantushevega integrala. Matematične značilnosti rešitve za neskončni in končni radij vpliva črpalnega vodnjaka omogočajo, da izraze združimo tako, da lahko prikažemo relativne in absolutne razlike med obema rešitvama. V primeru, da zaradi pomanjkanja podatkov ne moremo sprejeti odločitve o tem, s kakšnim radijem vpliva imamo opraviti, nam te razlike omogočajo interpretacijo različnih napak izbranih analitičnih modelov.

Introduction

The most important and reliable in situ methods for groundwater investigations are pumping tests. During them water is pumped from the well constructed in the soil or rock and groundwater drawdown in the surrounding of the pumping well is observed. Pumping tests are intended for determination of aquifer physical characteristics, aquifer water balance and groundwater chemical status. These are reasons why pumping tests and the theory which connected with them is central to the hydrogeological science. The theory of pumping test is well developed and very complex. Since the very beginning when Theis published first mathematical model for unsteady groundwater flow toward the well (Theis, 1935) many conceptual and mathematical models of pumping tests were developed (for the review see Batu, 1998; Lebbe, 1999; Yeh & Chang, 2013 and references there in).

The appearance of water in intergranular porosity is conceptualized with the aquifer model which usually consists of three main elements: saturated part, unsaturated part and hydrogeological barriers. Different combinations of these elements represent different hydrodynamical models of aquifers. In general, we are talking about two main hydrodynamical types of aquifers with transitions between them. The simplest one is confined aquifer where saturated part is confined between two impermeable hydrogeological barriers. The other main aquifer type is unconfined aquifer where groundwater level fluctuates depending on the recharge. In natural conditions aquifers are complex entities consisting of beds with very different geometries and hydraulic characteristics. Aquifers where several beds with different hydraulic characteristics and contrasts are present are often conceptualised as leaky aquifers. In real aquifers drawdown of groundwater level during the pumping test or full well operation is complex.

The very first study on leaky aquifers under steady-state groundwater flow was presented by De Glee (1930). Jacob (1946) extended the work on leaky aquifers by introducing transient effect of leakage. In his treatment the key assumption was that the vertical flow rate in the upper hydrogeological barrier defined as an aquitard is proportional to the drawdown distribution in the same bed. Later Hantush and Jacob (1955) and Hantush (1959) derived analytical solutions for unsteady-state groundwater flow in leaky aquifer for fully penetrating well of infinitely small diameter. In addition, Hantush (1960, 1964) and DeWiest (1965) assumed that the piezometric head in the aquitard overlying permeable part of the aquifer does not change during water withdrawal from the underlying pumped part. The validity of the assumption that Darcian groundwater flow in the permeable pumped part of the aquifer is horizontal and in the overlying aquitard is vertical was tested by Neuman and Witherspoon (1969). The errors introduced by this assumption are less than 5 % if the difference in permeability between confined bed and semiconfining beds is of at least two orders of magnitude. Herrea and Figueroa (1969) and Herrea (1970) presented a correspondence principle where only the storage in the confining layers was taken into consideration. Şen (2000) has widened leaky aquifer hydraulic theory to non-Darcian flow and latter this analysis was extended based on volumetric approach by Birpinar and Şen (2004). For recent review on leaky aquifer hydraulic see Yeh & Chang (2013).

During mathematical simulations of the drawdown the well radius of influence is very often represented as limiting factor in calculations. This parameter is difficult to determine in nature. It is also difficult to determine whether to use analytical model of finite or infinite radius of influence. Radius of influence is very often defined from empirical formulas such as Sichardt equations (Powers et al., 2007) or it's estimation is based on the expert judgement from the field study. From the theoretical and practical point of view it is interesting to observe differences in drawdown calculations between mathematical models which include finite or infinite radius of influence.

In the paper mathematical analysis of drawdown in leaky aquifer during pumping test under steady-state conditions is presented. The analysis for the pumping tests with fully penetrating well in leaky aquifers with finite and infinite radius of well influence is extended based on solutions of Jacob (1946) and Hantush (1960, 1964). The comparisons are represented based on the various ratios between the drawdown for each of the different radius types under assumption that all other physical characteristic and pumping rate are the same. Ratios between different drawdowns are interpreted with various types of differences that can be interpreted as error analysis. Theoretical concepts are illustrated with numerical simulation. Finally, theoretical and numerical results are discussed.

Mathematical model

Conceptual model

If the aquifer is not perfectly confined with upper and lower impermeable hydrogeological barrier leakage to the central water yielding unit – confined bed – may occur through the underlain or overlain semiconfining layer or aquitard. Leaky aquifers being either single or part of multi-layered aquifer systems and the degree of leakage between beds may become significant depending on the thickness and hydraulic conductivity of the confined bed which gives the main part of the aquifer yielding water. During pumping water from the aquitard water is also extracted through the confining layer. The conceptual model of the leaky aquifer is shown in the fig. 1. In parallel to this model several other leaky aquifer conceptual models are available in the literature (Yeh & Chang, 2013) but are not taken in consideration.

The leakage rates from the semiconfining layer – aquitard may be significant depending on hydraulic gradients around the pumping well. In the mathematical model of the pumping test from the leaky aquifer the thickness of the saturated part *b'* and vertical hydraulic conductivity of the aquitard K_z^p are taken into the account. It is hypothesised that leakage of water from the aquitard is strictly vertical and that no storage in this bed is present. The latter condition means that change of piezometric potential in the aquifer is simultaneous to change in the confined part of the aquifer. This part has transmissivity T that is defined as T=Kb; a product of hydraulic conductivity K and the thickness b of the confined part of the aquifer. Storage coefficient S of this defines vertical elastic properties of the aquifer. As a consequence of pumping from the aquifer the drawdown s appears on starting piezometric head h_0 that is horizontal at any distance r from the well. The drawdown s at r at time t is defined as $s(r,t)=h_0-h(r,t)$. Radius of influence of groundwater pumping R is defined as the distance from the well where $s(R,t)=0$. Under steady-state pumping conditions at any time two models of radius of influence of groundwater pumping R can be defined. In the first mathematical model of the leaky aquifer R is finite and constant; R=*const*. In the second mathematical model of the leaky aquifer R is infinite; $R=\infty$.

Together with boundary and initial conditions already presented in the fig. 1 the following assumptions are applied in the mathematical model (Batu, 1998): the confined part of the aquifer is homogenous and isotropic, the extraction rate of the well Q is constant, the aquifer is horizontal, has constant thickness b and is overlain by an aquitard with constant vertical hydraulic conductivity K_z^p and constant thickness of the saturated part *b'*, the well penetrates entirely confined part of the aquifer, the diameter of the well is infinitesimally small with no storage and the groundwater flow in the confined part of the aquifer is horizontal.

Governing equation

Basic governing equation of the leaky aquifer in the vertical plane of the x, y, z Cartesian coordinate system is defined as (for derivation see Miletić & Heinrich Miletić, 1981)

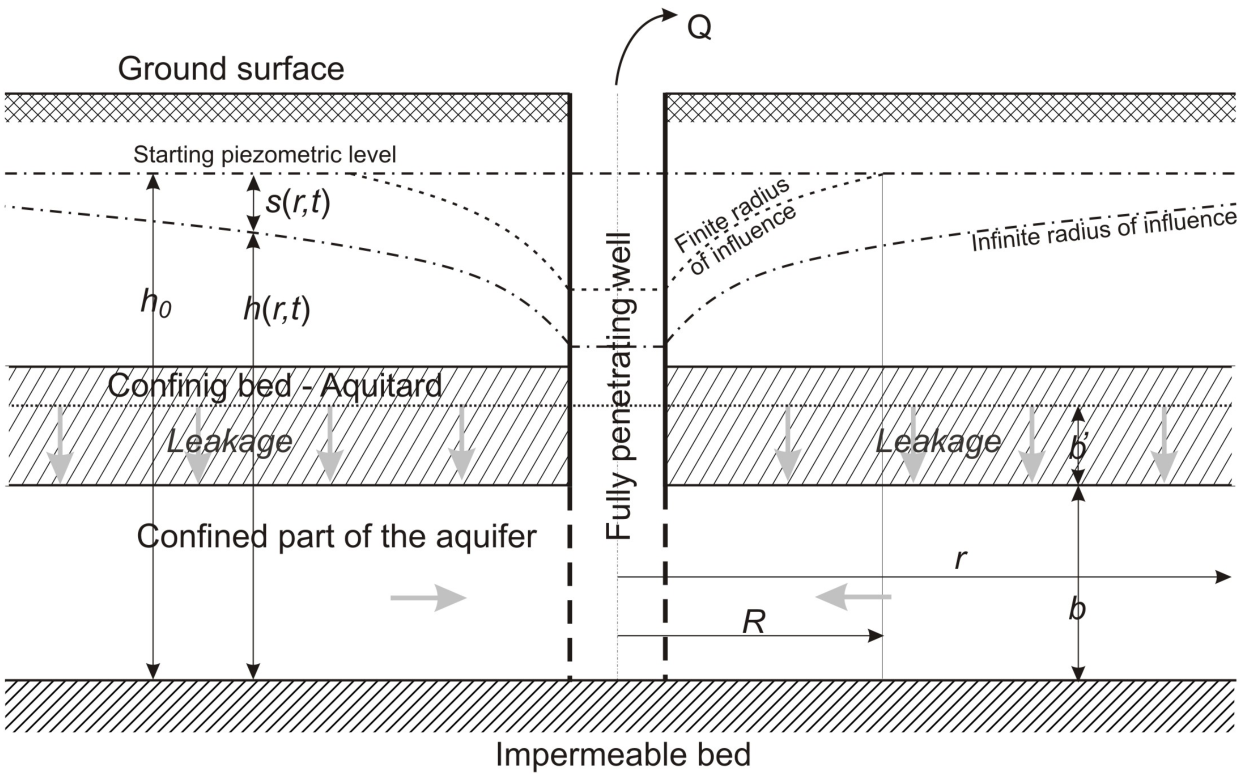

Fig. 1. Schematic cross section of a leaky confined aquifer with finite and infinite radius of influence.

$$\frac{\partial^2 s}{\partial x^2}+\frac{\partial^2 s}{\partial y^2}-\frac{s}{B^2}=\frac{S}{T}\frac{\partial s}{\partial t} \quad (1)$$

where

$$B=\sqrt{T\frac{b'}{K_z^p}} \quad (2)$$

is defined as leakage factor. In the cylindrical system of the coordinates r and φ the equation (1) can be rewritten as (Hantush, 1964)

$$\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r}+\frac{1}{r^2}\frac{\partial^2 s}{\partial \varphi^2}-\frac{s}{B^2}=\frac{S}{T}\frac{\partial s}{\partial t} \quad (3)$$

and in the case of homogenous and isotropic aquifer according to ϕ

$$\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r}-\frac{s}{B^2}=\frac{S}{T}\frac{\partial s}{\partial t} \quad (4)$$

Equation (4) can be recognized as modified Bessel equation of zero order (Lebedeev, 1970). For parameters and other symbols see fig. 1.

Basic solution

In the solution of governing equation (4) following Hantush (1964) valid boundary and initial conditions are defined as:

$$\begin{gathered} s(r,0)=0, \qquad r\geq 0 \\ s(r,t)=0, \qquad r\to\infty, \qquad t\geq 0 \\ \lim_{r\to 0}\left(r\frac{\partial s}{\partial r}\right)=-\frac{Q}{2\pi T}, \qquad t\geq 0 \end{gathered} \quad (5)$$

In (5) last condition is consequence of Darcy law. Final solution of the governing equation (Hantush, 1964) is

$$s=\frac{Q}{4\pi T}\int_u^\infty \frac{\exp\left(-u-\frac{r^2}{4B^2u}\right)}{u}du \quad (6)$$

where u is defined as

$$u=\frac{r^2S}{4Tt} \quad (7)$$

Integral (6) is known also as Hantush integral. It is important in many fields of mathematical physics and hydrology (Harris, 1997, 2001; Prodanoff et al., 2006). Detailed derivation of basic solution of leaky aquifer partial differential equation is given elsewhere (Hantush 1964; Batu 1998; Lebbe, 1999).

Steady state-solution in infinite leaky aquifer

In real aquifers steady-state conditions are reached only after longer time t. If we suppose that $t\to\infty$ than the limit of u is defined as

$$\lim_{t\to\infty}u=\lim_{t\to\infty}\left(\frac{r^2S}{4Tt}\right)=0 \quad (8)$$

and at sufficiently large time t u is small enough that $u\approx 0$. Consequently, integration borders become from 0 to ∞ and (6) becomes

$$s=\frac{Q}{4\pi T}\int_0^\infty \frac{\exp\left(-u-\frac{r^2}{4B^2u}\right)}{u}du \quad (9)$$

Based on Gradshteyn and Ryzhik (1994; equation 3.471.9)

$$\int_0^\infty \frac{\exp\left(-u-\frac{\eta}{u}\right)}{u}du=2K_0\left(2\sqrt{\eta}\right) \quad (10)$$

From (9) and (10) also follows

$$\eta=\frac{r^2}{4B^2} \quad (11)$$

and K_0 is modified Bessel function of second kind of zero order. After short manipulation in (10) and (11) it can be shown that drawdown for the infinite leaky aquifer s_I in steady-state conditions is

$$s_I=\frac{Q}{2\pi T}K_0\left(\frac{r}{B}\right) \quad (12)$$

Which is the same results as de Glee (1930) defined initially through another derivation of equations.

Steady state-solution in finite leaky aquifer

General solution of modified Bessel equation of zero order (4) is (Lebedev, 1972)

$$s=C_1I_0\left(\frac{r}{B}\right)+C_2K_0\left(\frac{r}{B}\right) \quad (13)$$

where are

C_1,C_2 – constants

I_0 – modified Bessel function of first kind of zero order.

Boundary conditions are defined as (Jacob, 1946)

$$\begin{gathered} s(r,0)=0 \quad r\geq 0 \quad t=0 \\ s(R)=0 \\ \lim_{r\to 0}\left(r\frac{\partial s}{\partial r}\right)=-\frac{Q}{2\pi T} \end{gathered} \quad (14)$$

Determination of C_1 and C_2 of (13) from (14) leads to the equation of drawdown s_F in finite leaky aquifer. Constants are determined in the area where $r\leq R$. Elaboration of constants is not simple and straightforward, it is based on derivatives of s and limit properties of $K_0(x)$ and $I_0(x)$

functions. Derivation of C_1 and C_2 is first given in Jacob (1946) and thoroughly summarised and elaborated in Batu (1998) and Miletić and Heinrich-Miletić (1981). Presentation of this derivation is out of the paper's scope. After definition of constants it follows:

$$s_F = \frac{Q}{2\pi T}\left[K_0\left(\frac{r}{B}\right) - I_0\left(\frac{r}{B}\right)\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)}\right] \quad (15)$$

Comparison of the drawdown for finite and infinite radius of influence

Definitions

In hydrogeology we are frequently encountering problem of choosing a proper aquifer conceptual model. Dealing with results of pumping test it is a question whether to use finite or infinite model of well radius of influence. Available geological data are often not detailed enough or some information are missing for choosing the proper conceptual model. In such situation for calculations several models are used and their results are compared with the actual field measurements.

In the engineering practice measurements and calculated values are often expressed together with certain errors, among them are relative difference ε_r or absolute difference ε_a. The expression of those help us to understand the reliability of predictions preformed based on measurements and differences among them in their application of the mathematical models. These concepts can be used also in the comparison between drawdown calculations in leaky aquifers with finite and infinite radius of well influence under steady state pumping conditions.

We can define following differences and quotients. If x is any quatitative measure absolute difference ε_a is defined as the absolute difference between two measured values x_1 and x_2

$$\varepsilon_a = |x_1 - x_2| \quad (16)$$

If reference value x_{ref} is present absolute difference ε_a' is defined as

$$\varepsilon_a' = |x - x_{ref}| \quad (17)$$

where x is any value from the model. The generalized relative difference ε_r is defined as

$$\varepsilon_r = \frac{\varepsilon_a}{|x_1 + x_2|} = \frac{|x_1 - x_2|}{|x_1 + x_2|} \quad (18)$$

Alternatively, average relative difference ε_r^{avg} can be defined as

$$\varepsilon_r^{avg} = \frac{2\varepsilon_a}{|x_1 + x_2|} = \frac{2|x_1 - x_2|}{|x_1 + x_2|} = \frac{\varepsilon_r}{2} \quad (19)$$

If the reference value x_{ref} is defined than relative difference ε_r' is

$$\varepsilon_r' = \frac{|x - x_{ref}|}{x_{ref}} = \left|\frac{x}{x_{ref}} - 1\right| \quad (20)$$

Sometimes ε_r' is defined as

$$\varepsilon_r' = \frac{\varepsilon_a}{\max|x_1, x_2|} = \frac{|x_1 - x_2|}{\max|x_1, x_2|} \quad (21)$$

Differences and ratios between s_F and s_I

From mathematical point of view equations (12) and (15) are bearing some similarities. They can be easily used for the comparison between the modelled drawdown s in the aquifer with finite radius of influence - s_F with the aquifer with infinite radius of influence - s_I under steady state conditions and the same pumping rate Q.

After short manipulation it can be shown from (12) and (15) that

$$s_F = \frac{Q}{2\pi T}\left[s_I - I_0\left(\frac{r}{B}\right)\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)}\right] \quad (22)$$

From that point right hand part of the (22) in the brackets can be understood as factor which is correcting infinite aquifer drawdown s_I to the finite aquifer drawdown s_F. Based on this we can define correction factor c_F

$$c_F = I_0\left(\frac{r}{B}\right)\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} \quad (23)$$

and consequently

$$s_F = \frac{Q}{2\pi T}[s_I - c_F] \quad (24)$$

c_F is independent of Q and depends only on B and R which are geometrical and physical characteristics of the leaky aquifer. Due to aquifer physical characteristics relation $s_I \geq c_F$ is always present and due to the characteristics of modified Bessel functions $K_0(x)$ and $I_0(x)$ functional relation $s_I \geq s_F$ is always valid. Consequently, head in the leaky aquifer with the same hydraulic characteristics under the same pumping rate Q is higher in the aquifer with finite radius of influence than in the aquifer with infinite radius of influence. It can be illustrated that under some circumstance heads around the well in both cases can be nearly equal.

We can further elaborate relations by dividing equation (15) with (12) and gaining

$$\frac{s_F}{s_I} = 1 - \frac{I_0\left(\frac{r}{B}\right)}{K_0\left(\frac{r}{B}\right)}\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} \quad (25)$$

or

$$\frac{s_I - s_F}{s_I} = \frac{I_0\left(\frac{r}{B}\right)}{K_0\left(\frac{r}{B}\right)}\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} \quad (26)$$

From the properties of $I_0(x)$ and $K_0(x)$ in (25) and (26) follows

$$\frac{s_F}{s_I} \leq 1, \quad \frac{s_I - s_F}{s_I} \leq 1, \quad s_I - s_F \geq 0 \quad (27)$$

From mathematical point of view equations (20) and (26) are similar. If we accept s_I as a reference value than (27) is relative error with s_I as a reference value x_{ref} can be defined as

$$\varepsilon_r'(s_I) = \frac{I_0\left(\frac{r}{B}\right)}{K_0\left(\frac{r}{B}\right)}\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} \quad (28)$$

Because $s_I \geq s_F$ same conclusion as in (28) follows from (21).

Equation (28) is not just a mere mathematical expression. It explains relation between two drawdown curves. If we have two leaky aquifers; with infinite and finite radius of influence under the same pumping rate and the same hydraulic characteristics $\varepsilon_r'(s_I)$ explains relative difference between both drawdown curves. Depending on r in the interval $0< \varepsilon_r'(s_I)<1$ ratio explains relative differences between both drawdown curves. If the $\varepsilon_r'(s_I)$ is close or equal to 1 the curves have the same spatial distribution, and if $\varepsilon_r'(s_I)=0$ drawdown curve of s_I is beyond the radius of influence R of the finite leaky aquifer.

With the analogies of equations from (16) to (19) and according to the definition in (16) subtracting (15) from (12) following expression for ε_a can be derived

$$\varepsilon_a = \frac{Q}{2\pi T}\frac{I_0\left(\frac{r}{B}\right)K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} = \frac{Q}{2\pi T}c_F = s_I \frac{I_0\left(\frac{r}{B}\right)}{K_0\left(\frac{r}{B}\right)}\frac{K_0\left(\frac{R}{B}\right)}{I_0\left(\frac{R}{B}\right)} = s_I \varepsilon_r'(s_I) \quad (29)$$

Absolute difference ε_a is expressed in length units. Comparing to $\varepsilon_r'(s_I)$ in (28) which is independent on pumping rate Q absolute difference ε_a depends on it. Relation between ε_a and $\varepsilon_r'(s_I)$ is also obvious.

Generalized relative difference ε_r from (18) and with the help of (12) and (15) can be defined as

$$\varepsilon_r = \frac{\left[I_0\left(\frac{r}{B}\right)K_0\left(\frac{R}{B}\right)\right]}{\left[2K_0\left(\frac{r}{B}\right)I_0\left(\frac{R}{B}\right) - I_0\left(\frac{r}{B}\right)K_0\left(\frac{R}{B}\right)\right]} \quad (30)$$

Generalized relative difference ε_r is also dimensionless quantity. It can be applied for analysis when no preference to s_I or s_F are given. This is the case when we are not sure if model of finite or infinite radius of influence is valid and we want to keep both results. Consequently, average relative difference ε_r^{avg} followed from definitions above is defined as

$$\varepsilon_r^{avg} = \frac{\varepsilon_r}{2} = \frac{\left[I_0\left(\frac{r}{B}\right)K_0\left(\frac{R}{B}\right)\right]}{\left[4K_0\left(\frac{r}{B}\right)I_0\left(\frac{R}{B}\right) - 2I_0\left(\frac{r}{B}\right)K_0\left(\frac{R}{B}\right)\right]} \quad (31)$$

Results and discussion

In the following chapter we are presenting numerical simulation results based on the previous mathematical theory. Simulations were performed with build in numerical functions of modified Bessel functions of the first kind I_0 and the second kind K_0 in Excel for Mac 16.16.1. and with the program for symbolic and numerical computation Mathematica for Mac version 11.3.0. Numerical results are discussed from the hydrogeological point of view.

Estimation of leakage factor B

Main physical parameter in simulations is leakage factor B defined in (2) which is combination of two other physical parameters and one variable which in our simulation can be considered as a constant. Those parameters are: transmissivity T of the confined unit and K_z^p which is vertical permeability of semi-confining layer while b' defines head in the later. Based on the expert judgement of T, K_z^p and b' we have estimated values of B. For simulations $b' = 2$ m was used. As expected in the real aquifers T was considered on the interval between $5{\cdot}10^{-2}$ m^2/s and 10^{-5} m^2/s and K_z^p was considered in the interval from 10^{-9} m/s to 10^{-6} m/s. Calculated values of B are represented on double logaritmic scale in fig. 2.

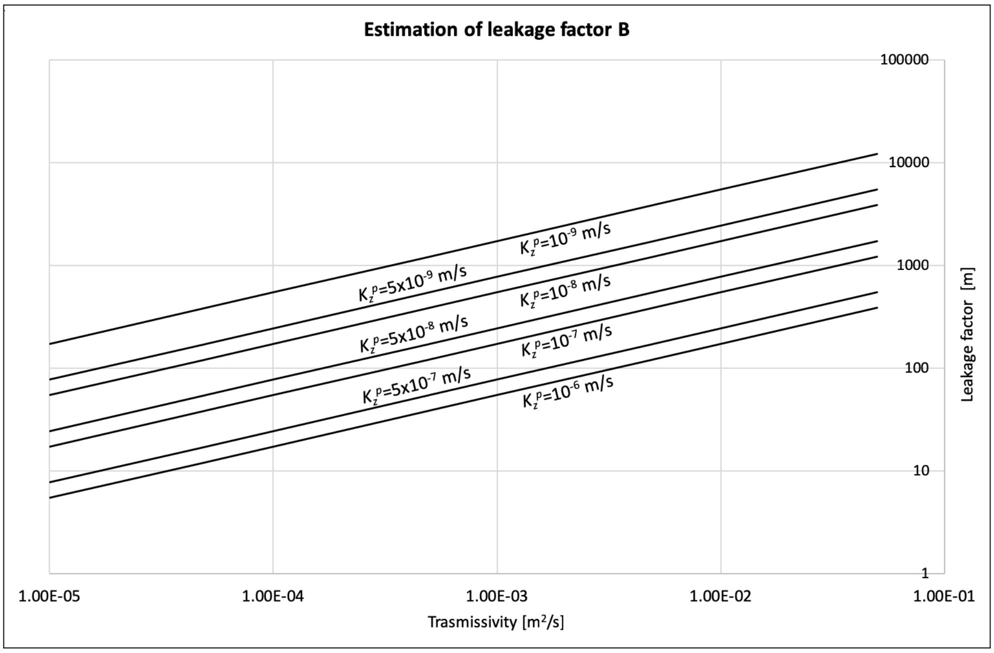

Fig. 2. Estimation of leakage factor B at different transmissivity values T for confined layer and permeability of K_z^p of semi-confining layer at b'=2 m.

In the range of applied T highest values of B are present at K_z^p = 10^{-9} m/s. In this case B values are calculated in the interval between 173 m and 12,247 m. Lowest B values are present at K_z^p = 10^{-6} m/s. In this case B values are calculated in the interval between 5.5 m and 387 m. Therefore, total simulated range of B is from 5.5 m to 12,247 m. From the simulated values we can see that B is influenced by the K_z^p. In leaky aqufers semi-confining layer with vertical permeability K_z^p = 10^{-6} m/s due to the depression in confined layer it is highly unlikely that vertical flow will appear. Consequently, values of B in real aquifers tend to be in the higher part of the interval.

Estimated values of B can be considered also in the evaluation of ratio R/B which is important in presentation of simulation results on the relative scale r/R. Expected radius of influence R in real aquifers under the steady state conditions are in the range of 500 m to 20,000 m. Consequently, expected approximate range of R/B is in the interval from 0.005 to 20.

Simulation of relative difference $\varepsilon_r'(s_I)$

To illustrate behaviour of $\varepsilon_r'(s_I)$ given by equation (28) we have chosen aquifer with influence radius R of 5,000 m. Such radius of influence can be expected in many natural aquifers. Results of calculations are presented in the fig. 3 for leakage factors B from 50 m to 20,000 m. At relatively small values of B large part of the curve is flatter reflecting $\varepsilon_r'(s_I)$=0. At higher r curve sharply turns up to values near $\varepsilon_r'(s_I)$=1. With higher values of B curvature is becoming flatter and values of $\varepsilon_r'(s_I)$ are becoming to rise slowly. Curves below B=5,000 m which is the same value as chosen R are concave with higher B they become convex. For high B values and at lower r values $\varepsilon_r'(s_I)$ starts to rise quickly and then at middle values of r the curve flattens and become nearly linear.

By simple reasoning it can be shown from (28) that results for different radius of influence R can be presented on the relative scale r/R. Diagram presented in fig. 4 is valid for any R at the same ratio R/B between radius of influence and leakage factor. Shape of lines are the same as they are on the fig. 3 and therefore reflecting the same relations as they are in the diagram for exact radius of influence. The diagram in fig. 4 can be understood as scaled diagram. Similarly, as before at relatively small values of B large part of the curve is equal to $\varepsilon_r'(s_I)$=0 and then at the right side of the diagram the curve sharply turns up to values near $\varepsilon_r'(s_I)$=1. From the diagram we can observe that for values of $R/B < 1$ the curves are concave and for values $R/B > 1$ the curves turn to be convex.

Curves on both figures (figs. 3 and 4) are representing comparison of the drawdown s_F in the aquifer with finite influence of well and the drawdown s_I in the aquifer with infinite radius of influence. Values around 0 are showing that practically no difference is present among drawdowns when values of B or R/B are relatively small. Consequently, if we are dealing with relatively extensive leaky aquifer it is not important if we calculate drawdowns for finite or infinite radius model. In such cases the difference among drawdowns become important only near the radius of influence R. Estimation whether we can describe aquifer with finite or infinite aquifer radius of in-

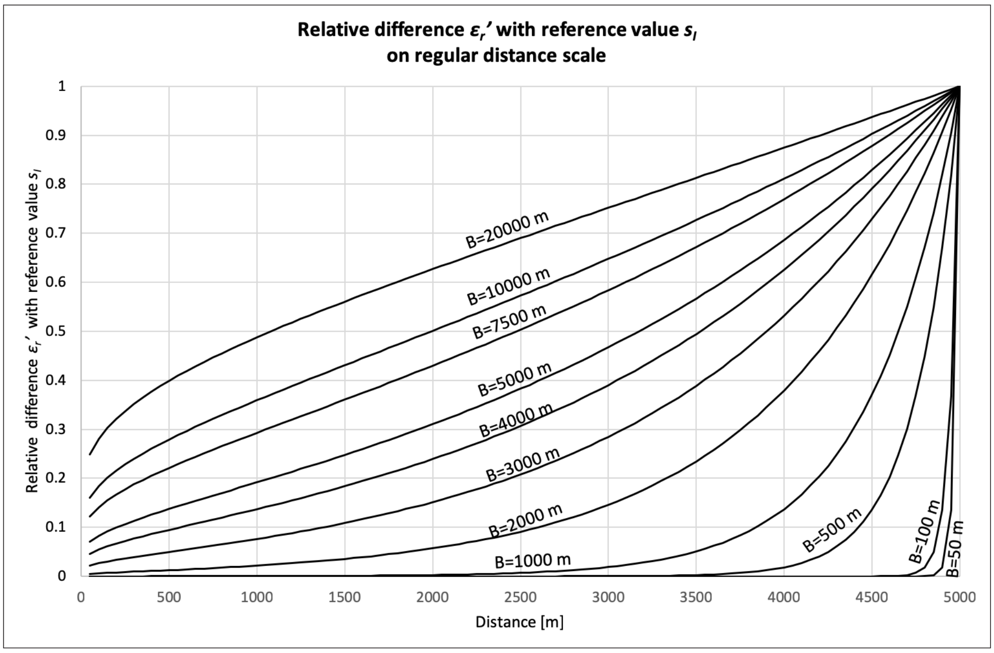

Fig. 3. Relative difference ε_r' with reference value s_I plotted on the regular distance scale.

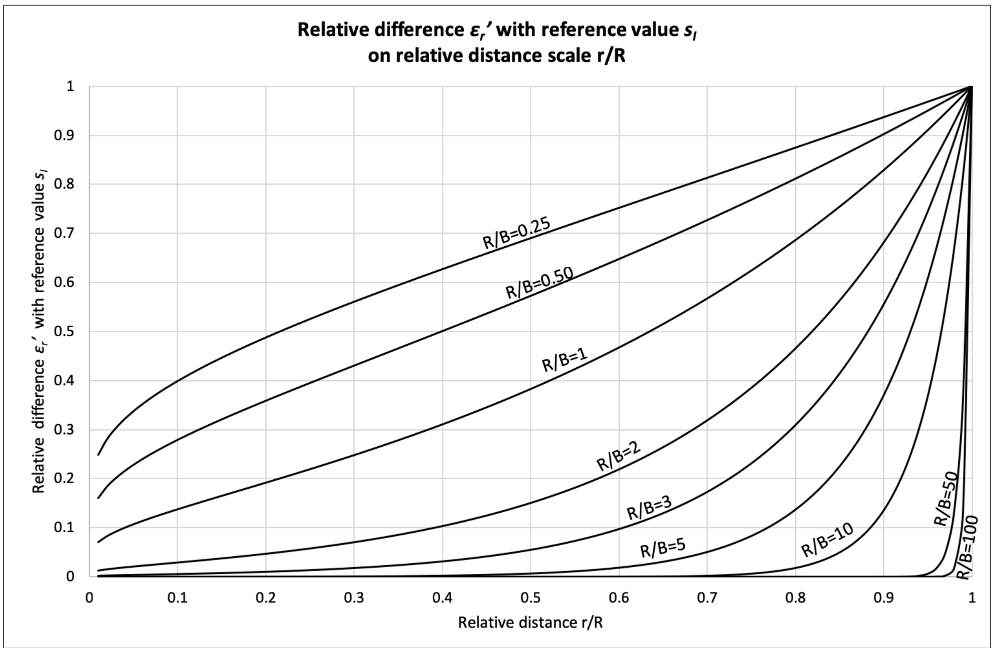

Fig. 4. Relative difference ε_r' with reference value s_I plotted on the relative distance scale

fluence becomes important with larger B values. Therefore, when semiconfining layer has several orders of magnitude lower vertical permeability than in confined layer it become important which analytical model for radius of influence is used. Differences become bigger close to the well comparing to higher B values where differences are important far away from the pumping well.

Simulation of generalized relative difference

Generalized relative differences are presented only for relative distance r/R and are given in the fig. 5. Shape of the lines for different ratios R/B are nearly similar to the lines in fig. 4 where relative difference is shown. They are more convex comparing to relative difference $\varepsilon_r'(s_I)$.

Comparison between relative differences

Lines in fig. 4 and fig. 5 have similar shape therefore one may ask question whether there is any difference between the lines. For the comparison we have calculated both differences for two different ratios $R/B = 1$ and $R/B = 0.25$ respectively. Results are shown on the fig. 6. In spite of the similar shapes of the curves differences among curves exist. From the equations (28) and (30) it can be shown that for the same physical parameters R and B relative difference $\varepsilon_r'(s_I)$ is always larger than ε_r. In the theoretical part of the paper we are not representing derivatives of (28, 30) but it can be illustrated that $\varepsilon_r'(s_I)$ always approach value of 1 (right part of the curve) slowly than ε_r. Behaviour of ε_r is the consequence of its definition in (18) where comparing to (20) value is weighted by s_I.

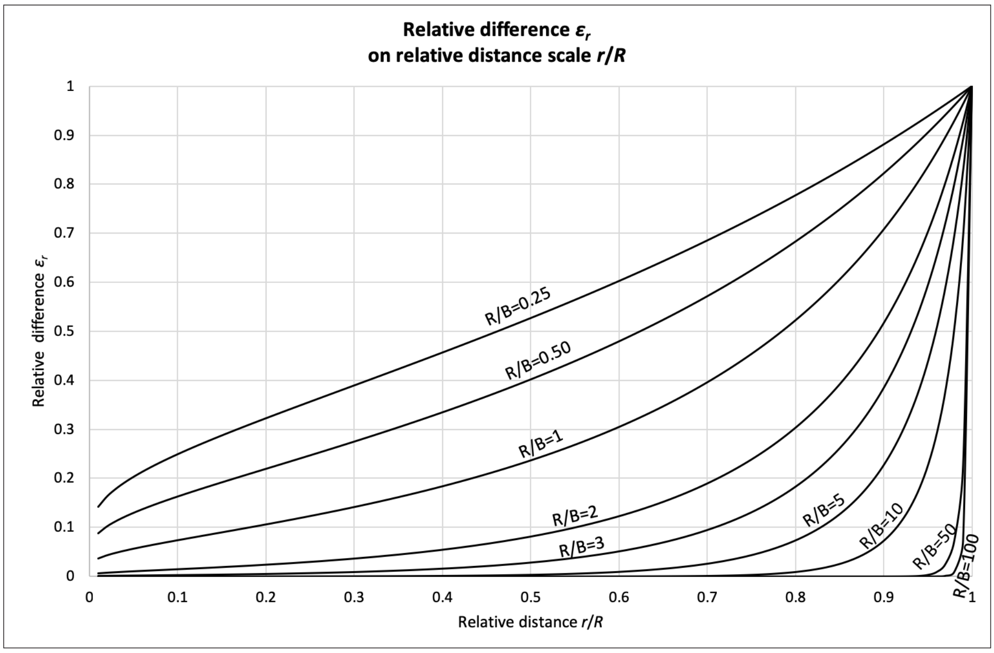

Fig. 5. Relative difference ε_r' plotted on the relative scale r/R.

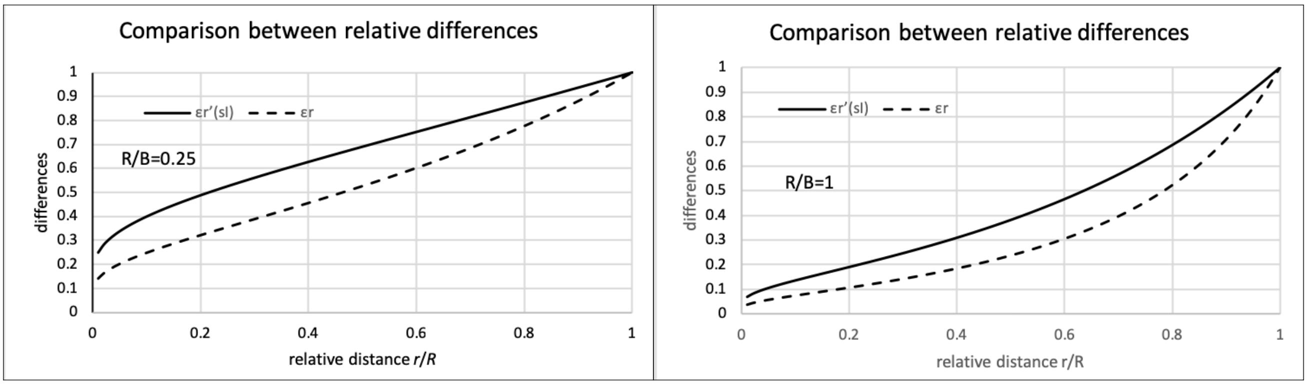

Fig. 6. Comparison of simulation between ε_r'(s_l) and ε_r with the same ratio R/B plotted on the relative scale r/R.

Conclusions

In spite of the fact that in hydrogeological quantification of aquifers and their groundwater flow numerical models are widely applied, development of analytical mathematical models is still important. Analytical approach to groundwater flow enables different and deeper insight into the relations between different geometrical elements in the aquifers and their conceptual models. Analytical models are important for the control of numerical results and are very often applied as a scoping calculation representing first step in the consideration of hydraulic conditions in the aquifer.

In the paper we have presented classical derivation of the head distribution in the leaky aquifer under steady state pumping conditions. We have shown that infinite limit of Hantush integral which represents solution of the non-steady state pumping conditions in the leaky aquifer is solution for the steady state conditions. We have shown that solutions for steady state conditions under finite and infinite pumping well radius of influence are mathematically similar and that based on this characteristics comparison between them can be performed. They can be represented as relative and absolute differences of drawdowns for each model. In the case when available data do not allow us to make a decision on the type of the radius of influence of the pumping well, they can help us in the interpretation of various errors due to application of different analytical models of pumping test. We have shown that at larger leakage factors *B* determination of radius of influence *R* for the large part of the aquifer is not important, they become important at larger factors *B* when contrast between permeabilities in the semi-confining unit and confined unit becomes larger. Under such condition differences in drawdown are important in the vicinity of the pumping well.

For further consideration similar relation for non-steady solutions of the leaky aquifer are also interesting.

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Primerjava rezultatov modeliranja vsebnosti nitrata v vodi pod koreninskim območjem tal v lokalnem in regionalnem merilu

Comparison of the modeling results of nitrate concentrations in soil water below the root zone in the local and regional scale

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Ključne besede: podzemna voda, nitrat, tla, aluvialni vodonosnik, Spodnje Savinjska dolina
Key words: groundwater, nitrate, soil, alluvial aquifer, Spodnje Savinjska dolina

Izvleček

Na raziskovalnem območju plitvega aluvialnega vodonosnika Spodnje Savinjske doline v osrednjem delu Slovenije, predstavljamo primerjalno analizo rezultatov modeliranja vsebnosti nitrata v vodi pod koreninskim območjem tal, v lokalnem in regionalnem merilu z enodimenzijskim modelom DNDC (ang. Denitrification – Decomposition) in z regionalnim modelom GROWA–DENUZ (nem. Großräumiges wasserhaushalt – Denitrifikation im durchwurzelten Boden). Ob uporabi koncepta hidroloških enot HRU (ang. Hydrological Response Unit) in Cohenove Kappa statistične analize ujemanja ter ocenjevanja zanesljivosti rezultatov prostorskega modeliranja nitrata v vodi pod koreninskim območjem tal smo ugotovili in interpretirali predele največjega ujemanja in razhajanja modelskih rezultatov. Dobro ujemanje je bilo ugotovljeno pri najvišjih modeliranih vrednostih, odstopanja pa so bila zaznana predvsem v nižjem delu razpona modeliranih vrednosti nitrata v vodi. Vzroke odstopanja lahko domnevno iščemo predvsem v razlikah pri ocenah denitrifikacijskih pogojev v anaerobnih pogojih hipoglejev in psevdoglejev s podzemno vodo plitvo pod tlemi in v razlikah pri scenarijih gnojenja ter kmetijske prakse.

Abstract

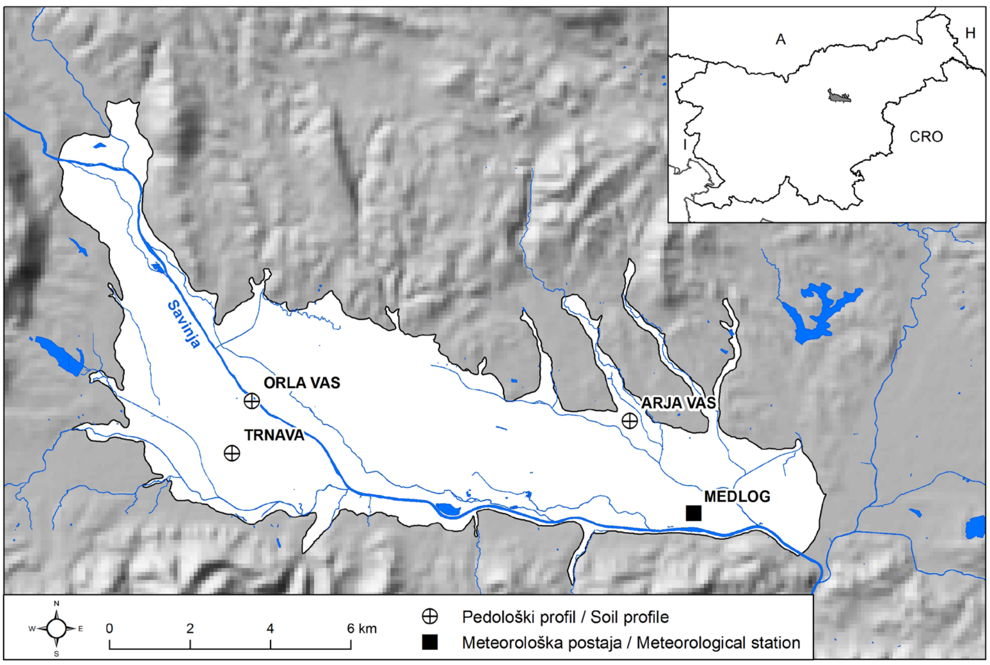
The article presents a comparative analysis of the modeling results of nitrate concentrations in water below the root zone of the soil in the local and regional scale. In this research, the field-scale DNDC (Denitrification – Decomposition) and the regional-scale GROWA–DENUZ (ger. Großräumiges wasserhaushalt – Denitrifikation im durchwurzelten Boden) models were applied to the study area of the shallow aluvial aquifer of the Spodnje Savinjska dolina in the central part of Slovenia. Using the concept of Hydrological Response Unit (HRU) and Cohen Kappa statistical analysis of the degree of agreement and assessment of the reliability of the results of spatial modeling of nitrate in soil water below the root zone, we determined and interpreted the areas of maximum agreement and disagreement of model results. A good agreement was found at the highest modeled concentrations of nitrate in soil water, whereas the greatest deviations were detected primarily in the lower part of the range. The main reasons for disagreement were differences in the estimation of the denitrification conditions in the anaerobic environments of gley-soils with the shallow groundwater and differences in fertilisation scenarios and agricultural practices.

Uvod

Vsebnost nitrata v podzemni vodi predstavlja resno grožnjo okolju na regionalni in lokalni ravni (Kurkowiak, 2017). Tudi ocene kemijskega stanja podzemnih voda, kot jo zahteva okvirna direktiva o vodah (Direktiva 2000/60/ES), v načrtih upravljanja voda Slovenije že desetletje izpostavljajo več vodnih teles, kjer vsebnost nitrata v podzemni vodi presega mejno vrednost (MOP, 2011, 2016). Vzroke najpogosteje povezujemo s pomanjkljivo komunalno urejenostjo in intenzivnim kmetovanjem ob uporabi manj primernih kmetijskih praks. Obe področji se urejata v okvirih, ki jih predpisujeta evropski direktivi o čiščenju komunalne odpadne vode (Direktiva 91/271/EGS) in direktiva o varstvu voda pred onesnaževanjem z nitrati iz kmetijskih virov (Direktiva 91/676/EGS). Poročevalske sheme terjajo tudi strokovno argumentirane ocene učinkov načrtovanih ukrepov in napoved časovnic izboljšanja kemijskega stanja voda s skrajnim časovnim mejnikom 2027, ko naj bi dosegli zastavljene cilje dobrega stanja voda (Matoz et al., 2016). Agencija Republike Slovenije za okolje je v sodelovanju z nemškim raziskovalnim središčem JÜLICH za območje celotne Slovenije prilagodila modelski sistem GROWA-DENUZ/WEKU (Kunkel & Wendland, 2006; Wendland et al., 2008), ki poleg bilance vode upošteva bilanco dušika ter modelira tok dušika preko tal in vodonosnika v površinska vodna telesa. Za prvo oceno zanesljivosti rezultatov tega kompleksnega modelskega sistem smo na območju plitvega aluvialnega vodonosnika Spodnje Savinjske doline s podzemno vodo v slabem kemijskem stanju izdelali primerjalno analizo rezultatov regionalnega modeliranja toka dušika preko koreninskega območja tal GROWA-DENUZ (Kunkel & Wendland, 2006; Andjelov et al., 2014, 2015) in rezultatov lokalnega modela toka dušika iz koreninskega območja tal DNDC (Li et al., 1992) v posameznih talnih profilih. Zanimala nas je stopnja ujemanja modelskih rezultatov v lokalnem in regionalnem merilu v izbranem letu 2008, ko so bile opravljene tudi obsežne terenske meritve, laboratorijske analize in študijske raziskave (Uhan, 2011), ter primernost uporabe modelskega sistema GROWA-DENUZ/WEKU za potrebe simuliranja učinkov ukrepov v smeri izboljšanja kemijskega stanja podzemnih voda.

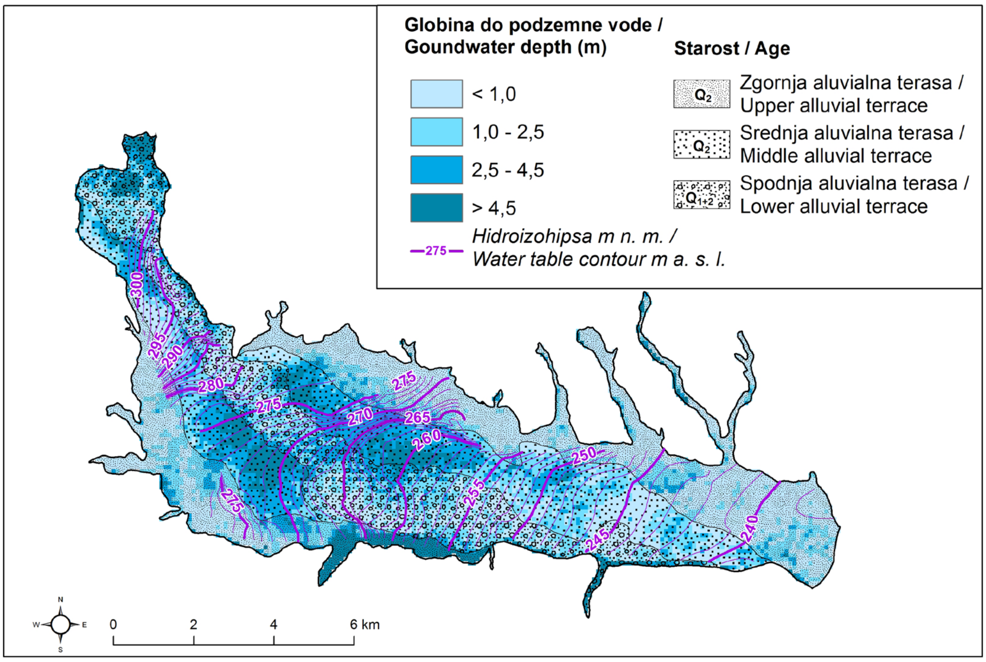
Raziskovalno območje

Raziskovalno območje obsega 73,5 km^2 velik aluvialni vodonosnik Spodnje Savinjske doline (sl. 1) s tremi izrazitimi nivoji aluvialnih teras v holocenskih in pleistocenskih peščeno-prodnih rečnih naplavinah (sl. 2). Zanj so značilne obsežne kmetijske obdelovalne površine: travniki (24 %), njive in vrtovi (33 %) ter hmeljišča (15 %), urbaniziranih površin je okoli 19 % (MKGP, 2007) (sl. 3). V primerjalno analizo rezultatov modeliranja vsebnosti nitrata pod koreninskim območjem tal so vključene le kmetijske površine. Plitva tla so pretežno rjava evtrična (41 %) in obrečna (25 %), predvsem v obrobnih delih pa so prisotni hipogleji in psevdogleji (21 %) (MKGP, 2007) (sl. 4). Debelina tal reprezentativnih profilov omenjenih talnih enot v Trnavi, Orli vasi in Arji vasi je v razponu od 50 do 64 cm (Zupan et al., 2008), globina koreninjenja pa v posameznih primerih presega omenjeno debelino tal (Andjelov et al., 2016a). Globina do podzemne vode je po podatkih državnega monitoringa Agencije Republike Slovenije za okolje v razponu od 0,7 do 7,5 m, s povprečjem 2,4 m in standardnim odklonom gladine podzemne vode 2,0 m (sl. 2). Aluvialni vodonosnik z medzrnsko poroznostjo pleistocenskih in holocenskih peščenih in prodnatih sedimentov s povprečno 21.450.000 m^3 obdobno razpoložljivih količin podzemne vode (Uhan, 2015), zagotavlja pomembne vodne vire regionalne oskrbe, s sicer zahtevnim varovanjem in zagotavljanjem standardov pitne vode.



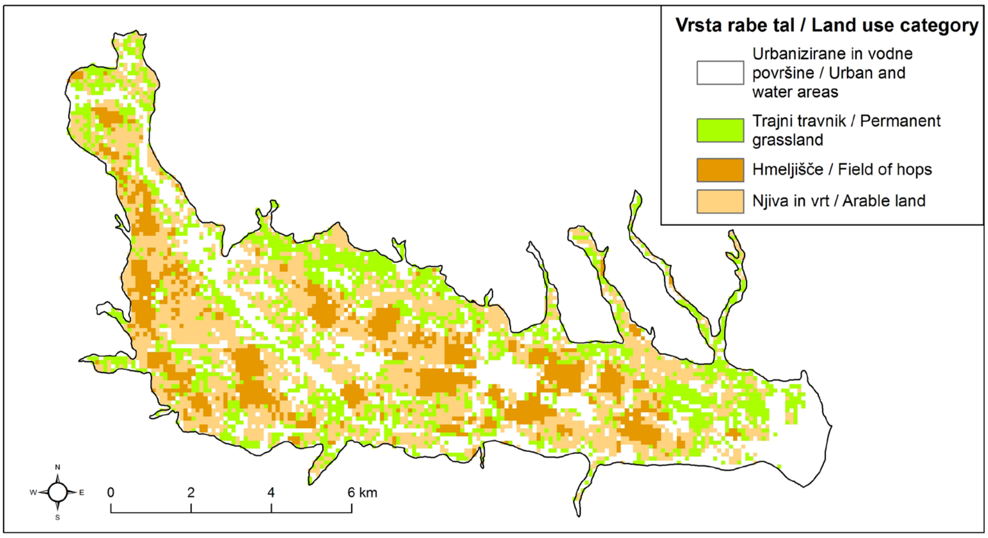
Sl. 1. Študijsko območje Spodnje Savinjske doline.

Fig. 1. Study area of Spodnje Savinjska dolina.



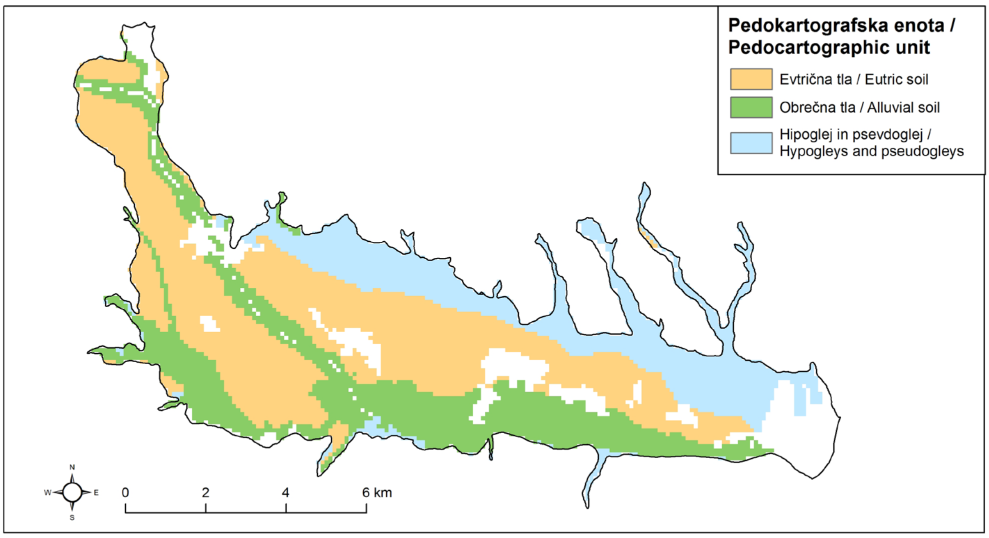
Sl. 2. Hidrogeološka karta Spodnje Savinjske doline (Viri podatkov: Uhan, 2011; Souvent et al., 2014).

Fig. 2. Hydrogeological map of Spodnje Savinjska dolina (Data sources: Uhan, 2011; Souvent et al., 2014).



Sl. 3. Raba prostora (Vir podatkov: MKGP, 2007).

Fig. 3. Land use (Data source: MKGP, 2007).



Sl. 4. Vrsta tal (Vir podatkov: MKGP, 2007; Vidic et al., 2015).

Fig. 4. Soil types (Data source: MKGP, 2007; Vidic et al., 2015).

Podatki

Podatki za regionalno modeliranje toka nitrata preko koreninskega območja tal, so črpani iz uradnih nacionalnih podatkovnih zbir ministrstev, agencij, uprav, zavodov, inštitutov in fakultet ter nekaterih mednarodnih inštitucij (Tabela 1). Merila in ločljivosti prostorskih podatkovnih slojev so različna: merila kart so v razponu od 1: 25.000 do 1: 250.000, ločljivosti prostorskih rastrov pa so od 100 × 100 metrov do 50 × 50 kilometrov. Osnovne vhodne podatke za model GROWA-DENUZ so predstavljali podatki o neto bilanci dušika v kmetijstvu (Sušin et al., 2015) na ravni grafične enote rabe kmetijskega gospodarstva GERK, ki jih zbirajo na Agenciji Republike Slovenije za kmetijske trge in razvoj podeželja. Podatki o staležu goveda so vzeti iz zbirke GOVEDO, ki jo vodijo na Kmetijskem inštitutu Slovenije. Atmosferski nanos pa je bil na kmetijskih območjih Slovenije za potrebe regionalnega modeliranja ocenjen na podlagi podatkovne zbirke EMAP (EEA, 2002).

Lokalno modeliranje toka nitratov preko reprezentativnih profilov tal pa je podatkovno temeljilo predvsem na podatkih iz zbirke pedoloških profilov Centra za pedologijo in varstvo okolja Biotehniške fakultete (Zupan et al., 2008), na podatkih iz smernic za strokovno utemeljeno gnojenje (Mihelič et al., 2010), na razpoložljivih modelskih podatkovnih knjižnicah o fiziologiji izbranih rastlin (Li, 2009) in na zbirkah meteoroloških podatkov Agencije Republike Slovenije za okolje.

Primerjalna analiza vključuje obdobje hidrološkega leta 2008, ko so bile na območju vodonosnika Spodnje Savinjske doline opravljene tudi obsežne študijske raziskave (Uhan, 2011). Hidrološko leto 2008 se po količinskem obnavljanju podzemne vode uvršča med zmerno vodnate s +18 % odstopanjem od obdobnega povprečja 1981-2010 (Uhan, 2015).

Tabela 1. Podatkovne zbirke za modeliranje toka nitratov v Spodnje Savinjski dolini z modeloma GROWA-DENUZ in DNDC.
Table 1. Databases for nitrogen flux modelling in Spodnje Savinjska dolina with GROWA-DENUZ and DNDC model.

Model GROWA-DENUZ			
Vrsta podatkov / Type of data	**Podatkovna zbirka / Database**	**Merilo za vektorski podatek ali prostorska ločljivost za rasterski podatek / Scale for vector data or spatial resolution for raster data**	**Vir podatkov / Data source**
Klimatski podatki (1971-2000) / Climate data (1971-2000)	Padavine (maj - oktober), padavine (november - april), potencialna evapotranspiracija / Precipitation (May - October), precipitation (November - April), potential evapotranspiration	100 × 100 m	Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo / Slovenian Environment Agency, Meteorology and Hydrology Office
Pokrovnost tal / Land cover	Vrsta rabe tal / Land use category	1: 100.000	Zbirka podatkov CORINE / CORINE data base
Podatki o tleh / Soil data	Tipi tal, tekstura tal, efektivna poljska kapaciteta, globina koreninjenja / Soil types, soil texture, effective field capacity, rooting depth	1: 25.000	Ministrstvo za kmetijstvo, gozdarstvo in prehrano; Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za agronomijo; Kmetijski inštitut Slovenije / Ministry of Agriculture, Forestry and Food; University of Ljubljana, Biotechnical Faculty, Centre for Soil and Environment Science; Agricultural Institute of Slovenia
Podatki o površju / Relief data	Digitalni model višin / Digital elevation model	100 × 100 m	Geodetska uprava Republike Slovenije / Surveying and Mapping Authority of the Republic of Slovenia
Geološki podatki / Geological data	Geološka karta Slovenije / Geological map of Slovenia	1: 100.000	Geološki zavod Slovenije / Geological Survey of Slovenia

Hidrološki podatki / Hydrological data	Prispevna območja, dnevni pretoki (1971 - 2000) / Catchment areas, daily runoff (1971 - 2000)	1: 25.000	Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo / Slovenian Environment Agency, Meteorology and Hydrology Office
Hidrografski podatki / Hydrographical data	Rečna mreža, umetno izsušena območja / River network, artificially drained areas	1: 25.000	Geodetska uprava Republike Slovenije, Ministrstvo za kmetijstvo, gozdarstvo in prehrano / The Surveying and Mapping Authority of the Republic of Slovenia, Ministry of Agriculture, Forestry and Food
Hidrogeološki podatki / Hydrogeological data	Hidrogeološka karta Slovenije, tipologija podzemne vode, hidroizohipse, globina do podzemne vode, hidravlična prepustnost / Hydrogeological map of Slovenia, groundwater typology, water table contours, groundwater depth, hydraulic permeability	1: 250.000 1: 100.000 1: 25.000	Geološki zavod Slovenije; Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo / Geological Survey of Slovenia, Slovenian Environment Agency, Meteorology and Hydrology Office
Podatki o kakovosti voda / Water quality data	Kakovost podzemnih in površinskih voda (1995 - 2011) / Groundwater and surface water quality data (1995 - 2011)	1: 25.000	Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo / Slovenian Environment Agency, Meteorology and Hydrology Office
Točkovni viri dušika / Point sources of nitrogen	Čistilne naprave komunalnih in industrijskih odpadnih voda, greznice / Municipal waste water treatment plants, industrial treatment plants, cesspools	1: 25.000	Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo; Ministrstvo za okolje in prostor / Slovenian Environment Agency, Meteorology and Hydrology Office; Ministry of environment and spatial planing
Razpršeni viri dušika / Diffuse sources of nitrogen	Atmosferski nanos dušika, presežek dušika v kmetijstvu / Atmospheric N deposition, agricultural N surpluses	50 × 50 km, 100 × 100 m	European Monitoring and Evaluation Programme (EMEP), Kmetijski inštitut Slovenije / European Monitoring and Evaluation Programme (EMEP), Agricultural Institute of Slovenia

Model DNDC

Vrsta podatkov / Type of data	**Podatkovna zbirka / Data base**	**Vir podatkov / Data source**
Podatki o podnebju (leto 2008) / Climate data (year 2008)	Dnevna višina padavin, dnevno povprečje temperature zraka / Daily precipitation, daily average air temperature	Agencija Republike Slovenije za okolje, Urad za meteorologijo in hidrologijo / Slovenian Environment Agency, Meteorology and Hydrology Office
Podatki o tleh / Soil data	Talni informacijski sistem Slovenije / Soil information system of Slovenia	Univerza v Ljubljani, Biotehnična fakulteta, Center za pedologijo in varstvo okolja / University of Ljubljana, Biotechnical Faculty, Centre for Soil and Environment Science
Podatki o rastlinah / Crop data	Podatki o fiziologiji in fenologiji rastlin / Crop phenology and physiology data	Knjižnica rastlin DNDC (Li, 2009) / Crop library of DNDC (Li, 2009)
Podatki o kmetijski praksi / Agricultural management data	Podatki iz slovenskih smernic za strokovno utemeljeno gnojenje / Data from Slovene guidelines for expert based fertilization	Ministrstvo za kmetijstvo, gozdarstvo in prehrano (Mihelič in sod., 2010) / Ministry of Agriculture, Forestry and Food (Mihelič et al., 2010)

Metode

Modeliranje toka nitrata v regionalnem merilu

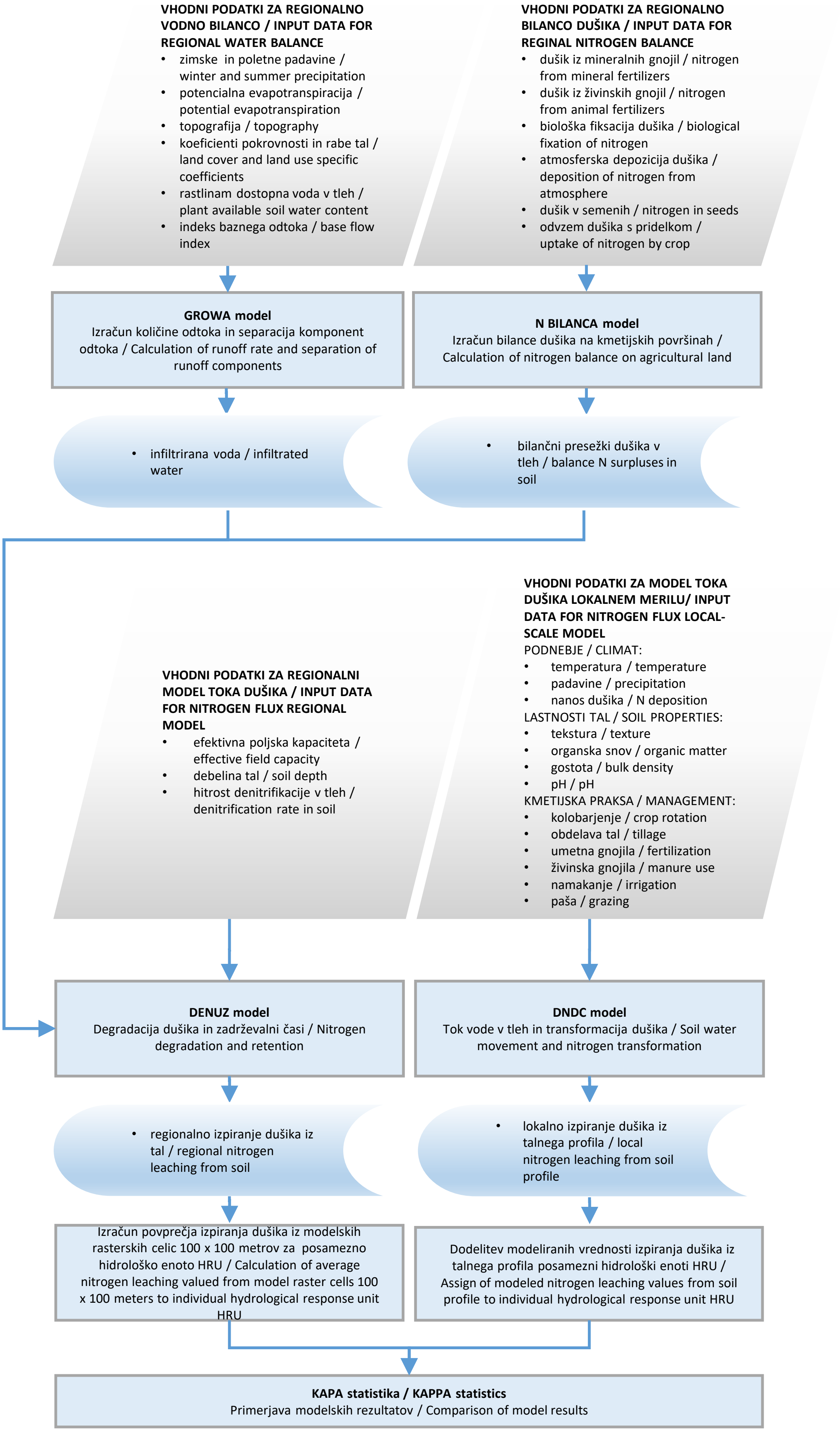
Tok nitrata preko koreninskega območja tal je bil v regionalnem merilu v prostorski ločljivosti 100 × 100 metrov modeliran v okolju GROWA-DENUZ (Kunkel & Wendland, 2006; Kunkel et al., 2010), ki je temeljil na prostorskih podatkovnih slojih regionalne vodne bilance (Andjelov et al., 2016a) in neto bilance dušika v kmetijstvu (Sušin et al., 2015). Ob upoštevanju Michaelis-Mentenove kinetike (Michaelis & Menten, 1913) so bili ocenjeni denitrifikacijski pogoji kombinirani z izračunanimi presežki dušika (Sušin et al., 2015) in zadrževalnimi časi pronicanja vode v območju korenin ter predstavljeni kot funkcija povprečne poljske kapacitete in hitrosti odtoka s pronicanjem (sl. 5). Kot referenčne vrednosti so bile uporabljene ocenjene hitrosti denitrifikacije za srednjeevropske tla (Wienhaus et al., 2008). Ocene hitrosti denitrifikacije, ki so letno v razponu od okoli 10 do preko 100 kg N na hektar, temeljijo na vrsti tal in geološki podlagi ter vplivu plitve podzemne vode. Zadrževalni časi izcedne vode so v koreninskem območju tal ocenjeni preko efektivne poljske kapacitete (Müller & Raissi, 2002; Hennings, 2000). Ocena relativne denitrafikacijske izgube v tleh temelji na razmerju med iznosom dušika iz tal po denitrifikaciji, ki jo prinaša rešitev Michaelis-Mentenove enačbe, in vnosom dušika iz razpršenih virov. Vsebnosti nitrata v izcedni vodi so v modelu GROWA-DENUZ ocenjene ob upoštevanju hitrosti pronicanja vode preko koreninskega območja tal za celotno območje Slovenije (Andjelov et al., 2016a, 2016b). Za vrednotenje rezultatov modela GROWA-DENUZ smo primerjali modelske rezultate z rezultati terenskih meritev nitrata v podzemni vodi (Uhan, 2011) in neparametrični Spermanov koeficient nakazuje korelacijo ranga 0,87 (α=0,05).

Modeliranje toka nitrata v lokalnem merilu

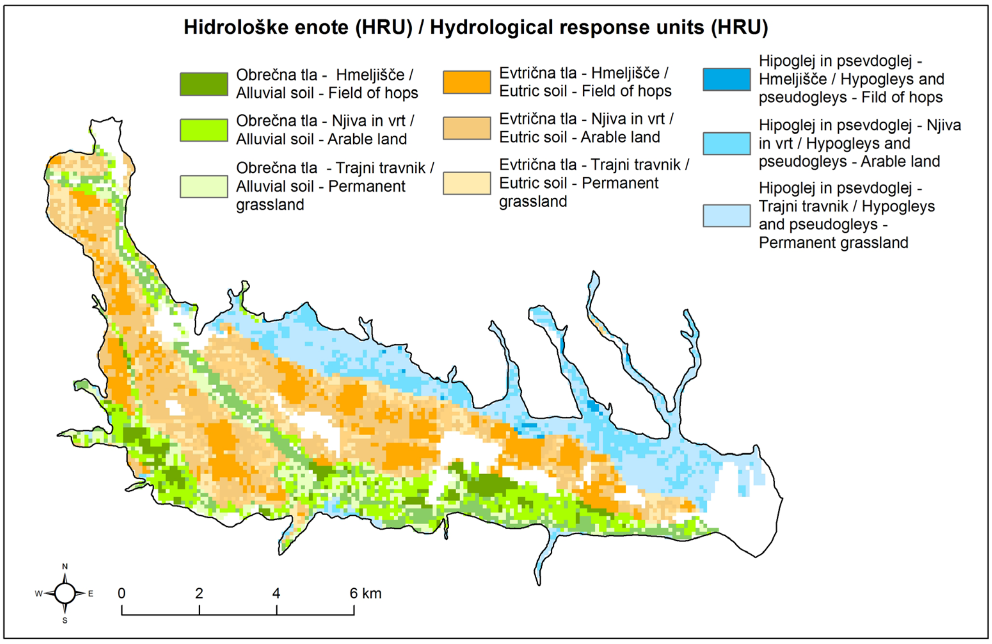
Za simuliranje biogeokemijskih procesov dušikovega kroga v lokalnih pogojih kmetijskih ekosistemov na plitvem vodonosniku Spodnje Savinjske doline smo na posameznih reprezentativnih profilih tal v Trnavi, Orli vasi in Arji vasi (Zupan et al., 2008) (sl. 1) uporabili enodimenzijski model DNDC (Li et al., 1992). Model omogoča povezavo med vhodnimi parametri okolja in izhodi iz dušikovega kroga tal v obliki biomase, plinov in izpiranja. Modelske procese poganjajo primarne gonilne sile v okolju, kot so procesi v ozračju, tleh in vegetaciji, ob upoštevanju kmetijske prakse oz. človekove aktivnosti (sl. 5). Model DNDC sestavljata dve osnovni komponenti, ki rešujeta enačbe klime tal z izračunom iztoka vode in enačbe biogeokemijskih procesov dušika v tleh. Prvo modelsko komponento sestavljajo trije podmodeli: klima tal, rast vegetacije in dekompozicija. V okviru te komponente je možna napoved faktorjev tal: temperature in vlage tal, pH in oksidacijsko-redukcijskega potenciala ter vsebnosti substratov na podlagi vedenja o tleh, rastlinstvu in podnebju, ki lahko pomembno vpliva na rezultate biogeokemijskih procesov (Uhan, 2018). Druga komponenta je sestavljena iz nitrifikacijskega, denitrifikacijskega in fermentacijskega podmodela, ki omogočajo napoved emisije plinov iz sistema tla – rastline. Model predstavlja povezavo med ogljikovim in dušikovim biogeokemijskim ciklom in primarnimi gonilnimi silami ter med drugim simulira tudi količino letnega izhoda dušika iz koreninskega območja tal, ki ogroža kakovost podzemne vode tudi v zasičenem delu vodonosnika. Pri tem je pomemben proces denitrifikacije, ki se povezuje z nasičenostjo tal in pojavom anaerobnosti. Model DNDC preko Nernstove enačbe (Nernst, 1889) oceni oksidacijsko-redukcijske pogoje tal (Eh), nato pa ob upoštevanju Michaelis-Mentenove kinetike (Michaelis & Menten, 1913) simulira aktivnosti anaerobnih mehanizmov in izračuna stopnjo denitrifikacijske redukcije nitrata (Stumm & Morgan, 1981; University of New Hampshire, 2017). Analiza občutljivosti modela DNDC je z metodo Monte Carlo (Metropolis & Ulam, 1949) v primeru reprezentativnega pedološkega profila v Latkovi vasi izpostavila pomemben vpliv na izpiranje dušika predvsem s strani dveh vhodnih parametrov: hidravlične prevodnosti tal in količine uporabljenih gnojil (Uhan, 2011). Umerjanje modela oz. vrednotenje rezultatov modela DNDC je bilo izvedeno preko primerjave z merjenimi podatki poljskega poskusa v Latkovi vasi leta 2000 (Pintar et al., 2005) in neparametrični Spermanov koeficient korelacije ranga je dosegel vrednost 0,76 (α=0,05).

Statistična primerjalna analiza modelskih rezultatov

Primerjava rezultatov modeliranja vsebnosti nitrata v vodi pod koreninskim območjem tal v regionalnem in v lokalnem merilu je zahtevala posplošitev oz. prenos modelskih izhodnih podatkov na primerljive prostorske enote. Primerljive enote prostora, znotraj katerih naj bi bile vhodne veličine hidrološkega modela predpostavljeno homogene, so z enako vrsto tal, rabo prostora in naklonom površja definirane kot hidrološke enote HRU (angl. Hydrological Respon-



Sl. 5. Shema modelskih postopkov in primerjava modelskih rezultatov (po: Kunkel & Wendland, 2006; Salas, 2010).
Fig. 5. The scheme of model procedures and comparison of the model results (after: Kunkel & Wendland, 2006; Salas, 2010).



Sl. 6. Hidrološke enote (HRU) za določene tipe tal in rabe prostora v Spodnje Savinjski dolini.

Fig. 6. Hydrological response units (HRU) for a given soil types and land uses in Spodnje Savinjska dolina.

se Unit) (Arnold et al., 1998) (sl. 6). Prostorskim enotam z enako vrsto tal, rabo prostora in naklonom površja lahko pripišemo enake hidrološke značilnosti prostora. Hidrološkim enotam HRU študijskemu območju Spodnje Savinjske doline so bila v primeru modeliranja v regionalnem merilu izračunana prostorska povprečja letnega izpiranja dušika iz modelskih rastrskih celic 100 × 100 metrov, v primeru modeliranja v lokalnem merilu pa so bile hidrološkim enotam HRU pripisane vrednosti modeliranja letnega izpiranja dušika iz reprezentativnih profilov tal (sl. 3) s prevladujočimi rabami prostora (sl. 4). Statistična primerjalna analiza modelskih rezultatov je v tako pripravljenem rastrskem zapisu temeljila na matriki pravilnosti razvrščanja oz. matriki zamenjav, iz katere je izračunana mera ujemanja ali skladnosti (sl. 5). Cohenov koeficient κ (kapa) pokaže stopnjo ujemanja klasifikacij dveh modelskih rezultatov oz. za koliko je ujemanje med modelskima rezultatoma boljše od naključnega ujemanja. Z izračunom koeficienta κ smo opredelili delež ujemanja modelskih rezultatov, ki presega pričakovano naključje (Cohen, 1960):

$$\kappa = \frac{P_o - P_c}{1 - P_c},$$

kjer je P_o delež opazovanega ujemanja, P_c pa je delež naključnega ujemanja.

Podobno kot korelacijski koeficient je tudi Cohenov koeficient κ v razponu od -1 do +1, kjer negativne vrednosti govorijo o ujemanju, ki je slabše od naključja, vrednost +1 pa nakazuje odlično ujemanje. Primerjalna analiza rezultatov modeliranja vsebnosti nitrata v vodi pod koreninskim območjem tal v regionalnem in v lokalnem merilu Spodnje Savinjske doline je bila v GIS okolju izvedena s sistematičnim in robustnim postopkom Kappa Stats (Jenness & Wynne, 2007).

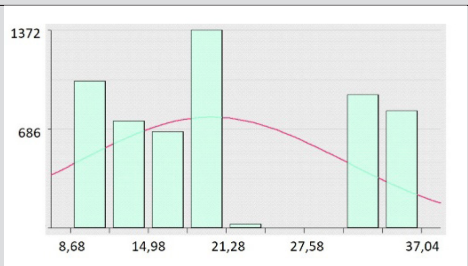
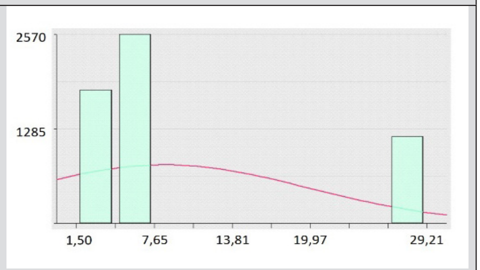
Rezultati in razprava

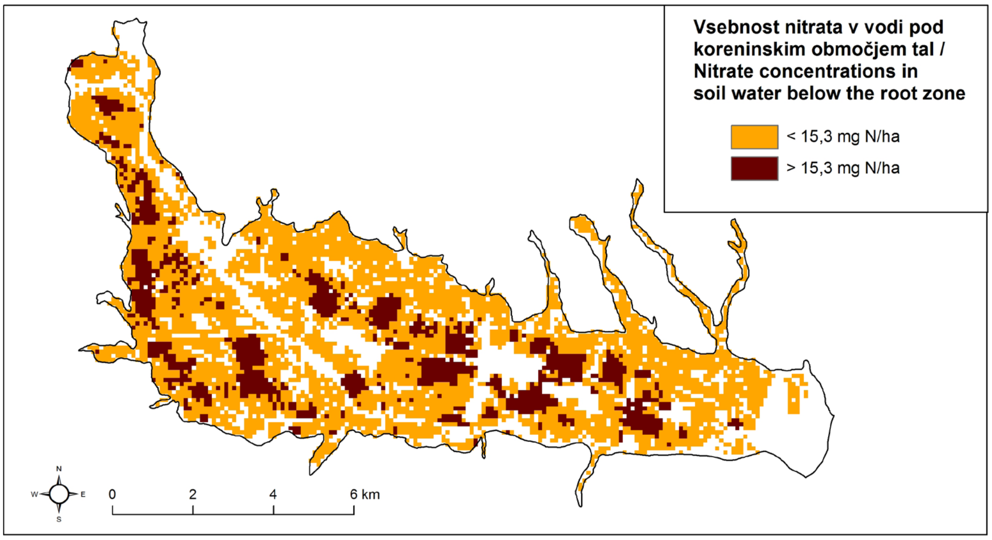
Vsebnosti nitrata v vodi pod koreninskim območjem tal smo v enodimenzijskem modelskem okolju DNDC najprej modelirali v posameznih reprezentativnih profilih tal ob izbranih scenarijih rabe prostora in kmetijske prakse (Uhan, 2011). Ob tem smo za potrebe regionalizacije modelskih rezultatov letnega izpiranja dušik iz talnega profila privzeli poenostavljen koncept hidrološke enote HRU. Hidrološke enote HRU so osnovne enote izračunov v modelskem okolju SWAT, ki izvorno temeljijo na vrstah tal, rabah prostora in naklonih površja, znotraj katerih naj bi bile vse vhodne veličine modela predpostavljeno homogene (Arnold et al., 1998). S tremi reprezentativnimi vrstami tal Spodnje Savinjske doline (obrečna tla, evtrična rjava tla, hipoglej) in tremi vrstami kmetijske rabe prostora (hmeljišče, njiva in vrt, trajni travnik) smo vzpostavili prostorsko shemo devetih prevladujočih hidroloških enot HRU (sl. 6), s katerimi smo uspeli pokriti 89 % celotnega raziskovalnega prostora. Rezultati modelskih simulacij DNDC so za izbrano analizirano leto 2008 v razponu od 1,7 do 36,9 kg N/ha. Pri pregledu površin obdelovalnih kmetijskih zemljišč posameznih hidroloških enot in modelskih izračunov izpiranja dušika iz reprezentativnih pedoloških profilov močno izstopajo hmeljišča (sl. 7 in 9) z obravnavano površino 1.212 ha in izpiranjem dušika v razponu od 13,6 kg N/ha na hipogleju Arje vasi do 36,9 kg N/ha na obrečnih tleh Orle vasi.

Koncept hidroloških enot HRU smo zaradi potreb primerjalne analize uporabili tudi za posplošitev rezultatov modela GROWA-DENUZ z izvorno prostorsko ločljivostjo 100 × 100 metrov (Andjelov et al., 2014, 2015). Rezultati regionalnega modela GROWA-DENUZ so za izbrano analizirano leto 2008 po posameznih hidroloških enotah HRU v razponu od 8,7 do 37,0 kg N/ha. Tudi v tej modelski simulaciji izstopajo hidrološke enote s hmeljišči in sicer v razponu od 23,8 do 37,0 kg N/ha. Model GROWA-DENUZ simulira tok dušika v manjšem razponu, vendar pa je standardni odklon rezultatov obeh modelih zelo podoben: 10,2 kg N/ha pri modelu DNDC in 9,6 kg N/ha pri modelu GROWA-DENUZ (Tabela 2).

Statistična primerjalna analiza podatkovnih slojev je terjala prostorsko klasifikacijo rezultatov obeh modelskih simulacij, ki je bila izvedena glede na število izhodiščnih karakteristik hidroloških enot HRU (trirazredna klasifikacijska shema) in glede na verjetnostno porazdelitev modeliranih vrednosti (dvorazredna klasifikacijska shema). Podlaga dvorazredni klasifikacijski shemi (sl. 7 in 8) je vrednost prevoja logaritemske verjetnostne porazdelitve (Panno et al., 2006), podlaga trirazredni klasifikacijski shemi (sl. 9 in 10) pa je Fisher-Jenksov algoritem naravnih mejnih vrednosti (Slocum et al., 2005). Mejne vrednosti razredov so prikazane v legendah na slikah od 7 do 10.

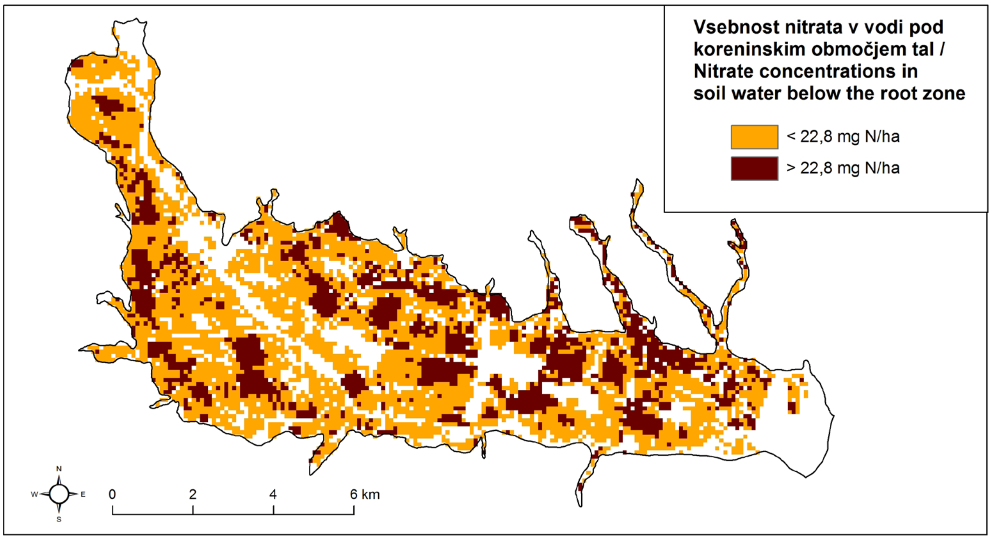
Tabela 2. Statistike rastrske karte posplošenih modelskih vrednosti iz modela GROWA–DENUZ in modela DNDC (v kg N/ha).
Table 2. Statistics of raster maps of generalized raster map from GROWA–DENUZ and DNDC model (in kg N/ha).

	Posplošena rastrska karta iz modela GROWA–DENUZ / Generalized raster map from GROWA–DENUZ model	Posplošena rastrska karta iz modela DNDC / Generalized raster map from DNDC model
Statistike / Statistics		
Število celic / Number of cells	5.565	5.563
Aritmetična sredina / Mean	20,37	9,20
Mediana / Mediana	18,69	5,52
Min. vrednost / Min. value	8,68	1,50
Max. vrednost / Max. value	37,05	29,21
Razpon / Range	28,60	27,72
Standardna napaka ocene sredine / Standard error of mean	0,12	0,14
Varianca / Variance	92,37	103,30
Standardni odklon / Standard Deviation	9,61	10,16



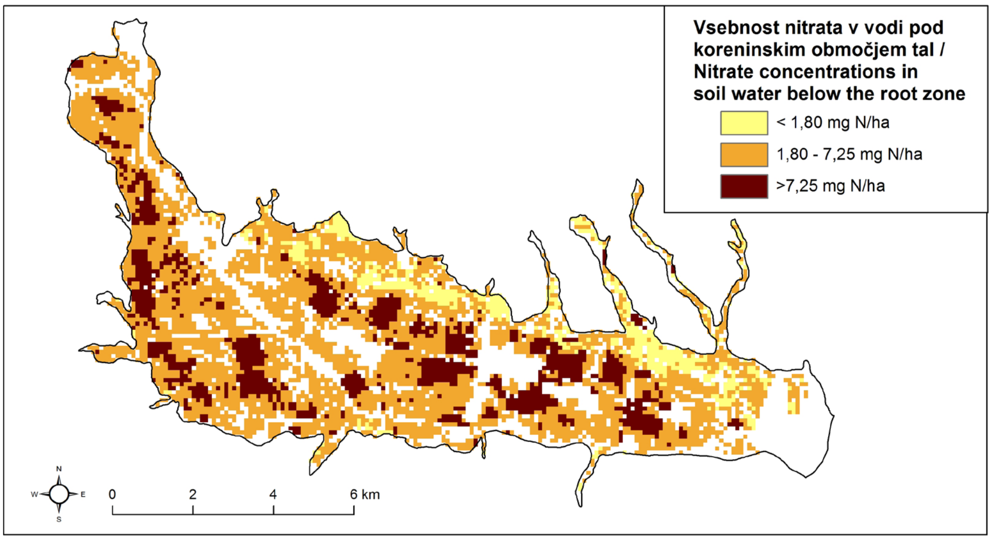
Sl, 7. Modelski rezultat DNDC v dvorazredni klasifikacijski shemi.

Fig. 7. DNDC model result in two-class classification scheme.



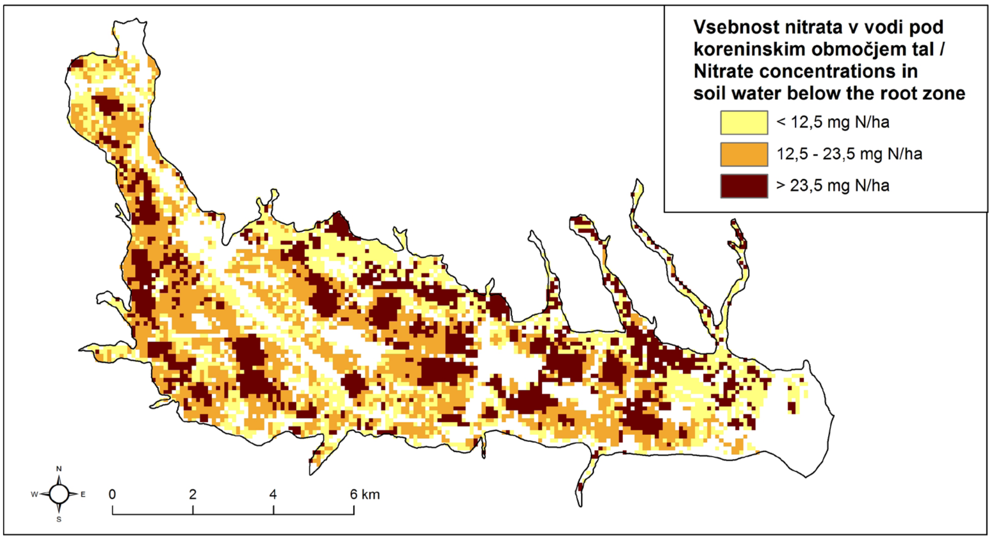
Sl. 8. Modelski rezultat GROWA-DENUZ v dvorazredni klasifikacijski shemi.

Fig. 8. GROWA-DENUZ model result in two-class classification scheme.



Sl. 9. Modelski rezultat DNDC v trirazredni klasifikacijski shemi.

Fig. 9. DNDC model result in three-class classification scheme.



Sl. 10. Modelski rezultat GROWA-DENUZ v trirazredni klasifikacijski shemi.

Fig. 10. GROWA-DENUZ model result in three-class classification scheme.

Za oceno ujemanja prostorskih podatkovnih slojev dveh modelskih simulacij (DNDC in GROWA-DENUZ) in dveh klasifikacijskih shem (dvorazredna in trirazredna shema) smo uporabili Cohenovo Kappa statistiko (Cohen, 1960) in ArcGIS orodje ocenjevanja zanesljivosti prostorskih modelov (Jenness & Wynne, 2005). V primeru trirazredne klasifikacijske sheme je stopnja zanesljivosti ujemanja 71,7 % s Cohenovim Kappa koeficientom 0,57, v primeru dvorazredne klasifikacijske sheme pa je stopnja zanesljivosti ujemanja 89,5 % s koeficientom 0,73, kar se že lahko interpretira kot razred dobrega ujemanja (Landis & Koch, 1977) (Tabela 3) (sl. 7 do 10).

Primerjalna analiza rezultatov modeliranja toka dušika preko koreninskega območja tal v regionalnem in lokalnem merilu Spodnje Savinjske doline odkriva dobra medsebojna ujemanja predvsem pri višjih modeliranih vrednostih, to je v velikostnem območju nad okoli 23 kg N na hektar. Skoraj popolno ujemanje je ugotovljeno za povprečja hidroloških enot s hmeljišči na obrečnih tleh in zelo prepustnem vodonosniku s podzemno vodo plitvo pod tlemi (sl. 7 do 10). Večja odstopanja pa so bila ugotovljena pri nižjih vrednosti modeliranega dušika pod koreninskim območjem, predvsem na območju hipoglejev in psevdoglejev. To so območja na severnem obrobju doline z bolj anaerobnimi talnimi pogoji in regionalno modeliranimi vrednostmi pod 12 kg N na hektar. Z obsežnimi terenskimi meritvami raztopljenega kisika v podzemni vodi so bila na teh območjih že dokazana izrazita redukcijska okolja, pomembna za regionalno porazdelitev nitrata v podzemni vodi (Uhan, 2010, 2011; Uhan et al., 2011).

Tabela 3. Kappa statistike za različne klasifikacijske sheme.
Table 3. Kappa statistics for different classification scheme.

Klasifikacijska shema / Classification scheme	K_{HAT} / Kappa statistics	Varianca / Variance	Z-vrednost (%) / Z-score (%)	P	Spodnja meja intervala zaupanja (95 %) / Lower confidence interval (95 %)	Zgornja meja intervala zaupanja (95 %) / Upper confidence interval (95 %)	Ocena zanesljivosti / Accuracy assessment
Dvorazredna klasifikacijska shema / two-class classification scheme	0,73	0,00010	71,87	< 0,00001	0,714	0,754	0,895
Trirazredna klasifikacijska shema / three-class classification scheme	0,57	0,00008	62,60	< 0,00001	0,549	0,584	0,717

Ocenjujemo, da je stopnja denitrifikacije v območju korenin v primeru bolj glinastih talnih razmer z nizko vsebnostjo kisika in visoko vsebnostjo vode, kot tudi visoko vsebnostjo organskih snovi, zaznavno višja, kot jo prikazujejo rezultati regionalnega modela. V regionalnem modelu GROWA-DENUZ so denitrifikacijski pogoji v tleh Slovenije ocenjeni na podlagi referenčnih vrednosti, pridobljenih z meritvami na srednjeevropskih tleh, kar je nedvomno lahko velik vir variacije oz. odstopanja od rezultatov lokalnega modela, ki temelji na raziskanih reprezentativnih profilih tal študijskega območja. Poleg razlik v vhodnih podatkih o gnojenju in kmetijski praksi v obeh modelskih simulacijah lahko tudi v tem iščemo razloge za razlike med povprečnimi vrednostmi obeh modelskih rešitev (Tabela 2). V prihodnje je priporočljivo terensko raziskati območja z ugodnimi denitrifikacijskimi pogoji in v regionalnem modelu bolj natančno opredeliti potencial za redukcijo nitrata v koreninskem območju in posledično tudi v podzemni vodi vseh plitvih vodonosnikov s slabim kemijskim stanjem. Ob tem pa se je potrebno zavedati, da je proces denitrifikacije modularnega značaja, kar dodatno otežuje meritve in modeliranje ter terja razširitev raziskav tudi na izotopsko sestavo vode, predvsem na stabilne izotope ^{18}O v NO_3 ter ^{15}N in ^{11}B. Znotraj t.i. »izotopskega triptiha« je za razlikovanje virov nitrata in frakcionacijskih procesov, kot je denitrifikacija, pomembno poznavanje predvsem izotopske sestave ^{11}B, na katero biogeokemijski transformacijski procesi ne vplivajo (Widory et al., 2013; Van Groenigen et al., 2015).

Sklep

Zaradi odsotnosti dolgoročnega trenda izboljševanja stanja voda po oceni Evropske komisije nitrat v podzemni vodi še vedno predstavlja resno grožnjo okolju na regionalni in lokalni ravni. Regionalna modelska simulacija toka nitrata preko koreninskega območja v vodonosnik je pomemben pristop ocenjevanja učinkovitosti načrtovanih ukrepov zmanjšanja tveganja za onesnaženje podzemne vode, predvsem v primerih intenzivnega kmetovanja na plitvih prepustnih vodonosnikih s slabim kemijskim stanjem podzemne vode in regionalnimi vodooskrbnimi viri. V poročilu na podlagi evropske direktive Sveta 91/676/EEC, ki se nanaša na varstvo voda pred onesnaženjem z nitrati iz kmetijskih virov za obdobje 2012-2015, je Slovenija tovrstni modelski pristop že napovedala. Ob tem pa je pomembno poznavanje omejitev modelskega sistema in zanesljivosti modelskih rezultatov. Z rezultati lokalnega modela DNDC smo podprli analizo vrednotenja rezultatov regionalnega modeliranja izpiranja dušika na območju celotne države. Primerjalna analiza rezultatov modeliranja v regionalnem merilu z rezultati modeliranja v reprezentativnih profilih tal je ena od pomembnih stopenj v procesu preizkušanja modela oz. ocenjevanja zanesljivosti rezultatov regionalnih modelov. Primerjalna analiza je na tej stopnji potrdila primernost uporabe rezultatov regionalnega modelskega sklopa GROWA-DENUZ v procesu priprave ukrepov potrebnega zmanjšanja obremenitev na nivoju vodnih teles s slabim kemijskim stanjem podzemnih voda, ob tem pa je izpostavila potrebo po boljši karakterizaciji denitrifikacijskih pogojev po posameznih delih vodnih teles, kar lahko izboljša napovedovanje učinkov ukrepov tudi v nižjem velikostnem razredu vsebnosti nitrata v vodi pod koreninskim območjem tal.

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Korespondenca med Vasilijem Vasilijevičem Nikitinom in Vladimirjem Ivanovičem Vernadskim

Correspondence between Vasily Vasilyevich Nikitin and Vladimir Ivanovich Vernadsky

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Key words: geochemistry, biogeochemistry, scientific correspondence, exchange of scientific literature, transliteration of letters, Slovenia, Russia

Izvleček

V članku je predstavljeno dopisovanje med mineralogom, petrologom in strokovnjakom za kovinske mineralne surovine, rudarskim inženirjem Vasilijem Vasilijevičem Nikitinom (1867-1942) in znamenitim ruskim geologom, mineralogom, geokemikom in filozofom Vladimirjem Ivanovičem Vernadskim (1863-1945). V Arhivu Ruske Akademije znanosti v korpusu arhivskega gradiva o Vernadskem je ohranjenih šest dopisov Nikitina Vernadskemu, ki so v članku prevedeni, dokumentirani in kritično interpretirani. V omenjenem arhivu sta Nikitinu pripisani še dve pismi, za kateri pa smo dokazali, da nista njegovi. Korespondenca dokazuje, da je Nikitin tudi po prihodu v Ljubljano ohranjal stike s svojim nekdanjim delovnim okoljem v Rusiji, hkrati pa je to dokaz, da so si prvi profesorji, ki so poučevali na Univerzi v Ljubljani, intenzivno prizadevali za stik z razvojem znanosti po svetu.

Abstract

The article presents the correspondence of mineralogist, petrologist and mineral resource expert mining engineer Vasily Vasilyevich Nikitin (1867-1942) with the famous Russian geologist, mineralogist, geochemist and philosopher Vladimir Ivanovich Vernadsky (1863-1945). In the Archive of the Russian Academy of Sciences in the corpus of Vernadsky's archival material, six letters of Nikitin to Vernadsky have been preserved. In the paper they are translated, documented and critically interpreted. In the archive, two other letters are also attributed to Nikitin, but we have proved that they are not his. The correspondence proves that after joining University of Ljubljana, Nikitin maintained contact with his former working environment in Russia, and at the same time it is a proof that the first professors who taught at the University of Ljubljana have sought contact with the development of science around the world.

Uvod

Starejša pisma predstavljajo izjemno zgodovinsko gradivo. Nudijo nam vpogled tako v intimne odnose med dopisovalci kot tudi v značilnosti obdobja, v katerem so pisma nastala. Nemalokrat nam posredujejo podatke, ki se v drugem arhivskem gradivu niso ohranili, ali pa so pisma kot dokument zanimiva sama po sebi. Zlasti v literarni znanosti bomo našli številne kritične izdaje pisem pomembnih literatov in njihovih dopisnikov, pri tem slovenska literarna znanost ni nobena izjema. Mnogo redkeje bomo naleteli na korespondenco znanstvenikov in raziskovalcev, zlasti naravoslovcev; in tehnikov. Takšne objave in kritične analize tega gradiva so prej izjema kot pravilo, ne le v slovenščini, temveč tudi v drugih jezikih. V slovenskem jeziku je kritičnih izdaj pisem slovenskih naravoslovcev ali tujcev, ki so delovali na slovenskem ozemlju, zelo malo. Izjema je korespondenca Antonija Scopolija z Linéjem (Soban, 2004) ter korespondenca Žige Zoisa (Kidrič, 1939; 1941). Predvsem korespondenca slednjega je podrobno obdelana, zaradi njegovega velikega pomena za slovenski narodni preporod ter zaradi njegove mecenske vloge pri porajajoči se slovenski literaturi. V Zoisovi korespondenci naletimo tudi na naravoslovno pomembne informacije.

Pisemsko dopisovanje je bilo dolga stoletja pomemben način komunikacije. Zlasti med izobraženci in intelektualci so bila pisma medij, s katerim so si sporočali številne informacije ter razmišljanja. Nemalokrat so bila pisma pravi znanstveni ali literarni članki, ki so jih avtorji ali prejemniki zbrali in nato objavili v knjigah. Nekatere med temi knjigami so bile zelo brane in pogosto ponatisnjene. Žal je takšen način dopisovanja z razvojem sodobne tehnologije zamrl, in vprašanje je, koliko današnjega intenzivnega elektronskega dopisovanja se bo ohranilo zanamcem.

Če so v splošni zgodovini, še zlasti pa v literarni zgodovini, pisma pomemben vir za preučevanje, v zgodovini naravoslovnih znanosti ni tako. Pred zgodovino naravoslovja je na tem področju še veliko dela. Sistematično zbranih pisemskih zbirk v svetovni literaturi skorajda ni. Izjema so le najpomembnejši znanstveniki, kot sta Albert Einstein in Isaac Newton, toda tudi v njunem primeru zbirke pisem še vedno niso objavljene v celoti. Nekoliko bolje so se pri tem odrezali znanstveniki, ki so v preteklosti delovali na področju današnje Rusije, a so te zbirke pisem za nerusko govoreče in pišoče raziskovalce skorajda nedostopne. Obstoj zbirk ruskih naravoslovnih korespondenc je tudi vzrok za odkritje pisem, ki jih predstavljamo v članku.

Vasilij Vasilijevič Nikitin je bil rudarski inženir, v svojem času mednarodno znan in uveljavljen mineralog in petrolog, strokovnjak za mineralogijo rud, ki je po Oktobrski revoluciji zapustil Sovjetsko zvezo in se je proti koncu svoje kariere zatekel na Tehnično fakulteto novoustanovljene Univerze v Ljubljani, kjer je vse do svoje smrti skrbel za izobrazbo prihodnjih inženirjev geologije in rudarstva (sl. 1). Znano je, da je že v času svojega dela na Rudarskem inštitutu v Peterburgu imel številne stike z raziskovalci po celem svetu, te stike pa je vzdrževal tudi po svojem prihodu v Ljubljano. Žal je ta korespondenca izgubljena, bolj ali manj po naključju se je ohranil le del njegovega dopisovanja z Vladimirjem Ivanovičem Vernadskim, ruskim geologom, geokemikom in filozofom svetovnega slovesa, katerega najznamenitejše delo je knjiga Biosfera. Ruska zgodovina znanosti Vernadskega postavlja ob bok Einsteinu in drugim najpomembnejšim znanstvenikom 20. stoletja. Že iz tega razloga je korespondenca med obema znanstvenikom pomembna, toliko bolj zato, ker moramo Nikitina obravnavati kot enega od začetnikov sodobne geološke znanosti v Sloveniji.

V članku je predstavljen transkript in slovenski prevod šestih Nikitinovih pisem Vernadskemu. Pisma so komentirana in interpretirana. Objavljena so le Nikitinova pisma, odgovorov Vernadskega na Nikitinova pisma ne poznamo. Nikitinov arhiv je verjetno v celoti izgubljen, saj je umrl leta 1942, sredi vojne vihre. Iz ohranjenega pisemskega gradiva lahko sklepamo le, da je bila korespondenca med obema znanstvenikoma obojesmerna.

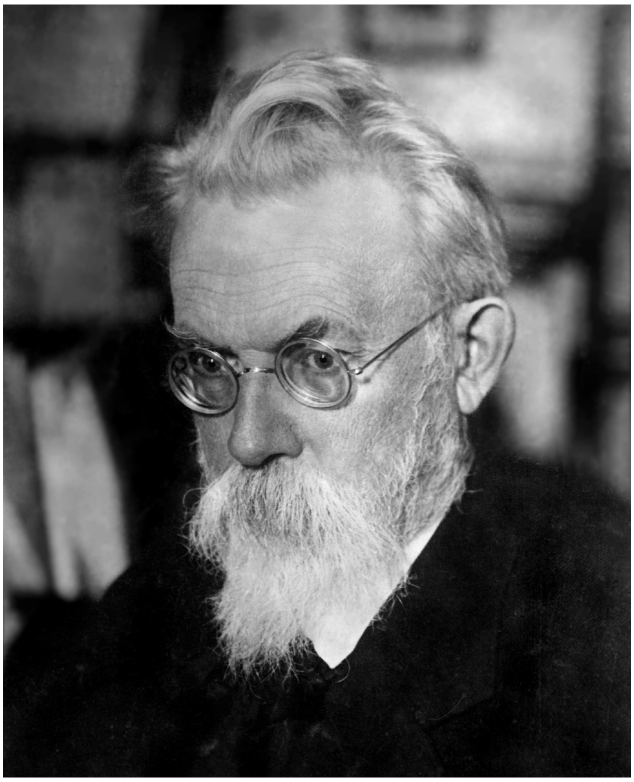
Sl. 1. Vasilij Vasilijevič Nikitin (1867-1942) – Zgodovinski arhiv Univerze v Ljubljani.

Življenjepisa

Preden se podrobneje lotimo prevodov pisem in komentarjev, si na kratko oglejmo življenjepisa in znanstvene dosežke obeh korespondentov.

Vasilij Vasilijevič Nikitin se je rodil 18. marca 1867 v Sankt Peterburgu, v tedanjem Ruskem imperiju. Leta 1886 je maturiral na klasični gimnaziji in se vpisal na fizikalno-matematični oddelek Petrograjske univerze, vendar je po sedmih mesecih študija prestopil na Rudarski inštitut, ki je imel status visoke rudarske šole. Kot rudarski inženir je leta 1895 diplomiral, vendar kasneje stopnje akademskega doktorata ni nikoli dosegel. Raziskovalno delo je začel že kot študent, kmalu pa se je zaposlil na svojem matičnem inštitutu. Sodeloval je pri intenzivnih geoloških raziskavah v Sibiriji, na Uralu ter v okolici Moskve. Leta 1917 je postal tudi direktor Rudarskega inštituta, vendar je že leta 1919 zaradi težkih delovnih razmer odstopil. Izselil se je na Poljsko, vendar se je leta 1920 vrnil v Peterburg in nato do leta 1922 poučeval na Rudarskem inštitutu. Leta 1923 je zaprosil za dovoljenje za izselitev in ga tudi dobil, skupaj z ženo sta se preselila na njeno poljsko posestvo. Od tod je leta 1925 na povabilo prof. Karla Hinterlechnerja odšel v Ljubljano, kjer je začel poučevati predmete s področja mineralnih surovin na Univerzi v Ljubljani. Na njej je poučeval vse do svoje smrti leta 1942 (Duhovnik, 1953). Nikitin je bil plodovit avtor, napisal je večje število strokovnih in znanstvenih člankov, obsežen nabor študijskega gradiva ter tudi knjig, ki so izšle pri takrat pomembnih znanstvenih založbah, prevedene pa so bile v več jezikov. Bil je velik strokovnjak za metodo Fedorova, to je posebnega nastavka petrografskega mikroskopa, s katerim so se določale značilnosti kristalov. Nastavek je bil sestavljen iz vrtljivih mizic, ki so bile vgnezdene druga v drugo, na njih pa so bile vgravirane številke z oznakami kotov. To je omogočalo odčitavanje optičnih značilnosti kristalov pod različnimi koti. Njegovo znanje na tem področju je bilo tako pomembno, da so se k njemu v Ljubljano prihajali šolat številni evropski mineralogi in kristalografi.

Vladimir Ivanovič Vernadski (sl .2) se je rodil 12. marca 1863 v Sankt Peterburgu profesorju politične ekonomije, ki je bil po poreklu iz Ukrajine. Osnovno znanje je pridobil v rodnem mestu, prav tako pa je tam leta 1885 diplomiral na Državni peterburški univerzi. Kmalu po diplomi je, iščoč snov za doktorat, odpotoval v Italijo, Francijo in Nemčijo. Usmeril se je predvsem v mineralogijo, kristalografijo in uporabo teh ved v pedologiji. Leta 1889 je doktoriral in počasi začel širiti področje svojega znanstvenega delovanja. Dokaj kmalu se je angažiral tudi na političnem področju in bil leta 1905 tudi član prve demokratične državne Dume. V času Oktobrske revolucije je odšel na Krim ter nato v tujino, vendar se je nato vrnil v domovino. V obdobju let 1922 do 1926 je kot gostujoči profesor predaval na Sorboni v Franciji. Ves čas svojega izredno plodovitega in delovnega življenja, vse do smrti



Sl. 2. Vladimir Ivanovič Vernadski (1863-1945) – Arhiv Ruske akademije znanosti.

6. januarja 1945 v Moskvi, je bil izredno ustvarjalen. S svojim delom je posegel na številna področja znanosti. Ukvarjal se je tako z osnovnimi geološkimi vedami, kot so mineralogija, geokemija, radiogeologija, pedologija in rudna geologija, kot tudi s filozofijo, politično mislijo in zgodovino znanosti. Bil je izjemen organizator znanosti, ustanovil je številne muzejske zbirke in raziskovalne inštitute, nekateri med njimi delujejo še danes, zaslužen je bil tudi za organizacijo številnih znanstvenih odprav po obsežnih prostranstvih Sovjetske zveze. Njegovo najznamenitejše delo je knjiga Biosfera, ki je prevedena v številne svetovne jezike. Knjiga obravnava biosfero kot dejavnik preoblikovanja Zemlje in človeka kot geološki dejavnik. To njegovo delo je dobro znano tudi na zahodu, medtem, ko so nekatera druga njegova dela, zaradi tega, ker so dostopna le v ruščini ali pa v zelo okrnjenih prevodih, manj znana. Njegova zbrana dela obsegajo štiriindvajset knjig in ločene zbirke pisem.

Prevod pisem

Vir pisem

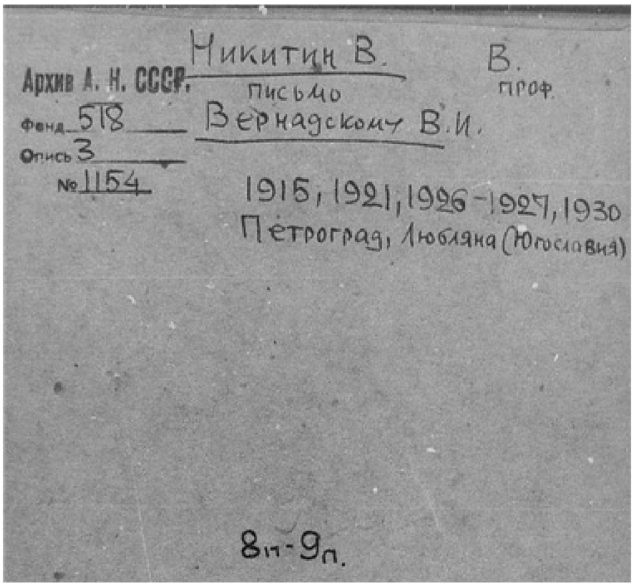
Originali pisem so v Arhivu Ruske akademije znanosti (Arhiv RAZ) v Moskvi. Dopisnico, ki jo je Nikitin napisal Vernadskemu leta 1915, je konec leta 2016 avtor članka po naključju našel na internetni strani Arhiva RAZ. Žal internetna stran, na kateri je bilo najdeno pismo, v času priprave članka ni več aktivna. Na tej strani je bil predstavljen zelo obsežen arhiv korespondence Vernadskega s številnimi sodobniki, nekatera od pisem so bila na voljo tudi v faksimilni obliki. V kazalu arhiva pisem je bil kot dopisnik Vernadskega naveden tudi Vasilij Vasilijevič Nikitin. Poleg omenjenega faksimila je bil pripet še kataložni listek (sl. 3), iz katerega je bilo razvidno, da je v arhivu ohranjena tudi druga Nikitinova korespondenca. Na listku so nanizana leta, v katerih je bila poslana ohranjena korespondenca (leta 1915, 1921, 1926, 1927 in 1930) in kraj, od koder je bila poslana (Petrograd in Ljubljana). To je nakazovalo, da sta imela dopisovalca pismeni stik tudi po tem, ko je Nikitin že prevzel mesto univerzitetnega profesorja na Univerzi v Ljubljani. To odkritje je bilo spodbuda za nadaljnje iskanje kopij pisem.

Avtor članka je v letih 2016 in 2017 večkrat skušal navezati stik z Arhivom RAZ, vendar neuspešno. Šele pomoč avtorjevih znancev v Moskvi je pripeljala do tega, da so mu bili decembra 2017 po elektronski pošti posredovani faksimili ostalih ohranjenih pisem. Vendar pri tem težav s korespondenco še ni bilo konec. Izkazalo se je, da je Nikitinov rokopis izredno težko čitljiv. Za prepis pisem je bilo treba najti nekoga, ki je vešč branja težko čitljivih ruskih rokopisov. Rokopisu pisem niso bili kos niti avtorjevi znanci, ki so naravni govorci sodobne ruščine. Prepis pisem je v maju 2018 opravila Tatiana M. Dianova sodelavka Geografske fakultete Moskovske državne univerze - MGU. Kljub temu so nekatere besede ostale neprebrane. Na teh mestih je bila glede na kontekst besedila podana najverjetnejša beseda ali pa je bila ta rekonstruirana s pomočjo drugih virov. V okviru prepisa ruskega besedila pisem ni bil opravljen prepis neruskih delov pisem. Ta del besedila je rekonstruiral avtor članka sam s pomočjo bibliografije del Vernadskega, ki so jo pripravili Bebih in sodelavci (1992).

Pri pripravi članka so bile na voljo le kopije pisem (skeni v elektronski obliki), zaradi tega njihovega pravega formata in velikosti ne poznamo. Na obliko in format pisma lahko sklepamo le iz posnetka pisma. Vsaka stran pisma je bila posredovana v svoji slikovni datoteki. Pri nekaterih pismih ni bilo jasno, kateremu pismu pripada določen naslov, zato je bilo treba opraviti tudi usklajevanje naslova in besedila. Kot ilustracijo podajamo le posamezne kopije pisem.

Izhodišča

Pisma Nikitina Vernadskemu so v Arhivu RAZ v fondu št. 518, inventar št. 3, pod tekočo številko 1154. Skupaj je bilo iz arhiva posredovano 18 posnetkov (skenov) ki sestavljajo 8 enot korespondence. Prva enota korespondence je dopisnica datirana z datumom 2. XII. 1915 in zadnja enota je dopisnica datirana z datumom 29. XI. 1930. Skrbna analiza in primerjava besedil z življenjepisom Nikitina ter medsebojna primerjava rokopisov so pokazali, da sta v arhivu 2 enoti korespondence, ki ne pripadata Vasiliju Vasilijeviču Nikitinu, mineralogu in petrologu, ki je deloval v Ljubljani. Pripadata V. Nikitinu, ki je deloval na raziskovalni postaji Akademije v Sevastopolu na krimski obali Črnega morja. O tem avtorju nam ni znanega ničesar. Čeprav je bil prepis teh pisem narejen, njihovega prevoda ne podajamo. Ta pisma so povzeta na kratko, predvsem z namenom dokazovanja, da v primeru obeh Nikitinov ne gre za isto osebo.


Архив А. Н. СССР Никитин В. В. проф.
Письмо
Фонд 518 Вернадскому В. И.
Опись 3
№ 1154
1915, 1921, 1926-1927, 1930
Петроград, Любляна (Югославия)
8л-9п.

Sl. 3. Faksimile kataložnega listka korespondence med Nikitinom in Vernadskim (arhiv RAZ).

V nadaljevanju podajamo prevode posameznih enot korespondence. Za vsako enoto so povzete osnovne informacije o naslovniku in obliki dopisa. Sledi prevod enote in nato komentarji ter opombe. Pisma so nanizana v kronološkem zaporedju.

Prevodi pisem

Pismo 1

Vrsta dopisa: dopisnica. *Odposlano*: iz Petrograda. *Naslov*: Tukaj. Carska akademija znanosti. Geološki muzej; njegovemu prvopredpostavljenemu Vladimirju Ivanoviču Vernadskemu. *Datum*: 2. XII. 1915.

Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Z obžalovanjem vam sporočam, da zaradi pomanjkanja časa ne bom sodeloval na današnjem zasedanju komisije. Nadvse se vam zahvaljujem za vaš čas, ki ste ga potratili s pisanjem vabila.

S spoštovanjem

VNikitin

Opombe

Vernadski je bil leta 1913 izbran za direktorja Geološkega in mineraloškega muzeja Akademije znanosti in umetnosti. V času, ko je bila napisana dopisnica, je v vlogi direktorja vodil številne znanstvene in strokovne komisije, zato ni možno ugotoviti, za katero komisijo je Nikitin dobil vabilo.

Pismo 2

Vrsta dopisa: pismo na pisemskem papirju. *Odposlano*: neznano. *Naslov*: Vladimirju Ivanoviču Vernadskemu od Nikitina *Datum*: 16. XI. 1921.

Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Upoštevajoč vašo naklonjenost, se na Vas obračam z veliko prošnjo, da bi me oskrbeli z drugim delom vaših »Vaj iz splošne mineralogije«.

Vse najboljše

s spoštovanjem VNikitin

Opombe

Gre za delo »Опыт описательной минералогии. Т. 2. Сернистые и селенистые соединения« (Vaje iz splošne mineralogije, drugi del, žveplovi in selenovi minerali), ki je izšlo leta 1918. V času nastanka tega pisma sta se oba korespondenta že vrnila v Peterburg. Nikitin iz Poljske, kamor se je zatekel leta 1919 (Duhovnik, 1953) in Vernadski s Krima, kjer je v letih 1920 – 1921 opravljal funkcijo rektorja Tavrijske univerze v Simferopolu (Bebih et al., 1992).

Pismo 3

Vrsta dopisa: dopisnica. *Odposlano*: iz Ljubljane. *Naslov*: Akademiku Vladimirju Ivanoviču Vernadskemu, Geološki muzej Akademije znanosti, Leningrad. Rusija. *Pošiljatelj*: V.V. Nikitin, Mineraloški inštitut Univerza v Ljubljani, Jugoslavija. *Datum*: 17. VIII. 1926. *Prejeto*: 24. VIII. 1926.

Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Po daljši prekinitvi sem se v vlogi kontraktualnega rednega profesorja mineralogije in petrologije na Tehnični fakulteti Ljubljanske Univerze ponovno vrnil k prejšnjim dejavnostim. V Mineraloškem inštitutu, katerega direktor je prof. Hinterlechner, imam na razpolago dovolj opreme, ki mi omogoča dokaj dobro nadaljevanje mojega dela. Če vzamemo v obzir mladost univerze, v knjižnici ni veliko periodičnih in avtorskih publikacij. Zelo pogrešam rusko literaturo. Bil bi zelo hvaležen, če bi si lahko ustvaril vtis o vašem delu. S sprejemom na univerzi in v sami Ljubljani v celoti sem zelo zadovoljen. Vse najboljše. S spoštovanjem. VNikitin.

Opombe

Zaradi nejasnih poštnih žigov je pri dataciji tega dopisa nekaj težav. Glede na vsebino je bilo poslano pred naslednjim pismom (pismo 4). Nikitin se je leta 1926 zaposlil na Tehnični fakulteti Univerze v Ljubljani. Ker je imel pogodbo o zaposlitvi le za določen čas, je nosil naziv pogodbenega ali kontraktualnega profesorja s plačo in položajem rednega profesorja. V Ljubljano je prišel na povabilo profesorja Hinterlechnerja, ki je bil v tem času rektor Univerze v Ljubljani.

Pismo 4

Vrsta dopisa: dopisnica. *Odposlano*: iz Ljubljane. *Naslov*: Akademiku Vladimirju Ivanoviču Vernadskemu, Geološki muzej Akademije znanosti, Leningrad. Rusija. *Pošiljatelj*: V.V. Nikitin, Mineraloški inštitut Univerza v Ljubljani, Jugoslavija. *Datum*: 10. X. 1926. *Prejeto*: 16. X. 1926.

Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Najlepše se zahvaljujem za pošiljko vaših del. Dobil sem:

- O vodikovih mineralih.
- O psevdomorfozi curita.
- O analizi tal z vidika geokemije.
- O kemijski sestavi živih bitij v odvisnosti od kemizma zemeljske skorje.

- Vpliv toplote na kaolinit in kaolinitne gline.
- Zapisi o preučevanju živih organizmov z vidika geokemije.
- Mendeljevit, nov radioaktiven mineral.
- O razmnoževanju organizmov in njegovem pomenu v mehanizmih biosfere.
- Biogeokemijske razprave. O hitrosti spreminjanja življenja v biosferi.

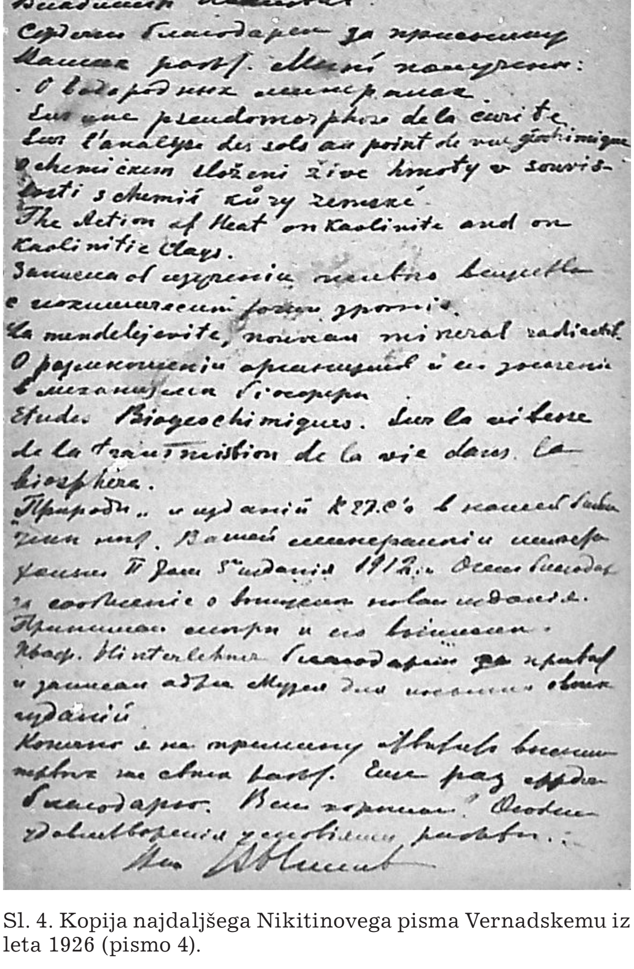
Prirod in izdaj v vrstici 27 v naši knjižnici ni. Vaša mineralogija - dopolnjeni drugi del tretje izdaje iz leta 1912. Zahvaljujem se vam za obvestilo o izidu nove izdaje. Uporabljam dopolnitve te izdaje. Prof. Hinterlechner se zahvaljuje za pošiljko in na naslov Muzeja pošilja svoja dela.

Seveda v zameno ne bom uspel poslati svojih prvih del. Še enkrat se vam zahvaljujem. Ali ste dobro? Še posebno, ugodni pogoji za delo ...

Vaš VNikitin

Opombe

Pismo predstavlja odgovor na obsežnejšo pošiljko prispevkov Vernadskega, ki jih je ta poslal Nikitinu na podlagi prošnje, posredovane z dopisnico dne 17. VIII. 1926. Novo nastalo Univerzo v Ljubljani je pestilo veliko pomanjkanje znanstvene in strokovne literature. Pri tem profesorja Nikitin in Hinterlechner, ki sta delovala na Tehniški fakulteti, nista bila nobeni izjemi. Profesorji so si pri nabavi prepotrebnega gradiva pomagali na različne načine, ne nazadnje tudi tako, da so prosili za kopije različnih del in separate člankov. To je bil nekoč ustaljen način izmenjave znanstvene literature. Tako je Nikitin, kmalu po prihodu v Ljubljano, izkoristil svoje znanstvo z Vernadskim, da bi mu ta posredoval čim večje število svojih del. V pismu se mu zahvaljuje za posredovano literaturo in pri tem našteva, katera dela je prejel.


10 X 1926 4

Sur une pseudomorphose de la curite

Sur l'analyse des sols au point de vue géochimique

O chemickém složeni žive hmoty v souvislosti s chemií kůry zemské

The Action of Heat on Kaolinite and on Kaolinitic Clays.

La mendeléjévite, nouveau minéral radioactif

Etudes Biogeochimiques. Sur la vitesse de la transmission de la vie dans la biosphère.

Sl. 4. Kopija najdaljšega Nikitinovega pisma Vernadskemu iz leta 1926 (pismo 4).

Oglejmo si, kdaj in kje so v pismu naštete dela Vernadskega izšla. Dela so navedena v zaporedju, kakor so naštete v pismu. Delo »O vodikovih mineralih« je izšlo kot kratek članek v ruščini pod naslovom »О водородных минералах« v reviji Доклады. РАН (Prispevki Ruske akademije znanosti - april/junij 1924; 74-76). Delo »O psevdomorfozi curita« je izšlo v Parizu v francoščini pod naslovom »Sur une pseudomorphose de la curite« v publikaciji Comptes rendus de l'Académie des Sciences (vol. 178; 1726-1728). Tudi naslednje delo »O analizi tal z vidika geokemije« je članek, ki je izšel v francoščini z naslovom »Sur l'analyse des sols au point de vue géochimique«. Delo je izšlo v zborniku 4. mednarodnega pedološkega kongresa v Rimu (Acte de la IV Conférence internationale de pédologie), ki je potekal v maju 1924, zbornik pa je izšel šele leta 1926 (vol 2., 570-577). Članek »O kemijski sestavi živih bitij v odvisnosti od kemizma zemeljske skorje« je izšel leta 1925 v Pragi v češčini z naslovom »O chemičkém složeni žive hmoty v souvislosti s chemii kůry zemské« Sbornik příroda - Česká Akademie Věd a Uměni (zv. 1-16). Članek »Vpliv toplote na kaolinit in kaolinitne gline« je prispevek, ki je bil objavljen v angleščini leta 1925 pod naslovom »The Action of Heat on Kaolinite and on Kaolinite Clays« v publikaciji Transactions of Ceramical Society (vol. 24, 13-22). Članek »Zapisi o preučevanju živih organizmov z vidika geokemije« je izšel leta 1921 v ruščini (Записка об изучении живого вещества с геохимической точки зрения) v publikaciji Известия РАН (Izvestija Ruske akademije znanosti – serija 6, vol. 15, 43-44). Članek »Mendelejevit, nov radioaktivni mineral« je izšel v francoščini (Le mendéléjévite, nouveau minéral radioactif) leta 1923 v reviji Comptes rendus de l'Académie des Sciences (vol. 176; 993-994). Članek »O razmnoževanju organizmov in njegovem pomenu v mehanizmih biosfere« je izšel v ruščini

(О размножении организмов и его значении в механизме биосферы) leta 1926 v reviji Известия АН СССР (Izvestija Akademije znanosti SSSR – serija 6, vol. 20, zv. 9, 697–726 in vol. 20, zv. 12, 1053–1060). Delo »Biogeokemijske razprave. O hitrosti spreminjanja življenja v biosferi« je izšlo v francoščini (Études biogéochimiques. 1. Sur la vitesse de la transmission de la vie dans la biosphère) leta 1926 v reviji Известия АН СССР (Izvestija Akademije znanosti SSSR – serija 6, vol. 20, zv. 9, 727–744). Večina teh del je bila v knjižnici Oddelka za geologijo tudi katalogizirana, žal so bila v času obnove knjižničnih prostorov leta 2017 vsa izločena in odpisana ter uničena. Zaradi tega ni mogoče ugotoviti, ali so bila na separatih zapisana kakšna posvetila ali celo kakšna daljša pojasnila.

Iz Nikitinovega pisma izhaja, da mu je Vernadski poleg separatov del posredoval tudi pismo, v katerem našteva, kaj pošilja. Na to lahko sklepamo iz omembe vrstice 27, v kateri Nikitin omenja revijo Priroda. Vernadski mu je verjetno odpisal, da si lahko nekatere njegove članke prebere tudi v reviji Priroda. Vendar Nikitin odgovarja, da v knjižnici Prirode ni. Za katere članke Vernadskega pri tem gre, ni mogoče natančno ugotoviti. Verjetno gre vsaj za članek »Potek življenja v biosferi« z ruskim naslovom »Ход жизни в биосфере«, ki je izšel leta 1925 (Природа – Priroda vol. 10, zv. 12; 25–38).

V Nikitinovem pismu je omenjen tudi učbenik mineralogije. Tretja dopolnjena in predelana izdaja tega učbenika je izšla že leta 1912 (Минералогия; izdala založba Печатня Яковлева). Ali sta imela dopisovalca v mislih kakšen kasnejši natis, saj je med izdajo učbenika in njunim dopisovanjem poteklo že štirinajst let, na podlagi razpoložljivih podatkov ni mogoče ugotoviti.

Pismo 5

Vrsta dopisa: dopisnica. *Odposlano*: iz Ljubljane. *Naslov*: Akademiku Vladimirju Ivanoviču Vernadskemu, Mineraloški muzej Akademije znanosti, Leningrad. Rusija. *Pošiljatelj*: V. Nikitin, Mineraloški inštitut Univerza, Jugoslavija. *Datum*: 9. V. 1927. *Prejeto*:. 17. V. 1927 (najverjetnejša datacija)

Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Iskreno se vam zahvaljujem za pošiljko vaših zanimivih del: O razpršitvi kemijskih elementov, Mnenje o sodobnem pomenu zgodovinskega življenja in živi snovi ter O razmnoževanju organizmov in njegovem pomenu v mehanizmih biosfere. Vse najboljše. VNikitin

Opombe

Tudi v tem primeru gre za dopisnico, v kateri se Nikitin zahvaljuje za prejeto pošiljko. Ali je, pred tem poslal Nikitin prošnjo za omenjena dela nam ni znano. Vsa tri posredovana dela so izšla v ruščini. Delo »O razpršitvi kemijskih elementov« (О рассеянии химических элементов) je izšlo leta 1927 kot priloga k Poročilu o dejavnosti Akademije znanosti – Splošno poročilo za leto 1926 (Отчет о деятельности Академии наук за 1926: Общий отчет; 1–15). Delo »O razmnoževanju organizmov in njegovem pomenu v mehanizmih biosfere« je Nikitin prejel že leta 1926, saj je njegov prejem Vernadskemu potrdil že z dopisnico z dne 10. X. 1926 (glej pismo 4). Poleg tega je zanimivo, da dela »Mnenje o sodobnem pomenu zgodovinskega življenja in živi snovi« (Мнение о современном значении исторической жизни и живое вещество) v nobeni od razpoložljivih bibliografij Vernadskega ni mogoče najti, prav tako ni bilo zavedeno v kataložnih listkih knjižnice Oddelka za geologijo. Verjetno je Nikitin napačno napisal naslov.

Pismo 6

Vrsta dopisa: dopisnica. *Odposlano*: iz Ljubljane. *Naslov*: Akademik V.I. Vernadski, Biogeokemijski laboratorij Akademije znanosti, Leningrad. Rusija (USSR). *Pošiljatelj*: V. Nikitin, Mineraloški inštitut Univerza, Ljubljana, Jugoslavija. *Datum*: 29. IX. 1930. *Prejeto*: neznano.

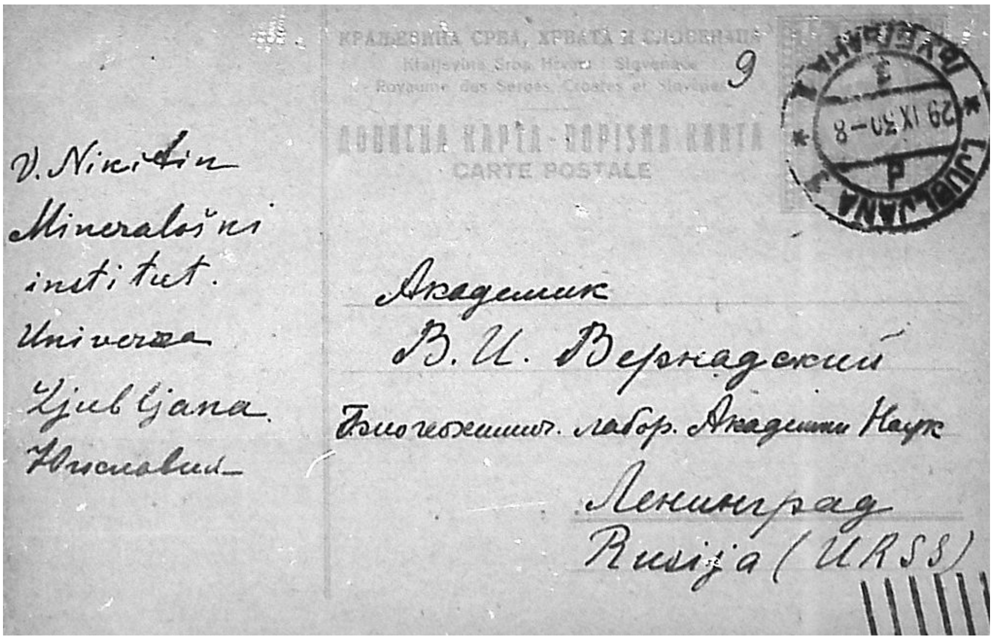
Prevod besedila

Nadvse spoštovani Vladimir Ivanovič

Z iskrenim zadovoljstvom vam sporočam, da sem prejel pošiljko prve izdaje Prispevkov biogeokemičnega laboratorija in Vašega članka »Vsebnost radija v naravnih vodah«. Vse najboljše! VNikitin

Opombe

Ali je Vernadski Nikitinu posredoval nekatere zvezke publikacije Prispevki biogeokemičnega laboratorija (Труды Биогеохимической лаборатории) ali pa le posamezni separat članka, ni mogoče ugotoviti. Glede na način pošiljanja separatov s strani Vernadskega v letih pred tem lahko domnevamo, da je bil posredovan le en članek. Vernadski je leta 1928 laboratorij ustanovil in ga vodil vse do svoje smrti leta 1945. Morda



Sl. 5. Kopija naslovnice dopisnice, poslane iz Ljubljane 29. IX. 1930 (pismo 6).

je Nikitin zapisal, da je prejel publikacijo zaradi tega, ker je dobil celoten izvod, saj je ta začela izhajati prav v letu 1930. Vernadski je v tem letu v tej publikaciji objavil članek »Splošni premisleki o študiju kemijske sestave žive materije«, ki je izšel v francoskem jeziku (Considérations générales sur l'etude de la composition chimique de la matière vivante - Труды Биогеохимической лаборатории; vol.1, 5-32). Drugi članek, ki ga navaja Nikitin, je prav tako izšel v francoščini in sicer v Parizu v reviji Comptes rendus de l'Académie des Sciences (vol. 190; 1172-1175).

Pisma, pripisana Vasiliju Vasilijeviču Nikitinu

Poleg zgoraj prevedenih in komentiranih pisem sta v Arhivu RAZ še dve pismi, ki sta pripisani Vasiliju Vasilijeviču Nikitinu in sta podpisani s podpisom VNikitin. Prvo pismo je bilo odposlano dne 18. II. 1921 in drugo 25. VI. 1926. Obe sta napisani na listih, iztrganih iz šolskega zvezka s črtami. Od kod so bila pisma odposlana, ni navedeno, iz vsebine pa lahko sklepamo, da je bil pisec v Sevastopolu na Krimu, kjer je vodil in upravljal raziskovalno postajo za raziskave Črnega morja pod okriljem RAZ. V pismih pisec Vernadskemu sporoča o težavah, s katerimi se mora soočati pri upravljanju postaje in raziskavah, ki so jih izvajali. Iz biografije Vasilija Vasilijeviča Nikitina (Duhovnik, 1953) in njegovega življenjepisa izhaja, da se z raziskavami morskih sedimentov ni ukvarjal, poleg tega je bil v letih 1921 in 1926 na Poljskem, v Petrogradu in nato v Ljubljani. S tega razloga pisem ni mogel napisati on. Ti dve pismi sta v fond pisem Vasilija Vasilijeviča Nikitina verjetno uvrščeni zaradi izredno podobnega rokopisa obeh piscev pisem, ki sta se za nameček še oba podpisovala z zelo podobnim podpisom VNikitin. Avtor članka je skušal identiteto tega drugega pisca pisem preveriti, vendar je priimek Nikitin izredno pogost ruski priimek in ugotavljanje, kdo je avtor drugih dveh pisem s podpisom VNikitin, bi terjalo izredno veliko časa. Glede na vsebino pisem pa je očitno, da ne gre za istega avtorja, zato smo to vprašanje pustili nerešeno.

Razprava

V arhivu Ruske akademije znanosti v Moskvi se je ohranilo šest enot korespondence, ki jih je Vasilij Vasilijevič Nikitin poslal Vladimirju Ivanoviču Vernadskemu. Dve, najstarejši enoti korespondence sta bili odposlani iz Peterburga, preostale štiri pa so bile poslane iz Ljubljane v Sankt Peterburg, tedanji Leningrad. Pisma, ki jih je pošiljal Vernadski Nikitinu, nam za sedaj ostajajo neznana. Velika verjetnost je, da tudi vsa Nikitinova pisma Vernadskemu niso ohranjena. Iz vsebine Nikitinovih dopisov nedvomno izhaja, da je bilo dopisovanje med obema znanstvenikoma obojesmerno in v obdobju po Nikitinovem prihodu v Ljubljano tudi nekoliko intenzivnejše.

Čeprav sta se dopisnika osebno poznala, saj iz dopisnice, poslane v letu 1915, izhaja, da sta v Peterburgu sodelovala v istih delovnih telesih, je njuna korespondenca zelo formalna. Večina besedila dopisov je posvečena seznamom znanstvene literature in potrditvi prejema pošiljk. Kljub temu iz pisem razberemo nekaj osebnih informacij. Nikitin v prvem pismu iz leta 1926 (pismo 3) poroča, da je prispel v Ljubljano in v kakšnih pogojih deluje, pritožuje se tudi nad pomanjkanjem literature in prosi Vernadskega za kopije njegovih znanstvenih del. V naslednjem pismu se, sicer skopo, sprašuje o pogojih, v katerih dela Vernadski. Iz zapisanega izhaja, da so ta vprašanja zapisana zelo previdno, skorajda, kot da bi spraševal med vrsticami. Tudi te besede dokazujejo, da sta se oba dopisnika poznala več kot zgolj formalno. Ali mu je na ta vprašanja Vernadski kaj odgovoril, nam ostaja neznano.

Vzrok za rezerviranost Nikitina izhaja iz dejstva, da se je zavedal, da mora biti kot politični emigrant pri dopisovanju s svojimi znanci v Rusiji zelo previden, ne glede na to, da je bil položaj Vernadskega v Rusiji privilegiran, saj je bil eden redkih državljanov SSSR, ki je lahko v tujino potoval prosto, se udeleževal številnih konferenc, predaval po univerzah in imel neomejene stike z drugimi znanstveniki po svetu. To je obdobje, ko je Stalin že prevzel oblast trdno v svoje roke in ko se že kažejo obrisi brutalnega totalitarnega režima pred drugo svetovno vojno.

Pregled del, ki jih je Vernadski pošiljal Nikitinu v Ljubljano, pokaže, da je izbor bolj ali manj naključen. Predstavlja izbor člankov, ki so značilni za delovanje Vernadskega v obdobju od leta 1920 do 1930. V tem času nastane njegovo znamenito delo Biosfera (ruska izdaja 1926), ki ga spremljajo tudi številni drugi članki s podobno tematiko. Ti članki v naboru del, posredovanem v Ljubljano močno prevladujejo. Poleg tega so bili v Ljubljano poslani tudi članki, ki so se tako ali drugače ukvarjali z radioaktivnimi minerali in naravno radioaktivnostjo. Na tem področju je bil Vernadski neverjeten vizionar, saj je že leta 1922 ustanovil Radijev inštitut, ki je imel nalogo raziskovati pojavljanje naravnih radioaktivnih mineralov. V času dopisovanja je bil Vernadski ustvarjalen tudi na področju zgodovine znanosti in filozofije znanosti. Nobenega od teh del Vernadski ni poslal v Ljubljano.

Nikitinov arhiv je skoraj v celoti izgubljen. Ohranjenih je le nekaj arhivskih drobcev v Zgodovinskem arhivu Univerze v Ljubljani. Vsa dosedanja preverjanja arhivskega gradiva o Nikitinu v Ruski federaciji niso obrodila nobenih sadov. Izjema je le predstavljena korespondenca. Nasprotje pa predstavlja ohranjeno arhivsko gradivo Vernadskega. Njegova zbrana dela obsegajo kar 24 knjig, veliko je tudi zbirk njegove korespondence, njen velik del pa ni niti obdelan. Velika verjetnost je, da se nam bo v tem gradivu v prihodnosti razkrila še kakšna zanimiva in pomembna informacija o sodelovanju med Nikitinom in Vernadskim.

Sklep

V članku smo predstavili prevod in komentar šestih dopisov, ki jih je profesor mineralogije in petrologije na Univerzi v Ljubljani Vasilij Vasilijevič Nikitin (1867-1945) poslal znamenitemu ruskemu geologu, geokemiku in filozofu Vladimirju Ivanoviču Vernadskemu (1863-1945). Do sedaj nam ta korespondenca ni bila znana. Iz korespondence je razvidno, da sta se oba znanstvenika osebno poznala, in da sta si izmenjevala svoja dela. Korespondenca je po številu enot in po vsebini skromna. Ne glede na to, da je imel Vernadski v Rusiji privilegiran položaj in da je v primerjavi z drugimi imel relativno veliko intelektualno svobodo, lahko to pripišemo dejstvu, da je bil Nikitin politični emigrant, ki je po svoji poroki spadal v razred nižjega ruskega plemstva in veleposestništva. Bil je tudi neproletarskega izvora, kar je bil še dodaten vzrok, da je zapustil Rusijo. Verjetno sta bila zaradi tega dopisovalca v svojih pismih zelo previdna.

Predstavljena korespondenca nam odkriva pomemben drobec iz delovanja in poučevanja geologije pred drugo svetovno vojno na Univerzi v Ljubljani. Čeprav je šlo za mlado in relativno majhno univerzo, nam stiki med Nikitinom in Vernadskim dokazujejo, da so se takratni učitelji trudili vzpostaviti stike s svetom in tedanjim razvojem geološke znanosti.

Zahvala

Velika zahvala gre prof. dr. Sergeyu A. Sokratovu s Fakultete za geografijo Moskovske državne univerze – MGU, ki je vztrajno podpiral avtorjevo dolgoletno zanimanje za delo Vladimirja Ivanoviča Vernadskega. Po naključnem odkritju obstoja Nikitinovih pisem je prof. Sokratov organiziral njihovo iskanje, kopiranje in prepis. Brez njegove pomoči članka ne bi bilo. Do pisem ne bi prišli brez angažirane pomoči Irine N. Sokratove z Oddelka za znanosti o Zemlji Predsedstva Ruske akademije znanosti, ki je poiskala ljudi z dostopom do arhiva Vernadskega. Prepis pisem je opravila sodelavka Oddelka za geokemijo pokrajine in geografijo tal Fakultete za geografijo Moskovske državne univerze – MGU Tatiana M. Dianova, brez njene pomoči prevodi in kritični pretres pisem ne bi bili mogoči. Za posredovanje pisem in dovoljenje za objavo prevodov se avtor zahvaljuje Arhivu Ruske akademije znanosti v Moskvi, Ruska federacija.

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Sistematičen pregled geoloških učnih ciljev in učbeniških vsebin v osnovnih šolah in v splošnih gimnazijah

Systematic overview of geological learning objectives and textbook contents for primary schools and gymnasiums

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Ključne besede: izobraževanje, geologija, kurikulum, učbeniki, osnove šole, gimnazije, matura
Key words: education, geology, curriculum, textbooks, primary school, gymnasiums, matura examination

Izvleček

Poučevanje geoloških vsebin v osnovni šoli in na splošnih gimnazijah do sedaj še ni bilo sistematično obravnavano. V okviru Skupine za popularizacijo geologije, ki deluje pod okriljem Slovenskega geološkega društva, smo si zastavili cilj, pridobiti vpogled v poučevanje geoloških vsebin v osnovnih šolah in na splošnih gimnazijah. Pri pregledu smo zajeli tudi splošno maturo, saj le-ta predstavlja zaključek srednješolskega izobraževanja. Da bi zagotovili pregled nad poučevanjem geoloških vsebin, smo najprej pregledali predmetne učne načrte ter izpitne kataloge za maturitetne predmete. Pregledali smo tudi veljavne učbenike in maturitetne izpitne pole pri predmetih, kjer se geološke vsebine pojavljajo. Dobljene geološke vsebine smo razvrstili v šest splošnih geoloških vsebinskih sklopov. Vse vsebine so bile vrednotene po Bloomovi taksonomiji, ki na podlagi strukturiranosti omogoča prepoznavanje taksonomske zahtevnosti učnih ciljev in preverjanj znanj. Vrednotili smo tudi medpredmetno povezanost. Ugotovili smo, da se geološke vsebine v osnovni šoli obravnavajo pri obveznih predmetih Družba, Naravoslovje in tehnika, Naravoslovje, Geografija in Biologija ter izbirnem predmetu Okoljska vzgoja, v splošnih gimnazijah pa pri predmetih Geografija in Biologija, kjer se znanje preverja tudi na maturi. Učni cilji in vsebine se večinoma smiselno nadgrajujejo, vendar pa besedila v učbenikih pogosto nezadostno in strokovno pomanjkljivo predstavijo posamezno tematiko. Kar nekaj za družbo pomembnih geoloških tematik je v formalnem izobraževanju izpuščenih. Pri posameznih medpredmetno povezanih sklopih smo podali priporočila za promotorje znanosti, kako prispevati k boljšemu in strokovno pravilnemu razumevanju vsebine sklopa. Predstavitev geologije v učbenikih je nezvezna, strokovno pomanjkljiva in vsebinsko zelo okrnjena. Pričujoča raziskava nam daje izhodišče za začetek umeščanja posodobljenih in združeno predstavljenih geoloških vsebin v formalno izobraževanje.

Abstract

Teaching of geological contents in elementary school and gymnasiums has not yet been systematically addressed. Under the auspices of Slovenian Geological Society, members of the Task Group for the Popularization of Geology, have set themselves the goal of gaining insight into the teaching of geological contents in elementary schools and gymnasiums. Review also covered general matura examination as it represents the completion of secondary education. In order to provide an overview of the teaching of geological contents, we first reviewed the subject curricula and the knowledge catalog for general matura subjects. We also reviewed valid textbooks and general matura exam questions. The extracted geological contents were classified into six general geological content assemblages. All extracted geological content was evaluated according to Bloom's taxonomy, which, on the basis of structure, enables the recognition of the taxonomic complexity of learning objectives and knowledge tests. We also evaluated cross-curricular relationships. We have discovered that geological contents are taught in elementary school in obligatory subjects such as Society, Natural sciences and engineering, Natural sciences, Geography, Biology and in optional subject Environmental education. In gymnasiums geological contents are taught in the subjects Geography and Biology, where knowledge is also checked at general matura. Learning objectives and contents are mostly appropriately upgraded, but the content presented in textbooks is often insufficient and professionally inadequate. There is also a lack of the important geological topics in the field of formal education. For individual cross-curricular sections, we have made recommendations for promoters of science to contribute to a better understanding and the correct and professional content presentation in public. The presentation of geology in the textbooks is discrete, often professionally flawed, and the content is very limited. This research provies a starting point for starting the placement of updated and appropriate geological contents into formal education.

Uvod

Poučevanje geoloških vsebin v formalnem izobraževanju je ključno, saj lahko le tako zagotovimo, da posameznik razume vlogo geologije pri soustvarjanju uspešne sodobne družbe. Čeprav so geološke teme zelo privlačne in prisotne v javnosti, le-te še zdaleč ne dosegajo prepoznavnosti drugih naravoslovnih tematik. Eden izmed razlogov za takšno situacijo je nejasna predstavitev geologije kot vede v osnovnih in srednjih šolah. Med letoma 1982 in 1990 je obstajal samostojen 4-letni srednješolski program za geološkega tehnika. Danes se geologija v šolah poučuje razdrobljeno, geološke vsebine se pojavljajo pri družboslovnih in naravoslovnih predmetih, največ pri predmetu Geografija.

Geološke vsebine se v slovenskem šolskem sistemu pojavijo že v vrtcih, kjer so navezane na geologijo posredno, skozi spoznavanje materialov in pokrajine. Prvi učni cilji, neposredno vezani na geološke tematike, so definirani na razredni stopnji osnovne šole, v 4. razredu pri predmetih Družba ter Naravoslovje in tehnika (Zvonar et al., 2017). Majcen (2003) je prvi podal pregled poučevanja geoloških vsebin. Omejil se je na osnovno šolo, kjer ugotavlja, da so vsebine med predmeti preveč razdrobljene in učencu ne omogočajo jasnega pregleda nad geološkimi tematikami, geologije kot vede pa ne predstavijo zadovoljivo. Da je poučevanje geoloških vsebin v formalnem izobraževanju na način, ki bi učencem omogočil povezovanje naravnih pojavov in življenja na Zemlji v razumljive in zaključene celote, izjemnega pomena za razumevanje procesov na Zemlji, njene zgodovine v navezavi na sedanjost, in zavedanja o pomembnosti mineralnih surovin v našem vsakdanjem življenju, opozarja tudi Novak (2013). Poleg tega je raba geoloških terminov v učni literaturi pogosto neusklajena in neprimerna (Popit, 2005). Raziskava nacionalnih učnih načrtov v naravoslovju, ki je bila opravljena v okviru projekta ESTEAM kaže, da je geološkim tematikam v osnovnošolskem izobraževanju skupno namenjenih le 30 ur (Catana & Vilas Boas, 2017). Pri tem se moramo seveda zavedati, da so tako ure kot vsebine porazdeljene med več predmetov. Ali je takšen način poučevanja primeren, pa bi lahko ocenili s študijo trajnosti znanja. Trajnost znanja je odvisna od veliko dejavnikov. Zelo je povezana s tem, ali je bilo učenje snovi aktivno navezano na predznanje, ali je posameznik učenje tematike dojemal kot smiselno, ali je bilo povezano s problemi iz prakse ter ali je bilo navezano na dosedanje izkušnje. Trajnost znanja se poveča tudi s smiselnim medpredmetnim povezovanjem (Marentič Požarnik, 2001a).

Glavni raziskovalni cilj Skupine za popularizacijo geologije, ki deluje pod okriljem Slovenskega geološkega društva, je bil sistematičen vpogled v poučevanje geoloških vsebin v osnovnih šolah in na splošnih gimnazijah. Pregledali smo učne načrte ter analizirali vsebine učbenikov za osnovne šole in splošne gimnazije. Učne načrte in vsebine smo vrednotili po Bloomovi taksonomiji (Kennedy, 2015), z namenom analize stopnje zahtevnosti. Ker matura predstavlja zaključek srednješolskega izobraževanja, smo pregledali, v kakšnem obsegu in na kakšni stopnji zahtevnosti se preverjajo geološke vsebine na splošni maturi.

Želeli smo ugotoviti pričakovano stopnjo predznanja po končanem srednješolskem izobraževanju. Zato smo z namenom pridobitve vpogleda v nadgrajevanje učnih ciljev in vsebin v učbenikih po posameznih tematskih sklopih pregledali, ali se vsebine smiselno nadgrajujejo in ali je medpredmetna povezanost poučevanja zadostna, da lahko učenec oz. dijak pridobi celostni pregled nad poučevano tematiko.

Metode dela

Učni načrt je šolski dokument, ki za posamezen predmet predpisuje obseg in stopnjo znanja ter zaporedje učne snovi. Njegova temeljna vloga je, da zagotavlja sistematično poučevanje ter ciljno usmerja učenje v vsebinsko povezane sklope. Znotraj učnih načrtov so učni cilji razdeljeni na splošna znanja in posebna znanja. Splošna znanja so opredeljena kot znanja potrebna za splošno izobrazbo, in so namenjena vsem učencem in dijakom, zato jih mora učitelj obvezno obravnavati. Posebna znanja opredeljujejo dodatna ali poglobljena znanja, ki jih učitelj obravnava glede na zmožnosti in interese dijakov (MIZŠ – učni načrti, 2018). Vloga učbenikov se skozi napredek v tehnikah poučevanja spreminja, a učbenik še vedno ostaja ena od prvih knjig, s katero se v formalnem izobraževanju sreča posameznik. Zato učbenik za učenca predstavlja osnovno sredstvo v procesu učenja, s pomočjo katerega na aktiven način pristopi k učenju snovi. Pregled učnih načrtov in učbenikov ima velik pomen, saj s tem lahko ugotovimo pričakovano stopnjo predznanja ter postopnost in smiselnost nadgrajevanja razdrobljenih geoloških vsebin.

Učni načrti in učbeniki

V okviru raziskave smo pregledali in analizirali 18 predmetnih učnih načrtov in 73 učbenikov za osnovne šole ter 14 učnih načrtov in 26 učbenikov za splošne gimnazije (Tabela 1). Vse v šolskem letu 2017/2018 veljavne učbenike za predmete, pri katerih smo ugotovili pojavljanje geoloških ciljev in vsebin (Trubar – učbeniški sklad, 2018), smo analizirali z namenom pridobitve vpogleda v obseg vsebin, definiranih z učnimi cilji, zapisanimi v predmetnih učnih načrtih (MIZŠ – učni načrti, 2018). Posamezne cilje smo vrednotili, jih povezali z vsebinami v učbenikih in preučili njihovo ujemanje. Preko tega smo vrednotili tudi medpredmetno povezanost.

Matura

Analizirali smo izpitna kataloga za predmeta Biologija in Geografija, pri katerih se na maturi preverja znanje geoloških tematik. Pregledanih je bilo tudi 60 maturitetnih pol med letoma 2008 in 2017, za katere veljata trenutna učna načrta za predmeta Geografija in Biologija. Vprašanja in pričakovane odgovore smo glede na strokovno ustreznost vrednotili z: I. – ustreza, II. – delno ustreza in III. – ne ustreza.

Geološke tematike

Vse izdvojene učne cilje v učnih načrtih, učne vsebine z geološkimi tematikami, cilje iz izpitnega kataloga za maturo ter maturitetna vprašanja in odgovore smo na podlagi strokovne presoje razvrstili v šest osnovnih geoloških tematik. S tem smo ustvarili smiselno povezan sklop ciljev in snovi, znotraj katerega smo nato iskali medpredmetno povezovanje in nadgradnjo ciljev. Razvrščene osnovne geološke tematike so:

- Osnove geologije, ki zajemajo vsebine, povezane z zgradbo Zemlje, oblikovanostjo površja, s procesi, ki se odvijajo na Zemlji, in vse vsebine regionalne geologije.
- Paleontologija, ki zajema vsebine povezane s fosili, izvorom življenja na Zemlji in evolucijo.
- Petrologija in mineralogija, ki zajemata vsebine o mineralih in kamninah ter njihovem prepoznavanju, vsebine o uporabi mineralnih surovin, posredno pa smo v to tematiko uvrstili tudi del pedoloških vsebin, ki se nanašajo na matično podlago in nastanek tal.
- Hidrogeologija, kamor smo razvrstili cilje povezane s podzemno vodo, njenim onesnaževanjem in izkoriščanjem, kot tudi splošne tematike povezane z vodonosniki in pitno vodo.
- Kras smo ločili zaradi njegove specifike in pomembnosti v slovenskem prostoru. V to temo so uvrščene vsebine povezane z nastankom površinskih in podpovršinskih kraških oblik ter z geološkim razvojem kraških pokrajin.
- Ekologija in varstvo okolja zajemata tematiki o vlogi geologije pri ohranjanju naravnih

Tabela 1. Število pregledanih učbenikov za posamezen predmet v osnovni šoli in v splošni gimnaziji.
Table 1. Number of textbooks examined for each subject in Primary school and at Gymnasium.

Predmet Subject	Št. učbenikov v osnovni šoli Num. of textbooks in primary school	Št. učbenikov v splošni gimnaziji Num. of texbooks in general Gymnasiums
Družba Society	20	/
Naravoslovje in tehnika Natural sciences and engineering	16	/
Naravoslovje Natural sciences	13	/
Geografija Geography	21	14
Biologija Biology	3	12

virov in vrednotenju posledic prekomernega izkoriščanja le-teh ter pri vplivih na okolje in vsebine povezane z varstvom geološke dediščine.

Vrednotenje

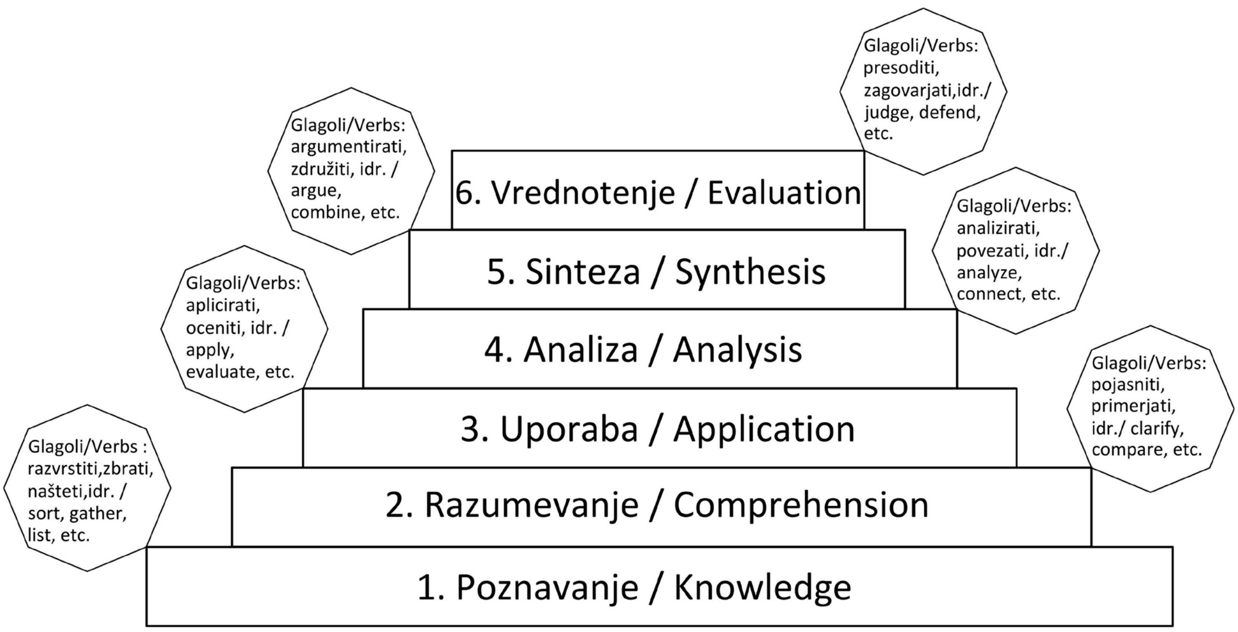
Vse izdvojene cilje in vsebine z geološko tematiko v učnih načrtih v osnovnih šolah in na splošnih gimnazijah ter maturitetni izpitni katalog in izpitna vprašanja na maturi z geološko tematiko, smo vrednotili po Bloomovi taksonomiji (Kennedy, 2015). Ta razvršča kompleksnost miselnih procesov v hierarhijo, od najnižje stopnje poznavanja, ki od posameznika zahteva le priklic posameznih dejstev, do najvišje stopnje vrednotenja, kjer se pričakuje, da je učenec sposoben presojanja o vrednosti ter pomembnosti določne tematike. Da bi učenec lahko dosegal višje taksonomske cilje, mora biti najprej vzpostavljeno osnovno predznanje na nižjih stopnjah. Bloomova taksonomija se uporablja za pisanje učnih ciljev in izidov, pripravo strukturiranih preverjanj znanja in pripravo evalvacijskih gradiv. Z vnaprej pripravljeno strukturo in seznamom glagolov nam omogoča, da cilje sistematsko zastavimo po taksonomskih stopnjah. Strukturiranost glagolov pri pisanju ciljev nam omogoča tudi njihovo prepoznavanje (sl. 1). Primerjali smo stopnje vrednotenja med učnimi cilji v učnih načrtih in maturitetnem izpitnem katalogu ter učnimi vsebinami v učbenikih in izpitnimi vprašanji na maturi, ter analizirali, ali učbeniške vsebine ustrezajo zahtevnosti učnih ciljev.

Rezultati in diskusija

Geološke vsebine in njihova zahtevnost po posameznih predmetih v osnovni šoli

Po pregledu učnih načrtov smo ugotovili, da se geološke vsebine v osnovni šoli poučujejo pri obveznih predmetih Družba, Naravoslovje in tehnika, Naravoslovje, Geografija in Biologija (Tabela 2). Skupaj je vseh geoloških ciljev v osnovni šoli 62, njihova povprečna zahtevnost pa je na taksonomski stopnji razumevanja. Največ geoloških ciljev in vsebin je pri predmetu Naravoslovje v 6. razredu (9) ter pri predmetu Geografija v 6. razredu (11). Zahtevnost ciljev je za vsako od tematik prikazana na sliki 2. Geološke vsebine se poučujejo tudi pri predmetu Okoljska vzgoja, a v statistični pregled in medpredmetno nadgrajevanje niso bile zajete, saj zaradi nedostopnosti podatkov o izvajanju ter številu vključenih učencev ne ustrezajo ciljem raziskave.

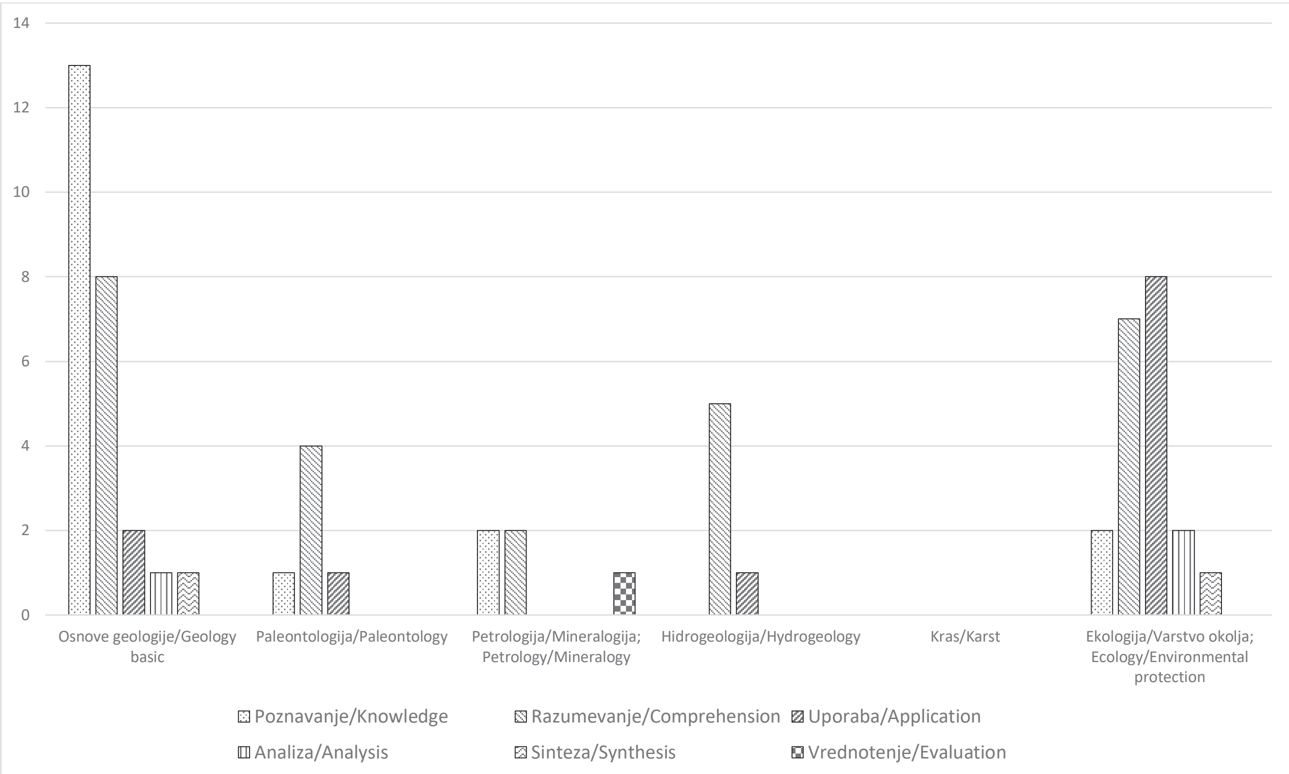
Pri predmetu Družba (Budnar et al., 2011), ki se izvaja v 4. in 5. razredu, so v okviru geoloških vsebin zastopane tematike osnov geologije ter ekologije in varstva okolja. Vseh geoloških ciljev je 7. Vsebine iz ekologije in varstva okolja vsebujejo višje taksonomske cilje na stopnji uporabe, medtem ko so cilji, vezani na vsebine osnov geologije, povprečno na stopnji poznavanja in razumevanja. Povprečna zahtevnost učnih ciljev je na taksonomski stopnji med poznavanjem in razumevanjem. Učenci pri predmetu Družba spoznajo naravne enote Slovenije, podrobneje pa spoznajo domačo pokrajino. Tukaj se od geoloških tem obravnavajo kamnine, relief, vode in tla. Srečajo



Sl. 1. Hierarhična ureditev kompleksnosti miselnih procesov po Bloomu (prirejeno po Kennedy, 2015).
Fig. 1. A hierarchical arrangement of the complexity of thought processes after Bloom (modified after Kennedy, 2015).

Tabela 2. Geološki učni cilji, razvrščeni po tematskih sklopih, pri posameznem predmetu v osnovni šoli.
Table 2. Geological learning objectives classified by topics, for individual subjects in Primary school.

Predmet/Tema Subject/Topic	Osnove geologije Geology Basics	Paleontologija Paleontology	Petrologija/ Mineralogija Petrology/ Mineralogy	Hidrogeologija Hydrogeology	Kras Karst	Ekologija/ Varstvo okolja Ecology / Environmental protection
Družba 4. in 5. r Society 4. and 5. cl.	6	0	0	0	0	1
Naravoslovje in tehnika 4. in 5. r Natural sciences and engineering 4. and 5. cl.	0	1	0	4	0	0
Naravoslovje 6. in 7. r Natural sciences 6. and 7. cl.	6	0	3	2	0	4
Geografija 6., 7., 8. in 9. r Geography 6., 7., 8., and 9. cl.	11	0	1	0	0	13
Biologija 8. in 9. r Biology 8. and 9. cl.	2	5	1	0	0	2



Sl. 2. Število geoloških učnih ciljev v osnovni šoli, razvrščenih po tematskih sklopih, predstavljenih po stopnji zahtevnosti.
Fig. 2. Number of geological learning objectives in Primary school, classified according to topics, presented by level of difficulty.

se z razlago procesov, ki vplivajo na oblikovanost površja. Posredno se omenijo tudi kraške oblike. Spoznajo območja rudarjenja v Sloveniji. Znotraj vsebin varovanja okolja se obravnavajo posledice rudarjenja, varovanje geoloških naravnih vrednot ter nujnost recikliranja za zmanjšanje vpliva na okolje. Geološke tematike so v okviru predmeta Družba predstavljene razdrobljeno in ne tvorijo celote, ki bi predstavila geologijo kot vedo.

Predmet Naravoslovje in tehnika se poučuje v 4. in 5. razredu osnovne šole (Vodopivec et al., 2011). Predmet obravnava vsebine paleontologije in hidrogeologije. Vseh geoloških učnih ciljev je 5. Zahtevnost učnih ciljev iz vsebin paleontologije je na taksonomski stopnji uporabe, učni cilji iz hidrogeologije pa na stopnji razumevanja. Povprečna zahtevnost vseh ciljev je na taksonomski stopnji razumevanja. Paleontološke vsebine zajemajo izvor življenja na Zemlji in primere živih bitij v preteklosti. Na kratko je razložen tudi postopek fosilizacije. Hidrogeologija zajema vsebine izvora vode na Zemlji, vodnega kroga in pretakanja vod. Razloženo je, koliko vode imamo na Zemlji ter kakšno. Predstavljene so lastnosti vode in od kje pride voda v tla, razloženo pa je tudi, kaj je vodonosnik. Opisana sta pojma prepustnost in gladina podzemne vode. Pojasnjeno je, kako vodo črpamo na površino ter kaj so vodnjaki. Opisano je še, kako se voda pretaka po površini ter pod njo. Predstavljen je problem onesnaženosti voda. Geološke tematike so pri tem predmetu bolj strnjene, geologija pa kljub temu ni predstavljena kot veda.

Pri predmetu Naravoslovje v 6. in 7. razredu (Skvarč et al., 2011) je obseg geoloških vsebin relativno širok. Obravnavane so vsebine osnov geologije, petrologije in mineralogije, hidrogeologije ter ekologije in varovanja okolja. Vseh učnih ciljev z geološko tematiko je 15. Največ ciljev je iz vsebin osnov geologije, ki so na taksonomski stopnji poznavanja, enako kot vsebine petrologije in mineralogije. Povprečna zahtevnost vseh ciljev je na taksonomskih stopnjah poznavanja in razumevanja. Učenci spoznajo sestavo Zemlje na osnovnem prerezu. Učijo se o mineralih kot gradnikih kamnin, razložena je Mohsova trdotna lestvica. Kamnine razčlenijo glede na nastanek, spoznajo njihove lastnosti ter možnosti uporabe. V okviru kamninskega kroga so razloženi procesi in nastanek kamnin. Preko kamnin je razložen tudi nastanek tal v povezavi z matično podlago. Hidrogeološke vsebine zajemajo razlikovanje virov voda v naravi. Predstavljena je kemijska sestava vode na primerih mehke in trde vode ter pretakanje voda v kraškem svetu. Vsebine zajemajo tudi onesnaževanje podzemne vode. Vsebine varovanja okolja zajemajo fosilna goriva ter njihov vpliv na okolje, pa tudi prekomerno izkoriščanje naravnih virov. Geološke vsebine so jasno predstavljene, pogosto pa se pri kompleksnejših razlagah v učbeniških tekstih pojavljajo strokovne netočnosti. Kljub večjemu obsegu geoloških vsebin geologija kot veda ni omenjena.

Predmet Geografija (Kolnik et al., 2011), ki se v osnovni šoli poučuje od 6. do 9. razreda, zajame največ geoloških vsebin. Te so v 8. razredu izvzete iz učnega načrta in se v učbenikih pojavljajo samo kot zanimivosti. Vsebine so zgoščene v tematskih sklopih osnove geologije ter ekologija in varovanje okolja, delno pa tudi petrologija in mineralogija. Vseh učnih ciljev, povezanih z geološkimi tematikami, je 25. Taksonomsko najzahtevnejše so vsebine ekologije in varstva okolja, ki so na stopnji uporabe. Druge obravnavane vsebine so na taksonomski stopnji razumevanja. Povprečna zahtevnost ciljev pri predmetu je med razumevanjem in uporabo. Učenci spoznavajo notranjo zgradbo Zemlje na osnovnem geološkem prerezu. Obravnavana je tematika potresov z razlago premikanja tektonskih plošč. Razložen je pojem epicenter. Na tektoniko plošč je navezan tudi nastanek vulkanov, ki pa je obravnavan zgolj na posameznih primerih. Obravnava se tudi paleogeografska in geotektonska razčlenitev Slovenije. Razložena sta osnovna razčlenitev kamnin in nastanek krasa. Kot posledica podnebnih sprememb je navedeno spreminjanje okolij, učenci se učijo pomena ohranjanja okolja za trajnostni razvoj družbe ter razumevanja vpliva človekovih posegov v naravo. Vsebine so med razredi zelo razdrobljene in ne predstavljajo zaključene celote, iz katere bi učenec lahko prepoznal geologijo kot vedo.

Predmet Biologija (Vilhar et al., 2011) se poučuje v 8. in 9. razredu. Zajema vsebine osnov geologije, paleontologije, petrologije in mineralogije ter ekologije in varstva okolja. Vseh učnih ciljev, povezanih z geološkimi vsebinami, je 10. Najvišje taksonomske stopnje dosegajo vsebine ekologije in varstva okolja, in sicer so na stopnji od razumevanja do uporabe. Najnižjo stopnjo zajamejo cilji osnov geologije, ki so na stopnji poznavanja. Vsebine obsegajo teorijo tektonike plošč, ki je predstavljena skozi vpliv na razširjenost vrst. Predstavljeni so geološke dobe, nastanek planeta Zemlja in spreminjanje atmosfere z vplivom na izvor in razvoj življenja. Tematika evolucije je obravnavana zelo skopo oziroma posredno. Predstavljana je na nekaj dejstvih, predvsem na predstavitvi petih velikih izumiranj v geološki zgodovini. Predstavljeni so fosilizacija ter posamezni tipi fosilov. Vsebine ekologije in varstva okolja so predstavljene skozi človekov vpliv na okolje. Poudarek je na kroženju snovi v naravi med posameznimi ekosistemi in okolji. Obravnavajo se tudi kopičenje strupenih snovi v organizmih ter nastanek kislega dežja, tople grede in posledice uporabe fosilnih goriv. Vsebine so strokovno ustrezne, vendar niso celostno predstavljene, zato predvsem pri tematiki o evoluciji ne ponujajo zadostnega razumevanja.

Predmet Okoljska vzgoja se poučuje v 7., 8. in 9. razredu. Obravnavane vsebine zajemajo obnovljive in fosilne energetske vire, kjer učenci spoznajo pomen in načine varčevanja in gospodarnega ravnanja z naravnimi viri. Vsebine o mineralnih surovinah so navezane na prepletenost ekoloških ter ekonomsko-družbenih vidikov izkoriščanja, ter razumevanju nastanka in reševanja okoljskih problemov.

Zaskrbljujoče je dejstvo, da niti v enem osnovnošolskem učbeniku ni podane definicije geologije kot vede.

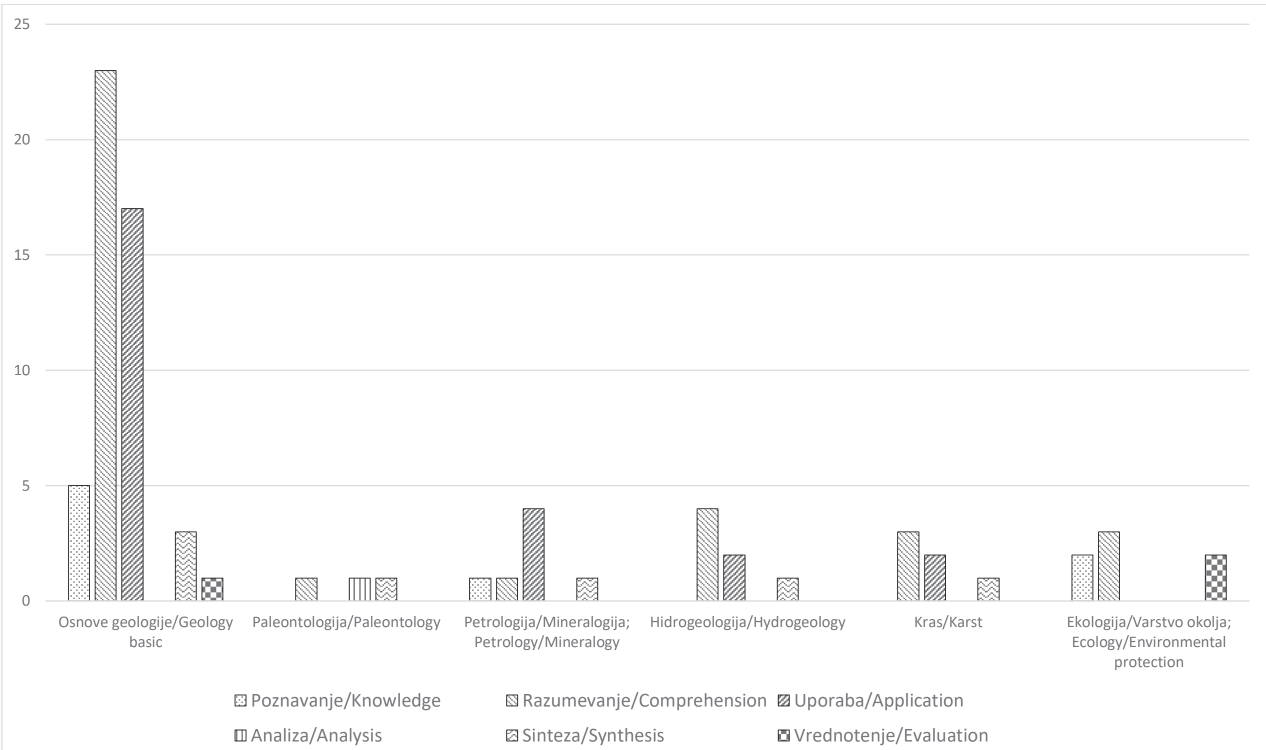
Geološke vsebine in njihova zahtevnost po posameznih predmetih v splošnih gimnazijah

S pregledom učnih načrtov smo ugotovili, da se geološke vsebine na splošnih gimnazijah poučujejo pri predmetih Biologija in Geografija (Tabela 3), kjer se znanje preverja tudi na maturi. Na splošnih gimnazijah je največ geoloških ciljev pri predmetu Geografija (1., 2., 3. in 4. letnik), in sicer 67. Njihova povprečna zahtevnost je na taksonomski stopnji uporabe. Pri Biologiji (1., 2., 3. in 4. letnik) je geoloških ciljev 12, zahtevnost pa na stopnji razumevanja. Največ tematik je razvrščenih v sklopu osnov geologije, ki je po taksonomski zahtevnosti med vsemi najmanj zahteven. Taksonomsko najbolj zahteven sklop so vsebine ekologije in varstva narave. Te dosežejo povprečno zahtevnost do stopnje uporaba. V primerjavi z osnovno šolo se povprečna zahtevnost ciljev na gimnaziji pri vseh sklopih poviša za eno taksonomsko stopnjo. Zahtevnost ciljev je predstavljena pri vsaki tematiki posebej in je prikazana tudi na spodnji sliki (sl. 3).

Pri predmetu Biologija (Vilhar et al., 2008), ki se poučuje od 1. do 3. letnika ter izbirno v 4. letniku, je poudarek na vsebinah paleontologije ter ekologije in varstva narave. Obravnavajo se tudi vsebine osnov geologije ter hidrogeologije. Paleontološke vsebine zajemajo izvor in razvoj življenja. Podana je definicija fosila in načini fosilizacije. Pri evoluciji so opisana množična izumrtja v geološki zgodovini, razvoj življenja pa je podan razdrobljeno, a kljub temu dokaj podrobno. Sistematično je opisana evolucija človeka. Vsebine ekologije in varstva okolja so zajete s kroženjem snovi in elementov med ekosistemi. Podrobno so razloženi nastanek in vpliv kislega dežja, tople

Tabela 3. Geološki učni cilji, razvrščenih po tematskih sklopih, pri posameznem predmetu v splošnih gimnazijah.
Table 3. Geological learning objectives classified by topics, for individual subjects in Gymnasiums.

Predmet/Tema Subject/Topic	Osnove geologije Geology Basics	Paleontologija Paleontology	Petrologija/ Mineralogija Petrology/ Mineralogy	Hidrogeologija Hydrogeology	Kras Karst	Ekologija/ Varstvo okolja Ecology/ Environmental protection
Biologija Biology	1	3	0	3	0	5
Geografija Geography	48	0	7	4	6	2



Sl. 3. Število učnih ciljev, razvrščenih po tematskih sklopih, predstavljenih po stopnji zahtevnosti v splošnih gimnazijah.
Fig. 3. Number of geological learning objectives in Gymnasiums, classified according to topics, presented by level of difficulty.

grede in toplogrednih plinov ter ozona, in onesnaženje zraka. Natančno so predstavljene vsebine o škodljivosti in izvoru radona, o problematiki radioaktivnih odpadkov ter koncentriranja toksičnih kovin v tleh in v organizmih. Predstavljena je remediacija tal na onesnaženih področjih. Obravnavana sta onesnaževanje okolja ter vpliv človeka na ekosisteme v navezavi na fosilna goriva. Vsebine so predstavljene strokovno točno in v večini primerov zelo podrobno.

Pri predmetu Geografija (Polšak et al., 2008), ki se poučuje od 1. do 3. letnika ter izbirno v 4. letniku, je obseg geoloških vsebin največji. Predstavljeni so vsi tematski sklopi z izjemo paleontologije. Osnove geologije zajemajo zelo širok nabor geoloških vsebin. Predstavljeni so zunanji in notranji procesi, ki vplivajo na oblikovanost površja. Paleogeografski razvoj sveta je podan na nekaj primerih. Na tektoniko plošč so navezane vsebine o potresih in vulkanih. Obsežneje so predstavljeni tipi površja in njihove glavne značilnosti z navezavo na njihov nastanek. V okviru geografije Evrope so predstavljene posamezne geološke značilnosti regij oz. držav ter njihov nastanek. Tako je omenjen nastanek Alp, Baltskega ščita, stare orogenetske faze, geološke značilnosti Islandije in celinska poledenitev Severne Evrope. Pri obravnavanju geografije sveta se, podobno kot pri Evropi, vsebine učbenikov osredotočajo na predstavitev posameznih geoloških značilnosti regij. Dijaki spoznajo cone subdukcije, glavne orogenetske faze dviga gorovij v Ameriki, Himalaji in Andov ter tamkajšnji vulkanizem. Predstavljeni so nastanek avstralskega kontinenta ter glavne geološke enote Afrike. Pogosto so kot zanimivosti podana tudi različna rudna bogastva držav, arteški vodonosniki, nastanek atolov ter glavni energetski viri. Pri obravnavanju značilnosti Slovenije je predstavljena njena geološka zgodovina. Razložen je nastanek površja Slovenije skozi Zemljino zgodovino, podana je tudi razčlenitev na geotektonske enote. Opisani so primeri hujših geoloških naravnih nesreč. Pri izbirnih vsebinah v 4. letniku so podane posebnosti geološke sestave in njihov vpliv na oblikovanost površja po posameznih pokrajinah Slovenije. Petrološke tematike zajemajo opis nastanka različnih tipov kamnin, kjer so predstavljeni tipični predstavniki posameznih kamninskih skupin. Podrobneje so tipi kamnin razloženi pri obravnavanju pokrajin Slovenije, kjer sta podana natančna razčlenitev in njihov nastanek. Predstavljena je povezava kamnin z nastankom različnih tipov tal. Zelo skopo so opisani viri mineralnih surovin. Hidrogeološke vsebine se začnejo z vodnim krogom in deležem posameznih tipov voda na Zemlji. Vsebine so navezane na onesnaževanje pitne vode. Pri obravnavanju geografije Slovenije je predstavljeno, kje v Sloveniji dobimo pitno vodo ter opisano onesnaženje podzemne pitne vode. Kras je podrobno obravnavan v celotnem poglavju o pokrajinah Slovenije. Vsebine ekologije in varstva okolja zajemajo analiziranje posledic posegov v okolje, izkoriščanja in predelave rud, posledice uporabe fosilnih goriv, podnebne spremembe in njihov vpliv na okolje. Velik del vsebin je namenjen trajnostnemu gospodarjenju z okoljem in surovinami. Kljub večjemu obsegu vsebin so te naravnane na učenje podatkov in niso zadosti usmerjene v razumevanje. To lahko pripišemo vsebinski zasičenosti predmeta.

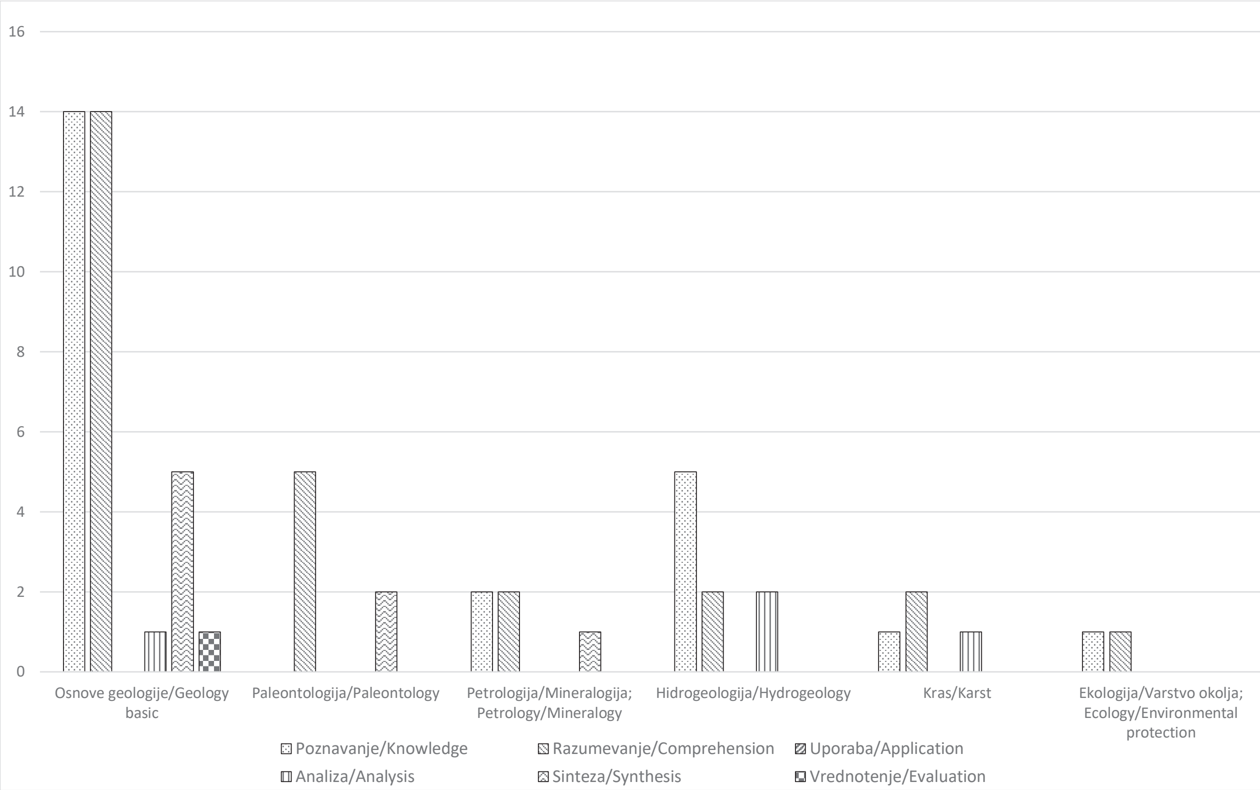
Zopet velja poudariti, da podobno kot v osnovni šoli tudi v gimnazijskih učbenikih ni niti v enem primeru podana definicija geologije kot vede.

Geološke vsebine in njihova zahtevnost na maturi

Pregled maturitetnih izpitnih katalogov za predmeta Biologija (Bavec et al., 2015) in Geografija (Balažič et al., 2014) nam je omogočil definiranje pričakovane stopnje znanja ob zaključku srednješolskega izobraževanja. Geološke cilje, ki se preverjajo na maturi (Tabela 4), smo enako kot učne cilje v učnih načrtih vrednotili po Bloomovi taksonomiji ter jih razvrstili na šest tematik. Zahtevnost ciljev je predstavljena pri vsaki tematiki posebej (sl. 4).

Tabela 4. Število učnih ciljev pri posameznem predmetu na maturi, razvrščenih po tematskih sklopih.
Table 4. Geological learning objectives classified by topics, for individual subjects on matura examination.

Predmet/Tema Subject/Topic	Osnove geologije Geology Basics	Paleontologija Paleontology	Petrologija/ Mineralogija Petrology/ Mineralogy	Hidrogeologija Hydrogeology	Kras Karst	Ekologija/ Varstvo okolja Ecology/ Environmental protection
Biologija Biology	2	7	0	0	0	1
Geografija Geography	33	0	5	9	4	4



Sl. 4. Število učnih ciljev, razvrščenih po tematskih sklopih, predstavljenih po stopnji zahtevnosti na maturi.

Fig. 4. Number of geological learning objectives in matura examination, classified according to topics, presented by level of difficulty.

Kar 64 odstotkov vprašanj je iz vsebin osnov geologije. Nanašajo se večinoma na temo oblikovanosti površja, sledijo vsebine regionalne geologije, energetike ter ostale, kjer je za razumevanje pomembno osnovno geološko znanje. Druga kategorija po zastopanosti je petrologija, ki je zastopana s 13 odstotki. Vprašanja se pretežno navezujejo na matično oziroma kamninsko podlago in nastanek tal na kamninah. Vsebine ekologije in varstva okolja zajemajo 11 odstotkov vprašanj, dotikajo se okoljskih problematik in so geološko naravnana. Sklopi hidrogeologija, kras in paleontologija se na maturi pojavljajo redko. Pri paleontologiji se pojavijo vprašanja o fosilih, evoluciji in nastanku življenja. Hidrogeološki sklop vsebuje vprašanja v zvezi s podzemno vodo in njeno povezavo s kamninsko podlago, iz tematike krasa pa se vprašanja nanašajo na nastanek in značilnosti kraškega sveta.

Večina vprašanj doseže prvo taksonomsko stopnjo v kognitivni domeni – poznavanje. Sledi stopnja razumevanja, redkeje pa tudi analiza in sinteza. Stopnjo uporabe doseže malo vprašanj, nobeno vprašanje pa ne doseže stopnje vrednotenja. Večina ciljev v izpitnem katalogu, povezanih z geološkimi vsebinami, je zastavljena na višji taksonomski stopnji zahtevnosti, kot so postavljena maturitetna vprašanja, ki te cilje preverjajo.

Zastavljena vprašanja in pričakovani odgovori so v 95 odstotkih strokovno ustrezni. Pri delno ustreznih, ki jih je 5 odstotkov, gre za problematiko različnega poimenovanja določenih pojavov. Neustrezno zastavljenih vprašanj ni.

Medpredmetna povezanost in nadgradnja znanja po tematikah

Izmed 141 prepoznanih učnih ciljev z geološko vsebino sta bili nadgradnja in medpredmetna povezanost ugotovljeni pri kar 110 ciljih. Drugi so omejeni samo na spoznavanje s tematiko, njihov cilj pa je zgolj priklic dejstev. Z ugotovljeno medpredmetno povezanostjo pričakujemo, da lahko definiramo tudi pričakovano stopnjo predznanja posamezne tematike, pri kateri je bilo ugotovljeno nadgrajevanje. V nadaljevanju podajamo teme, ki jih lahko geološke inštitucije, muzeji in posamezniki nadgrajujejo ter s svojimi dejavnostmi zapolnjujejo ugotovljene vrzeli v znanju učencev in dijakov. Z aktivnim vključevanjem v pripravo strokovnih in poljudnih člankov ter poučevanjem učiteljev pa prispevajo k višji stopnji prepoznavnosti geologije in strokovno pravilni predstavitvi za splošno javnost. S tem pripomorejo k nadgradnji znanja o podanih tematikah v družbi.

Vsebine iz osnov geologije zajemajo 52 odstotkov vseh učnih ciljev z geološko vsebino. Vsebine, kjer je bila ugotovljena medpredmetna povezanost, so: zgradba Zemlje in tektonika plošč, vulkani in potresi, oblikovanost površja, geološki razvoj Slovenije ter geološka karta.

S sestavo Zemlje se učenci in dijaki srečajo v 6. razredu pri predmetih Naravoslovje in Geografiji, kjer spoznajo prerez Zemlje. Tematika se ponovi na isti stopnji v 9. razredu pri predmetu Geografija. Na splošni gimnaziji je pri predmetu Biologija predstavljen vpliv tektonike plošč na evolucijo, pri predmetu Geografija pa je znanje nadgrajeno s predstavitvijo natančnejše razčlenitve notranjosti Zemlje z omembo diskontinuitet ter premikanja litosferskih plošč. Tematika se zaključi na taksonomski stopnji razumevanja. Glede na vsebine v učbenikih ocenjujemo, da so učni cilji doseženi. Priložnost nadgradnje znanja je predvsem pri predstavitvi stikov litosferskih plošč, kjer ni zadostno opisana dinamika premikanja ter vpliv različnih stikov na oblikovanost površja.

Vulkani in potresi so prvič obravnavani v 7. razredu pri predmetu Geografija. Vsebina zajema opis ognjenega obroča ob Tihooceanskih litosferskih ploščah ter primere v Južni Evropi. V splošni gimnaziji se pri predmetu Geografija vsebina nadgradi, saj morajo dijaki prepoznati razloge za nastanek potresov in vulkanov ter prikazati glavna potresna in vulkanska območja na svetu. Spoznajo tudi osnovne tipe vulkanizma. Tematika je močno navezana na geološko pogojene nevarnosti. Če lahko ugotovimo, da je tema vulkanizma prikazana korektno, pa se pomanjkljivosti pojavijo pri predstavljanju nastanka potresov. To je omejeno na tektoniko plošč in tako ni podana vsebina, ki bi jo posameznik lahko apliciral na naše območje. Učni cilji so delno doseženi, a prostora za nadgradnjo je precej. Še posebej zaskrbljujoče je, da drugi, še pogostejši pojavi, kot npr. pobočni masni premiki, v formalnem izobraževanju niso obravnavani na nivoju razumevanja. Tako večina pojavov geološko pogojenih nevarnosti ni zadostno razložena. Na tem mestu je zato še posebej pomembno poljudno informiranje učencev in dijakov.

Oblikovanost površja je tematika, ki si jo geologi delimo z drugimi vedami, ki se ukvarjajo s preučevanjem površja. Le-tej je med cilji, uvrščenimi v osnove geologije, namenjeno daleč največ pozornosti. Na stopnji poznavanja se začne obravnavati že v 4. razredu pri predmetu Družba. Pri predmetu Geografija pa se v 9. razredu in na splošnih gimnazijah močno nadgradi. Pričakuje se, da so učenci in dijaki sposobni razložiti nastanek današnjega reliefa. Razlaga procesov, ki vplivajo na relief, je prikazana skozi razlago zunanjih in notranjih dejavnikov, pri čemer je tektonika izpuščena ali omenjena zgolj bežno. Pričakuje se, da dijaki na podlagi kamninske zgradbe opišejo njen vpliv na oblikovanje površja. Tematika sicer doseže visok taksonomski cilj sinteze, česar pa z vsebinami, predstavljenimi v učbenikih, ni mogoče doseči. V učbenikih so vsebine v mnogih primerih nestrokovno poenostavljena. Tako je oblikovanost površja tematika, kjer bi lahko geologi z vključevanjem v poučevanje veliko pripomogli k zavedanju, da je za razumevanje oblike površja potrebno poznavanje dogajanja pod površjem in pravilno dojemanje tektonskih dejavnikov. Le tako bi se lahko dosegla stopnja razumevanja, ki je definirana v učnih načrtih.

Vsebine o geološkem razvoju Slovenije se obravnavajo pri predmetu Geografija v 9. razredu in v 3. letniku gimnazij. Učni cilji so na osnovnih stopnjah poznavanja in razumevanja, vsebine v učbenikih pa so predstavljene na višji taksonomski stopnji ter zelo površno poenostavljene. Strokovne netočnosti v učbenikih so zelo pogoste. Del učnih ciljev pri tej tematiki je izbiren. Raziskava učnih načrtov v naravoslovju (Catana & Vilas Boas, 2017) je pokazala, da si jih učitelji ne izberejo za poučevanje, saj se zanje počutijo premalo strokovno podkovani. Tako lahko zaključimo, da iz obstoječega gradiva brez dodatnih aktivnosti učiteljev učni cilji ne morejo biti doseženi. Priložnosti za nadgradnjo so široke, od izobraževanja učiteljev do poljudnih predstavitev in delavnic na to temo.

Poznavanje in uporaba geološke karte sta v učnem načrtu opredeljena v 9. razredu in na gimnaziji pri predmetu Geografija. Uporaba geološke karte je namenjena umeščanju v prostor. Od učencev v osnovni šoli se pričakuje osnovno poznavanje geološke karte, medtem ko se v gimnazijah od dijakov pričakuje tudi sposobnost branja karte ter njena uporaba pri terenskem delu. Osnove razumevanja geološke karte v analiziranih učbenikih niso razložene, zato iz obstoječega gradiva učni cilji ne morejo biti doseženi. Nujna je poljudna in strokovno ustrezna predstavitev te tematike.

Vsebine paleontologije zajemajo 6 odstotkov vseh učnih ciljev z geološko vsebino. Tematiki, ki predstavljata medpredmetno povezanost, sta nastanek življenja in evolucija. Da bi postavili primerne osnove, je pomembna celostna predstavitev fosilov in fosilizacije. Te teme se pojavljajo zgolj kot razdrobljena snov v 5. razredu pri predmetu Naravoslovje in tehnika ter kasneje v 9. razredu in v splošni gimnaziji, pri predmetu Biologija. Nastanek življenja na Zemlji in evolucija sta obravnavana predvsem pri predmetu Biologija. V učbenikih sta temi večinoma predstavljeni razdrobljeno. Osredotočata se na velika izumiranja, nikjer pa razvoj življenja ni prikazan zvezno. Tematiki nastanka življenja in evolucije tako ne dosežeta primerne stopnje za razumevanje in kljub temu, da delno ustrezata zapisanim učnim ciljem, ne ponudita pregleda nad tematiko. Priložnosti nadgradnje znanja so tudi tukaj široke in potrebne.

S področja petrologije in mineralogije je v učnih načrtih definiranih 9 odstotkov izmed vseh geoloških ciljev. Učenci se z minerali in kamninami srečajo prvič pri predmetu Družba v 4. razredu, pri obravnavanju domače pokrajine. V 6. razredu so s to tematiko povezani prvi učni cilji pri predmetu Naravoslovje. Ker je poznavanje mineralov ključno za prepoznavanje kamnin, je zaskrbljujoče dejstvo, da se z lastnostmi mineralov učenci srečajo samo tukaj. Ta vsebina ni razložena na primerni stopnji in je omejena zgolj na trdoto mineralov in Mohsovo trdotno lestvico. Prepoznavanje kamnin in njihova klasifikacija se tako skozi ves izobraževalni sistem obravnavata brez predhodno utrjenih osnov. V 6. razredu pri predmetu Naravoslovje in v 9. razredu pri predmetu Geografija se vsebine obravnavajo na enaki stopnji in znanje se ne nadgradi. Cilji se zaključijo na taksonomski stopnji uporabe, ta stopnja pa brez dobrih osnov ne more biti dosežena. Učbeniki ponujajo korektno razlago procesov nastanka kamnin z manjšimi pomanjkljivostmi, vendar brez praktičnega dela ti cilji ne morejo biti doseženi. Zato je v učnem procesu nujna uporaba šolskih geoloških zbirk (Rman, 2010a, b; Rman & Novak, 2016; Madronič, 2018). Te so pogosto neurejene in skrbniki zbirk nimajo potrebnega znanja za njihovo ureditev (Rman et al., 2014). Tematika kamnin je navezana na matično podlago kot osnovo za nastanek tal. Cilji, povezani s tem delom, so v učbenikih ustrezno predstavljeni in zadoščajo učnim ciljem. Zaskrbljujoča je šibka predstavitev mineralnih surovin. Le delno so omenjene pri predmetu Naravoslovje v 6. in 7. razredu in predstavljene na nekaj primerih. Širše se obravnava njihovo izkoriščanje in negativen vpliv na okolje. Tematika se nadgradi v splošnih gimnazijah pri predmetih Biologija in Geografija. Vsebine v učbenikih so zadostne za doseganje ciljev v učnih načrtih. Kljub odvisnosti sedanje družbe od mineralnih surovin, se učni načrti osredotočajo na primere iz preteklosti, ko so rudniki in topilnice onesnaževali okolje. Današnja negativna konotacija rudarjenja je predvsem posledica zastarelih vsebin v učbenikih. Poučevanje bi moralo temeljiti na primerih zaprtih zank recikliranja mineralnih surovin, a ta ideja v učbenikih zaenkrat še ni predstavljena.

Hidrogeologija zajema 9 odstotkov vseh učnih ciljev z geološko vsebino. Poleg splošnih vsebin z vodnim krogom je medpredmetna povezanost ugotovljena pri podzemni vodi. Vsebine so obravnavane pri predmetih Naravoslovje in tehnika v 5. razredu, Naravoslovju v 7. razredu ter na gimnaziji pri predmetih Biologija in Geografija. Učni cilji se pri prehodu iz osnovne šole na gimnazijo nadgradijo ter dosežejo taksonomsko stopnjo sinteze. Dijaki naj bi bili sposobni preko kamninske zgradbe pojasniti načine oskrbovanja s podzemno vodo v različnih delih Slovenije. Pri tem različni tipi vodonosnikov v učbenikih niso zadostno razloženi. Pri različnih tematskih sklopih dijaki spoznajo kraški vodonosnik, medzrnski tip pa kljub svoji pogostosti ni zadostno razložen. Vsebine ne ponudijo zadostne razlage za sposobnost presojanja o tej tematiki. Onesnaževanje podzemne vode je predstavljeno skladno z učnimi cilji. V učbenikih so pogoste terminološke napake pri poimenovanju podzemne vode, kajti izraz podtalnica ni primeren. Primer dobre prakse, kako pristopati k nadgradnji geoloških učnih vsebin in strokovni ustreznosti, je strokovni članek Janže et al. (2017). Prostor za nadgradnjo je pri prikazu dinamike podzemne vode in ustrezni strokovni nadgradnji znanja učiteljev. Koraki v to smer so že narejeni (Rman, 2013) in lahko izboljšajo doseganje zahtevane stopnje učnih ciljev.

Kras je z neposrednimi učnimi cilji definiran v splošnih gimnazijah in predstavlja 4 odstotke vseh učnih ciljev z geološko tematiko. Predhodno se poučuje kot del obravnavanja površja Slovenije pri predmetu Geografija v osnovni šoli. Tako naj bi dijaki znali razložiti nastanek krasa, opisati površinske in podpovršinske kraške oblike ter utemeljiti ranljivost krasa za onesnaženje. Vsebine so predstavljene natančno in strokovno ustrezno ter zagotavljajo dovolj podlage za razumevanje na zahtevani taksonomski stopnji uporabe.

Vsebine ekologije in varstva okolja so v učnih načrtih zelo zastopane in predstavljajo kar 20 odstotkov vseh učnih ciljev, povezanih z geologijo. Povprečna zahtevnost tematike je najvišja med vsemi definiranimi tematskimi sklopi in doseže povprečno taksonomsko stopnjo uporabe. Medpredmetna povezanost je bila znotraj teme ugotovljena pri tematikah o obnovljivih in neobnovljivih energetskih virih ter vplivu izkoriščanja mineralnih surovin na okolje. Prvi so predstavljeni pri predmetu Naravoslovje v osnovni šoli ter pri Biologiji in Geografiji na gimnaziji. Vsebine v učbenikih ustrezajo ciljem v učnih načrtih. Zapostavljena je predstavitev geotermalnega potenciala, ki je omenjena zgolj pri predmetu Geografija. Učenci in dijaki dobijo vpogled v slabosti prekomernega izkoriščanja fosilnih goriv, spoznajo njegove posledice in so sposobni presojati o primernih načinih uporabe energetskih virov. Ne spoznajo pa geoloških naravnih vrednot in pomena njihovega varovanja. Priložnosti za nadgradnjo gradiva in znanja so tudi tu številne.

Geološke vsebine se pojavijo tudi pri predmetu Kemija v osnovni (Bačnik et al., 2011) in srednji šoli (Bačnik et al., 2008). Učnih ciljev z geološko tematiko ni, omenijo se kot izhodišče za povezavo znanja. Medpredmetne povezave so v osnovni šoli definirani z predmeti Naravoslovje, Geografija in Biologija, v splošnih gimnazijah pa pri predmetu Geografija in Biologija. Vsebine, kjer so v učnih načrtih definirane povezave z predmetom Kemija so: sestava zemeljske skorje, ogljikovodiki, kraški pojavi, okoljski problem onesnaženosti podzemne vode, fosilna goriva in mineralne surovine.

Primerjava z dosedanjimi študijami

Raziskava predstavlja temelj za nadaljnje delo na področju trajnosti znanja. Narejena je bila že raziskava za predmete Slovenščina, Zgodovina, Geografija, Biologija in Kemija, vendar geoloških vsebin ni zajela (Marentič Požarnik, 2001a, 2001b). Rezultati analize trajnosti gimnazijskega znanja kažejo, da so študentje z gimnazije ohranili zelo površinsko ter pogosto zelo nepopolno in napačno pojmovanje družbenih in naravnih pojavov. Zanimivo bi bilo na podlagi ugotovljene stopnje predznanja narediti podobno analizo tudi za geološke vsebine.

Predstavljena raziskava je izhodišče za umeščanje posodobljenih vsebin v učne načrte. Obstoječe so pogosto pomanjkljive in strokovno netočne. Dobili smo tudi vpogled v medpredmetno nadgrajevanje, ki je v trenutni obliki učnih načrtov zadostno, opozoriti pa gre na odsotnost predstavitve geologije kot vede. Tako se je pomislek, da bodo geološke vsebine zaradi nezadostne predstavitve pri učencih in dijakih dojete kot geografske (Majcen, 2003), verjetno že uresničil.

Kot opozarja že Popit (2005), smo tudi v pričujoči raziskavi prišli do ugotovitve, da je raba geoloških terminov pogosto neusklajena in neprimerna. To je še posebej izrazito pri vsebinah, katerih poenostavitev je zahtevnejša.

Kot ugotavlja že raziskava učnih načrtov v vrtcih in na razredni stopnji osnovne šole, je geologija, čeprav je v učnem sistemu ni, prisotna povsod, saj predstavlja bazo znanja in izhodišče za predmete, pri katerih se pojavljajo geološke vsebine (Zvonar, 2017). Podobno smo ugotovili tudi za predmetno stopnjo osnovne šole in splošne gimnazije. Vsebinsko je naša raziskava sorodna z raziskavo nacionalnih učnih načrtov v naravoslovju na Portugalskem, Norveškem in v Sloveniji, ki je bila narejena v okviru projekta ESTEAM (Catana & Vilas Boas, 2017). Avtorji pri projektu ESTEAM so z anketiranjem učiteljev ugotovili število ur, namenjenih poučevanju geoloških vsebin. Naša raziskava predstavlja komplementarno nadgradnjo tega projekta, saj učne cilje tudi vrednoti po taksonomski zahtevnosti in podaja povezavo z vsebino v učbenikih. Raziskavo smo dodatno razširili še na splošne gimnazije in splošno maturo.

Zaključek

Z opravljeno raziskavo smo dobili sistematičen vpogled v poučevanje geoloških vsebin v osnovnih šolah in v splošnih gimnazijah. Vrednoteni učni načrti ter geološke vsebine v učbenikih in na maturi so omogočili pregled nad pričakovano stopnjo predznanja po končanem srednješolskem izobraževanju. Raziskava je podala naslednje zaključke:

- Geološke vsebine se poučujejo v osnovni šoli pri obveznih predmetih Družba, Naravoslovje in tehnika, Naravoslovje, Geografija in Biologija ter izbirnem predmetu Okoljska vzgoja. Na splošnih gimnazijah se poučujejo pri predmetih Biologija in Geografija, kjer se znanje preverja tudi na splošni maturi.
- Vseh učnih ciljev z geološko vsebino je 141, takšnih, kjer je bilo ugotovljeno medpredmetno nadgrajevanje, pa kar 110. Razdrobljenosti vsebin in posledično nizka trajnost znanja je najverjetnejši vzrok za slabo stopnjo poznavanja geoloških vsebin v družbi.
- Medpredmetno povezanih sklopov vsebin je 15. V učbenikih so vsebine večinoma strokovno ustrezne, vendar pa so glede na vrednotenje ciljev v učnih načrtih na nižji taksonomski ravni in kot takšne pogosto ne predstavljajo ustreznega temelja za doseganje ciljev.
- Glede na opravljen pregled je očitna odsotnost nekaterih za družbo izjemno pomem-

bnih geoloških tematik. Pomanjkljiva je predstavitev tektonskih vplivov na oblikovanost površja, dinamika podzemne vode, ki določa tudi lastnosti pitne vode in načine njene zaščite, skoraj popolnoma je odsotna tematika geološko pogojenih nevarnosti in mineralogija, mineralne surovine imajo izredno negativno konotacijo. Učenci in dijaki v izobraževalnem sistemu dobijo premalo informacij o neposredni uporabnosti geološkega znanja.

- Maturitetno preverjanje znanja je glede na zastavljena vprašanja skladno z izpitnimi cilji. Opaziti je le taksonomsko odstopanje, saj so bila vprašanja zastavljena na nižji taksonomski stopnji. Kar 95 odstotkov vprašanj je zastavljenih strokovno ustrezno, 5 odstotkov je vrednotenih kot delno ustrezno, a le zaradi razlik v strokovni terminologiji.
- Opravljena raziskava lahko pomaga promotorjem geologije kot znanosti in stroke. Nakazane so priložnosti, kje lahko s svojim delovanjem pripomoremo k izboljšanju trenutnega stanja poznavanja geologije kot vede. Kaže se tudi potreba po močnejšem povezovanju in aktivnosti znotraj stroke, za namene promocije geološke vede v formalnem in neformalnem izobraževanju. K temu bi najbolj pripomogla priprava samostojnega učnega gradiva z geološko tematiko za osnovne šole in splošne gimnazije po najnovejših didaktičnih metodah.
- Anomalija, da Geologija kot predmet ni zastopana v osnovnih in srednjih šolah, a vsebinsko v učnih ciljih vsesplošno definirana tako pri družboslovnih kot pri naravoslovnih predmetih, nakazuje na neobhodno dejstvo, da je poučevanje geoloških vsebin osnova za razumevanje naravnih procesov na Zemlji in razvoja družbe. Njena predstavitev v učbenikih je nezvezna, strokovno pomanjkljiva ter vsebinsko zelo okrnjena. To nam daje izhodišča za začetek umeščanja posodobljenih in zvezno predstavljenih geoloških vsebin v formalno izobraževanje.

Zahvala

Zahvala gre Slovenskemu geološkemu društvu, ki je s finančnim prispevkom omogočilo reproduciranje učbenikov. Ravno tako se za pomoč pri raziskavi zahvaljujemo Narodni in univerzitetni knjižnici, ki je omogočila dostop do gradiva in dovolila njegovo reproduciranje. Anonimnim recenzentom se zahvaljujemo za temeljit pregled rokopisa. Za uvod v področje poučevanja ter komentar na članek se zahvaljujemo prof. ddr. Barici Marentič Požarnik.

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Provenance and characteristics of the pavement stone from the courtyard of the Ljubljana Castle

Izvor in značilnosti kamna v tlakovcih na osrednjem dvorišču Ljubljanskega gradu

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Abstract

The pavement stone used in the central courtyard of Ljubljana Castle originates from the Kukul area northeast of the town of Prilep in Republic of Macedonia. Several pavers were badly damaged and partly replaced by two other natural stones, because the original stone from Kukul is no longer available on the market. The natural stone that is recently used as a replacement is commercially named “Bianco Sardo” and differs from original rock from Kukul in both, structure and composition. The advancement of the replacement of original pavers with “Bianco Sardo” is resulting in extremely uneven and disturbing appearance of the courtyard. The original Kukul stone used in the central courtyard of Ljubljana Castle is of metamorphic origin and belongs to gneisses. Two types of pavers were identified, the light coloured and the dark coloured varieties. They have similar mineral composition consisting of quartz, feldspars (orthoclase, microcline and plagioclases), minerals of the epidote group, micas (muscovite and biotite), titanite, zircon, clinopyroxene, kyanite, pyrite and calcite. Light coloured pavers have porphyroclastic, protomylonitic to mylonitic structures. Dark coloured pavers display gneissic structure, contain more quartz and epidote, less feldspars, and no clinopyroxene. They show intensive recrystallization and granoblastic textures. Both analysed rock types belong to the same rock massif, only that the blocks were extracted from various parts of the rock massif. The variations are due to the process of metamorphic differentiation, which resulted in segregation and separation of light and dark coloured minerals. In the past, the natural stone that was coming from Kukul, was known and classifyed as a type of granite. The rock that is used in the central courtyard of Ljubljana Castle is not granite but granitic gneiss, therefore, we assume that in the last stages of quarrying in the Prilep area, they were extracting also the metamorphic country rocks for some time. The broader area of Prilep belongs to the Pelagonian massif. Its thick metamorphic complex contains also granitoid (granodiorite) intrusives, which crop out in the Prilep anticline and used to be quarried at the locality of Kukul. According to national regulations of the Republic of Macedonia the area is now protected as a natural monument and further exploitation was no longer possible. Today, there is only one open granite exploitation field in the wider surroundings of Prilep, the locality of Lozjanska Reka–Kruševica and a few localities of gneiss-granites of high potential. It would be necessary to consider these solutions for the conservation-restoration of the Ljubljana Castle central courtyard instead of using an inappropriate stone replacement.

Izvleček

Naravni kamen, s katerim je tlakovano osrednje dvorišče Ljubljanskega gradu, izvira iz območja Kukula, severovzhodno od mesta Prilep v Republiki Makedoniji. Ker prvotni kamen iz Kukula ni več na voljo na tržišču, so več poškodovanih tlakovcev nadomestili z dvema nadomestnima vrstama naravnega kamna. Naravni kamen "Bianco Sardo", ki so ga nedavno pričeli uporabljati kot nadomestek, se močno razlikuje od prvotne kamnine iz Kukula, tako po teksturi kot tudi po sestavi. Z napredovanjem menjave originalnih tlakovcev s kamnino "Bianco Sardo" postaja videz osrednjega dvorišča Ljubljanskega gradu izrazito neenoten. Izvirni kamen iz Kukula, ki je bil uporabljen v osrednjem dvorišču Ljubljanskega gradu, je metamorfnega izvora in pripada gnajsom. Ločili smo dve vrsti tlakovcev, tlakovce svetle in temne barve. Imajo podobno mineralno sestavo, ki jo sestavljajo kremen, glinenci (ortoklaz, mikroklin in plagioklazi), minerali iz epidotove skupine, sljude (muskovit in biotit), titanit, cirkon, klinopiroksen, kianit, pirit in kalcit. Svetli tlakovci so porfiroklastični, s protomilonitno do milonitno strukturo. Temno obarvani tlakovci imajo gnajsno strukturo, vsebujejo več kremena in epidota, manj glinencev in nič klinopiroksenov. Zanje je značilna intenzivna rekristalizacija in granoblastična struktura. Obe analizirani kamnini pripadata istemu kamninskemu masivu, le da so bili bloki med izkopom očitno odvzeti iz različnih delov kamnoloma. Razlike v teksturi in strukturi so posledica procesa metamorfne diferenciacije, ki je povzročila segregacijo in ločitev svetlih in temnih mineralov. V preteklosti je bil naravni kamen, ki je prišel iz Kukula, znan in klasificiran kot vrsta granita. Kamnina, ki se uporablja v osrednjem dvorišču Ljubljanskega gradu ni granit ampak granitni gnajs, zato predpostavljamo, da so v zadnji fazi obratovanja kamnoloma pri Prilepu zajeli tudi metamorfne prikamnine. Širše območje Prilepa pripada Pelagonskemu masivu. Njegov debeli metamorfni kompleks vsebuje tudi granitoidne (granodioritne) intruzije, ki izdanjajo v Prilepski antiklinali in so jih lomili v kamnolomu Kukul. V skladu z nacionalnimi predpisi Republike Makedonije je območje zdaj zaščiteno kot naravni spomenik in nadaljnje izkoriščanje ni več mogoče. Danes je v širši okolici Prilepa samo eno pridobivalno omočje granita v Lozjanski Reki-Kruševici in nekaj območij granitnih gnajsov z velikim potencialom. Te rešitve bi bilo treba pretehtati tudi za rekonstrukcijo osrednjega dvorišča Ljubljanskega gradu, namesto da se uporabljajo že na pogled neprimerni nadomestni naravni kamni.

Introduction

The appearance and the purpose of the Ljubljana Castle, located above the Ljubljana city center, have been changed several times since 1120, when Ljubljana and its medieval fortress were mentioned for the first time. Today the Ljubljana Castle is regularly visited by national and foreign tourists, as it has become a cultural and social center where numerous events are organized (Kralj, 2005).

Within the castle walls and towers there is an inner courtyard, which is in central part paved with natural stone originating from Kukul area near Prilep in Republic of Macedonia (Žiga Miklavc, personal communication, October 17, 2017). Many factors influence the degradation of natural stone when used as pavers, and at Ljubljana Castle one of the main reasons are mechanical damages. Some of the pavers were damaged to the extent that they had to be replaced. To the knowledge of the authors, this has been done without professional conservation-restoration guidance, but rather as individual repair works. As the original natural stone from Kukul is not available since 2017, they started to use two different stone replacements. Unfortunately, one of them ("Bianco Sardo"; Žiga Miklavc, personal communication, October 17, 2017) differs substantially in both, composition and structure from the original rock and is greatly disrupting the look of the courtyard itself (fig. 1). So far, from 10 to 15 pavers have been replaced, but the number of damaged pavers waiting for a replacement is still large and their number is increasing over time.

The Kukul natural stone was known commercially as granite and obviously they are replacing Kukul granite with another type of granite named "Bianco Sardo". The problem is that the rock from Kukul, which is used in the central courtyard in Ljubljana Castle, is not an igneous rock (granite) but displays obvious metamorphic structure.

In this paper, we present detailed mineralogical and petrographic, textural and structural characteristics of original natural stone used

Fig. 1. (a) View of the central courtyard of the Ljubljana Castle in moist weather conditions. The replaced stones in the central part are easy recognizable. They are significantly lighter and disturb the uniform appearance of the courtyard. (b) Typical mechanical damages on the pavers in form of cracks along the edges. (c) Example of inappropriate replacemets in the central courtyard of Ljubljana Castle.

in pavers. Precise macroscopic observations in the field and microscopic analysis of 13 polished thin sections were performed and correct petrographic classification of rocks used in pavers at the central courtyard of the Ljubljana Castle is defined. In order to compare these rocks with the original Kukul stone, the literature on the provenance, geological setting and petrology of the latter been studied.

Materials and methods

The macroscopic characteristics were observed on site. Original rock types as well as their macroscopic composition and structure were described and photo-documented. Types of damages and the current practice of repair works were listed and photographed.

In the central courtyard of Ljubljana Castle, several pavers were already replaced and stored in the Castle cellar. From the individual replaced pavers we cut the representative samples that were used for further petrographic analysis. The collected samples were first cut perpendicular to the observed structures. From the rock chips, 13 polished thin sections were prepared. Six thin sections from six samples of light coloured pavers (labelled as 1a, 2a, 4a, 5a, 6a, and 7a), and seven thin sections (labelled as 1b, 2b, 3b, 4b, 5b, 6b and 7b) from seven different samples belonging to a darker variation of Kukul stone were made. Petrographic analyses were carried out using the Nikon Eclipse E200 optical microscope in the plane polarized light. The thin sections were photographed using the Nikon DS-Fil camera and the NIS Elements Basic Research program.

Results

Observed damages of the pavers and current state of repair

Numerous mechanical damages of the pavers are clearly visible. In most cases, they are expressed as thin cracks along the edges and of the corners of pavers (fig. 2). Weathering along the cracks is commonly marked with intensive discoloration (fig. 2c). Some cracks only started to form, cutting only the surface of the pavers, while others cut deep into the pavers or even all the way through. In the latter case, the pavers will have to be replaced.

In several places, individual pavers were already replaced by two other rock types (fig. 3). Since the natural stone from the original source Kukul is no longer available, they choose two different types of natural stones that are used as a replacement for the damaged pavers. At first, the natural stones of unknown origin was used which is similar in appearance to the original rock from Kukul (fig. 3a – marked with a square). Recently, natural stone with a commercial name "Bianco Sardo" was applied as a replacement. It has a completely different appearance from the primary paving stone from Kukul, as well as to the previously used replacement rock of unknown origin, and is disrupting the uniform appearance of the central courtyard of the Ljubljana Castle (fig. 3a – marked with a circle and fig. 3b). "Bianco Sardo" which is quarried in Italy is noticeably brighter, without coloration, and has different compositional and structural characteristics compared to original paving stones. It has typical igneous holocrystalline structure, is homogeneous and medium-grained with sizes ranging from one millimeter to two centimeters. Macroscopically recognizable minerals are grayish quartz, white and brownish feldspars, muscovite, biotite, amphiboles and/or pyroxenes. Petrographic classification of rock with the commercial name "Bianco Sardo" is granite.

Macroscopic characteristics of the original pavement stone

From the macroscopic observation, original pavement stone may be divided into two groups, light coloured (fig. 4) and dark coloured pavers (fig. 5). Most rocks in this group display medium-grained porphyroclastic and protomylonitic to mylonitic structure (e.g. Trouw et al., 2010) (fig. 4b, c). Minor concentrations of femic minerals in forms of seams or bands are commonly observable (fig. 4c). Occasionally, primary phaneritic structure may still be recognized (fig. 4d), although quartz is obviously recrystallized and porphyroclasts of potassium feldspar show signs of rounding on the edges at closer inspection. In the light coloured variations, potassium feldspars and quartz prevail, and are responsible for the bright appearance and lighter colour of the rock (fig. 4a). Potassium feldspars form idiomorphic to hipidiomorphic crystals with sizes ranging from 5 cm to small crystals of only few mm in diameter. Other distinguishable minerals are quartz, forming nests or sometimes ribbons or just evenly distributed crystals in the matrix, minerals of epidote group, and minor amounts of pyrite and garnets.

In the dark varieties of pavement stone, the femic minerals are concentrated and segregated into lenses and bands resulting in a darker ap-

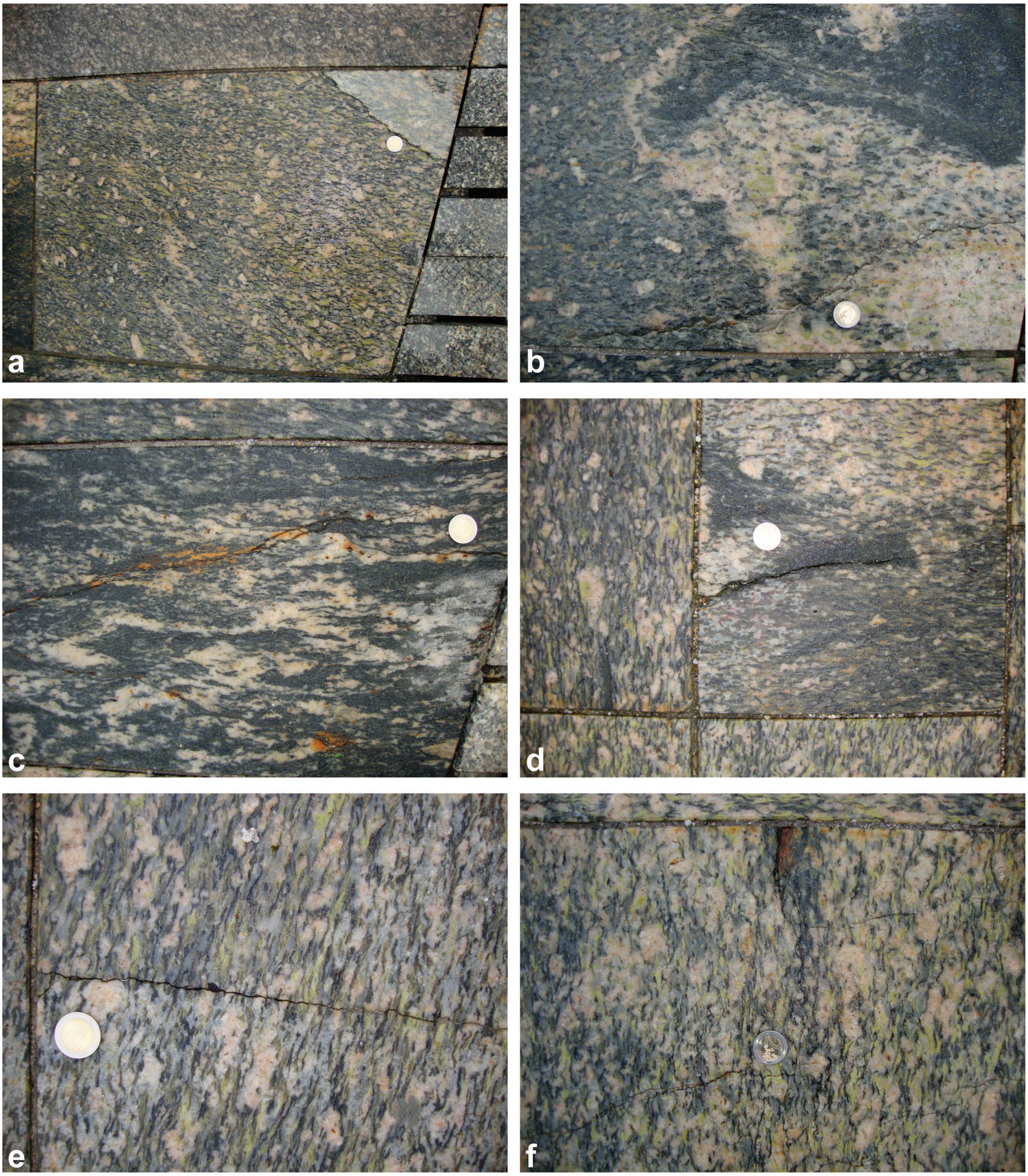

Fig. 2. Damages on original paving stones in form of cracks along the corners (a–b) or edges of the pavers (c–e). In several cases, cracks propagate deep into the body of the pavers (d).

pearance of the pavers (fig. 5). The segregation of femic minerals is forming gneissic structure, where bands formed during metamorphic differentiation often display complex deformation (figs. 5a–b). Most minerals are macroscopically indistinguishable (fig. 5c), apart from minerals in larger felsic bands and lenses, where pink potassium feldspars, greyish quartz, minor grains of pyrite and garnet may be recognized (fig. 5d).

Microscopic characteristics of original pavement stone

Light coloured pavers

All samples have heterogeneous texture and contain approximately 36 % of quartz, 35 % of potassium feldspars represented by microcline and orthoclase, 11 % of minerals from epidote group (epidote, clinozoisite, and allanite), 4 %

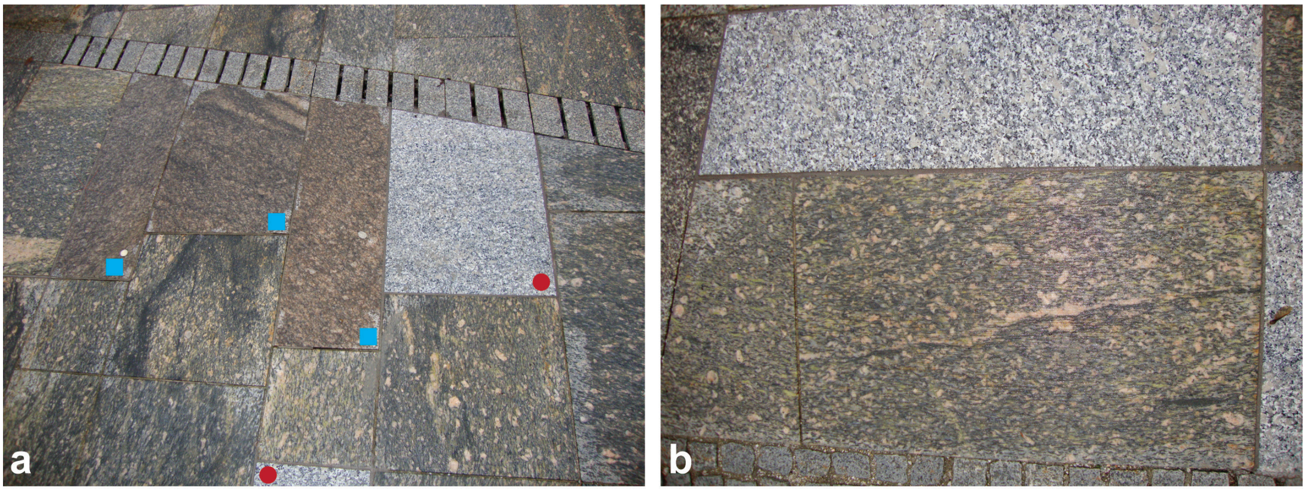

Fig. 3. Replaced pavers in the central courtyard of the Ljubljana Castle. (a) A natural stone with the commercial name “Bianco Sardo” (marked with a circle) and another natural stone of unknown origin (marked with a square). (b) The bright greyish appearance and the apparent magmatic texture of the natural stone “Bianco Sardo” are in strong contrast with the original coloured rock from Kukul.

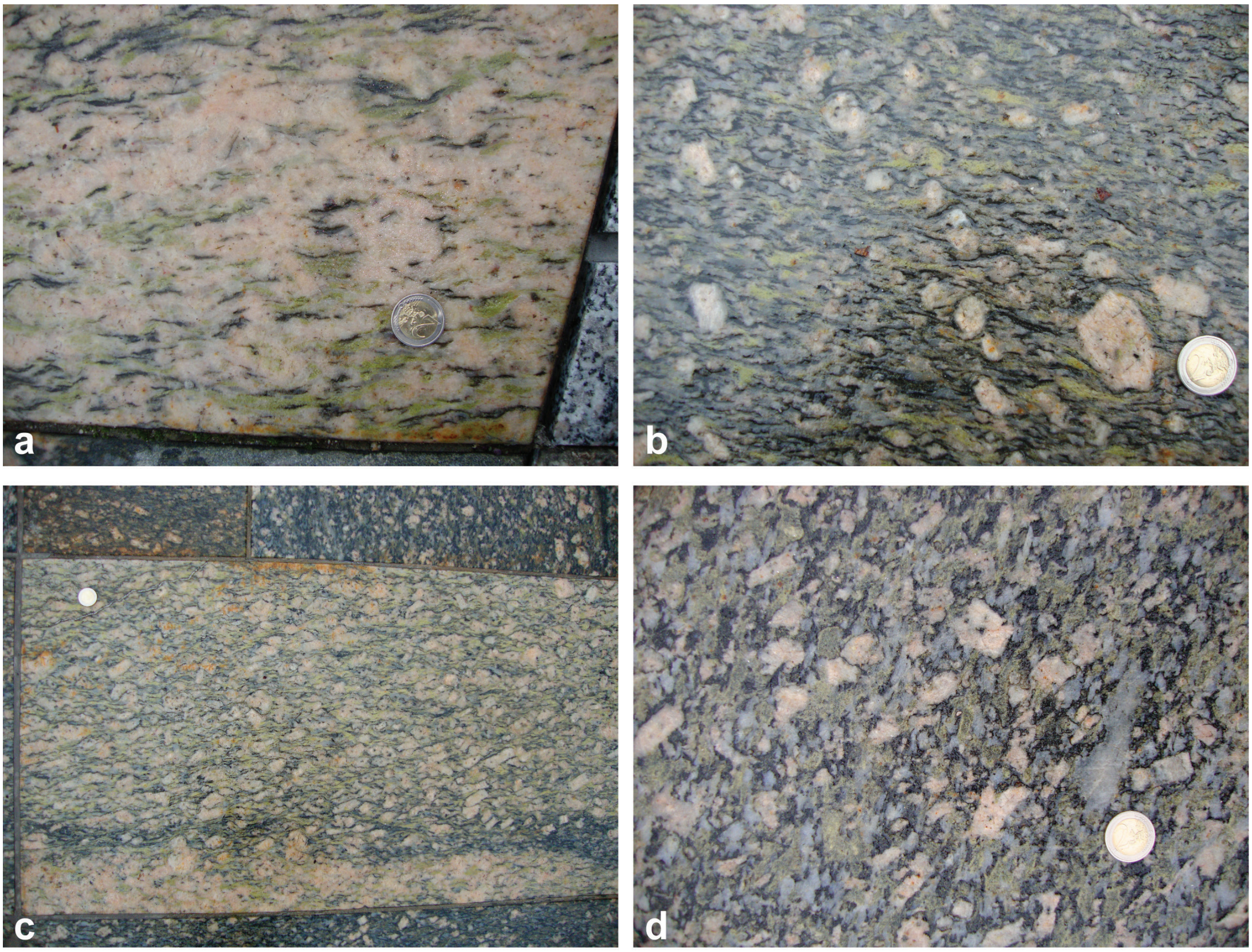

Fig. 4. Light coloured pavers used in central courtyard of Ljubljana Castle. (a) Potassium feldspars are giving the unique pinkish tint to the matrix of the rock, yellowish green colour is mostly from minerals of epidote group and thin black seams are due to minor femic minerals. (b) Mylonitic structure composed of porphyroclasts of potassium feldspar in the matrix of epidote, some femic minerals, and recrystallized quartz. Perfect delta clast of potassium feldspar is nicely visible on the right side, below the centre of the figure. (c) In some pavers, femic minerals are concentrated in seams or bands (lover part of the figure). (d) Igneous phaneritic structure is still clearly visible.

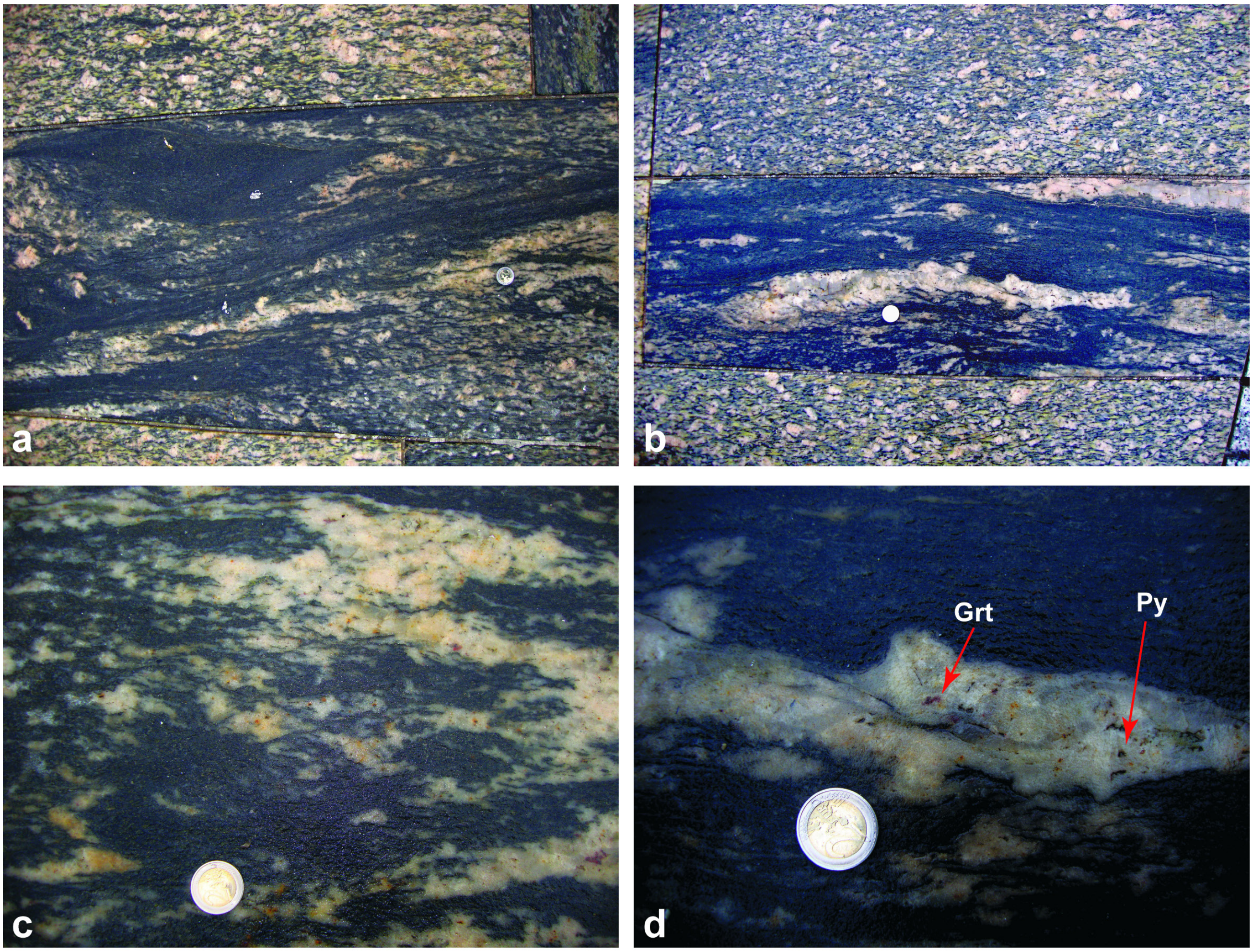

Fig. 5. Dark coloured pavers used in central courtyard of Ljubljana Castle. (a–b) Typical gneissic structure and contrast of dark pavers in contact with light coloured varieties (top and bottom border). (c) Most minerals in dark coloured pavers are macroscopically indistinguishable. (d) Reddish minerals in the felsic lens composed of white feldspars and quartz correspond to garnets (Grt), dark spots are pyrite (Py).

of plagioclase, 4 % of muscovite, 2 % of biotite which is partly chloritized and/or epidotized, 2 % of titanite, 2 % of calcite, and 1 % of each of minerals: clinopyroxene, zircon, kyanite, and pyrite.

Predominant polycrystalline and minor monocrystalline quartz is xenomorphic to hipidiomorphic and have uniform or undulatory extinction (fig. 6a). The latter is a result of recovery processes, which in places progressed all the way to the dynamic recrystallization (fig. 6a). Quartz either appears in recrystallized bands or surrounds feldspar and clinopyroxene porphyroclasts. In places, granoblastic texture is observable (fig. 6b). Among feldspars, microcline forms the largest crystals in all six thin sections, reaching 0.2 to 4.3 cm in length. They are xenomorphic and rounded on the edges due to the process of dynamic recrystallization (fig. 6c). Microcline is frequently twinned representing a rigid porphyroclast in an intensively recrystallized quartz matrix forming a protomylonitic to mylonitic texture (fig. 6c). Orthoclase also forms porphyroclasts, which are mostly xenomorphic and often twinned, with sizes ranging from 0.1 to 2 cm (fig. 6d). In some parts, orthoclase crystals show albite exolution lamellae and correspond to orthoclase perthite (fig. 6d). Plagioclases are smaller, reaching 0.02–0.1 cm in average. They are present as individual xenomorphic crystals randomly distributed within the recrystallized quartz matrix (fig. 6e), together with muscovite and minerals from epidote group. As bigger crystals, they appear in the role of porphyroblasts or poikiloblasts (fig. 6e).

Epidote group minerals are common and most typically occur in green, brown or mustard yellow colours. Epidote and clinozoisite form needle like and prismatic minerals in the matrix (figs. 6e, f), with sizes from 0.02 to 0.75 mm. Another epidote representative occurs in bigger isolated minerals with deep brown colour and distinct zoning, which are up to 1 cm long and most probably correspond to allanite (fig. 6f). Micas show strong parallel orientation and segregation in seams and bands

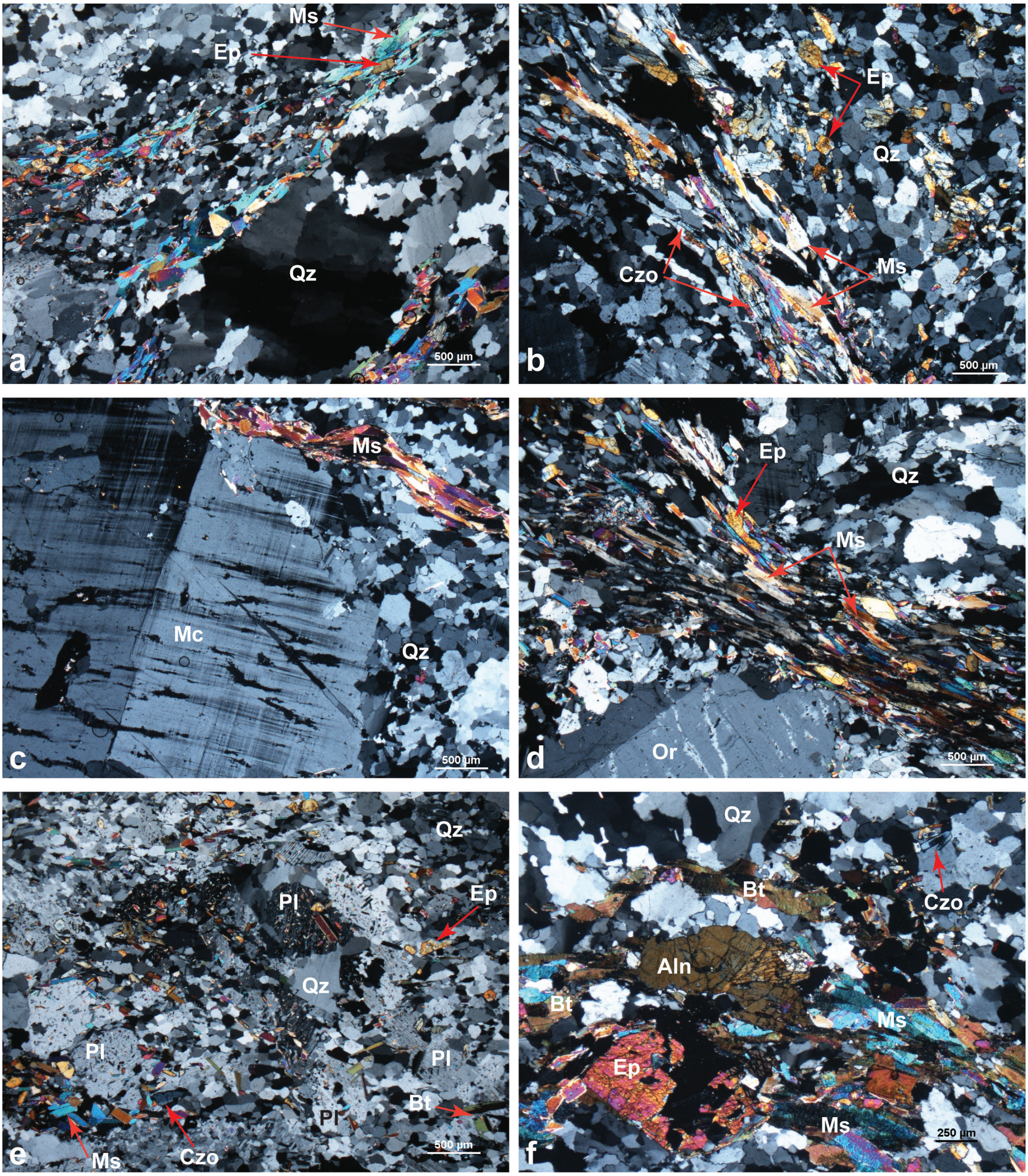

Fig. 6. Microphotographs of light coloured pavers. (a) Mono and polycrystalline quartz showing signs of recovery and recrystallization together with small elongated muscovite and minerals from epidote group. (b) Oriented muscovite is forming foliation. Quartz on the right-hand side is mostly idiomorphic, recrystallized and forming granoblastic texture. Higher relief prismatic minerals belong to epidote and clinozoisite. (c) Twinned microcline is forming a porphyroclast in intensively recrystallized quartz matrix forming protomylonitic to mylonitic texture. Microcline is rounded due to the recrystallization along the edges. (d) Porphyroclast of orthoclase-microperthite lies bellow the segregation of muscovite and some epidote group minerals defining foliation of the rock. (e) Individual plagioclase crystal in quartz matrix together with muscovite, biotites and epidote group minerals. Plagioclase poikiloblasts are full of small mineral inclusions. (f) Prismatic epidote group minerals in matrix and isolated crystal of allanite, in the centre of the figure. All figures were taken under crossed polars. Mineral abbreviations are according to Whitney & Evans (2010).

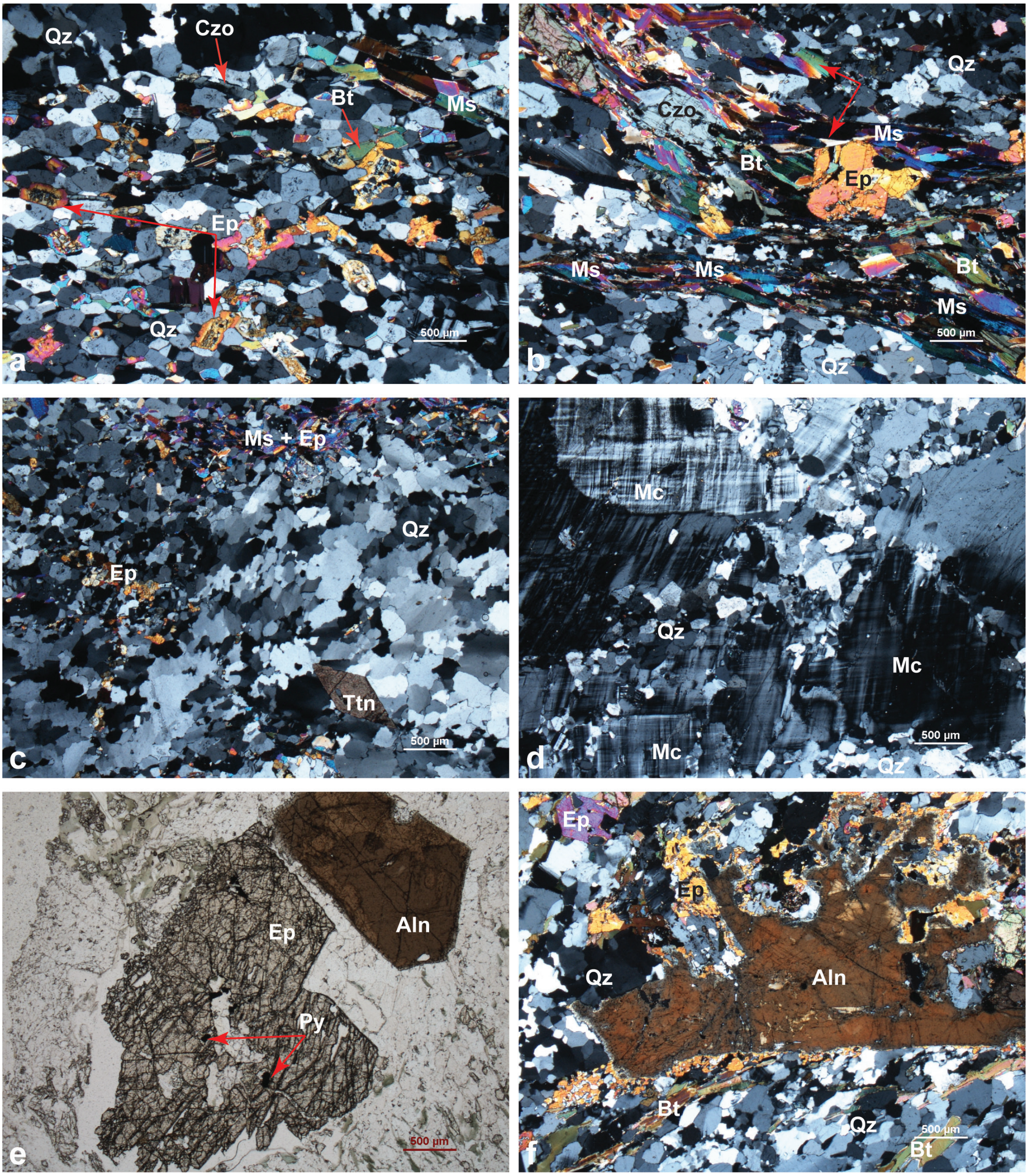

Fig. 7. Microphotographs of dark coloured pavers. Quartz is a predominant mineral. Intensive dynamic recrystallization resulted in granoblastic texture. (a) Granoblastic polygonal texture where the equidimensional quartz has well developed crystal faces resulting in straight grain boundaries; the triple junctions are common. Minerals with higher interference colors belong to muscovite, biotites, clinozoisite, and epidote (note the zoning). (b) Granoblastic interlobate texture where quartz grain boundaries are mostly irregular (lover left-hand side of the figure). The segregation of muscovite and biotite in the central part of the figure is forming foliation. (c) Idiomorphic titanite in quartz with granoblastic amoeboid texture, the rest of the minerals are xenomorphic. The dynamic recrystallization is not complete and in several places, signs of recovery are still visible. Minerals with higher interference colours are muscovite and epidote. (d) Deformed microcline porphyroclasts are replaced by dynamically recrystallized quartz along the edges. (e) Large epidote grains with small pyrite inclusions next to idiomorphic brown coloured allanite with slight zoning. The rock is composed mostly of dynamically recrystallized quartz with rare small micas and epidote group minerals. (f) Xenomorphic zoned allanite partly altered along the rim. Slightly chloritized biotite (lower part of figure) and epidote are also recognizable. Figures (a–d and f), were taken under crossed polars. Figure (e) was taken under plane polarized light. Mineral abbreviations are according to Whitney & Evans (2010).

resulting in pronounced foliation (figs. 6b, d). Muscovite has typical flaky appearance with sizes ranging from 0.10 to 0.8 mm. Biotites are often replaced by chlorite and/or epidote; therefore, they are unusually green, rarely brown, in colour. Biotites are a bit less common and smaller in size compared to muscovite, reaching maximal size of 0.6 mm, but they are mostly much smaller.

Titanite is hipidiomorphic to idiomorphic, frequently with rhombic form and 0.02 to 1 mm in size. It can occur as individual crystals in matrix or as inclusions in feldspars, epidote, and kyanite. Clinopyroxenes are hipidiomorphic and 0.02 to 0.75 mm in size. They occur as individual matrix minerals (fig. 6f). Small zircons do not exceed 0.08 mm in diameter, are mostly rounded and are heterogeneously distributed in the matrix or as inclusions in biotite. Rare kyanite minerals are present in hipidiomorphic form and are full of inclusions, mostly belonging to titanite. Their average size is 0.8 mm. Pyrite occurs in xenomorphic crystals, only seldom it is found in idiomorphic forms with well-developed crystal faces of a cube. Pyrite crystal size ranges from 0.05 to 0.45 mm. Pyrite is often limonitized and display partly transparent red coloured edges. Calcite occurs as secondary mineral phase, is xenomorphic and is reaching 0.10 to 1.25 mm in size. It is found in form of filling in thin veins or as accompanying mineral together with quartz in matrix around bigger feldspar porphyroclasts.

Dark coloured pavers

All samples display inhomogeneous texture, which show signs of intensive dynamic recrystallization processes. Quartz is the most abundant mineral in all samples, making up to 50 % of the rock. The other constituents are represented by epidote group minerals (18 %), feldspars (17 %), micas (at 8 %), and the remaining 7 % belong to titanite, calcite, zircon, kyanite, and pyrite.

Quartz is predominant mineral in all samples. Its extinction is mostly uniform and rarely undulatory. It shows signs of intensive dynamic recrystallization that resulted in different types of granoblastic texture (figs. 7a–c). Feldspars belong to orthoclase, microcline, and plagioclase series and have average size of 0.70 to 2.5 mm. Orthoclase and microcline porphyroclasts are usually deformed and appear rounded or with irregular boundaries due to the replacement by unstrained dynamically recrystallized quartz grains (fig. 7d). Plagioclases are mostly smaller, up to 0.7 mm, contain numerous small mineral inclusions and represent poikiloblasts. Minerals of epidote group belong to epidote, allanite and clinozoisite. Clinozoisite mainly forms individual elongated prismatic crystals in the matrix. Epidote size ranges from 0.02 to 3.5 mm and frequently shows zoning (fig. 7b). Allanite forms big distinctive brown coloured porphyroblasts, frequently with idiomorphic forms. They are reaching up to 3 mm in length and display distinctive zoning (fig. 7e–f).

Micas occur as elongated flaky crystals, 0.1 to 0.75 mm in size, and are heterogeneously distributed thorough the rock. Often they are segregated and concentrated in lenses and layers and are forming gneissic foliation (fig. 7b). Micas are represented by muscovite and minor biotites. Biotites are inferior and commonly replaced by epidote and chlorite. They contain inclusions of small zircon. Titanite is hipidiomorphic to idiomorphic with well-developed rhombic cross-sections (fig. 7c). Individual titanite crystals range in size from 0.10 to 1 mm and occur in matrix or as inclusions in other minerals, mainly kyanite. Zircon was found as small idiomorphic inclusions in biotite or as dispersed crystals in the matrix. Zircon size ranges from 0.05 to 0.1 mm. Rare xenomorphic kyanite crystals do not exceed 0.8 mm. Pyrite is mostly idiomorphic and 0.08 to 0.1 mm in size. Rare xenomorphic grains of calcite occur and are up to 0.5 mm in size. They are found in parts composed of plagioclase and quartz.

Discussion

Petrografic characterization of "Kukul granite" used in the central courtyard of Ljubljana Castle

The stone used in pavers displays macroscopically recognizable gneissic structure, which is a result of metamorphic differentiation. During the metamorphic processes, the dark coloured minerals become segregated into distinct bands, which may be straight or bent. The intensive dynamic recrystallization of the matrix in porphyroclastic parts of the rock resulted in the formation of protomylonitic to mylonitic texture.

The average mineral composition of the rock used for pavers in the central courtyard of Ljubljana Castle is 43 % of quartz, 28 % of feldspars, 14 % of minerals from the epidote group, 7 % of micas and 8 % of other minerals (Table 1). Based on mineral composition and texture characteristics, the investigated specimens of original rock are classified as gneisses (Winter, 2014).

For the purpose of possible future restoration-conservation works, we distinguished two rock varieties: the light coloured and the dark

Table 1. Mineral composition of the rocks used in the pavement stone of the central courtyard of the Ljubljana Castle. Mineral abbreviations are according to Whitney & Evans (2010).

Mineral	Qtz	Kfs	Pl	Ep	Ms	Bt	Ttn	Zr	Cpx	Ky	Py	Cal
Average composition (%)	43	25	3	14	5	2	2	1	1	1	1	2
Light colored pavers (%)	36	35	4	11	4	2	2	1	1	1	1	2
Dark colored pavers (%)	50	15	2	18	6	2	2	1	0	1	1	2

coloured pavers. Both have similar mineral composition, but the proportions between individual minerals are different (Table 1). In light coloured pavers, porphyroclastic, protomylonitic to mylonitic structures are present, while in dark coloured pavers gneissic structure is predominant. Samples of dark coloured pavers with regard to light coloured varieties contain more quartz and epidote and less feldspars, and have no clinopyroxene. They also display more intensive recrystallization that is obvious from common triple junctions, polygonal quartz and frequent granoblastic textures.

In several pavers the transitions between the light and dark variation of natural stone are displayed. These transitions are either sharp or gradual and mostly correspond to the transition between light coloured and undifferentiated to dark coloured and intensively metamorphically differentiated rock. Therefore, even though we considered paving stones as two varieties of rocks, we have to bear in mind that this is the same rock, except that the blocks were obviously taken from various parts of the rock massif during the extraction. The variations within the rock massif are the result of the metamorphic differentiation, which resulted in the formation of various textures due to the segregation and separation of light and dark coloured minerals.

Osojnik (2016) studied the radioactivity of 69 samples of the most used natural stone in the Republic of Slovenia, including samples of Kukul granite. Based on his petrographic observations the Kukul granite is uniform with igneous texture and containes 55 % feldspars, 30 % quartz, 13 % micas, 1 % of epidote minerals and 1 % hornblende, and was classified as monzogranite (Osojnik, 2016). Compared to the samples of "Kukul granite" taken from the Ljubljana Castle courtyard, the proportions of minerals are different, the texture of the rock is obviously metamorphic and the variability of the used natural stone is high.

It is obvious, that the rock described by Osojnik (2016) and rock type used for pavers in the central courtyard of Ljubljana Castle are different, although both have the same commercial name (Kukul granite) and are classified as granite in the market. Although manufacturers of finished products are obliged to demonstrate and ensure the consistency of their products, in the case of Kukul stone, they clearly failed. We assume that in the process of stone extraction in the quarry area, they started to extract not only the granite/granodiorite massif but also the country rocks, which are gneisses with completely different physical, mechanical and aesthetic characteristics.

The provenance of the pavement stone in the central courtyard of Ljubljana Castle

Locality Kukul is situated northeast of the town of Prilep in Rebublic of Macedonia in the direction of Drenova and towards Prisad and Dolneni, at an altitude of 953 m. The stone that has been quarried there under the commercial name Kukul granite is also known as Kukulj or Prilep granite.

According to national regulations of the Republic of Macedonia (the Law on Protection of the natural values since 1965), the Kukul area as part of the Prilep granite complex has been protected as an area of exceptional natural phenomena so that the state nullified the previous concession for the exploitation of the architectural stone (Kurtović, 2018).

The area of Kukul belongs to the Pelagonian massif, a relic of the Precambrian Earth crust in this part of the Dinaric-Helenic belt, also known under the name Pelagonian horst anticlinorium. This large NW–SE-trending, NW-plunging anticlinorium with high-grade metamorphic core consisting of amphibolite grade gneiss, augen gneiss, and schist formed from protoliths of Precambrian metasedimentary rocks. The complex is characterized by a thick section of marble in the upper part that partly frames the anticlinorium, and abundant granitic plutons, and is separated from its neighbouring tectonic units by deep regional faults (Rakičević et al., 1965a; Dumurdzanov et al., 2005). The metamorphic complex of the Pelagonian Massif in general (according to Arsovski, 1960 and Stojanov, 1960, 1974), can be subdivided into: a) the lower metamorphic complex composed of the lowest series of gneiss and granites-granodiorites and the superpositioned series of micaschists; and b) the upper metamorphic complex composed of the so-called mixed series and series of massive marbles. The mixed series, in general, is built from the albite-augen gneiss, white marbles and meta-rhyolites, while the series of the massive marbles is composed of dolomite, dolomite-calcite, and calcite marbles.

In the lower complex, that is, in the series of gneisses, granitoid intrusions are found around Prilep, while in the surrounding region (for example at the contacts of these granitoids and micashists), amphibolites and amphibolite-eclogites occur. The upper metamorphic complex lies concordant on the lower metamorphic complex with a sharp boundary between them (Jancev & Anastasovski, 2004).

It is believed that the metamorphic crystalline rocks (gneisses, micaschists, marbles and other regional metamorphic complexes) are about 1,500–720 million years old continental basement (Upper Proterozoic-Cambrian). These rocks have been intruded by granitoid magma probably about 250–300 million years ago during the Variscan orogeny (Jancev & Anastasovski, 2004; Schenker et al., 2014). Thus, the basic structural characteristics of the metamorphic phase in the Pelagonian massif are the result of syngenetic processes of high regional metamorphism and folding with plastic flow mechanism and contemporaneous intrusion of granodiorites of the first phase when large fold structures were formed (Arsovski, 1997; Spasovski & Dambov, 2011; Schenker et al., 2014).

Granitoid complex of Prilep is structurally a part of Prilep anticline, which covers about 65 km² in the territory north of Prilep (Arsovski, 1960; Rakičević et al., 1965a, b) (fig. 8). A large part of this structure is composed of massive coarse-grained or locally porphyroid granodiorite-adamelite (quartz monzonite). In between are rare occurrences of enclaves of various old schists in the granite. The length of the Prilep

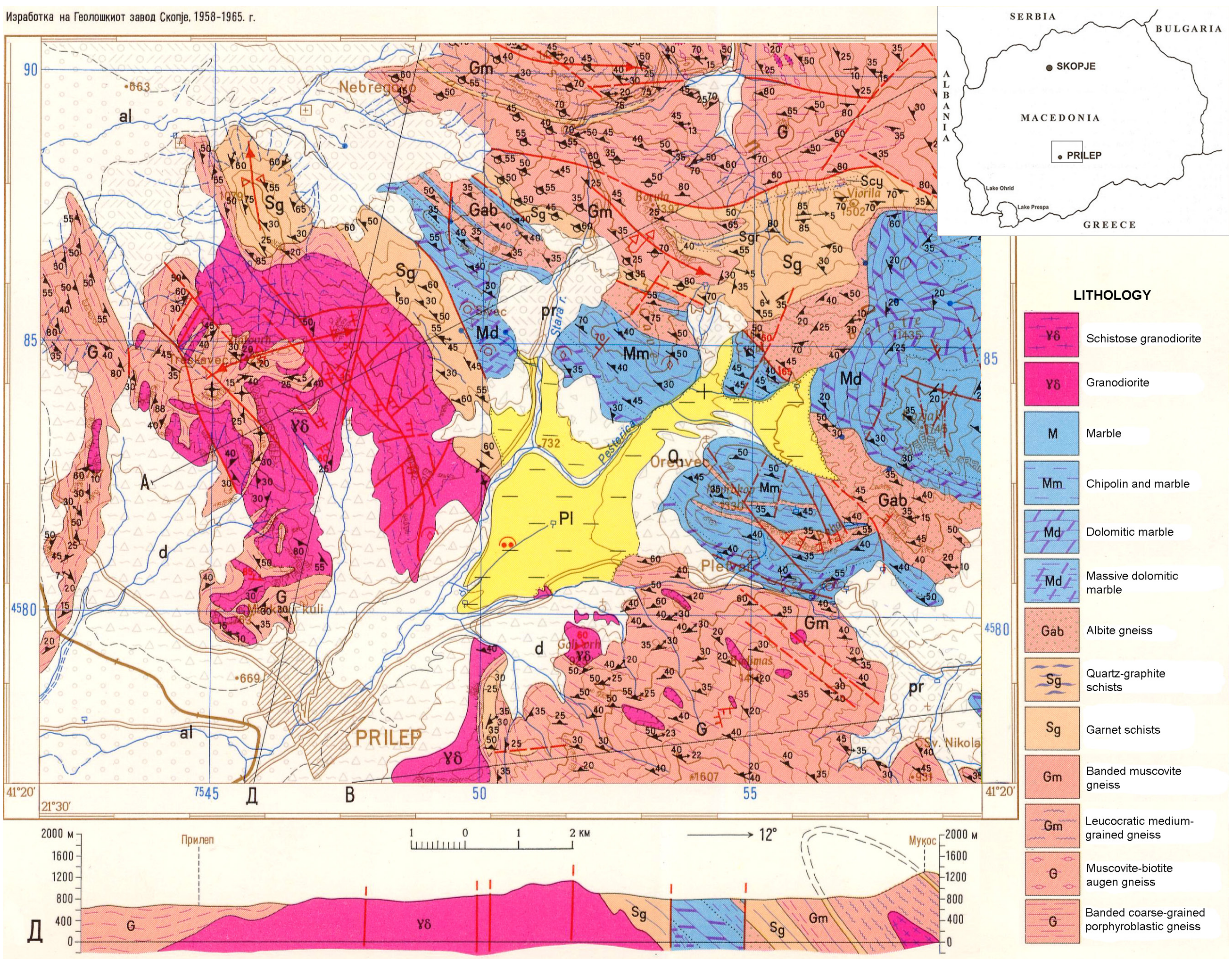

Fig. 8. Geological map and cross-section of the area of Prilep granitoids. Crop out from the Sheet Prilep of the Basic Geological Map 1: 100 000 (Rakičević et al., 1965a).

granodiorit-adamelite massif is about 8–9 km while the width is about 8 km. The contacts of the granite with the surrounding metamorphic rocks are accompanied by the granodiorite-adamelite sills and dykes. These contact zones are from about 10 to a few tens of meters wide and characterized by severe feldspatization in the surrounding rocks as well as other mineralogical manifestations (e.g. quartzites, epidotization, etc.) (Stojanov, 1974).

Suitable replacment pavement stone for conservation-restoration

The natural stones used for pavers in the important areas, like in the central courtyard of the Ljubljana Castle, should be durable and available for longer period, because only in this way the uniform appearance of the area can be maintained. This should be taken into account when important buildings and/or their parts are exposed to extensive conservation-restoration works in modern times.

When the stone from original quarry is not available on the market anymore, suitable replacement must be provided. It is suggested to first check the areas nearby the original quarry. In case that geological setting of the broader area is uniform, there is a great possibility to find a proper replacement stone in the vicinity in the quarry that is situated in the same geological unit (even if it is across the state border). If we have to find a replacement stone for conservation-restoration from the set of foreign rocks, then we must find a rock that will mimic the original rock in its composition and structure as much as possible. Therefore, basic mineralogical and petrological analyses and proper petrographic classification should be the rule and not the exception. Unfortunately, in most cases, the repair works are carried out without proper conservation-restoration guidance or any geological support and the result is what we can see in the central courtyard of Ljubljana Castle. A different type of granite (“Bianco Sardo”) replaces the commercially named “Kukul granite”, which is not a granite but gneiss. Because these two rock types differ much in the texture and in the quantitative mineral composition, it is not a surprise that the advancement of the replacement very much disrupts the uniform appearance of the central courtyard of the Ljubljana Castle (fig. 1).

The Faculty of Civil Engineering of the University of Sarajevo faced the same problem preparing the requirements for conservation-restoration of the prominent Square of Bosnia and Herzegovina in front of the Bosnia and Herzegovina Parliament building in Sarajevo (Kurtović, 2018). There, the pale rose to light brown paving tiles of Kukul granite were originally used in combination with dark Jablanica gabbro. Based on the detailed petrographic analysis of the pavers, the stone was identified as granite with the remark that due to the small amount of plagioclase, it could also be determined as granodiorite, but only after its chemical examination (Kurtović, 2018).

The only open granite-granitic gneiss exploitation field in the wider surroundings of Prilep is the locality of Lozjanska Reka–Kruševica in the area of Mariovo, south-east of Prilep. There, the surface exploitation of granite/granodiorite is producing stone commercially called Mariovo-Krin. The field investigation of the area showed that Kukul-Prilep and Mariovo-Krin represent quarries within the same geological unit. After the physical-mechanical analyses of the Mariovo-Krin stone has shown its high quality, this stone was approved for use as a replacement stone of on the Bosna and Hercegovina Square (Stojkov & Spasovski, 2014; Spasovski & Spasovski, 2015; Kurtović, 2018).

This solution is necessary to be considered also for the replacement of the pavers in the central courtyard of Ljubljana Castle, however it might prove not to be applicable, due to our results that the “Kukul granite” there is in fact gneiss.

According to the descriptions of other natural stones in the area of Prilep (in the Pelagonian massif) (Boev, 2006), the granitic gneiss from the locality of Mramorani is very promising. The locality is situated some 6 km north-west of Prilep in close proximity to the village of Mažučiste. Macroscopically this gneiss-granite possesses ornamental look with white-creamy-greenish color. The mineralogy of the rocks consists of quartz, potassium feldspars (orthoclase, anorthoclase, microcline), acid plagioclases (albite to andesine), muscovite, biotite, apatite, rutile, titanite, ilmenite, zircon and epidote (Boev, 2006).

Conclusions

Based on mineralogical, petrographic, textural and structural characteristics of original natural stone used in pavers as well as literature data on provenance and geological setting we can make the following conclusions:

1. Present appearance of the central courtyard of Ljubljana Castle is uneven and disrupted because the original pavement stone, from the Kukul area northeast of the town of

Prilep, is not available any more for conservation-restoration works. They are replacing it, without professional conservation-restoration guidance, with inappropriate replacement granitic rock with commercial name "Bianco Sardo" originating from Italy, which is completely different in colour, structural and compositional characteristics.

2. The original pavement stone contains on average 43 % of quartz, 28 % of feldspars, 14 % of minerals from the epidote group, 7 % of micas and 8 % of other accessory minerals. Based on the composition and structural characteristics it belongs to granitic gneiss.
3. Two types of pavers are recognized, the light and the dark rock types. They have similar mineral composition, only the proportions of the minerals are different; dark coloured pavers contain more quartz and epidote, less feldspars, and no clinopyroxene. Light coloured pavers have porphyroclastic, protomylonitic to mylonitic structures and dark coloured pavers display gneissic structure. The processes of dynamic recrystallization are more intensive in the dark coloured rock. Since in several pavers transitions between the light and dark rock types are displayed, we assume that this is in fact the same rock, but extracted from various parts of the structurally uneven rock massif. The obtained variations are the result of metamorphic differentiation, which produced the segregation and separation of light and dark coloured minerals.
4. Natural stone coming from Kukul (Republic of Macedonia) was known as a type of granite and/or granodiorite on the market. The rock that is used in the central courtyard of Ljubljana Castle is obviously gneiss, therefore, we assume that in the last stages of quarrying in the Prilep area, parts of the metamorphic counrty rocks were also exposed to quarrying activities.
5. Today, the only open granitic gneiss exploitation field in the wider surroundings of Prilep is the locality of Lozjanska Reka–Kruševica and there are a few localities of granitic gneiss of high potential. It would be necessary to consider these solutions for conservation-restoration of the Ljubljana Castle central courtyard instead of using an inappropriate stone substitutes.

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Poročila

Poročilo o I. strokovnem simpoziju o rudniku Sitarjevec

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V Litiji je dne 20.9.2018 je potekal I. strokovni simpozij o rudniku Sitarjevec in srečanje rudarskih mest, v okviru katerega so bile predstavljene aktivnosti ob ponovni oživitvi rudnika v raziskovalne, izobraževalne in turistične namene. Simpozija se je poleg geologov, biologov, rudarskih strokovnjakov, muzealcev, pedagogov in predstavnikov znanih rudarskih mest Litija, Zagorje, Idrija, Zreče in Črnomelj ter predstavnika iz Češke republike (Sanatorium EDEL, Zlaté Hory), udeležilo precej litijskih občanov.

Glede na to, da je bil Sitarjevec eden izmed največjih polimetalnih rudnikov v Sloveniji, je bil poudarek simpozija na mineralnem bogastvu in recentnih pojavih hitro rastočih limonitnih kapnikov v opuščenih rudniških rovih. Predstavljene so bile paleogeografske in paleoekološke razmere v obsežni rečni delti in v kateri so pred več kot 300 milijoni let v ekvatorijalnem pasu nadceline Pangea nastajale kamnine Sitarjevca. Njihovo poznokarbonsko starost dokazuje bogata fosilna flora, ki je bila najdena v neposredni okolici rudnika.

Pomemben prispevek simpozijskemu programu so prispevali biologi, ki so v rudniških rovih proučevali prisotnost žuželk, netopirjev in sledove bele kune, ki globoko v rudniške rove zahaja občasno. Del simpozija je bil namenjen recentnim geokemičnim raziskavam rudniških vod in vplivu rudarskih del in topilniške dejavnosti na razmere v okolju.

Simpozijski materiali so zbrani v bogato ilustrirani publikaciji, ki jo je izdala občina Litija.

Ob koncu so si udeleženci simpozija ogledali turistični del rudnika Sitarjevec, ki ga je občina Litija uredila v delu izvoznega rova na južni strani hriba Sitarjevec.

Simpozij je bil dobra popotnica evropskemu projektu MINETOUR v okviru Programa sodelovanja Interreg V-A Slovenija – Hrvaška 2014 - 2020, v katerem je poleg rudnika Sitarjevec vključen tudi premogovnik Labin na Hrvaškem.

Hidrogeološki kolokviji v obdobju od 2016 do 2018

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Hidrogeološki kolokvij je strokovni dogodek, ki se odvija proti koncu vsakega koledarskega leta. Organiziran je v sodelovanju med Oddelkom za geologijo Naravoslovnotehniške fakultete Univerze v Ljubljani in Slovenskim komitejem mednarodnega združenja hidrogeologov - SKIAH. Dogodek pritegne večje število udeležencev, študente, hidrogeologe iz prakse, strokovnjake iz različnih državnih ustanov in iz akademske sfere. Vsako leto se kolokvija udeleži okoli petdeset udeležencev iz cele Slovenije, pogosto pa tudi gostov iz tujine. Namen hidrogeološkega kolokvija je seznanjanje strokovne javnosti z rezultati aktualnih hidrogeoloških raziskav in z odprtimi hidrogeološkimi problemi na območju Slovenije. Hkrati je namen kolokvija tudi seznanjanje slovenske strokovne javno-sti z dosežki hidrogeološke stroke v svetu. Tako kolokvij skoraj vsako leto gosti vabljene predavatelje iz tujine, praviloma so to strokovnjaki iz širše soseščine Slovenije, s katerimi imamo slovenski hidrogeologi tudi najboljše povezave.

V zadnjih treh letih, od leta 2016 do leta 2018, se je v okviru kolokvija zvrstilo enajst predavanj in nekaj spremljevalnih dogodkov. 9. hidrogeološki kolokvij je potekal 20. decembra 2016. Sprva je bil dogodek v celoti namenjen predstavitvi regionalnega bilančnega modela GROWA-SI, ki ga je pripravila Agencija Republike Slovenije za okolje, žal pa smo morali organizatorji zaradi nenadne odpovedi glavnega predavatelja, avtorja nemškega modela GROWA, program kolokvija spremeniti. Od prvotne programske zasnove je na sporedu ostala le predstavitev Miša Andjelova z Agencije Republike Slovenje za okolje z naslovom: »Regionalni model napajanja vodonosnikov GROWA-SI; Uporaba regionalnega hidro(geo)loškega modela za izračun komponent vodne bilance v Sloveniji«. Temu predavanju je sledila predstavitev knjige »Groundwater recharge in Slovenia« (Napajanje podzemne vode v Sloveniji) na katero se je navezovalo tudi predhodno predavanje. Knjiga podaja sintezo bilančnih izračunov podzemne vode za območje celotne Republike Slovenije in tako predstavlja prvo temeljito sistematično študijo bilančnih komponet podzemne vode na območju celotne države. Sklopu, ki se je navezoval na vodnobilančni model GROWA-SI, je sledilo predavanje Barbare Čenčur Curk z Oddelka za geologijo, ki je predstavila rezultate evropskega projekta Drink Adria. V projektu so sodelovale skoraj vse države, ki so nastale na ozemlju nekdanje Jugoslavije ter države Jadransko Jonskega pasu Italija, Grčija in Albanija. Projekt se je ukvarjal s problematiko opredelitve prekomejnih vodnih virov pitne vode in prekomejne dobave pitne vode. Poleg teoretičnih sklepov in praktičnih analiz ter interpretacij so bile pomemben del rezultatov projekta tudi investicije na prekomejni infrastrukturi za oskrbo s pitno vodo. V okviru projekta Drink Adria je bila opravljena tudi podrobna analiza določanja in implementacije vodovarstvenih območij v vseh na projektu sodelujočih državah. To analizo je v kratkem predavanju z naslovom »Vodovarstvena območja – Mednarodni pogled« predstavil Mihael Brenčič z Oddelka za geologijo.

Naslednji 10. hidrogeološki kolokvij je potekal 30. novembra 2017 in je bil izveden v Tednu Univerze v Ljubljani. Na tem kolokviju so bila predstavljena tri obsežnejša predavanja. Prvi dve predavanji sta predstavili rezultate dela na znanstvenih magisterijih s področja hidrogeologije. V predavanju z naslovom »Vpliv geološke zgradbe na kemijsko stanje podzemne vode na primeru Pomurja« je Marina Gacin z Agencije Republike Slovenije za okolje predstavila temeljito sintezo vseh razpoložljivih hidrogeoloških podatkov na območju medzrnskega vodonosnika Pomurja. S pomočjo teh podatkov je pripravila karto porazdelitve nitratov v podzemni vodi. V naslednjem predavanju je Branka Bračič Železnik iz javnega podjetja Vodovod Kanalizacija iz Ljubljane predstavila predavanje z naslovom »Dinamika podzemne vode sistemov vodonosnikov Iškega vršaja«. Iški vršaj je pomemben vir pitne vode za južno obrobje mesta Ljubljana, predvsem pa za naselja na južnem obrobju Ljubljanskega barja. Pri tem gre za navidez enostaven medzrnski vodonosnik, za katerega pa so podrobnejše hidrogeološke raziskave v zadnjem desetletju pokazale, da je tok podzemne vode in njeno napajanje kompleksnejše od tega, kakor smo ta sistem razumeli do sedaj. Zadnje predavanje z naslovom »Izkušnje in izzivi upravljanja s podzemno vodo v Srbiji in na Balkanu« je pritegnilo veliko pozornost. Predaval je Zoran Stevanovič redni profesor Oddelka za hidrogeologijo Rudarsko geološke fakultete Univerze v Beogradu, ki predseduje Komiteju za kraško hidrogeologijo Mednarodnega združenja hidrogeologov in je avtor, soavtor in urednik številnih odmevnih člankov in knjig, predvsem s področja kraške hidrogeologije. Profesor Stevanovič je najprej predstavil razvoj hidrogeologije v Srbiji in njene glavne dosežke, nato pa se je dotaknil problematike globalne oskrbe s pitno vodo s poudarkom na kraških vodonosnikih. Na koncu predavanja je predstavil rezultate pomembnih hidrogeoloških projektov na območju Srbije in Črne gore. Po zaključku predavanj je bila izvedena še skupščina SKIAH.

V letu 2018 je kolokvij prvič potekal v prenovljenih prostorih Oddelka za geologijo na Aškerčevi cesti, pred tem je, vse do vključno 10. kolokvija leta 2017, dogodek potekal v prostorih Oddelka za geologijo na Prulah. 11. hidrogeološki kolokvij je bil izveden 29. novembra 2018. Ta kolokvij je bil v celoti posvečen problematiki vodovarstvenih območij. Na področju vodovarstvenih območij imamo v Sloveniji dolgoletne in bogate izkušnje. Prva vodovarstvena območja so bila določena že pred drugo svetovno vojno, vse od sredine petdesetih let 20. stoletja, ko so bila opredeljena območja v današnjem smislu, pa se je metodika njihovega določanja intenzivno razvijala. Slovenska hidrogeologija je na področju implementacije in razvoja metodologije varovanja virov pitne vode nedvomno v svetovnem vrhu. To pa ne pomeni, da ni možnosti za dopolnitve in korigiranje obstoječe prakse. Prav temu je bil namenjen 11. hidrogeološki kolokvij. V skladu z uveljavljeno prakso je prvi nastopil gostujoči predavatelj iz tujine. To je bil tokrat Jochen Schlamberger, vodja Oddelka za geologijo in monitoring voda pri Koroški deželni vladi v Avstriji. V predavanju z naslovom »Varovanje virov pitne vode v Avstriji« je predstavil metodologijo določanja vodovarstvenih območij in postopkov varovanja vodnih virov pitne vode v Avstriji. Nina Mali z Geološkega zavoda Slovenije je v predavanju »Vodovarstvena območja v Sloveniji – včeraj, danes in jutri« predstavila pregled trenutnega stanja vodovarstvenih območij na območju Slovenije, prikazala je njihovo prostorsko raztezanje in težave ter odprte probleme pri njihovem uveljavljanju v praksi. Branka Bračič Železnik je v predavanju »Vodovarstvena območja z vidika javne službe oskrbe s pitno vodo« na primeru vodovarstvenih območij severno od Ljubljane prikazala probleme in izzive, s katerimi se sooča Javno podjetje Vodovod Kanalizacija, ki upravlja po številu priključkov z največjim vodovodnim sistemom v Sloveniji. Analiza tveganja onesnaženja podzemne vode je pomemben inštrument presoje vplivov posegov v prostor na vodovarstvenih območjih. Čeprav je to mehanizem, ki je namenjen zlasti preverjanju predlaganih rešitev, se je v zadnjih letih pokazalo, da je ta postopek pogosto neustrezno implementiran. Problematiko analize tveganj je v predavanju z naslovom »Analiza tveganja kot sestavni del varovanja vira pitne vode – odprta vprašanja in problemi« predstavil Mihael Brenčič. Hidrogeološki kolokvij se je zaključil z okroglo mizo, ki jo je vodila Barbara Čenčur Curk. Kot panelisti so sodelovali predavatelji, svoja mnenja pa so prispevali tudi ostali udeleženci kolokvija. Razprava je oblikovala nekatere smernice za nadaljnje delo. Tudi v letu 2018 je bila po zaključku kolokvija skupščina SKIAH, ki je za naslednje mandatno obdobje petih let izvolila novo vodstvo društva.

Poročilo o 5. slovenskem geološkem kongresu, Velenje 3. – 5. oktober 2018

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Letos mineva 16 let od prvega kongresa slovenskih geologov, ki se je v organizaciji Geološkega zavoda Slovenije in Slovenskega geološkega društva odvijal v Črni na Koroškem. Že ob prvem nas je presenetil odziv, ki je pokazal, da je geološki kongres zaželen in potreben dogodek, saj omogoča predstavitev rezultatov znanstvenih raziskav z neposredno izmenjavo mnenj in izkušenj. Skozi leta je kongres rasel tako po številu udeležencev in predstavitev, kot obravnavanih tematik. Žal je bil od kongresa do kongresa opazen osip udeležbe predvsem tistih strokovnjakov, ki geološka znanja uporabljajo pri aplikativnem delu ali pa so končni uporabniki rezultatov geoloških raziskav.

Organizacija in cilji

Organizatorja 5. slovenskega geološkega kongresa, Geološki zavod Slovenije (GeoZS) in Slovensko geološko društvo (SGD), sta si za enega od glavnih ciljev zadala, da bi ta kongres poleg svojega osnovnega namena, predstavitev raziskovalnih dosežkov slovenskih in tujih geologov, prispeval tudi k premoščanju vrzeli in podiranju zidov med znanstveniki in strokovnjaki ter med geologi in snovalci politik ter najširšo javnostjo. V ta namen sta za prizorišče kongresa izbrala Velenje, mesto, ki živi z geologijo in v katerem obratuje še zadnji slovenski premogovnik, in k organizaciji kongresa povabila sorodne inštitucije in društva ter lokalne partnerje: Premogovnik Velenje (PV), Fakulteto za gradbeništvo in geodezijo (FGG), Slovensko rudarsko društvo inženirjev in tehnikov (SRDIT), Društvo slovenski komite mednarodnega združenja hidrogeologov (SKIAH) in Mestno občino Velenje (MOV).

Udeležba, teme in prispevki

Na 5. slovenskem geološkem kongresu, ki je potekal med 3. in 5. oktobrom 2018 v Hotelu Paka v Velenju, je sodelovalo 191 udeležencev iz 18 držav. Med prijavljenimi iz tujine so bili gostje iz Hrvaške, Albanije, Avstrije, Belgije, Bosne in Hercegovine, Črne gore, Islandije, Madžarske, Makedonije, Nemčije, Poljske, Portugalske, Republike srbske, Rusije, Slovaške, Švice, Velike Britanije in ZDA.

Predstavljenih je bilo 169 prispevkov, od tega 112 predavanj in 57 posterjev. Predstavitve so bile razvrščene v 12 sekcij in so obsegale naslednja področja: regionalna geologija, stratigrafija, mineralogija, petrologija, sedimentologija, paleontologija, strukturna geologija, tektonika, seizmologija, geologija kvartarja, geologija krasa, geokemija in okolje, hidrogeologija, geotermija, inženirska geologija, geotehnologija, mineralne surovine, materiali, geoenergenti ter geologija v šoli in širši javnosti. V sekciji Gospodarjenje z mineralnimi surovinami in varovanje podzemnih voda so sodelovali predstavniki ministrstev, dve sekciji z mednarodno zasedbo pa sta potekali pod okriljem mednarodnih združenj; ena pod okriljem Komisije za mineralne in termalne vode Mednarodnega združenja hidrogeologov (IAH CMTW) in druga pod okriljem Skupnosti znanja in inovacij (KIC) EIT RawMaterials. Na razpisanem natečaju za najboljše predstavitve smo podelili tri nagrade za najboljše posterske predstavitve in nagrado za najboljšo študentsko predstavitev. Nagrade za posterske predstavitve so prejeli Lan Zupančič s soavtorji (1. mesto), Nina Valand s soavtorji (2. mesto) in Tea Novaković s soavtorji (3. mesto). Nagrado za najboljšo študentsko predstavitev pa je za predavanje prejela Valentina Pezdir s soavtorjema.

Plenarna predavanja

Štiri plenarna predavanja so povezovala rdečo nit letošnjega kongresa, temo »Geologija in družba«, s katero smo opozarjali na vlogo in pomen geologije in geološkega profesionalizma za družbo in njen razvoj. Dr. Slavko Šolar, generalni sekretar Evropskega združenja geoloških zavodov (EuroGeoSurveys), je o tem govoril v predavanju z naslovom Interakcija med znanstveniki/strokovnjaki in družbo: neizkoriščene priložnosti za vse? (sl. 1), dr. Vitor Correia, predsednik Evropske zveze geologov (European Federation of Geologi-

Sl. 1. Dr. Slavko Šolar, generalni sekretar Evropskega združenja geoloških zavodov (EuroGeoSurveys)

sts), v predavanju Družbeni izzivi XXI. stoletja: geologija na piedestalu (sl. 2), dr. Ruth Allington, predsednica Delovne skupine IUGS za profesionalizem v geoznanosti (IUGS Task Group on Global Geoscience Professionalism), pa v predavanju z naslovom Brisanje meja med znanostjo in stroko – obveza družbeno odgovorne in koristne geoznanosti (sl. 3). V zadnjem plenarnem predavanju z naslovom Geoenergetski viri Slovenije je dr. Miloš Markič predstavil prispevek širše skupine, ki se na Geološkem zavodu Slovenije ukvarja s to, za družbo zelo aktualno tematiko (sl. 4).

Okrogla miza in predstavitev portala eGeologija

Osrednji dogodek v okviru kongresa je bila okrogla miza z naslovom Ali je Slovenija pripravljena na uporabo geološkega znanja pri svojem razvoju? Na njej smo 4. 10. 2018 soočili različne poglede in izkušnje predstavnikov geoznanosti in uporabnikov geoloških podatkov glede vloge in pomena zbiranja, interpretiranja in javne dostopnosti geoloških podatkov za razvoj družbe. V razpravi, ki jo je povezoval Igor E. Bergant, so sodelovali (sl. 5 z desne proti levi): mag. Joško Knez, Agencija RS za okolje (ARSO); Tomaž Prohinar, Direkcija za vode, MOP; Ervin Vivoda, Sektor za zmanjševanje posledic naravnih nesreč, MOP; dr. Leopold Vrankar, Direktorat za energijo, MZI; dr. Tomaž Žagar, Služba za načrtovanje in nadzor v GEN energija; Andrej Ločniškar, DRI upravljanje investicij; dr. Mihael Brenčič, Naravoslovnotehniška fakulteta UL in dr. Miloš Bavec, GeoZS. Cilj okrogle mize je bil, da bi mnenja razpravljavcev spodbudila snovalce politik k učinkovitejšemu prenosu znanja in kompetenc slovenske geoznanosti v prakso za potrebe državnih in lokalnih organov in gospodarskih subjektov. V skladu s tem ciljem so sodelavci Geološkega informacijskega centra GeoZS pred okroglo mizo predstavili spletni portal eGeologija, ki je razvit za namene zbiranja, urejanja in javne dostopnosti podatkov o geosferi. Portal eGeologija je bilo možno tudi preizkusiti ves čas kongresa v hotelski avli (sl. 6).

5.000.000.000 _ 5.0

5. SLOVENSKI GEOLOŠKI KONGRES, Velenje, 3.–5. 10. 2018

Do 5 milijard let z družbo 5.0

Sl. 5. Okrogla miza Ali je Slovenija pripravljena na uporabo geološkega znanja pri svojem razvoju?

Sl. 2. Dr. Vitor Correia, predsednik Evropske zveze geologov (European Federation of Geologists)

Sl. 3. Dr. Ruth Allington, predsednica Delovne skupine IUGS za profesionalizem v geoznanosti (IUGS Task Group on Global Geoscience Professionalism)

Sl. 4. Dr. Miloš Markič, Geološki zavod Slovenije

Sl. 6. Demonstracija spletnega portala eGeologija

Sl. 7. Udeleženci ekskurzije E-1 na bloku Termoelektrarne Šoštanj

Sl. 8. Razlaga na ekskurziji E-2

Sl. 9. Udeleženci ekskurzije E-3 ob profilu Velunja

Sl. 10. Razstava Geoznanost za družbo v velenjski galeriji na prostem

Sl. 11. Geološke delavnice na Dnevu geologije na Visoki šoli za varstvo okolja v Velenju

Ekskurzije

Tridnevni kongres so sklenile tri celodnevne kongresne ekskurzije in ena tridnevna pokongresna ekskurzija. Ekskurzija E-1: Velenjski lignit – geološka edinstvenost in njegova vloga v energetiki Slovenije, je tri ločene skupine vodila v aktivni del Premogovnika Velenje (jamo Pesje), Muzeja premogovništva Slovenije in Termoelektrarno Šoštanj (sl. 7), skupna pa sta bila uvoda predstavitev na sedežu Premogovnika in ogled območij z vidnimi posledicami rudarjenja in območij sanacije. Inženirsko-geološka ekskurzija E-2: Načrtovanje trase 3. razvojne osi in geološko pogojeni dejavniki tveganja pri umeščanju prometnic v prostor je potekala po trasi načrtovanega severnega odseka 3. razvojne osi, od priključka Velenje jug do Šentruperta (sl. 8). Stratigrafsko-sedimentološko-tektonska ekskurzija E-3: Geološki razvoj kenozojskih sedimentacijskih bazenov v širši okolici Velenja je potekala na območjih oligocenskega Smrekovškega bazena, preko Periadriatske prelomne cone do Slovenjgraškega miocenskega bazena in Velenjskega pliokvartarnega bazena (sl. 9).

Pokongresna ekskurzija je podrobneje opisana v ločenem prispevku v tej izdaji.

Obkongresne dejavnosti in dogodki

Eden od pomembnih ciljev 5. slovenskega geološkega kongresa je bil tudi ta, da geologijo kot znanost in stroko predstavimo najširši družbi. V ta namen je bila organizirana vrsta obkongresnih aktivnosti in dogodkov. Organizatorja kongresa sta razpisala fotografski natečaj Geoznanost za družbo, na katerem je sodelovalo 15 avtorjev, ki so poslali skupaj 41 fotografij. Ocenjevalna komisija je med njimi izbrala 12 fotografij. Zmagovalne fotografije natečaja in fotografije strokovnjakov Geološkega zavoda Slovenije, ki tematsko dopolnjujejo predstavitev različnih vej geoznanosti in področij njihovih raziskav, bodo do aprila 2019 razstavljene v velenjski Galeriji na prostem (sl. 10).

Tudi razstava Litosfera, ki jo je v sodelovanju z Muzejem Velenje pripravil Oddelek za geologijo NTF in bo na Velenjskem gradu razstavljena vse do oktobra 2019, je imela podoben cilj. Na razstavljenih vzorcih slovenskih kamnin iz študijskih zbirk Oddelka je predstavljeno, kako geologi beremo zgodovino Zemlje, procesov, ki jo oblikujejo in zgodovino življenja na njej.

Med najpomembnejšimi ciljnimi skupinami so bili učenci in dijaki osnovnih in srednjih šol. Zanje smo v okviru evropskega projekta RM@Schools3.0 – Raw Matters Ambassadors at Schools 3.0 v sodelovanju z Muzejem premogovništva Slovenije pripravili delavnico o mineralnih surovinah, v sodelovanju z Visoko šolo za varstvo okolja v Velenju pa je Skupina za popularizacijo geologije Slovenskega geološkega društva organizirala Dan geologije z geološkimi delavnicami. Na delavnice se je prijavilo skupaj kar 150 učencev in dijakov (sl. 11).

Ob tem smo z organizacijo GeoTEKa okrog Škalskega jezera, tradicionalne akcije Slovenskega geološkega društva, poskrbeli tudi za geološko obarvano rekreacijo.

Kongresna gradiva

Vse podrobnejše informacije o 5. slovenskem geološkem kongresu in obkongresnih dogodkih najdete na kongresni spletni strani www.geo-zs.si/5SGK. Tam so objavljene tudi elektronske izdaje vseh tiskanih kongresnih gradiv, video posnetki okrogle mize in dveh plenarnih predavanj, rezultati natečajev in fotografije.

Zahvala

Vsem sodelujočim inštitucijam in posameznikom, ki so na kakršen koli način pripomogli k uspešni izvedbi kongresa, se v imenu organizacijskega odbora najlepše zahvaljujeva. Zahvaljujeva se tudi vsem sponzorjem in donatorjem, ki so z denarnimi ali materialnimi prispevki omogočili izvedbo kongresa. To so: GEN energija, d.o.o.; Alpina, tovarna obutve; Atlantic Grupa; Dana, proizvodnja in prodaja pijač; Energetika Ljubljana; Fido; Gdi Gisdata; Geobrugg AG Switzerland; Geokop; Gradbeni inštitut ZRMK; Nikon Slovenija; Ocean Orchids; Petrol Geoterm; Pomgrad; Radenska; Skupnosti znanja in inovacij EIT RawMaterials; Ščurek; Tektonik pivovarna in Termit.

Short report on: Post-congress field trip of the 5th Slovenian Geological Congress, October 6th-8th 2018: Geology, hydrogeology and geothermy of NE Slovenia and N Croatia

Nina RMAN

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The 5th Slovenian Geological Congress was a great opportunity to promote also international exchange of experience. One of the reasons that 21 researchers in the fields of hydrogeology and geothermal energy from nine countries (Slovenia, Belgium, Croatia, Hugary, New Zealand, Poland, Slovakia, Switzerland and USA) spent an interesting prolonged weekend together, visiting sites in Slovenia and Croatia, was also the patronage of the Commission on Mineral and Thermal Water of the International Association of Hydrogeologists (CMTW-IAH).

The Commission on Mineral and Thermal Water is one of the two the oldest commissions of IAH, being established in August 1968 in Prague, Czechoslovakia, during the 23rd session of the International Geological Congress (IGC). The objective of the Commission is to bring together scientists, engineers and other professionals dealing with mineral and thermal waters, and is open also to young beginners. The traditional CMTW-IAH annual meetings are educational, with lots of scientific and technical knowledge exchange regarding also the host country of the meeting. In 2018, the annual meeting was organised during the presented post-congress field trip, however, many commission members contributed already to the scientific sessions of the 5th Slovenian Geological Congress with posters and presentations. The Commission is honoured to have among its members internationally recognized professionals, we may mention only some: the ambassador professor Jan Dowgiałło, professor Ladislaus Rybach, and dr. Jim LaMoreaux, the actual Chairman. More about the history of the CMTW-IAH can be found in the article of Dowgiałło (2013: Envir. Earth Sci. 70: 2923-2928).

On Saturday, we have learned about geology and hydrogeology along the Celje-Lenart highway, visited very promising but now closed geothermal well Be-2 in Benedikt in Slovenske gorice, tasted the mineral water of Ivanjševska slatina, listened to the natural CO_2 seeps at mofette Strmec, visited the bottling company Radenska d.o.o., heard about the shallow and deep geothermal energy use as well as coal and hydrocarbon exploration in NE Slovenia, visited the exhibition on 75 years of hydrocarbon exploitation at Lendava, and visited the geothermal doublet in Lendava. On Sunday, we stared at a natural oil spring in Peklenica, walked on the Quaternary sands "Đurđevački peski" and discussed the local drinking water supply, had a most interesting visit to a brand new nearly-opened geothermal power plant in Velika Ciglena, and listened to the geological evolution of the Croatian Zagorje Region in Stubičke Toplice. On Monday, we have learned about the bathing and heating technology in the AQUAE VIVAE Waterpark in Krapinske Toplice, visited the exhibition in the Krapina Neanderthal Museum, and tasted the natural mineral waters in Rogaška Slatina.

Fig. 1. Mofette Strmec (photo: D. Rajver).

Fig. 2. Natural oil spring in Peklenica (photo: N. Rman).

Fig. 3. Wells in geothermal power plant in Velika Ciglena (photo: L. Serianz).

Evaluation showed that the most interesting topics to the participants were: geothermal power plant in Velika Ciglena, chemistry, isotopic data and hydrogeological information, presentation of Mg rich natural mineral waters and natural oil spring in Peklenica. In future, more information is wanted also on the utilization of geothermal and mineral water in Slovenia in relation to Europe, operation of various geothermal systems for heat production in neighbouring countries, shallow geothermal heating and cooling practice, mitigation of scaling and environmental effects of geothermal fluid production and, of course, strategy and perspective of geothermal energy in the region. The journey was positioned in the pilot area of the project DARLINGe (http://www.interreg-danube.eu/approved-projects/darlinge), and we hope that with this international knowledge exchange we will help to support enhanced sustainable use of geothermal energy in this region with really high geothermal potential. As we see it, the interest in further development among experts is promising.

Organization of the field trip was the result of collaboration of several institutions and their representatives, dr. Nina Rman, dr. Tamara Marković and assoc. prof. dr. Mihael Brenčič as representatives from the Slovenian Geological Society, the Geological Survey of Slovenia, the Faculty of Natural Sciences and Engineering of the University of Ljubljana, the Slovenian Committee of the International Association of Hydrogeologists, the Croatian Geological Society and the Croatian Geological Survey. Beside them, we also thank to sponsors who supported the field trip in various ways: Atlantic Grupa d.d., Dana d.o.o., Krapina Neanderthal museum, Petrol Geoterm d.o.o. and Radenska d.o.o.

Fig. 4. Engine room in Aquae vivae waterpark in Krapinske Toplice (photo: D. Rajver).

Posvetovanje »Vloga in pomen geologije v formalnem izobraževanju«, Ljubljana 5. 12. 2019, Oddelek za geologijo NTF

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V okviru tedna Univerze v Ljubljani je v sredo, 5.12.2018 na Oddelku za geologijo Naravoslovnotehniške fakultete potekalo posvetovanje z naslovom »Vloga in pomen geologije v formalnem izobraževanju«. Dogodek sta organizirala Oddelka za geologijo (NTF, UL) in Slovensko geološko društvo (SGD). Posvetovanje je bilo namenjeno razpravi o tem, kakšna je vloga geologije pri izobraževanju na stopnji predšolske vzgoje, osnovne in srednje šole, predstavljen pa je bil tudi pomen geologije v srednješolskem in visokošolskem izobraževanju. Predstavljeni so bili rezultati dela v okviru različnih projektov in v zadnjih letih tudi Skupine za popularizacijo geologije, ki se je v okviru Slovenskega geološkega društva z letom 2018 formirala v Sekcijo za popularizacijo geologije. Med predstavitvami je potekala odprta razprava vseh sodelujočih. Uvodni pozdrav so izrekli namestnik predstojnice Oddelka za geologijo izr. prof. dr. Mihael Brenčič in v. d. predsednika Slovenskega geološkega društva dr. Matevž Novak. Dogodek je vodila in povezovala predsednica Sekcije za popularizacijo geologije doc. dr. Petra Žvab Rožič z Oddelka za geologijo.

V prvi predstavitvi se je mag. Mojca Bedjanič (Zavod RS za varstvo narave), osredotočila na vključevanje vsebin geologije in varstva geološke naravne dediščine v vrtce in 1. triado OŠ, ki je rezultat dolgoletnega izobraževanja na Zavodu RS za varstvo narave in UNESCO Globalnega Geoparka Karavanke. Predstavila je, na kakšen način se geološki cilji pojavljajo v vrtcih in 1. triadi OŠ. Ti so v kurikulumu za vrtce na geologijo navezani posredno, skozi spoznavanje materialov in pokrajine, v učnih načrtih za 1. triado OŠ pa posredno vezani na geološko tematiko pri predmetu Spoznavanje okolja skozi spoznavanje snovi. Opozorila je, da je vključevanje vsebin geologije v tem obdobju izobraževanja v veliki meri odvisno od vzgojitelja oz. učitelja. Da bi le te spodbudili k vključevanju geoloških vsebin v njihove programe, v Geoparku Karavanke že nekaj let pripravljajo in aktivno izvajajo Geo-projektne dneve v okviru projekta "Zabavno, poučno, nič mučno", ki so primer dobre prakse vključevanja geoloških vsebin v formalno izobraževanje. Njihov namen je spodbujati drugačen pristop k vzgoji in poučevanju, aktiven odnos do vsebin s področja geologije in dvigovanje ustvarjalnosti.

Sledilo je predavanje doc. dr. Tomislava Popita (Oddelek za geologijo NTF), ki je predstavil del rezultatov projekta ESTEAM Erazmus+. Eden od ciljev projekta je izdelati mobilno aplikacijo za poučevanje naravoslovnih vsebin v osnovnih šolah (ciljna skupina 3. triada). Predstavil je rezultate analize naravoslovnih vsebin nacionalnih učnih načrtov, izpostavil je pomen metodologij poučevanja naravoslovnih vsebin in prikazal rezultate vprašalnikov, ki so jih v okviru projekta pripravili za učence ter za obstoječe in bodoče učitelje. Rezultati nacionalnih učnih načrtov kažejo premajhen obseg pedagoških ur, ki so na razpolago za geološke vsebine. Rezultati vprašalnikov so pokazali, da se učenci radi učijo s pomočjo eksperimentov, z uporabo IKT tehnologij in v naravi, kar pa se v praksi redko ali nikoli ne izvaja. Pomemben in celo zaskrbljujoč rezultat pa je ta, da skoraj polovica vprašanih na leto za poučevane in učenje naravoslovnih vsebin na prostem preživi le od enega do dveh dni.

Rezultate natančnih analiz trenutno veljavnih učnih načrtov in vsebin učbenikov za osnovne in srednje šole je predstavil Rok Brajkovič (Geološki zavod Slovenije). Osredotočil se je predvsem na taksonomsko nadgradnjo geoloških vsebin, in ali le te ustrezajo zahtevanim stopnjam učnih ciljev, izpostavil je medpredmetno povezanost vsebin, ki je eden od pomembnih faktorjev za dvig trajnosti znanja, na primerih pa je predstavil nekaj vsebinskih nepravilnosti in pomanjkljivosti, ki se pojavljajo v obstoječih učbenikih. Učni cilji in vsebine se večinoma smiselno nadgrajujejo, vendar ostajajo predvsem na prvih treh taksonomskih stopnjah (poznavanje, razumevanje, uporaba). Medpredmetna povezava je precej pomanjkljiva, kar vodi v precejšnjo vsebinsko zmedo in predvsem nezmožnost povezovanja in nadgrajevanja vsebin. Poleg tega so geološke vsebine v učbenikih strokovno pomanjkljive in nezvezne.

Razvoj geološkega izobraževanja v slovenskem nacionalnem prostoru je predstavil izr. prof. dr. Mihael Brenčič (Oddelek za geologijo NTF). Izpostavil je pomen definicije geologije pri razumevanju razvoja geološkega izobraževanja ter vpliv družbeno ekonomskih in političnih razmer v poučevanju geologije. Pregled geološkega izobraževanja je začel z razvojem znanstvene geologije v 18. stoletju in pomenom idrijskega rudnika v tistem času. Geologija je bila v visokošolskem izobraževanju prisotna že pred ustanovitvijo Univerze v Ljubljani, v okviru drugih področij poučevanja ter v strokovnih revijah, pomemben del izobraževalnih vsebin pa je bila vse od začetka ustanovitve Univerze. V srednješolskem izobraževanju se je poučevanje geologije pojavilo z uvedbo realnih gimnazij sredi 19. stoletja, kar je privedlo tudi do prvih učbenikov s področja geologije v slovenskem jeziku. Geologija se kot samostojni predmet v srednjih šolah ne poučuje od konca 80. let 20 stoletja, kar pomeni, da je bila več kot 140 let del srednješolskega poučevanja. Dejstvo je, da geologija v sekundarnem izobraževanju nikoli ni bila v slabši poziciji kot je danes.

Razprava v okviru posveta je prispevala pomembna dejstva tudi s strani udeležencev, ki bodo poleg vseh prikazanih rezultatov predstavljala uporabne dopolnitve za načrtovanje dela in izzivov v bodoče. Predvsem bi si želeli vključevanja geologov v morebitno prenovo učnih načrtov, sodelovanja pri strokovnih recenzijah šolskih učbenikov ter povezovanja in vključevanja geologov v poučevanje bodočih učiteljev, ki geološke vsebine na osnovnih in srednjih šolah poučujejo. Dolgoročni cilj pa je ponovna uvedba samostojnega predmeta Geologija v srednje šole.

Navodila avtorjem

GEOLOGIJA objavlja znanstvene in strokovne članke s področja geologije in sorodnih ved. Revija izhaja dvakrat letno. Članke recenzirajo domači in tuji strokovnjaki z obravnavanega področja. Ob oddaji člankov avtorji predlagajo **tri recenzente**, uredništvo si pridržuje pravico do izbire recenzentov po lastni presoji. Avtorji morajo članek popraviti v skladu z recenzentskimi pripombami ali utemeljiti zakaj se z njimi ne strinjajo.

Avtorstvo: Za izvirnost podatkov, predvsem pa mnenj, idej, sklepov in citirano literaturo so odgovorni avtorji. Z objavo v GEOLOGIJI se tudi obvežejo, da ne bodo drugje objavili prispevka z isto vsebino.

Avtorji z objavo prispevka v GEOLOGIJI potrjujejo, da se strinjajo, da je njihov prispevek odprto dostopen z izbrano licenco CC-BY.

Jezik: Članki naj bodo napisani v angleškem, izjemoma v slovenskem jeziku, vsi pa morajo imeti slovenski in angleški izvleček. Za prevod poskrbijo avtorji prispevkov sami.

Vrste prispevkov:

Izvirni znanstveni članek
Izvirni znanstveni članek je prva objava originalnih raziskovalnih rezultatov v takšni obliki, da se raziskava lahko ponovi, ugotovitve pa preverijo. Praviloma je organiziran po shemi IMRAD (**I**ntroduction, **M**ethods, **R**esults, **A**nd **D**iscussion).

Pregledni znanstveni članek
Pregledni znanstveni članek je pregled najnovejših del o določenem predmetnem področju, del posameznega raziskovalca ali skupine raziskovalcev z namenom povzemati, analizirati, evalvirati ali sintetizirati informacije, ki so že bile publicirane. Prinaša nove sinteze, ki vključujejo tudi rezultate lastnega raziskovanja avtorja.

Strokovni članek
Strokovni članek je predstavitev že znanega, s poudarkom na uporabnosti rezultatov izvirnih raziskav in širjenju znanja.

Diskusija in polemika
Prispevek, v katerem avtor ocenjuje ali komentira neko delo, objavljeno v GEOLOGIJI, ali z avtorjem strokovno polemizira.

Recenzija, prikaz knjige
Prispevek, v katerem avtor predstavlja vsebino nove knjige.

Oblika prispevka: Besedilo pripravite v urejevalniku Microsoft Word. Prispevki naj praviloma ne bodo daljši od 20 strani formata A4, v kar so vštete tudi slike, tabele in table. Le v izjemnih primerih je možno, ob predhodnem dogovoru z uredništvom, tiskati tudi daljše prispevke.

Članek oddajte uredništvu vključno z vsemi slikami, tabelami in tablami v elektronski obliki po naslednjem sistemu:
- *Naslov članka (do 12 besed)*
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- *Izvleček (do 300 besed)*
- *Besedilo*
- *Literatura*
- *Podnaslovi slik in tabel*
- *Tabele, Slike, Table*

Citiranje: V literaturi naj avtorji prispevkov praviloma upoštevajo le objavljene vire. Poročila in rokopise naj navajajo le v izjemnih primerih, z navedbo kje so shranjeni. V seznamu literature naj bodo navedena samo v članku omenjena dela. Citirana dela, ki imajo DOI identifikator (angl. Digital Object Identifier), morajo imeti ta identifikator izpisan na koncu citata. Za citiranje revije uporabljamo standardno okrajšavo naslova revije. Med besedilom prispevka citirajte samo avtorjev priimek, v oklepaju pa navajajte letnico izida navedenega dela in po potrebi tudi stran. Če navajate delo dveh avtorjev, izpišite med tekstom prispevka oba priimka (npr. Pleničar & Buser, 1967), pri treh ali več avtorjih pa napišite samo prvo ime in dodajte et al. z letnico (npr. Mlakar et al., 1992). Citiranje virov z medmrežja v primeru, kjer avtor ni poznan, zapišemo (Internet 1). V seznamu literaturo navajajte po abecednem redu avtorjev.

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Primeri citiranja članka:

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Pleničar, M. 1993: *Apricardia pachiniana* Sirna from lower part of Liburnian beds at Divača (Triest-Komen Plateau). Geologija, 35: 65–68

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Jurkovšek, B., Toman, M., Ogorelec, B., Šribar, L., Drobne, K., Poljak, M. & Šribar, Lj. 1996: Formacijska geološka karta južnega dela Tržaško-komenske planote – Kredne in paleogenske kamnine 1: 50.000 = Geological map of the southern part of the Trieste-Komen plateau – Cretaceous and Paleogene carbonate rocks. Geološki zavod Slovenije, Ljubljana: 143 p., incl. Pls. 23, 1 geol. map.

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Slike, tabele in table: Slike (ilustracije in fotografije), tabele in table morajo biti zaporedno oštevilčene in označene kot sl. 1, sl. 2 itn., oddane v formatu TIFF, JPG, EPS ali PDF z ločljivostjo 300 dpi. Le izjemoma je možno objaviti tudi barvne slike, vendar samo po predhodnem dogovoru z uredništvom. Če avtorji oddajo barvne slike bodo te v barvah objavljene samo v spletni različici članka. Pazite, da bo tudi slika tiskana v sivi tehniki berljiva. Grafični materiali naj bodo usklajeni z zrcalom revije, kar pomeni, da so široki največ 172 mm (ena stran) ali 83 mm (pol strani, en stolpec) in visoki največ 235 mm. Večjih formatov od omenjenega zrcala GEOLOGIJE ne tiskamo na zgib, je pa možno, da večje oziroma daljše slike natisnemo na dveh straneh (skupaj na levi in desni strani) z vmesnim "rezom". V besedilu prispevka morate omeniti vsako sliko po številčnem vrstnem redu. Dovoljenja za objavo slikovnega gradiva iz drugih revij, publikacij in knjig, si pridobijo avtorji sami.

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