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Cover page: Votla stena, the middle part of the southeastern slope of the Nanos (Placer et al., paper in this issue, photo: Ladislav Placer).

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GPR survey to reveal a possible tectonic tilt of the Brežice Sava River Terrace in the Krško Basin

Georadarska raziskava za določitev možnega tektonskega nagiba Brežiške terase reke Save v Krški kotlini

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Ključne besede: Brežiška terasa reke Save, Krška kotlina, georadar, tektonski nagib, seizmično refleksijsko profiliranje

Abstract

It has been supposed that the Brežice Sava River Terrace (BSRT) is tectonically disturbed near the town of Brežice and tilted to the north. To confirm this tectonically induced tilt in a quantitative sense, low-frequency Ground Penetration Radar (GPR) was applied. A total of eight GPR profiles were recorded across the BSRT providing information of the lower boundary of the terrace, which consists of loose to poorly cemented Quaternary gravel, while its Tertiary basement consists of poorly cemented carbonaceous silt (marl). The premise of the study was the assumption that this lithological boundary could be detected by the GPR method. In addition to the upper surface of the BSRT being tilted to the north by 0.18°, GPR profiles also showed a 0.04° difference in the tilt between the upper surface of the terrace and its lower boundary with the basement, which we assigned to the sin-sedimentary tilt. Upon this information, a cumulative tectonically induced dip of the BSRT lower boundary was defined at 0.22°.

Izvleček

Domneva se, da je Brežiška terasa reke Save (BSRT) pri mestu Brežice tektonsko porušena oz. nagnjena proti severu. Da bi lahko ta tektonsko induciran nagib tudi kvantitativno določili, smo uporabili nizkofrekvenčni georadar (GPR). Po celotni BSRT je bilo posnetih osem georadarskih profilov, ki dajejo informacije o spodnji meji terase, ki je sestavljena iz slabo cementiranega kvartarnega proda, medtem ko je njena terciarna podlaga sestavljena iz slabo cementiranega karbonatnega melja (laporja). Predpostavka študije je bila domneva, da je z metodo georadarja mogoče zaznati omenjeno litološko mejo. Georadarski profili so poleg tega, da je zgornja površina BSRT nagnjena proti severu za 0,18°, pokazali tudi 0,04° razlike v nagibu med zgornjo površino terase in njeno spodnjo mejo s podlago, kar smo pripisali sin-sedimentacijskemu nagibu. Glede na te podatke je bila kumulativna tektonsko inducirana nagnjenost spodnje meje BSRT določena na 0,22°.

Introduction

The Brežice Sava River terrace (BSRT, Fig. 1) is an aggradation terrace of the Middle Pleistocene age that is locally exposed along the northern and southern margins of the Krško basin. The name was introduced by Kuščer in the year 1993, who supposed its Middle Pleistocene age. Later, it was determined, in the formational sense, by Verbič (1995; 2004; 2005; 2008) as the Brežice Alloformation, also of the Middle Pleistocene age. This determination was slightly modified by Poljak (2017a,b), when it was defined as the Brežice Allomember as one of the members of the Sava Alloformation (AFSV-AmBŽ in Fig. 1). Its age was then determined by radiometric (U/Th) dating, which confirmed the previously supposed Middle Pleistocene age. Lithologically, the terrace is composed of mixed silicate to carbonate gravel and sand that overlie various Tertiary and even Mesozoic rocks.

It has been supposed, by above listed authors, that the entire terrace is tectonically disturbed, i.e. that it is slightly dipping to the south and to the north in respect to the SW-NE axis of the Krško syncline. Thus, Kuščer (1993) noted that the terrace lies on the northern rim of the Krško basin 200 m above the sea level (a.s.l.), and that it dips toward the central part of the Krško basin where it is at 150 m a.s.l. Further to the south, it rises again, and at the town of Brežice it lies at 160 m a.s.l. The author explained these differences by tectonic rise and subsidence. The same position of the terrace was described by Verbič (1995; 2004; 2005; 2008) and Verbič et al. (2000), who presented quantitative values of these spatial anomalies. According to this author, the northern rim of the terrace dips to the south at an angle of 18.6 milliradians, and its southern rim dips to the north at the angle of 6.2 milliradians. Hereby, all authors refer to the upper surface of the terrace.

Regarding the Krško basin itself, it is in the structural sense, the southernmost km-scale fold of the tectonic belt known as the Sava folds.

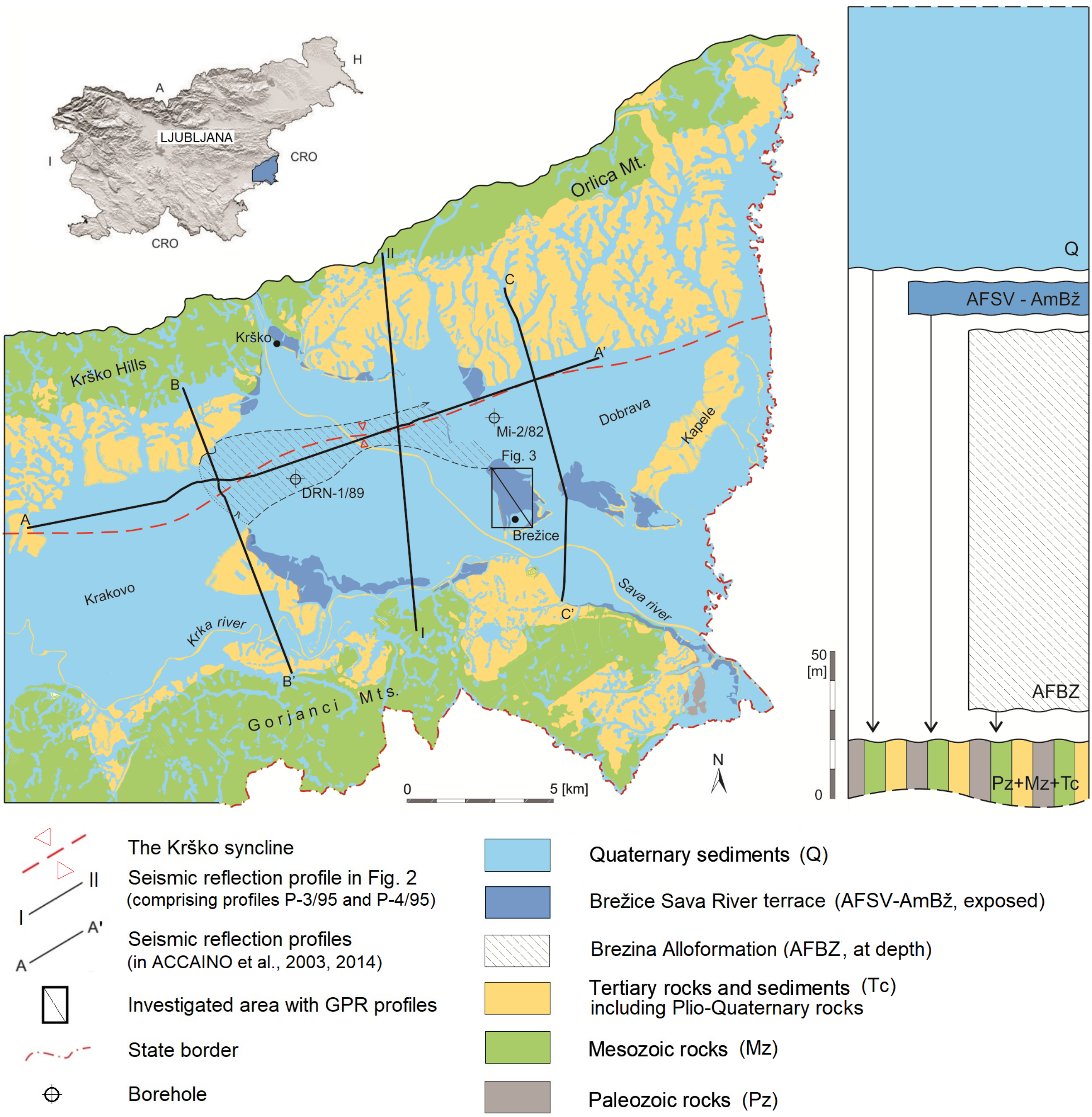

Fig. 1. Simplified geological map of the Krško basin (after Poljak, 2017a) with delineated exposures of the BSRT and a generalized geological column of described lithostratigraphic units showing their maximal thicknesses.

Sl. 1. Poenostavljena geološka karta Krške kotline (po Poljaku, 2017a) z razmejenimi izdanki BSRT in posplošenim geološkim stolpcem opisanih litostratigrafskih enot z največjimi debelinami.

These were formed within the so-called Sava compressional wedge (Placer, 1999) during Neogene and Quaternary with the culmination of folding at the end of Pontian (see Poljak, 2000; Placer, 2009 and Vrabec et al., 2009 for details). According to Tomljenović and Csontos (2001), the Sava folds were in their eastern part in Croatia formed by N – S oriented shortening during Late Pontian to Pliocene-Quaternary times that resulted in reverse faulting and fault related folding of pre-Miocene, Miocene and presumably even Plio-Quaternary sediments. The above mentioned presumed tectonic tilt of the BSRT would imply that the Middle Pleistocene sediments of the Krško basin have also been affected by the Neogene-Quaternary shortening at the southern margin of the Sava compressional wedge together with its pre-Neogene basement rocks.

The premise of our work was that, by means of a Ground Penetrated Radar (GPR) investigation, we could: a) differentiate various lithological units in a shallow subsurface, namely to locate the boundary between the Quaternary alluvial gravel and sand that belongs to the BSRT with its pre-Quaternary basement that consist of Tertiary (Pannonian) marl, and b) measure the spatial position of this BSRT lower boundary in the quantitative sense, which would confirm supposed tectonic disturbance of the BSRT. Both would be supported by published data from previous works providing geophysical data, such as seismic reflection profiling, detailed geological mapping and drilling data of the local area and of the entire Krško basin. Here, it should also be mentioned, that other possibilities of the BSRT genesis are possible, such as primary uneven (differential) sedimentation or erosion. However, the trend of tectonic deformations from Tertiary through Quaternary over the entire Krško basin to recent times favours the probability that the studied terrace is tectonically disturbed as well.

General geological framework

In the recent structural sense, the Krško basin represents a large syncline which is a part of the Sava folds tectonic unit and stretches from central Slovenia to northwest Croatia (Pleničar et al., 1976; Šikić et al., 1978; Aničić & Juriša, 1985a; Šimunić et al., 1982a). It bears various names, such as Krško syncline (Pleničar & Premru, 1977), Syncline Brezina – Veliko Trgovišče (Šikić et al., 1979), Bizeljsko – Zagorje syncline (Aničić & Juriša, 1985b) and Hrvatsko Zagorje synclinorium (Šimunić et al., 1982b). Its total length is approximately 100 km and its average width in the Krško basin is 15 km. In central Slovenia, its axis stretches in a general W – E direction, and in east Slovenia and northwest Croatia it bends into a SW – NE direction. The syncline is built up of Neogene (Lower Miocene to Pliocene) and Quaternary sediments including the pre-Neogene basement rocks of Mesozoic and Paleozoic age (Fig. 1). Here, it should be noted that the latter ones are, in the structural sense, built up of so-called "dinaric" longitudinal folds and faults of the Upper Eocene age, i.e. the structures that today stretch in the NW – SE direction. They are super-imposed by the so-called "south-alpine" structures of post-Pontian age, i.e. folds, faults and thrusts that in Slovenia stretch in a general E – W direction (see Poljak, 2000; Placer, 2009; Vrabec et al., 2009; Poljak, 2017b for details). These deform the Neogene beds but also their Mesozoic and Paleozoic basement. The following geologic description is given after the newest geological map of the Krško basin and its explanatory book (Internet 1; Poljak, 2017a,b). Only the Neogene sediments are described, as they in most cases represent the basement of the presented BSRT.

The oldest Neogene sediments here are the terrestrial sediments of the Ottnangian age, which consist of gravel, sand, and clay with coal. They occur as isolated and relatively thin (several tens of meters) remnants on the northern and southern rims of the Krško basin, to be more precise, on the southern slopes of the Orlica Mt. as well as on the northern slopes of the Gorjanci Mts. However, in the core of the syncline, they are much thicker, thus their thickness in the DRN-1/89 borehole equals 320 m (Kranjc et al., 1990). On the seismic profile presented in Fig. 3, a structural discordance between the pre-Tertiary basement (seismo-horizon C) and overlying Tertiary sedimentary sequence could correspond to the position of Ottnangian beds. The increase of their thickness from the limbs to the core of the syncline could be explained by initial folding and simultaneous subsidence with increased sedimentation of its core.

The Neogene sedimentary sequence corresponds to the Paratethys marine-brakish-sweet water sedimentary cycle in the time span from Lower Badenian to Upper Pontian. These sediments lie transgressively over Ottnangian sediments or over various Mesozoic end even Paleozoic rocks. Generally, they consist of Badenian to Sarmatian limestones and marls, Pannonian marls and Pontian sands. Locally, the Sarmatian marine to brakish sediments are missing, or they are replaced by terrestrial sediments such as coal, which is a consequence of differential uplift over the local and larger area in the western part of the Pannonian basin (e.g. Royden & Horvath, 1988). Thus, Pannonian marls representing sediments of the Pannonian lake (Magyar et al., 1999; etc.), which was formed at the beginning of Pannonian, lie locally discordantly over Badenian limestones and marls or even on the pre-Tertiary basement, as can be locally seen on the northern rim of the Krško basin (Poljak, 2017a). Pontian sediments consist mostly of quartz sands originating from a vast delta plain and a delta front environment. Structurally, this whole sedimentary sequence is, at least in the central part of the Krško basin, almost evenly folded into a relatively gentle fold, i.e. in a syncline which has a slightly steeper northern limb. At the Krško town, this fold is additionally folded into a smaller and local fold called the Libna fold. Here, it should also be mentioned that the Badenian sediments in the central part of the Krško basin consist of calcareous sandstones and silts (DRN-1/89 borehole), while those on its rims mostly consist of coarse-grained limestones corresponding to a reef facies. This lithological difference could indicate an initial folding of the Krško syncline and a sin-sedimentary infill of relatively deep-water sediments in the core of the syncline.

The youngest Tertiary sediments, which supposedly also encompass the Quaternary ones, are the so-called Plio-Quaternary beds. They consist of silicate gravels and sands that lie unconformably over various Tertiary and even Mesozoic rocks. They are also included in the folding of the whole Krško syncline but at a distinctly lower angle in comparison to those of the Tertiary beds (approx. 20°), as they dip to the south and north at a general angle of 8°. The structural position of these sediments was well seen, before surface weathering, in the abandoned coal mine at the village of Globoko (Poljak, 1999) and determined based on numerous boreholes in this area (Markič & Rokavec, 2002). This structural discontinuity confirms the before mentioned structural development of the entire Sava folds, i.e. the main phase of folding in the post-Pontian time and the continuation of folding, with lower intensity, in the post-Plio-Quaternary time.

Younger Quaternary sediments of the Krško basin are presented in Fig. 1 as one stratigraphic unit, except for Middle Pleistocene sediments (the Brezina Alloformation AFBZ and the BSRT). However, on the latest geological map of the Krško basin, they have been divided into several additional alloformations with alomembers, which correspond to the sedimentary infill of the Sava, Krka and Sotla Rivers (Poljak, 2017a,b). Quaternary sediments younger than the BSRT (Würmian and Holocene sediments) do not express any direct evidence of tectonic disturbance, specifically folding. However, some indirect evidence of inferred folding are present. These are discussed in the following chapters.

The Brežice Sava River terrace (BSRT)

As already mentioned, this terrace is exposed on the surface in the northern and southern rims of the Krško basin (Krško – Brežice plain, according to the geographic description in Senegačnik, 2012). The terrace is in its central part, i.e. along the core of the Krško syncline, covered by various younger Quaternary sediments, marked as one unit in Fig. 1. In the western part of the plain, in the Krakovo area, these younger sediments are represented by the Krka River gravels, sands and silts of Würmian to Holocene age (Poljak & Milanič, 2011; Poljak, 2017b). In the eastern part of the plain, called Dobrava, the terrace is covered by various prolluvial – alluvial – limnic sediments, which were defined as the Dobrava Alloformation with several allomembers of Würmian to Holocene age (Poljak, 2017a).

The BSRT itself consists of two levels which lie at two different height elevations with the height difference from 5 to 7 meters. According to the latest determination of Quaternary sediments of the Krško basin (Poljak, 2017a,b), these both built up the Brežice Allomember of the Sava Alloformation, representing two morpho-units that occupy various height elevations. The reason for such a determination was identical lithological content and similar age of the units. They both consist of mixed carbonate-silicate gravel with minor sand lenses. The gravel is locally cemented with the spar calcite cement. Poljak et al. (2013) analysed the calcite cement for age determination by the radiometric U/Th analysis. Several samples were taken from the terrace remnants on the northern rim of the Krško-Brežice plain. The most reliable results were obtained from the two samples, giving the age of 273 and 285 ka. However, the restrictions of the method are quite high, and we can only say for sure that the sediment is <350 ka old (see Poljak et al., 2013 for details). The terrace was also sampled for age determination by Verbič (2004; 2005) and analysed by infrared stimulated luminescence (IRSL) and thermoluminescence (TL) methods. The obtained results were: a) 51. 220 ± 2.18 and 71. 400 ± 3.850 for IRSL dating, and 95.920 ± 5.270 and 136.960

± 9.450 for TL dating (sample from sandy mud - soil), and b) 72.580 ± 11.640 and 79.100 ± 4.210 for IRSL dating and 139.500 ± 11.840 and 151.710 ± 14.810 years (sample from a sand lens). However, samples were taken from the fine-grained sediments and soil over the top of the Brežice terrace, which we consider to be a younger colluvial sediment covering the original surface of the terrace. In addition to this, the author himself noted that the methods used are not reliable for sediments older than 100 ka.

Structurally, the entire terrace is, as already mentioned, tilted to the south and to the north in relation to the axes of the main Krško syncline.

Previous seismic reflection profiling across the eastern part of the Krško basin

To improve the geologic model of the Krško basin, a high-resolution seismic reflection method was used in an earthquake hazard assessment study of the Krško NPP site in 1995 (Gosar, 1998). A 13 km long profile was recorded in two segments (P-3/95 and P-4/95) across the Krško basin (seismic profile I-II in Fig. 1) using engineering seismic equipment to reduce costs and enable measurements in areas with difficult access. Geophone arrays were necessary for the suppression of strong ground roll and guided waves generated in the thick layer of dry gravel (Gosar, 2002).

According to Gosar (1998) the most prominent reflector in both the P-3/95 and P-4/95 profile segments is named as the horizon (B) (Fig. 2), which corresponds to the stratigraphic boundary between the overlying Sarmatian-Pannonian marls and the underlying Badenian limestone. Horizon A represents the boundary between Plio-Quaternary clastic deposits and Pontian marl and sand, thus corresponds with the base Plio-Quaternary unconformity. In the central part of the syncline the boundary between the Pannonian marl and the Pontian sand is also seen, while the top of the pre-Tertiary basement (C) is not well imaged. All three interpreted horizons were correlated with outcrops at the northern margin of the Krško basin, with data obtained by geoelectric soundings, and with the lithostratigraphy of the borehole DRN-1 data (Fig. 1, Kranjc et al., 1990).

In the seismic profile interpreted by Gosar (1998) and converted to the depth profile shown in Fig. 2, the maximum depth to the Badenian limestone is 1200 m, while the depth to the top of pre-Tertiary basement reaches 1500 m. The northern limb of the syncline is steeper than the southern limb, where several tectonic displacements of reflectors in the Tertiary sequence and its basement are visible. The basic structural characteristics of the Krško basin by looking at this N-S trending profile are folding and a compressional tectonic style. No normal border faults were observed that would support previous hypotheses of a graben structure which were prevailing in literature (e.g. Pleničar & Premru, 1977). Two sub-vertical normal faults were interpreted in the central part of the syncline with downthrown northern blocks with the offset of 50 to 80 m. These were interpreted as so called “Dinaric”

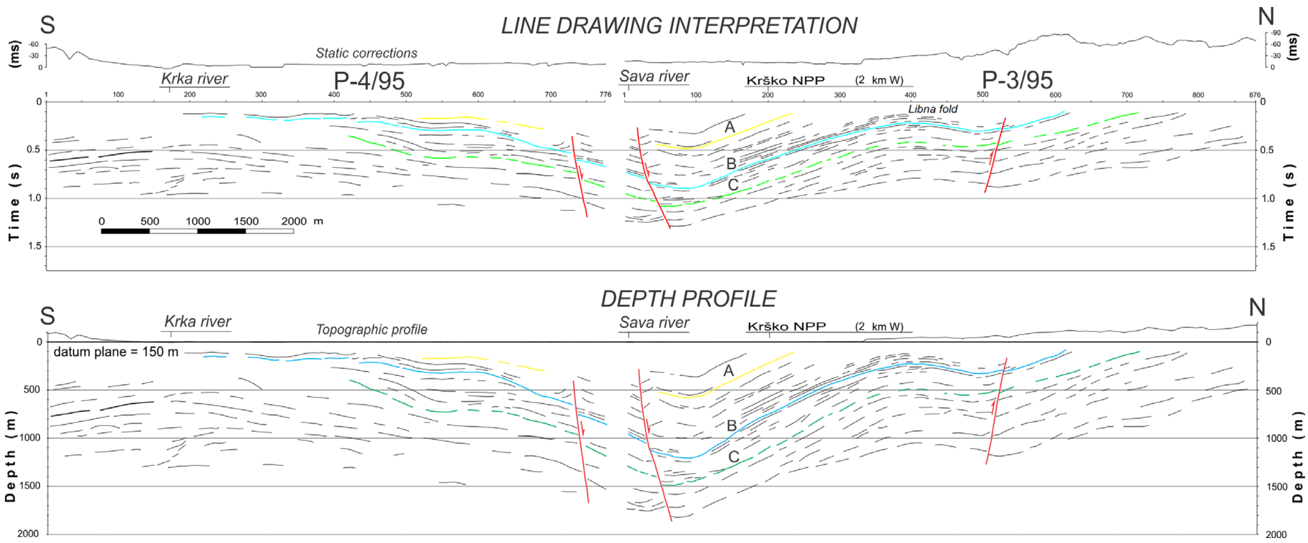

Fig. 2. Line drawing interpretation and depth conversion of the P-3/95 and P-4/95 seismic reflection profiles recorded across the eastern part of the Krško basin (from Gosar, 1998), depicted in Fig. 1 as a merged seismic profile marked I-II. Horizon A – the base Plio-Quaternary unconformity; horizon B – top Badenian limestone; horizon C – top pre-Neogene unconformity.

Sl. 2. Interpretacija in globinska pretvorba seizmičnih refleksijskih profilov P-3/95 in P-4/95, posnetih preko vzhodnega dela Krške kotline (iz Gosar, 1998), prikazanih na Sl. 1 kot združen seizmični profil z oznako I-II. Horizont A - osnovna plio-kvartarna diskordanca; horizont B - zgornji Badenijski apnenec; horizont C - zgornja predneogenska diskordanca.

Fig. 3. A – Position map of GPR profiles B1 to B8 recorded across the BSRT (lines), location of borehole used for depth calibration (circle east of B1) and location of outcrop image in B (star W of B1); B – Erosional contact (dashed line) between Pannonian marl and overlying Quaternary sediments of the BSRT in the newly-opened road cut through the BSRT.

Sl. 3. A - Zemljevid lokacij georadarskih profilov B1 do B8, posnetih čez BSRT (linije), lokacija vrtine, ki se je uporabila za kalibracijo globine (krog vzhodno od B1) in lokacija slike izdanka v sliki B (zvezda zahodno od B1); B - Erozijski stik (črtkana črta) med panonijskim laporjem in zgorajležečimi kvartarnimi sedimenti BSRT v odseku novoodprte ceste preko BSRT.

structures which originate from pre-Tertiary Mesozoic basement and stretch today in a NW – SE direction (Gosar, 1998). They had been formed at the end of Paleogene under the SW – NE compression. Afterward, within the "South-alpine" N – S compression during Neogene, with the peak after Pontian time, they become mostly dextral strike-slip ones, and propagated into Tertiary overlying sedimentary sequence. Thus, vertical displacement along these two faults is apparent, and it represents horizontally displaced core of the Krško syncline. The reflections in the northern part of the syncline are predominantly parallel and could be an indication of post-depositional folding. On the other hand, surface geological observations point to a condensed thinned Neogene section near the north margin of the basin, an argument for sin-sedimentary folding.

Within the EU-PHARE project (Persoglia et al., 2000), three additional regional scale reflection seismic profiles (Fig. 1) and four very-high-resolution reflection profiles were recorded in the year 2000 at selected locations where near-surface faulting was previously detected (see Accaino et al., 2003; 2014 for details). These profiles confirmed the synclinal shape of the Krško basin that is associated with the south-verging thrust structures that Accaino et al. (2014) correlated with the Artiče fault mapped along the southern slope of the Krško Hills, and along the northern limb of the Krško syncline as presented in Poljak & Gosar (2000). The results of this project were never fully published, therefore an interpretation of the older profile (Gosar, 1998), which is representative for the Krško area, is presented in this study.

Based on all seismic reflection profiles and gravity modelling available by 2005, a three-dimensional structural model of the pre-Tertiary basement was constructed by Gosar et al. (2005). In this model two structural depressions in the Krško syncline were distinguished: the Raka depression in the western part of the Krško syncline where the top of pre-Tertiary basement reaches max. depth of 1600 m, and the larger Globoko depression in the eastern part of the Krško syncline where the top of pre-Tertiary basement reaches max. depth of 2050 m. Additional study that comprises six interpreted seismic horizons was conducted by Gosar & Božiček (2006) and Gosar (2008) who presented structural maps of six seismic horizons starting from the top of pre-Tertiary basement unconformity up to the youngest horizon depicted within the Upper Pontian strata. Together with seismic velocity models, delineated seismic horizons served as input data for the construction of two-dimensional cross-sections that again proved about an asymmetric geometry of the Krško syncline, characterized by more steeply dipping norther limb (see Fig. 3 in Gosar & Božiček, 2006).

Methods

Ground Penetrating Radar (GPR) is a non-invasive geophysical method designed for shallow subsurface investigations. The working principle and its different applications are described in detail in various publications, e.g. in Annan (2002), Bristow & Jol (2003), Neal (2004) and Jol (2009). The measurements are based on emitting short electromagnetic pulses into the subsurface and recording the reflected signals at the surface. The signal reflections occur when the emitted signals reach an object or geological material with different electromagnetic properties, for instance at boundaries between sediments and rocks. The GPR unit records the time it takes the signals to travel from the transmitting antenna to the receiving antenna after reflecting from a boundary in the subsurface. This is called the two-way travel time (TWT) and is later converted to depth by applying the material's dielectric constant, which defines the propagation velocity of electromagnetic waves (Jol, 2009).

In this study, the Malå ProEx GPR recording unit with an unshielded 50 MHz rough terrain antenna (RTA) was used. Being tube-shaped and flexible, the RTA is easy to operate when maneuvering through rugged terrain without affecting the ground contact. The total length of the RTA is 9.25 m, while the distance between the transmitting and the receiving antenna is 4 m (MALÅ, 2009). The 50 MHz frequency antenna was used due to its ability to reach great penetration depths needed for such geological surveys while still maintaining a satisfactory resolution. This system has been successfully applied in previous tectonic surveys (e.g. Matoš et al., 2017).

For this study, eight GPR profiles (Table 1) were recorded (Fig. 3A). GPR measurements were recorded in a dry period in order to minimize signal attenuation that can be caused by soil moisture. In order to determine the thickness of the Quaternary sediments above the pre-Quaternary basement, a depth calibration GPR profile B1 (Fig. 4) was recorded where the erosional contact between pre-Quaternary basement and Quaternary strata, i.e. the base Quaternary unconformity that corresponds here with the base of BSRT, was clearly seen in the vertical-

Table 1. Basic information on GPR profiles.
Tabela 1. Osnovni podatki georadarskih profilov.

Profile		Coordinate y (G-K)	Coordinate x (G-K)	Altitude (m)	Length (m)
B1	Start	5547255	5084436	N/A	110
	End	5547231	5084550	N/A	
B2	Start	5547163	5084832	160.10	207
	End	5547123	5085034	N/A	
B3	Start	5547088	5085110	N/A	187
	End	5547050	5085291	N/A	
B4	Start	5546991	5085313	N/A	168
	End	5547001	5085480	N/A	
B5	Start	5546876	5085507	N/A	121
	End	5546829	5085616	N/A	
B6	Start	5546824	5085717	N/A	183
	End	5546726	5085777	N/A	
B7	Start	5546593	5085730	N/A	511
	End	5546388	5086197	N/A	
B8	Start	5546058	5085888	N/A	548
	End	5546065	5086433	153.79	

Table 2. Processing steps of GPR profiles.
Tabela 2. Postopki obdelave georadarskih profilov.

Processing step	Parameters
DC removal	Interval 400 – 700 ns
Time zero adjustment	48.9 ns
Background removal	Normal
Amplitude correction	AGC with 247 ns time window
Bandpass frequency	Low cut 25 MHz, low pass 50 MHz, high pass 150 MHz, high cut 300 MHz
Time to depth conversion	Signal velocity = 0.12 m/ns

ly opened road cut (Fig. 3B). Although this profile contains a high amount of air reflections, the base Quaternary unconformity that corresponds with the BSRT base could still be determined. The depth of this boundary was estimated at 4 m and verified by data from the nearest borehole, located about 100 m northeast from the B1 profile's north end-point (circle in Fig. 3A), where the same unconformity was found at the depth of 4.1 m (Borehole data archive, 2020). Based on this information we were able to define the GPR signal velocity at 0.12 m/ns, which is necessary for accurately defining the depth of the base of the BSRT in other GPR profiles.

When using an unshielded antenna, the objects above the surface, e.g. buildings, wires or trees, can cause noise in the form of air reflections. For the purpose of minimizing these outside influences, GPR profiles were recorded in the least urbanized part of the BSRT. The data acquisition was carried out with a distance-measuring mechanism using a biodegradable cotton string (MALÅ, 2009) with a signal triggering interval of 0.2 m. The x and y coordinates of starting and ending points of the GPR profiles were measured with a portable GPS receiver, while the surface altitude of the points was acquired from the new Slovenian LiDAR relief model (ARSO, 2015) with the vertical accuracy of 15 cm.

For the processing of the GPR profiles the *RadExplorer 1.4* software from *DECO Geophysical* was used. As the boundary between the Quater-

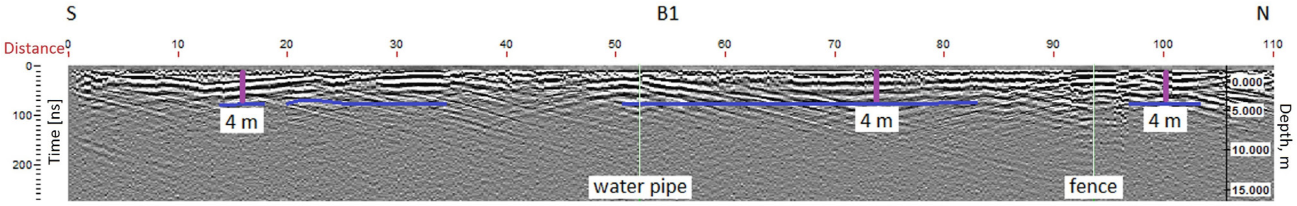

Fig. 4. Calibration GPR profile B1 used to define electromagnetic signal velocity based on measured lower BSRT boundary depth at outcrop (Fig. 3B).

Sl. 4. Kalibracijski georadarski profil B1, uporabljen za določitev hitrosti elektromagnetnega signala na podlagi izmerjene globine do spodnje meje BSRT v izdanku (sl. 3B).

nary and pre-Quaternary sediments was clearly visible in the radargrams, only basic processing steps were applied. These steps were the same for all profiles and are listed in Table 2. Topographic correction was not applied due to a small elevation difference in comparison to the profile lengths.

For determining the depth to the reflector representing the boundary between different sediments, the signal velocity obtained from the calibration profile B1 was applied. The velocity of the GPR signals within the upper Quaternary gravel layer was determined at 0.12 m/ns (Fig. 4). This corresponds to the material dielectric constant $\varepsilon = 6$. The acquired parameter is in accordance with published dielectric values for the type of sediment present in similar areas (e.g. Saarenketo, 2006). As the Quaternary gravel layer is more or less homogeneous across the entire study area, changes in the velocity of the signal are negligible.

Results

The GPR profiles B2 to B8 are presented in Fig. 5. For the interpretation of data obtained from these profiles, the schematic profile shown in Fig. 6 was constructed, excluding the data from the B1 profile. The B1 profile was recorded directly above the outcrop shown in Fig. 3B, where the depth to the base of the BSRT could be measured. It was used for calibration purposes, i.e. to obtain the signal velocity within the BSRT layer and the dielectric constant of the material in order to perform an accurate time-to-depth conversion in the rest of the GPR profiles. Unlike other GPR profiles, the B1 profile was recorded near an urban area, where it is possible that the local topography had been anthropologically changed and was therefore not included in the interpretation process.

The GPR profiles B2 to B8 with depicted changes in the depth to the base of BSRT are presented in Fig. 5. Due to the antenna being unshielded, noise in the form of air reflections is present in areas where profiles were recorded close to billboards, trees and electrical wires. As can be seen in Fig. 5, the depth of the BSRT base (blue lines), as interpreted in profiles B2 to B5, stays more or less at the depth of 4 m. There is an exception of a local deepening to 5 m in B4 in the area of the corn field (between 107 m and 135 m), where the chaotic reflections are the result of corn stalk stubs lifting the antenna off the ground. The first signs of the deepening of the BSRT base can be seen in the B6 profile, where the average depth increases to about 4.5 m with only a local point at the depth of 4 m in the central part of the profile. In the B7 profile the depth of the BSRT base reaches 5.5 m by the end of the profile. The reflector is not as prominent here as in other parts of the profile, probably due to the proximity of the billboards near the end of the profile (seen in Fig. 3A). This part of the profile runs parallel to the billboards and not perpendicular as in other parts, so their interference can be seen longer along the profile here than at its central part. A slight disruption in the continuity of the reflector representing the BSRT base was caused by crossing a paved road (between 160 and 170 m). Regarding the subsurface position of the BSRT base, a similar gradual change in depth is visible in the B8 profile, where the BSRT base also reaches the depth of 5.5 m in the northern part of the profile, which is the northernmost part of the studied area. Based on the GPR results it is therefore evident that the depth of the boundary between the overlying Quaternary gravel layer and the underlying pre-Quaternary basement, represented along profiles by Pontian marl, increases toward the north. The change in depth of the base of this Quaternary unconformity amounts to 1.5 m at the distance of about 2000 m.

Based on the new LiDAR relief model (ARSO, 2015), the surface altitude of the BSRT decreases from 160.10 m in the south to 153.79 m in the northernmost point (Table 1) of the surveyed area (Fig. 6). Hence, the surface elevation difference equals 6.3 m at a distance of about 2000 meters.

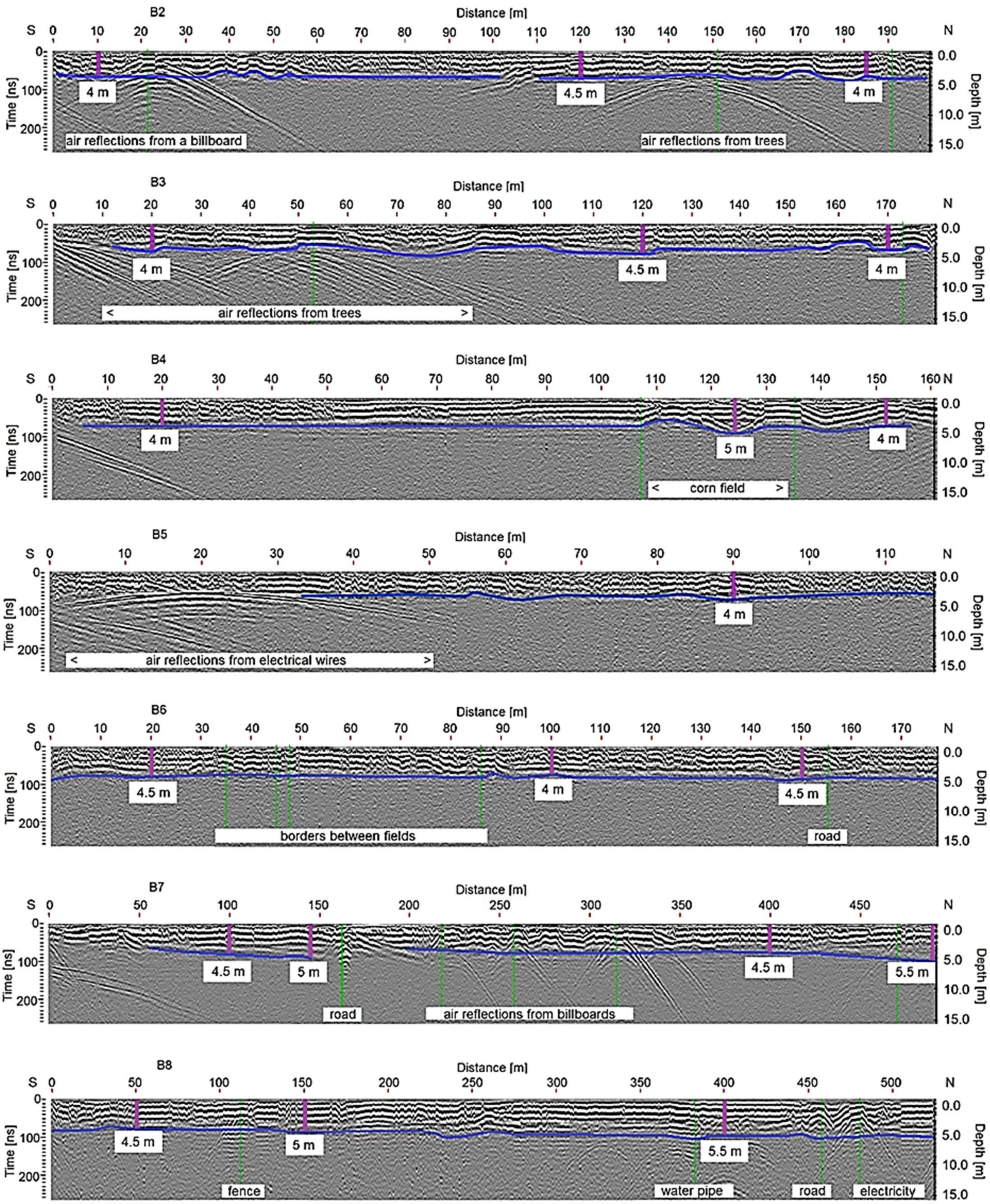

Fig. 5. GPR profiles B2 to B8 with marked BSRT base – boundary between BSRT gravel above and Pannonian marl below (blue line), depths to the BSRT base inferred from GPR profiles (purple lines), and markers (green lines).

Sl. 5. Georadarski profili B2 do B8 z označeno mejo s podlago BSRT – meja med gramozom BSRT zgoraj in panonijskim laporjem spodaj (modra linija), globine do podlage BSRT, določene iz georadarskih profilov (vijolične črte) in markerji (zelene črte).

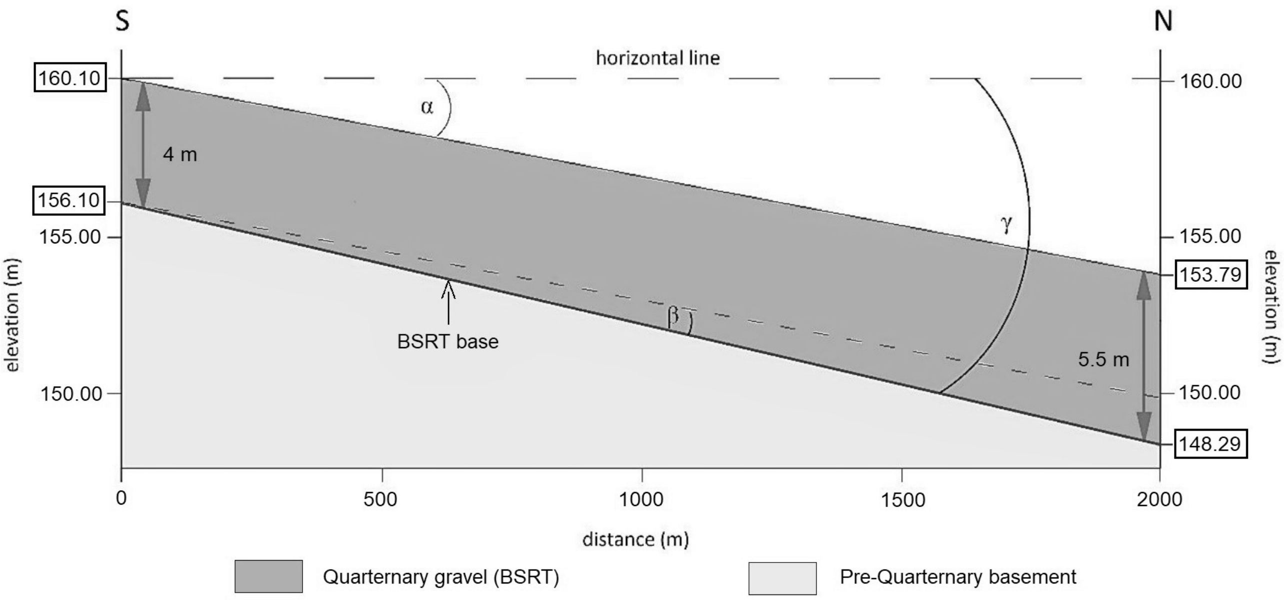

Fig. 6. Interpretation of LiDAR and GPR data showing the surface elevation difference of the present day topography in the area, tilt of the BSRT surface (angle α), the tilt of the surface during sedimentation (angle β) and cumulative northward tilt of the boundary between Quaternary sediments above and pre-Quaternary sediments below (angle γ). Vertical exaggeration is 60 ×.

Sl. 6. Interpretacija LiDAR in georadarskih podatkov, ki kaže višinsko razliko recentne topografije na območju, nagib površine BSRT (kot α), nagib površine med sedimentacijo (kot β) in kumulativni nagib meje med kvartarnimi sedimenti zgoraj in pred-kvartarnimi sedimenti spodaj (kot γ). Navpično povečanje je 60 ×.

The GPR results of this area indicate that the base of the BSRT also deepens towards the north for about 1.5 m (from the elevation of 156.10 to 149. 29 m; Fig. 6), which we interpret as a result of sin-sedimentary subsidence caused be tectonic tilting of the terrace. Based on results presented here, we can also estimate the rate of subsidence. By considering the age of the terrace sediments, which is approximately 273 to 285 ka, the subsidence rate equals 0.03 mm per year. Even though tectonically induced tilting is the most likely interpretation, it should be noted that the northward tilt of the terrace could also be the result of other processes. We discuss different possibilities in the following chapter.

Discussion

Here, we discuss the reasons, why we consider the northward tilt of the BSRT to be of tectonic origin.

Observing the exposed remnants of the terrace on the surface, we could delineate the original paleo-Sava flow during Middle Pleistocene time in the Krško basin. In the north, in the gorge between the Krško Hills and the Orlica Mt., the terrace stretches in the N – S direction. It preserves the same direction in the central part of the Krško basin, where the original estimated width of the paleo-Sava could be approximately 10 km, representing a wide flooded plain. Further to the east, the remnants of the terrace are preserved along the southern slopes of the Kapele Hills and northern slopes of the Gorjanci Mts. and stretch in a general W – E direction. The latter are covered by a relatively thick colluvial cover of 2 – 3 m of the Gorjanci Mts. (Poljak & Bavec, 2004), therefore the original position of the terrace surface cannot be determined for certain. However, at the southern slopes of the Kapele Hills, the terrace lies at the elevation of 160 meters. This difference in heights from 200 m a.s.l. at the Krško town on the north to 160 m a.s.l. at the Brežice and Dobova areas represents a normal gradient of a river flow. Therefore, the northward tilt of the upper surface of the terrace at the Brežice town could be considered as the anomalous one.

Considering the possibility that this anomalous northward tilt is the result of erosion and surface denudation, there are some arguments, which oppose such an interpretation. Firstly, the terrace surface is highly weathered with thick and well-developed soil horizons (Vrščaj, 1998), which indicates a long surface exposure of the terrace sediments and a lack of younger sediments, which could erode the surface of the terrace. However, the terrace is covered by fine grained sediments of the Krakovo and Dobova regions in the central part of the Krško – Brežice plain along the Krško syncline core. These consist of silts and clay with peat, which suggests a relatively calm deposition with low or no erosion.

These sediments have been dated by radiometric C^{14} analysis and are of Würmian and Holocene age (Poljak & Milanič, 2011). This indicates a syn-sedimentary subsidence of the central part of the Krško – Brežice plain, which is most likely a consequence of continuing folding during the Quaternary time.

The spatial position of the lower surface of the terrace cannot be exactly determined over the entire area. The contact between the terrace gravel with its Tertiary basement is exposed and directly seen only along the northern and southern margins of the Krško – Brežice plain. Its position is generally the same as that of the upper terrace surfaces, i.e. it is tilted to the south and to the north. However, in the central part of the Krško – Brežice plain, it is covered by various younger sediments, thus the interpretation of the position of the base of the BSRT is determined by subsurface data. According to several borehole data from this area (Petauer, 1983 – 1986), the contact between the BSRT gravel and its Tertiary basement or the Brezina Alloformation is also deeper in the central part of the Krško – Brežice plain compared to its rims. Using these data, we could also estimate the thickness of the terrace sediment. It is approximately 10 m thick over the whole Krško basin, with a smaller increase in its central part, which also indicates a relatively uniform deposition of the paleo-Sava sediment without distinct differential erosion of its basement.

From the structural point of view, the BSRT follows the general trend of deformations, of folding of the entire Sava folds during Neogene time. The initial folding, as said before, supposedly took place in Ottnangian followed by relative continuous folding of a much lesser intensity during Badenian, Pannonian and Pontian with the main phase of folding after Pontian, when the Krško syncline was finally formed. According to the spatial position of Neogene sediments in the Krško basin, we can also speculate the rate of the cumulative tectonic displacement. This way, we could compare this result with those obtained by GPR analysis for the BSRT. For instance, the Badenian sediments lie at the 520 m a.s.l. at the summit of the Orlica Mt., and in the central part of the Krško basin their base was determined at 660 m below the surface in the DRN-1/89 borehole, which is located at 150 m a.s.l. (Kranjc et al., 1990). Therefore, this difference of 1030 m represents a structural relief which has been formed in the time span from the beginning of Badenian (11.6 Ma) to present in case of continuous folding, or from the end of Pontian (5.3 Ma), when the main phase of folding took place, to present. In the first case, the rate of displacement is almost 0.1, and in the second case 0.2 mm per year (absolute ages of stratigraphic stages after Gradstein et al., 2012).

Regarding the spatial position of Quaternary sediments in the Krško basin, the position of the Brezina Alloformation sediments could be an indirect qualitative indicator for the Quaternary folding of the Krško synclinale. These sediments are deposited only in its core with the maximum thickness of 127 m (Mi-2/82 borehole – Petauer, 1983 – 1986). This suggests a syn-sedimentary subsidence supposedly caused by folding.

For the quantitative analysis of the rate of displacement, we could use a Quaternary (Würmian) sedimentary unit of the Krško basin. In one of numerous boreholes of the central part of the Krško-Brežice plain, a layer of peat has been drilled at the depth of 20 m (Krivic, 2011). Its age has been analysed by radiometric C^{14} method, and it gives the age of 40856 ± 800 years BP. Based on the assumption that the peat was formed on the surface during Würmian, and afterward subsided to this depth, the rate of subsidence is 0.5 mm per year. And again, we assign this subsidence to tectonic processes, more precisely to folding.

Regarding the Holocene sediments, they do not show any signs of tectonic disturbance. However, an indirect sign of Holocene subsidence could be, as said before, the deposition of fine-grained sediments (silt and clay with peat) in the central part of the Krško – Brežice plain in relation to its rims, where more coarse-sediments (sand and gravel) prevail.

Conclusions

GPR measurements of the surveyed area provided additional data for a better understanding of the structural built up of the Krško basin, both in the qualitative and quantitative sense, as well as information on its structural development through Quaternary time. In the structural sense, the Krško basin is a gentle syncline that formed in the South Alpine tectonic cycle during Neogene. The synclinal structure of the Neogene strata, together with the Mesozoic and Paleozoic basement, has been determined by geological mapping on the surface, and by geophysical research in the subsurface. The general dip of the Neogene strata, which can be seen on the seismic profiles presented in Fig. 2 is about 20°. Younger Quaternary sediments are also gently folded. The Plio-Quaternary sediments dip to the north and to the south at an angle of max. 8°, while the sediments of Middle Pleistocene have the same position but dip at a very low angle of < 1°. The latter have previously been determined by analysing the upper surface of the BSRT, which is, however, not quite reliable due to the possibility of a younger sedimentary cover over the Middle Pleistocene sediments.

The elevation analysis from the new Slovenian LiDAR relief model confirmed the northward dip of the upper surface of the BSRT, while the GPR investigations within this study determined a northward dip of the lower boundary of the BSRT as well. The angle of the surface equals 0.18° and the angle of the subsurface BSRT base is 0.22°. The latter indicates post-sedimentary folding, while the 0.04° difference indicates syn-sedimentary folding, which also took place at the end of the deposition of the given sediments. Since the average absolute age of the investigated Middle Pleistocene sediment is estimated at 250 ka, the rate of the vertical motion can be calculated at 0.0312 mm/yr.

The very low rate of the vertical motion is also in accordance with the data acquired by geodetic levelling along the railway line from Brestanica on the northern to Dobova on the southern rims of the Krško basin (Koler & Breznikar, 1999). These data also indicate a relative uplift of the Krško basin margins in relation to its central part at a very low rate of displacement (< 1 mm/year). Thus, we can assume that the Krško basin has been under a compressional regime since the end of Neogene to Quaternary, causing the folding of the Krško syncline, as well as of the entire Sava folds from Neogene to recent times.

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A model for the formation of the Pradol (Pradolino) dry valley in W Slovenia and NE Italy

Model nastanka suhe doline Pradol (zahodna Slovenija, severovzhodna Italija)

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Abstract

In tectonically active mountain ranges, the landscape is shaped by the interplay of erosion/sedimentation and tectonically driven crustal deformation. Characteristic landforms such as moraines, wind gaps, fault scarps, and river terraces can be used to decipher the landscape evolution. However, the available data often allow for different interpretations. Here we study the Pradol (Pradolino) Valley in Western Slovenia, a deeply incised canyon whose floor rests several hundreds of metres above the surrounding valleys. We use high-resolution digital elevation models, geomorphic indices and field observations to unravel the evolution of this peculiar landform. We present a six-stage evolution model of the canyon that includes the blockage of valleys by advancing glaciers, river diversion, and rapid incision due to a high discharge of post-glacial meltwater. The formation of the Pradol Valley was most likely facilitated by an underlying fault that serves as an easily erodible weakness zone in the Mesozoic limestones. Our model indicates that the formation of the canyon could have occurred during the last glaciation, which results in incision rates of several cm/yr. With the proposed model we can explain all remote and field observations available. Our study shows that a complex interplay of different landscape-shaping processes is needed to explain the occurrence of the Pradol dry valley and that rapid changes in the morphology occurred after the last glacial maximum.

Izvleček

V tektonsko aktivnih gorovjih površje oblikujejo interakcije med erozijo, sedimentacijo in tektonsko gnanimi deformacijami skorje. Časovni razvoj oblikovanosti površja lahko rekonstruiramo s študijem značilnih površinskih oblik kot so morene, suhe doline, prelomni robovi in rečne terase, vendar pa so razpoložljivi podatki pogosto dvoumni in dopuščajo različne interpretacije. V prispevku obravnavamo globoko vrezano sotesko Pradol (Pradolina) v zahodni Sloveniji, katere dno leži nekaj sto metrov nad okoliškimi dolinami. Da bi ugotovili nastanek te nenavade geomorfne oblike smo uporabili visokoločljive digitalne modele višin, geomorfne indekse in terenska opazovanja. V prispevku predstavljamo šestfazni razvoj soteske, ki vključuje zajezitev doline z napredujočim ledenikom, preusmeritev reke in njeno hitro vrezovanje zaradi velike količine vode ob postglacialnem taljenju ledu. Nastanek Pradola je bil najverjetneje pogojen s prisotnostjo preloma, katerega prelomna cona je predstavljala lahko erodibilno cono šibkosti v mezozojskih apnencih. Naš model kaže, da bi soteska lahko v celoti nastala v zadnji poledenitvi, kar bi pomenilo hitrosti vrezovanja do nekaj cm na leto. Predlagani model pojasni vsa dostopna daljinska in terenska opažanja. Študija nakazuje, da je nastanek Pradola posledica kompleksnih interakcij različnih geomorfnih procesov, ter da je v obdobju od zadnje poledenitve prišlo do hitrih sprememb v morfologiji površja.

Introduction

The Pradol Valley (also called Predol, Italian: Valle di Pradolino. In the following we only use the Slovenian names) is a wind gap located close to the village of Logje at the Slovenian-Italian border, approximately 12 km west of Kobarid (Fig. 1). It is a steep canyon with vertical to overhanging walls, bisecting the mountain ridge of the Vogel (Italian: Monte Voglu; 1124 m) and the Mija (Italian: Monte Mia; 1237 m). The recent valley entrance is approximately 200 m above the river course of the Nadiža River (Italian: Natisone), which is a tributary to the Torre River. The valley is oriented along-strike one of the largest and most active fault zones in the northern external Dinarides, the Predjama Fault (Buser, 1987, 2009). The remarkable morphology of the canyon (Fig. 2) and its location inevitably lead to the question of how it was formed. Previous studies suggested that melt water from the Isonzo glacier has flowed through the Pradol Valley (Tellini, 1898; Feruglio, 1929). However, the timing and mechanism of its formation have not yet been deciphered. This study aims to provide an insight into the formation process of the Pradol Valley from a geomorphological perspective. We constrain the role of major landscape forming processes, such as active tectonic deformation, glaciations, and fluvial erosion on the formation of the valley and the surrounding region and present a model that fits all available observations.

Study Area

The study area (Fig. 1) comprises the NW-SE trending Pradol Valley in the centre, the mountain ridge of Mija and Vogel and the surrounding valleys, forming the catchment of the Nadiža. The floor of the Pradol Valley is at an elevation of 400 – 450 m, gently tilted towards the south-east, and is filled by a layer of rock debris of unknown thickness. It is 200 to 250 m higher than those of the other valleys that host the recent riverbed of the Nadiža. The walls of the canyon are built up of massive, bedded limestones and occasionally calcarenites that dip towards the northeast (Fig. 2). The limestone layers, ranging from upper Triassic ages at the south-eastern valley entrance to upper Cretaceous units (Buser, 1987, Carulli, 2006) in the northwest are partly folded and faulted.

Besides the Pradol Valley, the study area features other noteworthy geomorphologic elements, which help to understand the processes that shaped the landscape. The main river draining the study area, the Nadiža, attracts attention due to its unusual flow path. It emerges in the mountains north-west of the study area. At Logje, close to the entrance of the Pradol Valley, it bends about 90° to the north-east. At the village of Robič the river again bends to the south at about 90° and flows into the valley between Mija and Matajur (Italian: Monte Matajur). Here it cuts through a bar of solid limestone rocks of approximately 200 m width, 500 m length and 50 m height (see inset in Fig. 1). This is especially noteworthy as there is a wide valley to the east that connects Robič and Kobarid that is situated at the Soča River (Fig. 2). The topographic high that separates the Nadiža and the Soča River is only a few metres above the river courses and coincides with a large

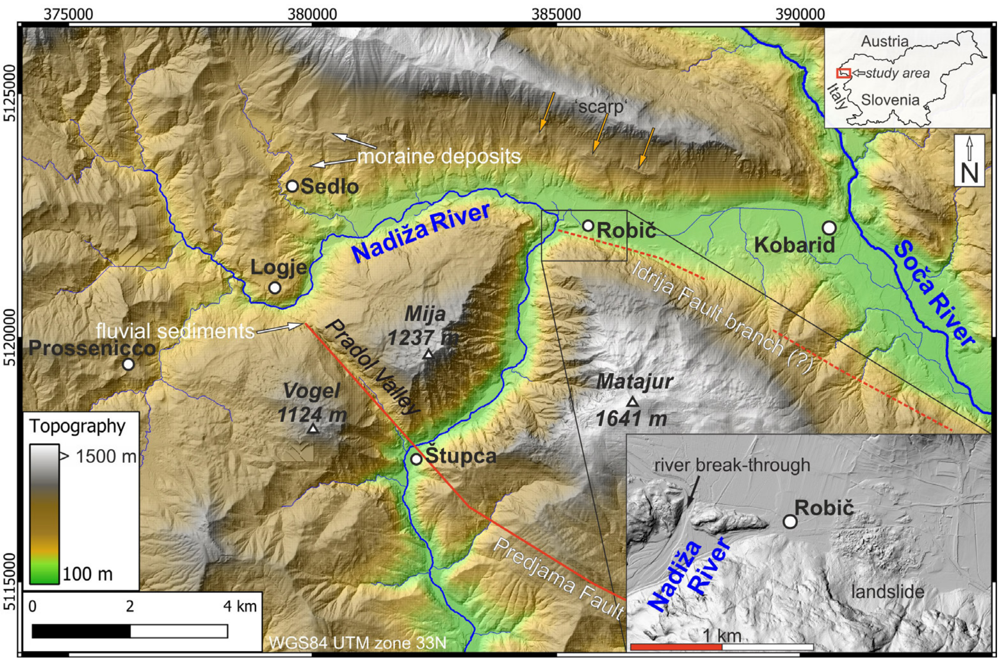

Fig. 1. Overview of the study area in north-western Slovenia, showing the location of the Pradol Valley, the flow path of the Nadiža, and the surrounding topography (coloured 1-m DEM hillshade). Orange arrows indicate the morphologic scarp formed by glacial processes. Red lines indicate known fault zones. Inset figure (bottom right) shows the elongated bedrock ridge at Robič, which is cut by the Nadiža, as well as the landslide deposits in the valley between Robič and Kobarid.

Fig. 2. A. View from Logje to the south-east across the Nadiža Valley towards the Pradol Valley. **B.** Valley between Matajur and Mija aerial view from Robič to the south **C.** U-shaped valley between Kobarid and Robič with the landslide W of Robič. View to the west. **D.** Outcrop of moraine deposits north of Sedlo at ~ 500 m a.s.l. **E.** The Nadiža near the incised rock bar at Robič, view to the south. The background shows the steeply incised valley between Mija and Matajur. **F.** Vertical wall in the Pradol Valley exhibiting folded limestones.

landslide (Fig. 2). As the Nadiža flows around the Mija, passing both entrances of the Pradol Valley, the obvious assumption is that the Nadiža might be related to the formation of the canyon.

An important aspect of this region is its location at the north-western end of the orogen-parallel active fault system in the northern external Dinarides. The study area features two active fault zones: the Predjama Fault, which most likely is located within the Pradol Valley (e.g. Buser, 1987, 2009, Carulli, 2006, Moulin et al., 2014), and the Idrija Fault. The exact location of the main strand of the Idrija Fault in this region is hard to pin down. One branch of the fault possibly strikes along the limestone rock bar at Robič. Both faults are neotectonically active (e.g. Moulin et al., 2014, 2016; Vrabec, 2012; Ribarič, 1979; Bavec et al., 2012) and form major topographic lineaments over distances of 100 to 120 km.

According to Penck & Brückner (1909), most of the study area was glaciated during the last glacial maximum (LGM). The ice, coming from the Soča Valley north of Kobarid, covered the entire valley of Kobarid, Robič, and Logje and reached up into the upper catchment of the Nadiža. The valley between Mija and Matajur was also glaciated (Penck & Brückner, 1909). More recent studies (e.g. Bavec et al., 2004) suggest that this glacial extent is overestimated, without however proposing an alternative extent. There is general agreement that glaciers reached our study area at some point during the Pleistocene (see discussion in Ferk et al., 2015). No glaciers were present in our study area during the Little Ice Age (Colucci & Žebre, 2016).

Methods

Data and software

The study focuses on geomorphological investigations. For overview purposes and first-order analyses, a 1-arcsecond ALOS 2 (Advanced Land Observing Satellite) digital elevation model (DEM) was used, which is provided by the Japanese Aerospace Exploration Agency (JAXA, 2019). For the Slovenian part, a 1m-DEM, which is provided by the Environmental Agency of the Republic Slovenia (ARSO, 2020) was used. The DEM is freely available via the ARSO web service as point cloud (ascii) files. The point clouds were processed with the open-source software CloudCompare (CloudCompare, 2019). For the Italian part of the study area, a 1m-DEM of the Friuli-Venezia region is available from the Friuli-Venezia Giulia Environmental Department (RAFVG, 2019). Both high-resolution DEMs are derived via airborne laser scanning (light detection and ranging, LiDAR). The geomorphological analyses were performed using the open-source software packages TecGEMs (Shahzad et al., 2011, Andreani et al., 2013) and Topotoolbox 2 (Schwanghart & Scherler, 2014), a Matlab-based toolbox. Further processing and visualization of the data were done with the free geographic information system QGIS (QGIS, 2020).

Morphometric Indices

For the characterisation of different topographic features, morphometric indices were calculated from the merged 1m-DEM, using TecGEMs toolbox. The surface roughness (SR), which describes the ratio of the 'real' surface to the flat (map view) surface area (Grohmann, 2004) was computed (Fig. 3). It is calculated for each pixel of a raster DEM, referring to a 'moving window' (2000 × 2000 m). An SR of 1 corresponds to entirely flat surfaces, whereas elevated values indicate rough, incised areas. The SR is presented in figure 3. Other indices indicated similar results and thus are not presented separately.

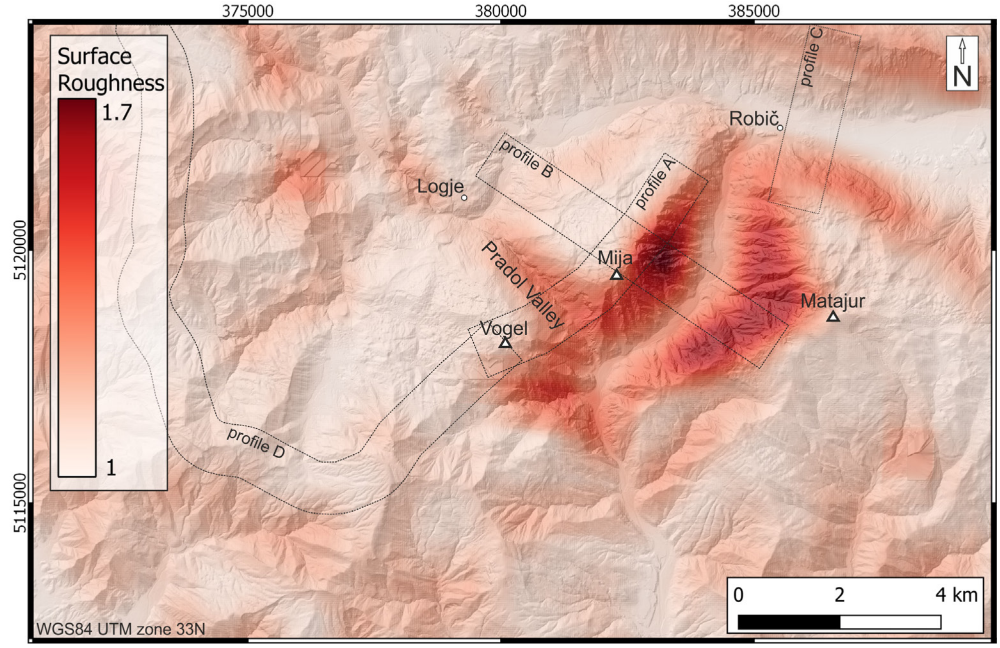

Fig. 3. Surface roughness (SR) map of the study area. SR is notably elevated in the valley between Mija and Matajur mountains, whereas the rest of the study area exhibits relatively low values. Dashed lines indicate positions of the swath profiles A to D, depicted in Fig. 4.

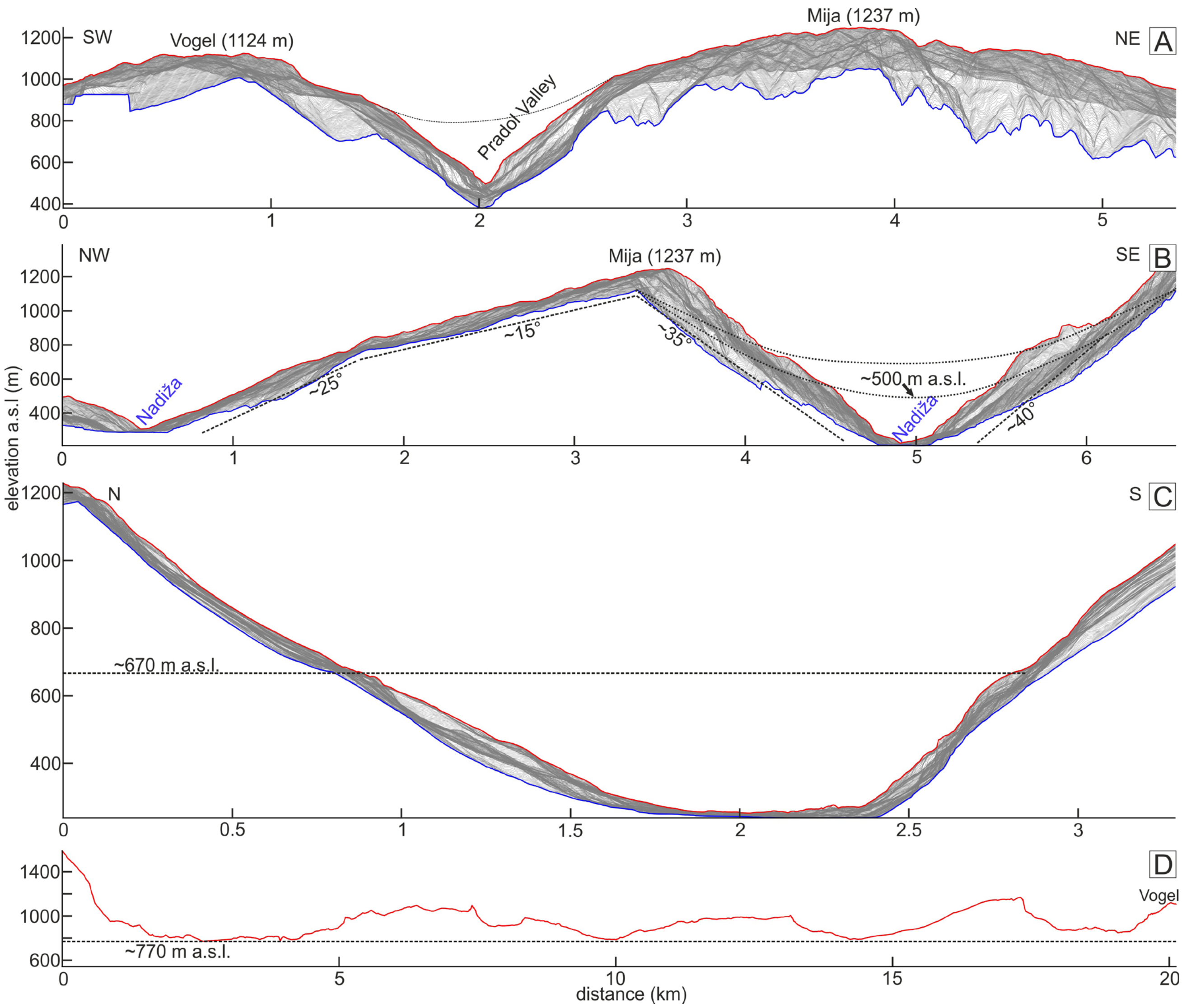

Fig. 4. Swath topographic profiles, A, B and C show maximum (red) and minimum (blue) elevation and single profiles. **A.** SW-NE-profile along the Vogel-Mija mountain ridge, crossing the Pradol Valley perpendicularly. The lowest part of the canyon is not represented accurately due to overhanging wall. Dashed line indicates a possible pre-incision morphology. **B.** Profile crossing the Mija from NW to SE. The ridge is asymmetric. On the south-eastern, steeper side, the amount of incision (difference between maximum and minimum elevation) is higher. Dashed lines indicate two scenarios of pre-incision valley morphology with valley floor elevations of ~500 to 700 m a.s.l. **C.** N-S profile across the valley east of Robič, dashed line indicates elevation of the scarp. **D.** Curved profile (max. elevations only) along the drainage divide of the south-eastern Nadiža catchment; dashed line indicates the lowest point of the ridge at 770 m a.s.l. Location of all profiles is indicated in figure 3, swath width is 1000 m.

Topographic swath profiles

Topographic swath profiles are commonly used for detailed topographic studies of selected areas. In contrast to single profiles, swath profiles sample a large number of parallel profiles to cover an entire area instead of a single line. The individual profiles are projected to a plane parallel to the profiles and maximum, minimum and mean elevations of all profiles are condensed to a single profile (Masek et al., 1994; Andreani et al., 2014). Swath profiles contain more information than single profiles, including the position of elevated paleo-surfaces, incised river beds, and the amount of regional incision (difference between maximum and minimum elevation). In this study, topographic profiles were used for detailed investigations of the morphology of the Nadiža and Pradol Valley and to determine the elevation of the mountain chains in the study area (Fig. 4).

River longitudinal profiles and analysis

For the stream profile analysis, the high-resolution DEM was resampled to 5 m-resolution to limit the computational demand. The profile was extracted using Topotoolbox 2 and Matlab. All streams with a minimum length of 1 km and a drainage area of at least 1 km² were extracted from the DEM. Longitudinal profiles of the Nadiža and the main tributaries were derived and knickpoints were calculated using the Topotool-

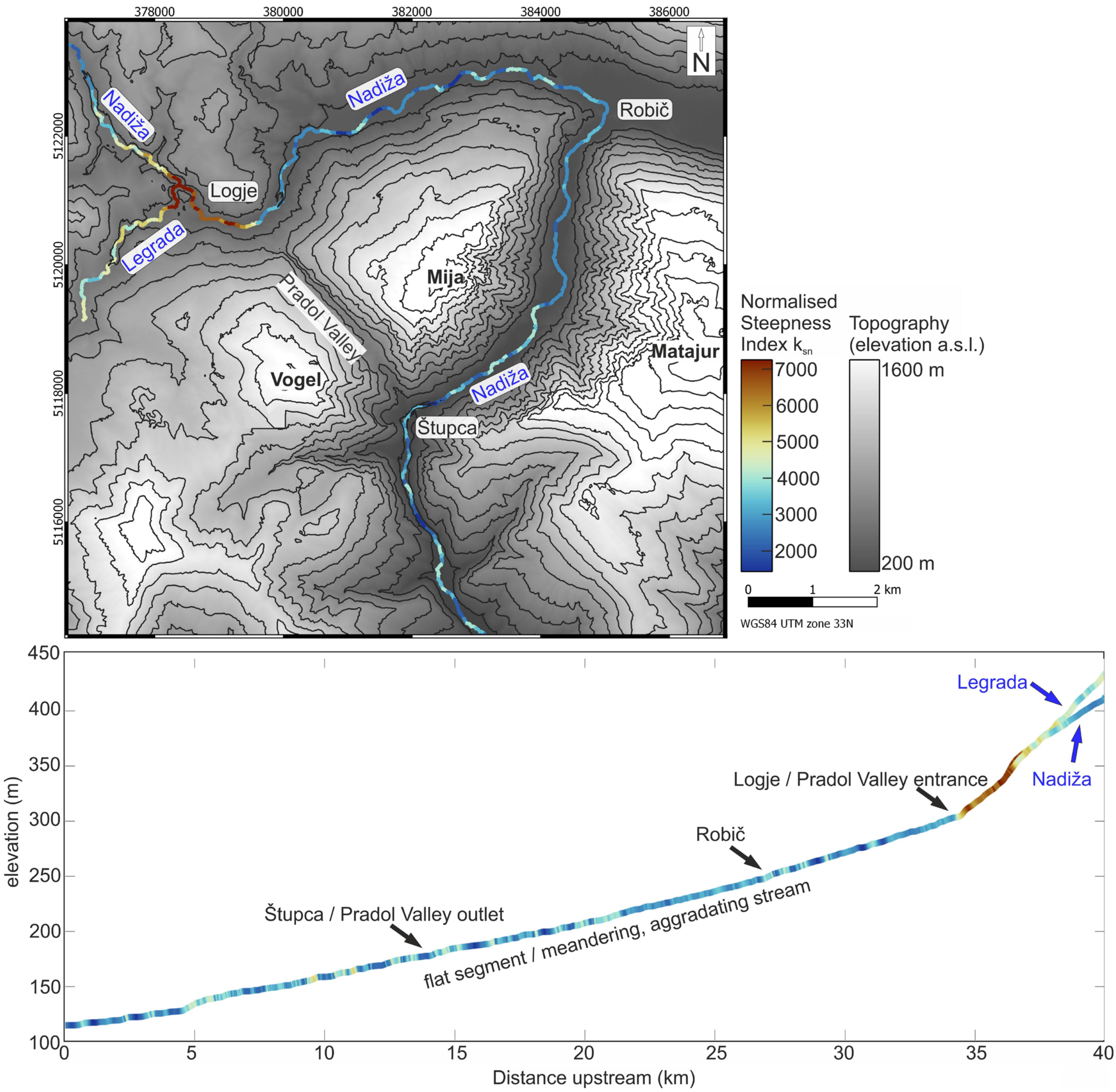

Fig. 5. Top: normalised steepness index (k_{sn}) map of the Nadiža and its tributary Legrada, merging west of Logje. Background contour map based on the 1 m LiDAR DEM. Below: Longitudinal profile of the Nadiža and Legrada, colour-coded by normalised steepness index (k_{sn}). The upper segment of the river is significantly steeper and exhibits high k_{sn}-values, whereas the lower segment is flat and meandering.

box 2 'knickpointfinder' function with different tolerance values between 20 and 40 m. The 'knickpointfinder' is a geometrical approach for knickpoint detection, comparing the real profile to an ideal (steady-state) stream profile, which is commonly described by the basic stream-power law (e.g. Whipple & Tucker, 1999; Kirby & Whipple, 2012).

The normalised steepness index (k_{sn}) was calculated, as described by Wobus et al., 2006. According to the stream-power law, the normalised steepness index includes the rock uplift and the coefficient of erosion (e.g. Wobus et al., 2006; Kirby & Whipple, 2012). Hence, elevated k_{sn}-values may be interpreted in terms of disequilibria within the stream profile. These might be caused by different factors, such as tectonic uplift or differences in channel bedrock lithology, but also by glaciations and by local or temporal changes in discharge. The k_{sn} was calculated with a concavity index of 0.6, which was previously determined via χ-transformation (Royden et al., 2000, Perron & Royden, 2013) of the Nadiža trunk channel. The longitudinal profile of the Nadiža and related k_{sn} values are presented in Fig. 5.

Field work

To complement the remote sensing studies, field work was carried out in the study area. The field work aimed at getting more precise knowledge of the morphology of the Pradol Valley, which cannot be precisely represented by airborne DEM due to the partly overhanging walls. Fluvial and glacial deposits were mapped at several points in the study area, providing important information on the glacial extent and previous river courses. The elevation of relevant features was measured at several points using combined handheld GNSS devices and barometric altimeter (Garmin eTrex and Suunto Traverse OW151). The GNSS positioning allowed a later verification with DEM and geological maps.

Results

The valley west of Kobarid has a typical glacial U-shape (Figs. 2C, 3, 4C). At an elevation between 670 and 730 m, a morphological scarp can be observed both in the topographic swath profile (Fig. 4C) and in the high resolution DEM (see orange arrows at the northern mountain ridge in Fig. 1). North of the village of Logje (close to the village Sedlo), we investigated several outcrops at an elevation between 500 and 700 m that exhibit poorly sorted sediments. The grain size varies between clay and boulders with 2 metres diameter. The sediments are unconsolidated and seem to have a weak layering with grains made of carbonates. The outcrops resemble typical moraine deposits. We found the highest outcrops at ~680 m a.s.l., which is close to the elevation of the morphologic scarp further to the east of the valley.

East of Robič, a landslide of unknown age with a head scarp on the southern side of the valley is visible both in the field (Fig. 2C) and in the DEM (Fig. 1). Although the landslide deposits are clearly visible on the valley floor, their influence on the overall valley morphology is low.

The valley south of Robič, between Mija and Matajur, has a different morphology. As seen in the topographic swath profile (Fig. 4B), the valley has a relatively steep V-shape with hillslope angles of 35° to 45° on both sides (see also photo in Figs. 2B, E). The lowest part of the valley is even steeper than the upper portion of the adjacent hills. The scarp, which is likely related to marginal moraines, cannot be observed in most parts of this valley. Compared to the surrounding region the valley has an increased surface roughness (Fig. 3) and incision (Fig. 4B).

While the Nadiža Valley is comparably wide and flat north of the Mija, it is steeply incised on the south-eastern side of the mountain. This leads to an overall asymmetric shape of the mountain ridge (Fig. 3B). The surface of the ridge is inclined ~15° on the north-western side and gets slightly steeper in the lowest section close to the river channel. The south-eastern flank of the valley is inclined ~35°, similar to the counterpart of the Matajur (~40°, Fig. 4B). If the Mija was symmetric, with an inclination between 15 and 25° on both sides, the south-eastern valley would have an elevation of at least 500 m (dashed curve in Fig. 4C).

The Nadiža stream (Figs. 1, 5) is steep in the upper segment, where it features elevated k_{sn}-values. The steep segment reaches downstream approximately to the location of Logje, where it enters the wide and flat valley. Here the stream character changes from steep and incising to a flat, meandering river with comparably low k_{sn}-values. Even in the strongly incised valley downstream of Robič, the recent river has a flat profile and aggradates river terraces.

The Pradol Valley itself has a remarkable morphology. The recent valley floor is at an elevation between 400 and 450 m a.s.l. and is covered by rock debris. The debris consists of angular limestone blocks from the adjacent walls and forms a layer covering the entire valley floor with irregular shape and thickness. The walls of the canyon, especially in the lower portion, are very steep (Fig. 2F), partly even overhanging. Due to the thick rock debris cover and dense vegetation, no remnants of fluvial sediments could be found within the valley. However, at the north-western valley entrance deposits of rounded, well-sorted carbonate pebbles, most probably fluvial sediments, crop out at elevations up to 400 m a.s.l. (see Fig. 1)

Interpretation

Several geologically viable explanations for the formation of the Pradol Valley appear plausible. However, most scenarios can be excluded due to at least one of the observed facts. Several studies of dry valleys around the world have shown that tectonic uplift may lead to the abandonment of river beds, reorientation of streams, and finally the formation of wind gaps (e.g., New Zealand: Tomkin & Braun, 1999; California: Keller et al., 1998; Greece: Goldsworthy & Jackson, 2001). Moulin et al. (2016) report in detail on the Čepovan Canyon, which is a large dry valley SE of our study area on the Trnovski Gozd Plateau. The canyon is cut by the Predjama Fault and its

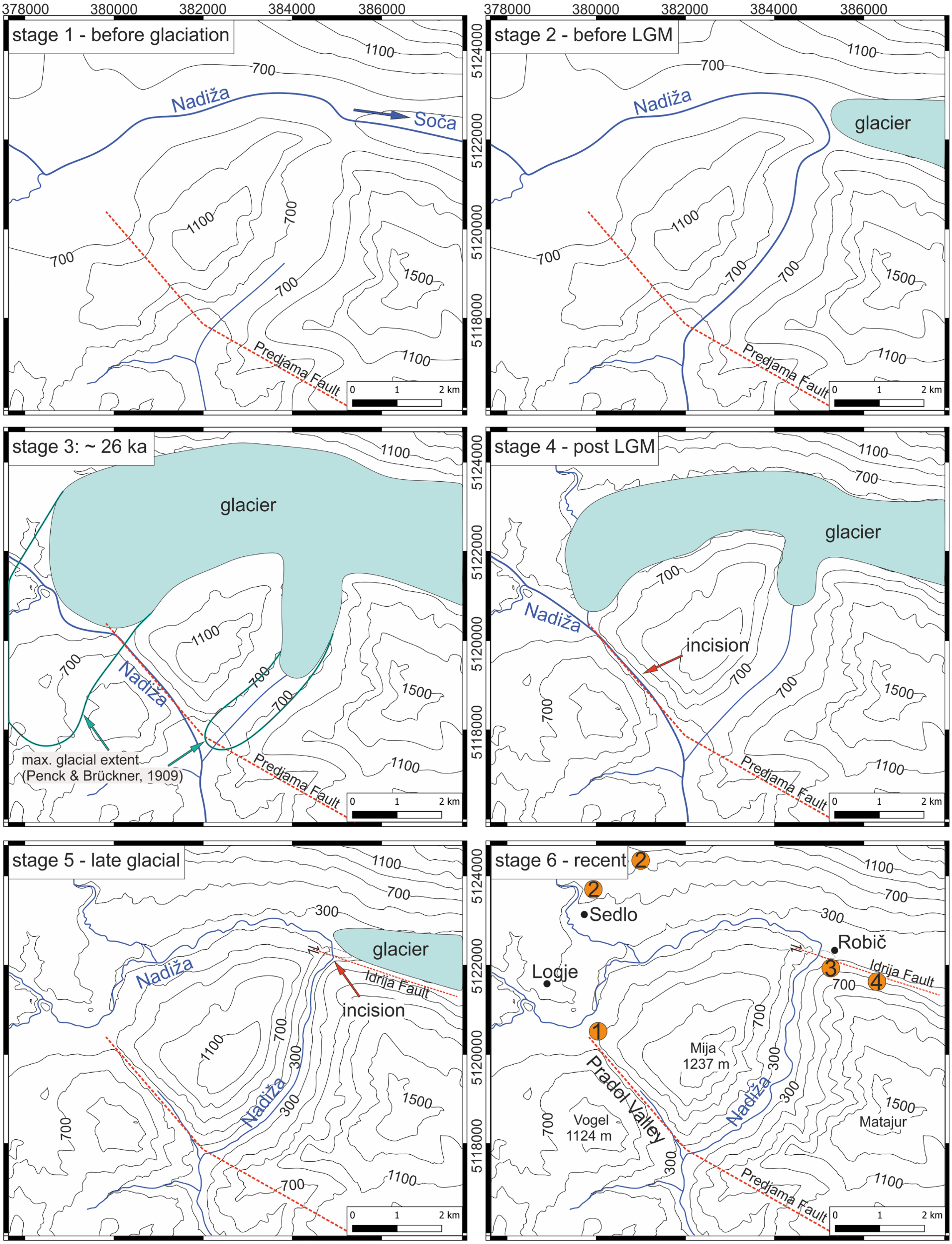

Fig. 6. Interpreted scenario of the formation of the Pradol Valley and the surrounding topography in six stages. Stage 6 features the recent topography (smoothed contour plot extracted from the 1 m DEM) and the location of the most important findings leading to the interpretation: 1) fluvial sediments at the north-western entrance of the Pradol Valley at 400 m a.s.l. 2) findings of glacial deposits (moraines) at 500 to 700 m a.s.l. 3) incised limestone rock at Robič 4) landslide in the Kobarid-valley. Stage 1 to 5 are constructed by stepwise modification of the recent topography based on the explained interpretations. (map projection: WGS 84 UTM zone 33N, north up).

slightly folded floor is also situated hundreds of metres above the surrounding valleys. This canyon is thought to have formed in the last 2.5 Ma and to have recorded several hundreds of metres of tectonic uplift and shortening (Moulin et al., 2016). In the case of the Pradol Valley, however, tectonic forcing can be excluded as the main driving force of its formation for two reasons:

First, the study area does not exhibit appropriately oriented thrust faults to uplift the Pradol Valley. The known active fault zones are predominantly strike-slip faults with minor uplift components only (Placer et al., 2010; Vrabec, 2012; Moulin et al., 2016). However, we cannot rule out the existence of blind thrust faults that do not reach the surface.

Second, the overall slip rate at the orogen-parallel fault system, induced by the collision of the Adriatic microplate and Eurasia, is too low to reach such amounts of uplift. Although the elevation of the mountain ridge before the incision of the Pradol Valley is unknown, the recent elevation of the two peaks (1124 and 1237 m) and the morphology of the ridge (see Fig. 4A) suggest that it was at least 700 m a.s.l., resulting in a necessary uplift of at least 300 m. The walls of the canyon are very steep and weakly eroded, which indicates that the formation is relatively young, probably post-glacial. This would result in unrealistically high uplift rates.

The irregular flow path of the Nadiža that cuts the bedrock ridge at Robič and which passes both entrances of the Pradol Valley as well as the remarkable shape of the valley south of Robič leads us to assume that the formation of all these morphologic features is related to the same process that incised the canyon. Here we propose a formation scenario, which takes into account all above-mentioned findings and explains the described morphologic features (Fig. 6).

The valley between Robič and Kobarid is wide and flat. The size and the morphology of the valley indicate that it was originally carved by a river and later further eroded by a glacier, leading to the typical U-shaped profile. It was most likely the original flow path of the Nadiža, before the glaciation and the change of the drainage pattern (stage 1 in Fig. 6). Hence, at this stage the Nadiža probably drained into the Soča instead of occupying the N-S-trending valley between Mija and Matajur. The incision of this valley was probably triggered by blocking of the Nadiža by glaciers coming from the north during a glacial advance (stage 2 in Fig. 6). According to the reconstruction of the valley with a symmetrical shape of the Mija ridge (Fig. 4B), the valley floor at this time was at an elevation of at least 500 m, about 300 m higher than today. This estimated elevation is plausible, considering that no major fluvial or glacial erosion took place before that stage. In an alternative model the Nadiža drained towards the south between Mija and Matajur already before the last glacial maximum. In this case the wide valley between Robič and Kobarid was dominantly shaped by a glacier. This alternative model does still comply with the stages 2–6 (Fig. 6).

The maximum glacial extent during the LGM is still debated (and further investigations are hindered by poor outcrop conditions and low chances of moraine preservation), but the Pleistocene glaciers advanced far enough to fill the entire valley, covering the recent locations of Robič and Logje (Bavec & Verbič, 2004a; Bavec et al., 2004b; Ferk et al., 2015; Penck & Brückner, 1909). The difference between the recent valley floor of the U-shaped valley (Fig. 4C) and the remnants of marginal moraines indicates an ice cover of at least 400 to 500 m. This blocked the outlet of the Nadiža (stage 3 in Fig. 6). Our interpretation is supported by the findings of lacustrine sediments near the village of Prossenicco (Fig. 1), as described by Feruglio (1929), who also proposed the idea that this glacial lake might have drained through the Pradol Valley. The glacier also advanced into the valley south of Robič, resulting in erosion of that valley.

The ice caps of the Alps reached their maximum extent at about 26 ka and lasted until approximately 20 – 19 ka BP (Clark et al., 2009). During this time (including an unknown amount of time before and after the maximum glacial extent), the Nadiža and the melt water from the glacier did not have an outlet. The lowest part of the mountain ridge south-west of Logje and the Vogel is at an elevation of 770 m (recent elevation, fig. 4D), so this could not have served as an outlet for the stream either. The only possible explanation for this is the formation of the Pradol Valley, which probably served as an outlet only for this limited time span (stage 3 to 4 in Fig. 6). Therefore, two main requirements must have been fulfilled: First, the mountain ridge must have been lower than the estimated maximum elevation of the glacier, otherwise it would be unlikely that the water drained through the mountain. The highest marginal moraine deposits are located slightly above 700 m a.s.l. Accordingly, the ridge between both peaks (Mija and Vogel) must have been indented to an elevation of ca. 700 (max. 770) metres before the LGM, which is plausible, as shown in figure 4A. Secondly, the bedrock probably had been weakened before the glaciation; otherwise the remarkably fast incision would be unlikely. The extraordinarily steep incised canyon with vertical to overhanging walls indicates that the incision rate was much faster than in common bedrock rivers. Both presumptions can be explained by the presence of the Predjama Fault, which is probably running through the Pradol Valley. The fault would form a natural weakness zone in the bedrock and hence become the preferred location for the river to start incising. Additionally, similar to the fault traces of the other main active faults, which can be observed in the modern topography (e.g., Cunningham et al., 2007; Moulin et al., 2014), the fault scarp formed an indentation in the mountain ridge. Although this assumption cannot be conclusively proven, it is the only valid explanation to date and is strengthened by the described findings.

The incision of the Pradol Valley lasted until the glacier retreated far enough for the Nadiža to again readjust its course and resume draining along its former flow path before its incision of the Pradol Valley (stage 5), thus abandoning it. At Kobarid, the glaciation lasted longer than in the western part of the valley, due to the glaciers coming from the Bovec Basin and the Soča Valley north of Kobarid. Accordingly, the outlet towards the Soča was still blocked, forcing the river to cut through the bedrock ridge at Robič and drain into the southern valley between Mija and Matajur (stage 5). This was enhanced by an increased discharge, due to the melting glaciers and the previous glacial erosion of the valley. This period of incision of the valley led to its steep morphology, the high surface roughness, and the asymmetry of the Mija ridge. In the alternative model that has the Nadiža draining this valley even before the LGM, the situation would be the same and intensified erosion would still lead to a deep incision. At this point it is worth noting that the limestone layers of Mija also dip towards the NW (Buser, 1987). However, these are much steeper (33-55°) than the surface (15-25°), so the morphology cannot be solely interpreted as a result of geologic properties. The landslide near Robič could also be interpreted as a possible cause of a blocked river, but it probably would be too small to withstand the combined discharge of a melting glacier and the Nadiža. Furthermore, the lack of an incised river bed indicates that the Nadiža did not take this path since the LGM.

After the glacial period the incision ceased and the Nadiža changed to a less steep, meandering river (at least in the lower parts), finally leading to the recent morphology (stage 6). We interpret the steep river segment in the upstream portion of the Nadiža (Fig. 5) as the remnant of higher discharge and stronger incision, which is now slowly migrating upstream. This steep segment is not affected by lithologic contrasts (Buser, 1987; Carulli, 2006) or other environmental effects. The lower part of the stream has already re-equilibrated since the end of the last glacial period.

The last stage (Fig. 6, stage 6) features the recent topography and all findings which led to the interpretation of this scenario: the fluvial sediments at the Pradol Valley entrance (1), the glacial deposits from the LGM (2), the position of the incised limestone rock at Robič (3) and the landslide (4).

Discussion

The previously explained scenario of the formation of the Pradol Valley is based on several assumptions. The main assumption necessary to explain the formation of the canyon is the indentation of the mountain ridge before the main episode of fluvial incision. To form the outlet of the blocked valley, the ridge must not have been higher than 700 to 800 m at its lowest point. This assumption is supported by the presence of the Predjama Fault zone. Further uncertainties of the interpretation are induced due to unknown timing of the expected events, especially stages 1 to 3 (Fig. 6).

Despite some uncertainties, several interpretations can be verified. First, the Nadiža is the only stream in the region which has enough discharge to force major erosion processes. This, along with the flow path passing both Pradol Valley entrances and the fluvial sediments, justifies the interpretation that the Nadiža is responsible for the incision of the valley. Secondly, although the maximum glacial extent is still debated, the blocking of the Nadiža during the Pleistocene is proven by the finding of marginal moraine deposits at elevations up to 700 m. Therefore, if this moraine is indeed from the LGM, the Pradol Valley forms the only possible outlet of the Nadiža and the glacier melt water for the time span between at least 26 ka and 19 ka BP.

The sub-vertical section of the canyon is approximately 150 m high (Fig. 3A). Above this part, the canyon profile has a steep V-shape, indicating that the original ridge was at least 700 m high. This results in an incision of at least

300 metres during the maximum glacial extend (~7 ka) plus an unknown amount of time before and after the LGM. Assuming a time span of 7 to 15 ka, an incision rate of 20 to 43 mm/a is derived. Incision rates in this order typically only occur within actively uplifting mountain belts or at larger rivers (e.g. Seong et al., 2008, Sanders et al., 2014 and citations therein). Studies of gorge formation in the French Alps showed less intense incision rates (Valla et al., 2010; up to 15 mm/a). None of the mentioned studies resembles the conditions given at the Pradol Valley, regarding bedrock erodibility, river discharge and sediment load, making a direct comparison pointless. However, these studies show that our calculated incision rates fall into a range that could possibly occur in a natural stream. The pre-existing weakness zone along the Predjama Fault combined with elevated discharge due to melting of the Soča Glacier likely accelerated the incision of the Pradol Valley.

Altogether, the scenario we propose explains all noteworthy morphologic and geologic findings of the study area, including the location of active fault zones, the occurrence of fluvial and glacial deposits, the rather uncommon recent river flow paths, and the strongly incised valleys.

Although our model can explain all the observations with a post-LGM formation of the Pradol Valley, we cannot rule out the possibility that the Pradol resulted from multiple incision phases during the last few glacial cycles, or that it formed in an earlier glacial advance in the Pleistocene that exceeded the one during the LGM. One argument for multiple cycles of incision is the extraordinary depth of the canyon and the very high incision rates resulting if it were all formed post-LGM. On the other hand, the almost vertical canyon walls indicate that no significant post-incision modification by mass movements took place, which would be expected if the canyon had undergone multiple ice advances or if it was significantly older than the LGM. We note that this question could perhaps be answered by systematic exposure dating along a vertical profile from the Pradol Valley floor up to the top of the canyon.

Conclusion

We conclude that the Pradol Valley must have had a major episode of incision during the LGM, lasting ca. 7-15 kyr due to the blocking of the Nadiža channel by glaciers coming from NE. The canyon probably incised at least 300 m, resulting in incision rates of 2 to 4 cm/a. The extreme incision rates appear plausible, as the canyon has very steep, partly overhanging walls, documenting fast erosion. Additionally, cataclastic abrasive wear of the bedrock caused by faulting along the Predjama Fault located along-strike the canyon likely contributed to this process. It remains unclear whether the entire canyon was carved by this one event, or if the formation started during earlier glacials.

Our study demonstrates that a complex interplay of glacial, fluvial and tectonic processes is the driving force of landscape evolution in this area. Accordingly, studies in related fields, such as tectonic geomorphology, should be treated carefully, especially in areas affected by former glacial processes.

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Tectonics and gravitational phenomena (Nanos, Slovenia)

Tektonika in gravitacijski pojavi (Nanos, Slovenija)

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Ključne besede: gravitacijski pojavi, geomorfologija, istrsko potisno območje, Nanos, Hrušica, razdol, Adria

Abstract

The Istra Pushed Area is a specifically deformed territory of the northwestern part of the External Dinarides. It formed due to the movement of the Istra block as part of the Adriatic Microplate (Adria) towards the Dinarides since the middle Miocene. The movement of the Istra block caused hereditary shifts along the old dislocations dating back to the early formation stage of the formation of the Dinarides at the end of the Eocene and their deformation. These deformations are reflected also in certain extreme gravitational phenomena along the boundary between the External Dinaric Imbricated Belt and the External Dinaric Thrust Belt, where Mesozoic carbonates are thrusted upon the Cenozoic flysch. The boundary zone between these two belts connects the Trnovo, Hrušica and Snežnik Thrust Fronts. Four specific gravitational phenomena that occurred in this boundary zone are presented here, as they are remarkable in terms of their size: Črna griža (Trnovo Nappe), Suhi vrh (Hrušica Nappe), Petelinje mlake and Ilirska Bistrica (both from the Snežnik Nappe). The phenomena at Suhi vrh is described in detail herein.

Izvleček

Istrsko potisno območje je specifično deformirano ozemlje severozahodnega dela Zunanjih Dinaridov. Nastalo je zaradi pomikanja istrskega bloka, ki je del Jadranske mikroplošče (Adria), proti Dinaridom. To se dogaja od srede miocena naprej. Pomikanje istrskega bloka je povzročilo nasledstvene premike po starih dislokacijah iz zaključka prvega obdobja nastajanja Dinaridov konec eocena in njihovo deformacijo. Te deformacije se odražajo tudi v ekstremnih gravitacijskih pojavih na meji med Zunanjedinarskim naluskanim pasom in Zunanjedinarskim narivnim pasom, kjer so mezozojski karbonati narinjeni na kenozojski fliš. Omenjeni mejni pas povezuje čela krovnih narivov Trnovskega, Hrušiškega in Snežniškega pokrova. V članku so prikazani štirje specifični gravitacijski pojavi, ki so izjemni po velikosti: Črni školj (Trnovski pokrov), Suhi vrh (Hrušiški pokrov) ter Petelinje mlake in Ilirska Bistrica (oba Snežniški pokrov). Natančneje je opisan pojav Suhi vrh.

Introduction

A formal boundary between the Adriatic Microplate (Adria) and the Dinarides in the NW Dinarides after Schmidt et al. (2008) runs along the External Dinarides thrust boundary in the Istra and Gulf of Trieste hinterland (Fig. 1). As the Adria rotates in a counterclockwise direction obliquely to the Dinarides (Weber et al., 2006) the movements against the Dinarides are released along two components: orthogonally (pushing, and con-

Uvod

Formalna meja med Jadransko mikroploščo (Adria) in Dinaridi poteka po Schmid-u in sodelavcih (2008) po narivni meji Zunanjih Dinaridov, ki se v severozahodnih Dinaridih nahaja v zaledju Istre in Tržaškega zaliva (sl. 1). Adria rotira v nasprotni smeri urinega kazalca poševno na Dinaride (Weber et al., 2006), zato se njeni pomiki nasproti Dinaridom sproščajo po dveh komponentah, pravokotno nanje (potiskanje in

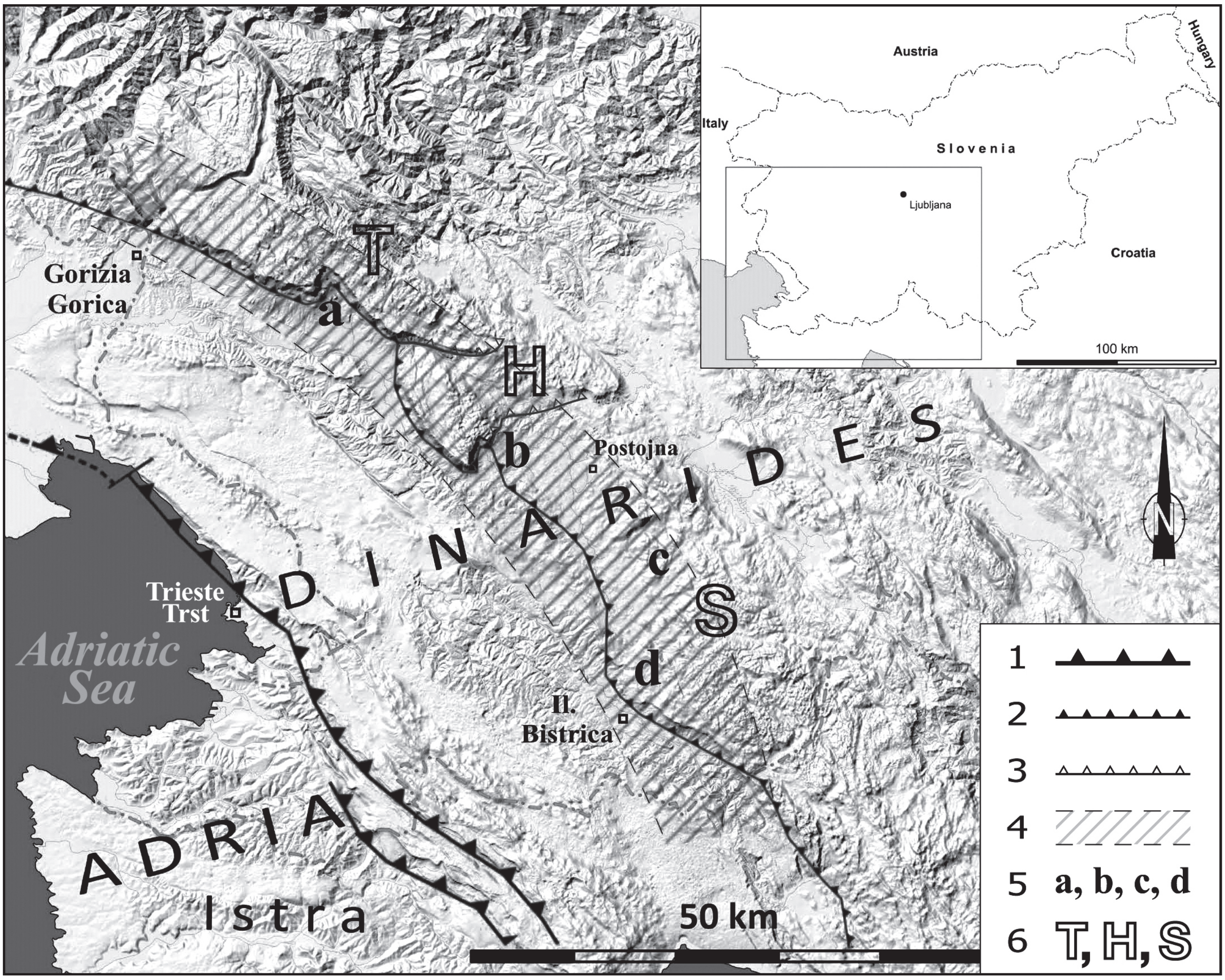

Fig. 1. The Adria (*sensu stricto*) and the northwestern Dinarides boundary zone. Belt of large gravitational phenomena.
Sl. 1. Mejno območje Adrie (*sensu stricto*) in severozahodnih Dinaridov. Pas velikih gravitacijskih pojavov.
1 External Dinarides boundary / meja Zunanjih Dinaridov
2 External Dinaric Thrust Belt boundary / meja Zunanjedinarskega narivnega pasu
3 Nappe boundary / meja pokrova
4 Belt of large gravitational phenomena / pas velikih gravitacijskih pojavov
5 Outstanding gravitaitional phenomena / izjemni gravitacijski pojavi: a – Črni školj, b – Suhi vrh, c – Petelinje mlake, d – Ilirska Bistrica
6 T – Trnovo Nappe / Trnovski pokrov, H – Hrušica Nappe / Hrušiški pokrov, S – Snežnik Nappe / Snežniški pokrov

sequential folding and underthrusting), and parallel to the Dinarides (via right lateral strike slip along subvertical faults) (Placer et al., 2010). Istra is a structural block within the Adria and moves against the Dinarides faster than the blocks SE of it. As a consequence, the External Dinarides in the Istra hinterland between the Southern Alps and the Velebit are cambered (bent) towards the NE. This bent part of the External Dinarides is called the Istra Pushed Area (Placer, 2010).

Formally, the assumed movement of the Istra against the Dinarides is evidenced by local block rotation in the Čičarija in the Istra hinterland by palaeomagnetic analysis of the cave sediments there (Vrabec et al., 2018). Using said analysis, the theory of the existence of the Istra Pushed Area

posledično gubanje ter podrivanje) in vzporedno z njimi (desno zmikanje ob subvertikalnih prelomih) (Placer et al., 2010). Istra je blok v okviru Adrie, ki se proti Dinaridom premika hitreje od blokov jugovzhodno od tod, zato so Zunanji Dinaridi v njenem zaledju med Južnimi Alpami in Velebitom usločeni proti severovzhodu. Ta predel Zunanjih Dinaridov se v strukturnem smislu imenuje istrsko potisno območje (Placer et al., 2010).

Domneva o premikanju Istre proti Dinaridom je bila formalno dokazana z lokalno rotacijo blokov v Čičariji v zaledju Istre, dokaz pa temelji na analizi starosti in paleomagnetizma jamskih sedimentov (Vrabec et al., 2018). S tem je bila potrjena teorija o obstoju istrskega potisnega ob-was confirmed and forms the basis of the study of the structures within the area. The principal feature within the Istra Pushed Area is the deformation of older brittle and ductile deformation. Block rotation analysis revealed a correlation between the local rotation and bending of the Čičarija Imbricate Structure. Regional data shows that other Dinaric structures within the Istra Pushed Area such as the Trieste–Komen Anticlinorium and the Vipava Synclinorium are also bent, so correlation between the surface structure and the local block rotation is expected there as well.

Istra's movement against the Dinarides is an uneven but continuous process that has been taking place since at least 5 Ma, which is the oldest age of the cave sediments analyzed. However, this age reflects the method range rather than the absolute duration of the described motion (Vrabec et al., 2018). The process started already in the Middle or even Lower Miocene; [and regarding the GPS measurements (Weber et al., 2006) takes place even nowadays], which is best reflected in the gravitational processes at work on the morphologically exposed boundary of the External Dinaric nappe thrusts, formally in the fore part of the External Dinaric Thrust Belt.

Belt (zone) of large gravitational phenomena

The boundary zone along the External Dinaric Thrust Belt comprised of the Trnovo, Hrušica and Snežnik Thrust Fronts, is particularly outstanding in the Istra Pushed Area (Fig. 1). The instability of the thrust fronts due to Mz carbonates thrust upon the siliciclastic flysch best characterise this belt. Local post-tectonic uplift and the denuding of the flysch footwalls have also played an important part in said development. These processes led to a significant geomorphologic step with a highly elevated risk of landslide (Komac & Ribičič, 2008); and at the same time came to constitute a highly attractive subject of research (Popit, 2016; 2017; Verbovšek et al., 2017; 2019). The thrust front zone is referred to as a "belt of large gravitational phenomena" due to the intense and diverse gravitational activity there. Its width is determined by the extent of these phenomena, where a wide variety of mass wasting forms is recognized, such as translational (planar) and rotational slides, rockfalls, rockslides and mass flows. Longer-term tectonic and denudational activity is reflected in the overlapping of multiple superimposed landslides following each other in different temporal increments. Peculiar "gravitational duplexes" (as they could be called) are the most interesting among these

močja in postavljeno je bilo stvarno izhodišče za študij deformacij v njem.

Glavna značilnost istrskega potisnega območja so deformacije starejših plikativnih in disjunktivnih struktur. Analiza rotacije blokov v Čičariji je pokazala na soglasje med lokalno rotacijo in bočno usločenostjo Čičarijskega antiklinorija. Regionalni podatki kažejo, da so bočno usločene tudi druge dinarske strukture istrskega potisnega območja, npr. Tržaško-Komenski antiklinorij in Vipavski sinklinorij, zato tudi tu pričakujemo soglasje med površinsko strukturo in lokalno rotacijo blokov.

Premikanje Istre proti Dinaridom je neenakomeren, vendar kontinuiran proces, ki je starejši od 5 milijonov let. Na to kaže najvišja starost analiziranih jamskih sedimentov v Čičariji (Vrabec et al., 2018). Pričetek tega procesa pa sega v srednji ali celo v spodnji miocen in je glede na meritve GPS (Weber et al., 2010), dejaven še danes. Slednje se najlepše kaže v gravitacijskih procesih na morfološko izpostavljeni meji Zunanjedinarskih krovnih narivov, formalno v čelnem delu Zunanjedinarskega narivnega pasu.

Pas velikih gravitacijskih pojavov

Znotraj istrskega potisnega območja posebej izstopa mejni del Zunanjedinarskega narivnega pasu, ki ga sestavljajo čela Trnovskega, Hrušiškega in Snežniškega pokrova (prej Snežniška narivna gruda) (sl. 1). Glavna značilnost tega pasu je nestabilnost čela krovnih enot, ki je posledica nariva mezozojskih karbonatov na siliciklastične flišne plasti. Poleg tega je imelo pomembno vlogo še krajevno omejeno postnarivno tektonsko dviganje in denudacija fliša talninskih krovnih enot. Ti procesi so pripeljali do izoblikovanja geomorfološke stopnje, ki predstavlja izrazito območje tveganja za proženje zemeljskih plazov (Komac & Ribičič, 2008) in hkrati privlačno območje njihovega proučevanja (Popit, 2016, 2017; Verbovšek et al., 2017, 2019). Zaradi raznolike in intenzivne gravitacijske dejavnosti, smo čelni rob opisanih krovnih enot poimenovali »pas velikih gravitacijskih pojavov«. Njegovo širino določa vplivno območje zdrsov. Tu je nastala cela vrsta gravitacijskih pojavov kot so planarni in rotacijski plazovi, odlomi, blokovni zdrsi in masni tokovi. Na daljšo tektonsko in denudacijsko aktivnost kaže sožitje fosilnih in recentnih plazov, od katerih so najbolj zanimivi svojevrstni »gravitacijski dupleksi« kot bi lahko imenovali plazove v nadstropjih, ki so "multistorey" landslides. Individual superimposed mass wasting events (phenomena) may also differ from among each other in terms of their various genetic types, like the rotational fossil Mala Gora landslide superimposed by an active translational Slano blato landslide (Placer et al., 2008), and a rotational fossil Reševnik landslide superimposed by an active translational Razdrto landslide (Placer, 2006).

The gravitational phenomena here are divided into two distinctive areas according to the prevailing mechanisms at work: the Trnovo and Hrušica Nappes Thrust Fronts on one side, and the Snežnik Nappe Thrust Front on the other. In the first case, large gravitational phenomena occur between Vitovlje above Šempas in the Vipava valley, and at Razdrto, in the western part of the Postojna basin. Two slopes stand out here, running parallel to the NNE–SSW trending regional fractures and hence close to the NW–SE trending thrust plane. The two areas share identical geomorphologic characteristics: the eastern slope of the Čaven high karst plane (plateau) between Mt. Črni školj (1180 m a.s.l.), Mt. Mali Modrasovec (1306 m a.s.l.) and Mt. Mala Gora (1032 m a.s.l.)

nastajali zaporedoma v krajših ali daljših časovnih presledkih. Ti so lahko genetsko istorodni ali raznorodni; taka večja pojava sta npr. rotacijski fosilni plaz Mala Gora na katerem leži aktivni planarni zemeljski plaz Slano blato (Placer et al., 2008) in rotacijski fosilni plaz Reševnik na katerem leži aktivni planarni zemeljski plaz Razdrto (Placer, 2006).

Gravitacijski pojavi obravnavanega pasu se po prevladujočem mehanizmu delijo na dve območji, na eni strani sta čeli Trnovskega in Hrušiškega pokrova, na drugi čelo Snežniškega pokrova. V prvem primeru nastopajo veliki gravitacijski pojavi med Vitovljami nad Šempasom v Vipavski dolini in Razdrtim v zahodnem delu Postojnske kotline. Tu izstopata dve pobočji, ki ležita v smeri prevladujočih regionalnih razpok SSW-NNE, torej blizu smeri narivanja SW-NE, v katerih je določljiva lega narivne ploskve. Območji imata identične geomorfološke značilnosti, pri Trnovskem pokrovu je to vzhodno pobočje visoke kraške planote Čaven med Črnim školjem (1080 m), Malim Modrasovcem (1306 m) in Malo Goro (1032 m) (sl. 1, a; sl. 2), pri Hrušiškem pokrovu jugovzhodno pobočje visoke

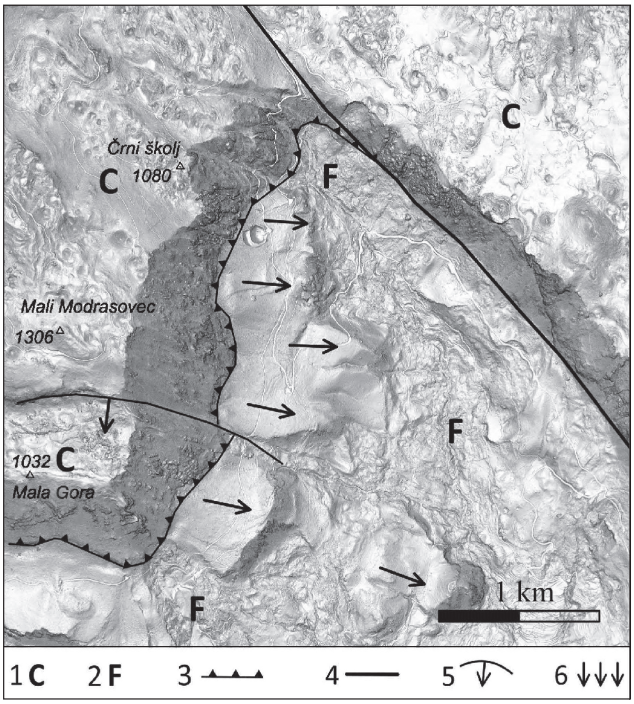

Fig. 2. Črni školj landslide area.
Sl. 2. Plazišče Črni školj.

1 C – Trnovo Nappe carbonates / karbonati Trnovskega pokrova
2 F – Flysch of the External Dinaric Imbricated Belt / fliš Zunanjedinarskega naluskanega pasu
3 Trnovo Nappe boundary /meja Trnovskega pokrova
4 Podgora (former Predjama) fault / Podgorski (prej Predjamski) prelom
5 Mala Gora rotational landslide / rotacijski plaz Mala Gora
6 Črni školj landslide area / plazišče Črni školj

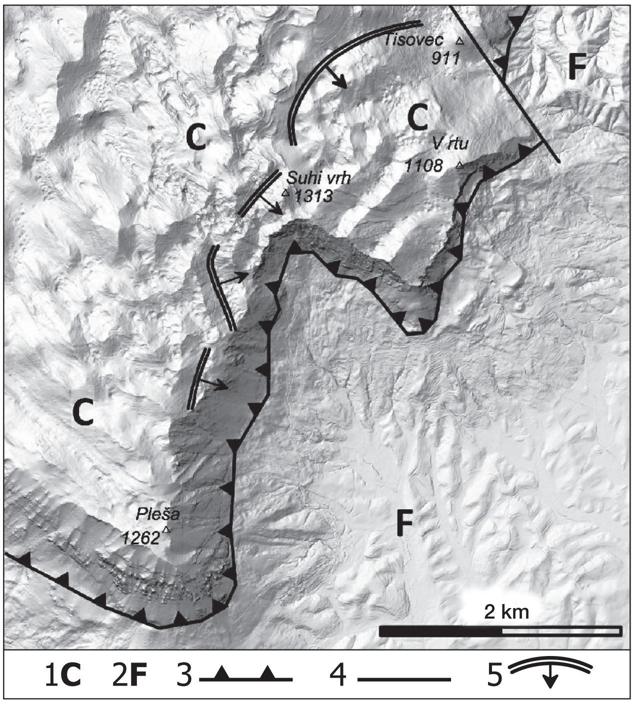

Fig. 3. Suhi vrh gravitational phenomena.
Sl. 3. Gravitacijski pojav Suhi vrh.

1 C – Hrušica Nappe carbonates / karbonati Hrušiškega pokrova
2 F – Flysch of the Snežnik Nappe and of the External Dinaric Imbricated Belt / fliš Snežniškega pokrova in Zunanjedinarskega naluskanega pasu
3 Hrušica Nappe boundary / meja Hrušiškega pokrova
4 Fault / prelom
5 Suhi vrh gravitational area / gravitacijsko območje Suhi vrh

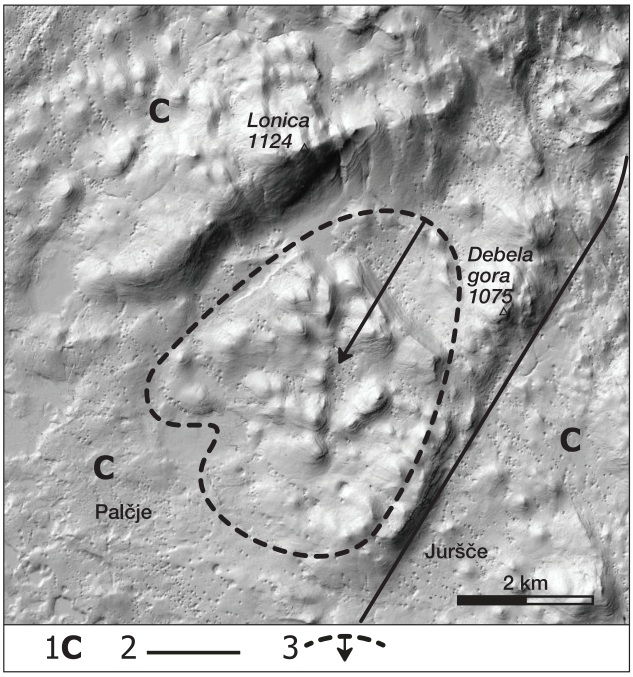

Fig. 4. Petelinje mlake rotational landslide.
Sl. 4. Rotacijski plaz Petelinje mlake.

1 C – Snežnik Nappe carbonates / karbonati Snežniškega pokrova
2 Juršče fault / Jurški prelom
3 Landslide mass / masa plazu

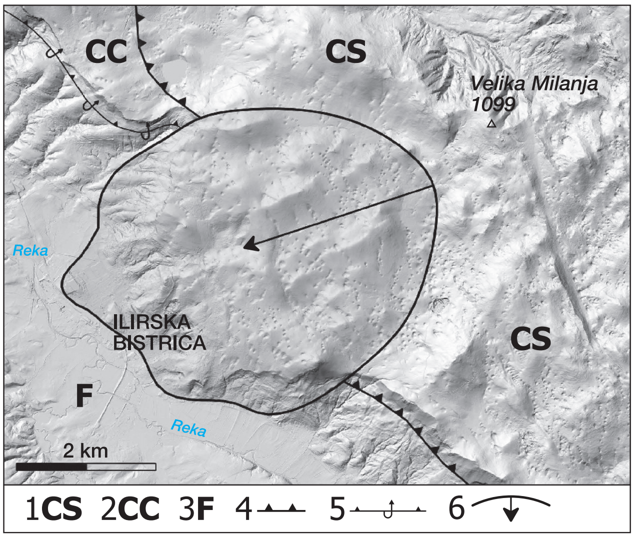

Fig. 5. Ilirska Bistrica rotational landslide.
Sl. 5. Rotacijski plaz Ilirska Bistrica.

1 CS – Snežnik Nappe carbonates / karbonati Snežniškega pokrova
2 CC – Carbonates of the External Dinaric Imbricated Belt / karbonati Zunanjedinarskga naluskanega pasu
3 F – Flysch of the External Dinaric Imbricated Belt / fliš Zunanjedinarskega naluskanega pasu
4 Snežnik Nappe boundary / meja Snežniškega pokrova
5 Tectonized boundary of the inverse beds within the External Dinaric Imbricated Belt / tektonizirana meja inverznih plasti znotraj Zunanjedinarskega naluskanega pasu
6 Landslide mass / masa plazu

(Fig. 1, a; Fig. 2) in the case of the Trnovo Nappe, and the SE slope of the Nanos high karst plane (plateau) between Mt. Pleša (1262 m a.s.l.) and Mt. V rtu (1108 m a.s.l.) (Fig. 1, b; Fig. 3).

In the thrust front of the Snežnik Nappe, gravitational phenomena comparable to those in the Trnovo and Hrušica Nappes Thrust Fronts are only found SE of Ilirska Bistrica. Two outstanding phenomena are present in the intermediate area between Razdrto and Ilirska Bistrica: an inferred fossil rotational landslide at Petelinje mlake (Fig. 1, c; Fig. 4), and the Ilirska Bistrica fossil rotational landslide (Fig. 1, d; Fig. 5), both formed under particularly specific conditions. Except for these two phenomena, the Snežnik Nappe Thrust Front does not exhibit any other large gravitational features, as the Snežnik Nappe flysch is thrust upon the flysch of the External Dinaric Imbricated Belt in the eastern part of the Postojna basin, where the relief between the two nappes is levelled due to the absence of carbonates there. Due south-east, between Hruševje and Šembije, at the edge of the Ilirska Bistrica fossil landslide, the geomorphological step is not yet high enough to pose a gravitational risk.

A brief, informative introduction of the tectonic environment for the four outstanding cases present in the belt of the large gravitational phenomena is necessary in order to understand the described differences in the geomorphology and

kraške planote Nanos med Plešo (1262 m) in vrhom V rtu (1108 m) (sl. 1, b; sl. 3).

V čelu Snežniškega pokrova nastopajo gravitacijski pojavi, ki jih je mogoče primerjati s tistimi v Trnovskem in Hrušiškem pokrovu, šele jugovzhodno od Ilirske Bistrice. Na vmesnem prostoru med Razdrtim in Ilirsko Bistrico nastopata dva izjemna pojava, domnevni fosilni rotacijski plaz Petelinje mlake (sl. 1, c; sl. 4) in ilirskobistriški fosilni rotacijski plaz (sl. 1, d; sl. 5), ki sta nastala pri specifičnih pogojih. Izven teh dveh pojavov so razmere umirjene, tu je na zahodni strani Postojnske kotline fliš Snežniškega pokrova narinjen na fliš Zunanjedinarskega naluskanega pasu, zaradi česar je površje obeh krovnih enot uravnano na skupni nivo, na jugovzhodu med Hruševjem in Šembijami na robu velikega ilirskobistriškega fosilnega plazu, pa geomorfološki prag v čelu Snežniškega pokrova še ni tako visok, da bi bil gravitacijsko ogrožen.

Za razumevanje opisanih razlik v geomorfologiji in gravitacijskih pojavih, je potrebno vsaj informativno predstaviti tektonsko okolje štirih izstopajočih primerov v pasu velikih gravitacijskih pojavov: Črni školj (a) v Trnovskem pokrovu, Suhi vrh (b) v Hrušiškem pokrovu ter Petelinje mlake (c) in Ilirska Bistrica (d) v Snežniškem pokrovu (sl. 1). Na območju Črnega škothe gravitational phenomena: Črni školj (a) in the Trnovo Nappe Thrust Front, Suhi vrh (b) in the Hrušica Nappe Thrust Front, Petelinje mlake (c), and Ilirska Bistrica (d) in the Snežnik Nappe Thrust Front (Fig. 1). The Trnovo Nappe thrust plane lies at approximately 650 m a.s.l. in the Mala Gora fossil rotational landslide in the Črni školj area (Fig. 2). The thrust plane rises along the Mala Gora rotational landslide rupture surface at the Mt. Mali Modrasovec slope some 100 m to a height of 750 m a.s.l., and to 770 m a.s.l. along the road below Črni školj. Generally speaking, the thrust plane simply rises gently upward. A large area with slided blocks referred to as the Črni školj landslide area is described in detail by Kocjančič et al. (2019). The landslide area was formed as the result of the uplifted carbonate block with flysch in its base, and the denudational lowering of the Vipava valley. The Mala Gora fossil rotational slide is younger and dissects (cuts) the Črni školj landslide area.

The thrust plane on the SE slope of Mt. Nanos (Fig. 3) rises from 750 m a.s.l. south of Pleša (1262 m a.s.l.), up to 1000 m a.s.l. below Suhi vrh (1313 m a.s.l.) and descends down to 770 m a.s.l. beneath Mt. Tisovec (911 m a.s.l.). The specific structure of the Suhi vrh area – the result of extremely uplifted thrusted carbonate block with flysch in its base – is a consequence of gravitational processes. However, the structure differs from classical slides beneath Mt. Pleša and the V rtu peak (1108 m a.s.l.), due to the erosion and denudation of this part of the Postojna basin. Namely, the thrust plane of the Trnovo and Hrušica Nappes are uplifted and convexly bent behind the thrust front, but far less so in the Hrušica than in the Trnovo Nappe.

Unfortunately, we do not have knowledge of the structural base that would help us better understand the landslide at Petelinje mlake (Fig. 4), as the area hasn't been mapped in detail. Its position, two kilometres behind the thrust front is remarkable, reflecting significant post-thrusting modifications and a specific type of formation. The Juršče fault is surprising, as it seems to have been formed after the triggering of the Ilirska Bistrica landslide. The Ilirska Bistrica landslide (Fig. 5) was formed by the slipping of the carbonate block belonging to the Snežnik Nappe along the flysch basement. There is no evidence of the convex thrust plane bending, but the erosional deepening of the Reka river is certain. A unique rotational landslide formed owing to the close proximity of the Raša right lateral strike-slip fault, and the opening up of the pull-apart basin within the fault zone. The pull-apart basin was situated just beneath the

lja (sl. 2) se narivna ploskev Trnovskega pokrova v fosilnem rotacijskem plazu Mala Gora nahaja približno na koti 650 m. V pobočju Malega Modrasovca se ob drsni ploskvi plazu Mala Gora dvigne za okoli 100 m na 750 m, ob cesti pod Črnim školjem pa sega do višine okoli 770 m. V splošnem lahko rečemo, da se rahlo dviga. Pod pobočjem med Črnim školjem, Malim Modrasovcem in Malo Goro je obsežno območje zdrselih blokov, ki ga imenujemo plazišče Črni školj. Podrobno so ga opisali Kocjančič in sodelavci (2019). Nastalo je zaradi dviga narinjenega karbonatnega bloka s flišem v podlagi in denudacijskega nižanja nivoja Vipavske doline. Fosilni rotacijski plaz Mala Gora je mlajšega datuma in seka plazišče Črni školj.

V jugovzhodnem pobočju Nanosa (sl. 3) se narivna ploskev od kote 750 južno od Pleše (1262 m) dvigne do 1000 m pod Suhim vrhom (1313 m), nakar se spusti na 770 m pod Tisovcem (911 m). Območje Suhega vrha ima zaradi ekstremnega dviga narinjenega karbonatnega bloka s flišem v podlagi specifično zgradbo, ki je posledica gravitacije, vendar se razlikuje od klasičnih pobočnih zdrsov pod stenami med Plešo in vrhom V rtu (1108 m), ki jih je povzročila erozija in denudacija tega dela Postojnske kotline. Pri Trnovskem in Hrušiškem pokrovu se je narivna ploskev za čelom pokrova dvignila in konveksno usločila, vendar pri Hrušiškem bistveno bolj kot pri Trnovskem.

Pri Petelinjih mlakah (sl. 4) strukturna osnova za nastanek plazu ni jasna, ker območje ni natančneje kartirano. Izjemna je njegova lega dva kilometra za čelom Snežniškega pokrova, ki kaže na velike postnarivne spremembe in na specifične pogoje nastanka. Preseneča Jurški prelom, ki je moral nastati po sprožitvi plazu. Ilirskobistriški fosilni plaz (sl. 5) je nastal tako, da je karbonatni blok Snežniškega pokrova zdrsnil po flišni podlagi. Tu nimamo dokazov, da bi se narivna ploskev konveksno izbočila, zagotovo pa se je erozijsko poglobila dolina reke Reke. Do nastanka edinstvenega rotacijskega plazu je prišlo zaradi bližine desnozmičnega Raškega preloma in razprtja bazena tipa pull-apart znotraj njegove širše prelomne cone. Bazen je ležal tik pod pobočjem narivnega čela, tako da je to ob razprtju izgubilo oporo in zdrsnilo navzdol (Placer & Jamšek, 2011). Pojav je moral biti hipen, kar ga povezuje s seizmičnim dogodkom. Bistriški pul-apartski bazen je pokrivWal osrednji del Bistriške kotline pod plazom.

thrust front slope, lost stability, and collapsed at the opening of the basin (Placer & Jamšek, 2011). The collapse had to be instantaneous which brings it in relation with a seismic event. The Ilirska Bistrica pull-apart basin covered the central part of the Ilirska Bistrica basin beneath the landslide.

Gravitational phenomena on the SE slope of Mt. Nanos

The SE slope of Mt. Nanos reveals some insight into the structure of the fore and rear parts of the Hrušica Nappe Thrust Front, as well as the morphology of its thrust plane, which was deformed in post-thrust processes. The gravitational phenomena at Suhi vrh reflects these deformation (processes).

Structure of Mt. Nanos and Mt. Hrušica

Mt. Nanos is part of a vast and extensive Hrušica Nappe Thrust Front composed of Jurassic and Cretaceous carbonate rocks and unconformably deposited Eocene flysch (Fig. 6). At the NW part a large NW-plunging anticline in the NW turns into a recumbent one thrusted upon the Snežnik Nappe Eocene flysch (in the central and eastern parts of the Postojna basin), and the External Dinaric Imbricated Belt, also referred to as parautochton (Rebrnice and W part of the Postojna basin). Also, part of the External Dinaric Imbricated Belt is the Jurassic carbonate Šmihel klippe (Čar & Juren, 1980). Jurassic and Cretaceous carbonate rocks, as part of the Trnovo Nappe, are thrust upon the Eocene flysch belonging to the Hrušica Nappe (Srednja gora, 1275 m a.s.l., Streliški vrh, 1266 m a.s.l.) (Fig. 6.).

The Snežnik Nappe thrust plane crosses the western part of the Postojna basin. The thrust plane is identifiable in the Hruševje area, where the carbonate rocks of the Snežnik Nappe are thrust upon the External Dinaric Imbricated Belt, but NW of Hrušica the flysches of both nappes meet, hence the trace is not identified there. Detailed sedimentological and paleontological mapping would be required to determine the Snežnik Nappe thrust plane trace there. A thrust plane trace is only provisionally shown in Figure 6.

The structure of the lower part of the Hrušica Nappe between Strane, Predjama, and Studeno differs from the upper part; however, there is not enough data on the Buser's (1967) geologic map to construct the correct structural interpretation. The unconformity between the Upper Cretaceous limestone and marl (*scaglia*), and the Eocene flysch between Strane and Studeno represents the main problem in the map. Following the bound-

Gravitacijski pojavi na jugovzhodnem pobočju Nanosa

Jugovzhodno pobočje Nanosa ponuja vpogled v notranjo zgradbo čelnega in začelnega dela krovne enote Hrušiškega pokrova in morfologijo njegove narivne ploskve. Ta je bila deformirana v postnarivnih procesih. Gravitacijski pojav Suhi vrh je odraz teh deformacij.

Zgradba Nanosa in Hrušice

Nanos leži v čelu obsežnega Hrušiškega pokrova, zgrajen je iz jurskih in krednih karbonatnih kamnin ter diskordantno odloženega eocenskega fliša (sl. 6). Plasti krovne enote tvorijo na severozahodu veliko proti SZ tonečo antiklinalo, na jugovzhodu pa veliko poleglo antiklinalo, ki sta narinjeni na eocenski fliš Snežniškega pokrova (osrednji in vzhodni del Postojnske kotline) in Zunanjedinarskega naluskanega pasu ali paravtohtona (Rebrnice, zahodni del Postojnske kotline). Del Hrušiškega pokrova je tudi Šmihelska tektonska krpa iz jurskih plasti (Čar & Juren, 1980). Severno od Nanoške antiklinale so na eocenski fliš Hrušiškega pokrova narinjeni jurski in kredni karbonati Trnovskega pokrova (Srednja gora 1275 m, Streliški vrh 1266 m) (sl. 6).

Preko zahodnega dela Postojnske kotline poteka narivnica Snežniškega pokrova, ki je določljiva na območju Hruševja, kjer so karbonati Snežniškega pokrova narinjeni na fliš Zunanjedinarskega naluskanega pasu. Od Hruševja proti severozahodu potek narivnice ni določen, ker se tu stikata fliša obeh krovnih enot. Za njeno določitev bi bilo potrebno izvesti detajlno sedimentološko in paleontološko profiliranje. Na sliki 6 je potek narivnice le nakazan.

Spodnji ustroj Hrušiškega pokrova med Stranami, Predjamo in naprej do Studenega je zgrajen drugače kot zgornji del, vendar na OGK, list Postojna (Buser et al., 1967) ne najdemo dovolj podatkov za korektno strukturno rešitev tega vprašanja. Glavni problem na karti predstavlja diskordantna meja med zgornjekrednim apnencem in laporjem (*scaglia*) ter eocenskim flišem med Stranami in Studenim, ki bi glede na vpad plasti in potek na površju (pravilo V) morala biti inverzna. Ker pa razvoj plasti nad diskordanco kaže na poševni rez, je Placer (1981) to mejo interpretiral kot krovno narivno ploskev, zgornjekredne in spodnjekredne plasti v krovni grudi pa razvrstil v tri vmesne krovne luske. Taka razdelitev bi po analogiji ustrezala spodnjemu ustroju Trnovskega pokrova na območju Idrije (Mlakar, 1969). Čar & Šebela

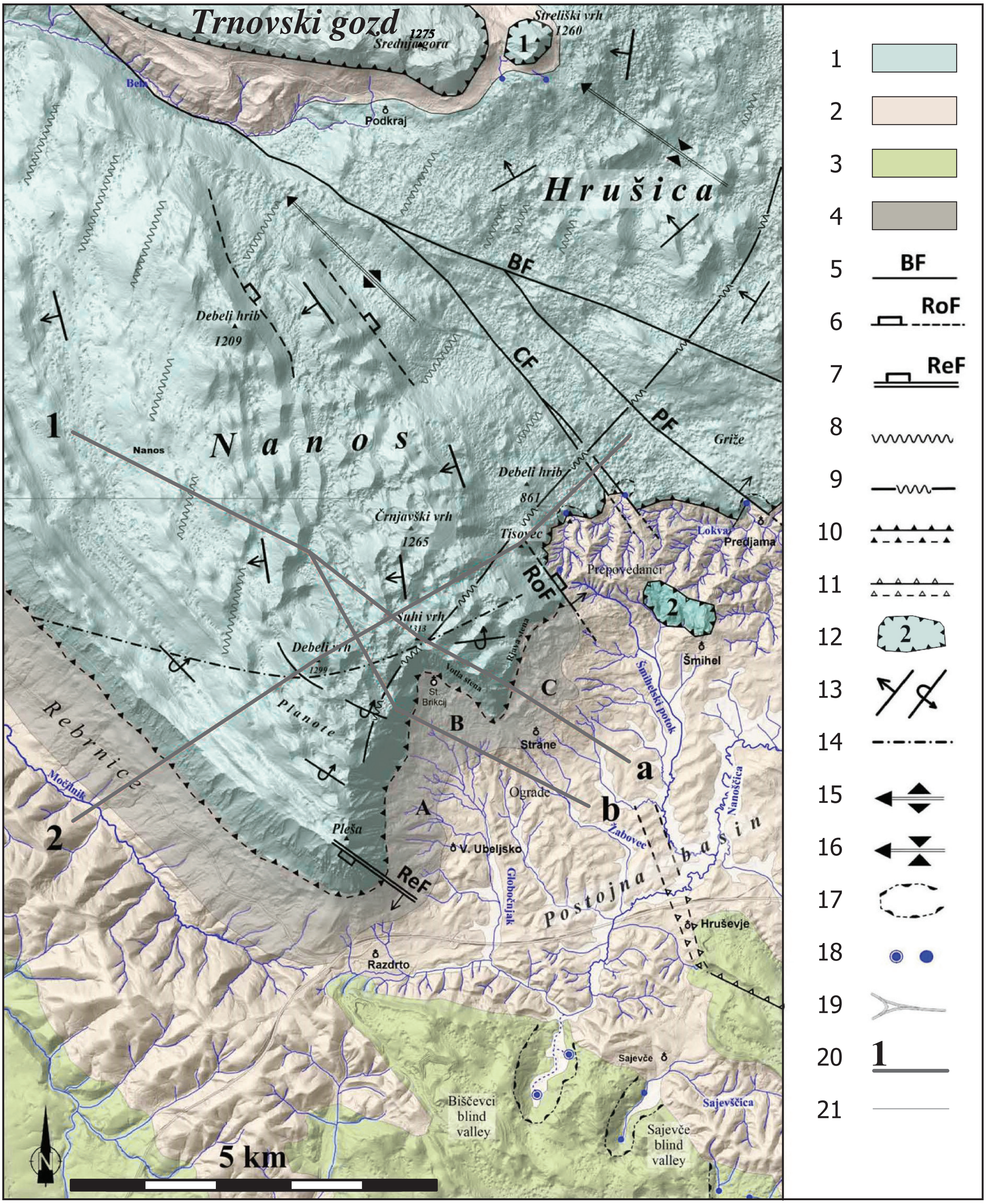

Fig. 6. Geological - geomorphological sketch of Mt. Nanos a part of Mt. Hrušica.
Sl. 6. Geološko-geomorfološka skica Nanosa in dela Hrušice.

1 Mesozoic carbonates / mezozojski karbonati
2 Eocene flysch / eocenski fliš
3 Mezozoic and Paleogene carbonates / mezozojski in paleogenski karbonati
4 Landslide areas / plazišča: Rebrnice, A – »Ubeljska stena«, B – Votla stena, C – Rjava stena
5 Strike-slip fault / zmični prelom: BF – Belsko fault / Belski prelom, CF – Črnjavska dolina fault / Črnjavski prelom, PF – Predjama fault / Predjamski prelom
6 Normal fault / normalni prelom: RoF – Roček fault and inferred faults of the similar mechanism / RoF – Ročkov prelom in domnevni prelomi enakega mehanizma
7 Normal fault with hereditary gravitational slide / normalni prelom z nasledstvenim gravitacijskim zdrsom: ReF – Reševnik fault / Reševniški prelom

8 Regional sub-vertical fractures (strike angle 20° - 40°) / regionalne subvertikalne razpoke smeri 20° do 40°
9 Deformational curve of the regional fractures with 20° to 40° strike angle due to right lateral offset along the Belsko fault / deformacijska krivulja regionalnih razpok 20° do 40° zaradi desnega premika ob Belskem prelomu
10 Hrušica Nappe boundary / meja Hruškega pokrova
11 Snežnik Nappe boundary / meja Snežniškega pokrova
12 Tectonic klippe / tektonska krpa: 1 – Streliški vrh t. k. / Streliška t. k., 2 – Šmihel t. k. / Šmihelska t. k.
13 Bedding: normal, inverse / plasti: normalne, inverzne
14 Axial plane of the recumbent frontal anticline / osna ravnina polegle krovne antiklinale
15 Mt. Nanos anticline axis / os Nanoške antiklinale
16 Hrušica syncline axis / os Hrušiške sinklinale
17 Blind valley rim / rob slepe doline
18 Spring, sinkhole / izvir, ponor
19 Motorway / avtocesta
20 Position of geological cross-sections 1a, 1b (Fig. 11) and 2 (Fig. 16) / lega profilov 1a, 1b (sl. 11) in 2 (sl. 16)
21 Geological boundary / geološka meja

ary course on the surface (according to the V-rule) it should be in inverse position. However, Placer, (1981) interpreted the boundary as a low-angle thrust fault (a sole thrust), since the structure above the unconformity indicates an oblique cut. The Upper and Lower Cretaceous beds in the hanging wall are interpreted as three intermediate duplexes. Such an interpretation is analogous to the structure of the lower part of the Trnovo Nappe in the Idrija area (Mlakar, 1969). Mapping the Predjama area (Čar & Šebela, 2001) confirmed a tectonic boundary between the Eocene flysch and the Cretaceous beds and, consequentially, Placer's (1981) interpretation. The upper level of the Hrušica Nappe structure between Studeno and Strane is simple: Upper Cretaceous and Jurassic carbonates are thrust upon the Upper and Lower Cretaceous carbonates of the lower level. In general, the described structure confirms the interpretation with intermediate duplexes, only they are fewer in number, with only one or two east of Tisovec and probably none between Tisovec and Strane. The duplexes are here included in the Hrušica Nappe, as these issues are not of particular importance for our purposes herein.

After the thrusting, a large recumbent Nanos anticline (Limanowski, 1910; Buser, 1967; Placer, 1981) in the thrust front of the Hrušica Nappe was regionally folded into the Nanos anticline and Hrušica syncline.

The principal structural elements of the Hrušica Nappe are presented in Figure 6. The recumbent Nanos anticline in the Hrušica Nappe Thrust Front is defined by the position of the northward dipping recumbent fold's axial plane, dividing the normal from the inverse strata. The Nanos anticline and Hrušica syncline axes plunge in the NW direction.

The Hrušica Syncline is cut by the Predjama fault, a dislocation named by Buser (1976), who defined the fault according to stratigraphic

(2001) sta pri Predjami s kartiranjem potrdila tektonsko mejo med zgornjekrednim apnencem in flišem kar je v splošnem potrjevalo Placerjevo domnevo. Zgradba zgornje etaže Hrušiškega pokrova je drugačna toda enostavna, na obravnavanem odseku jo sestavljajo zgornjekredni in jurski karbonati, ki so narinjeni na spodnje in zgornjekredne karbonate spodnjega ustroja. Vse to v splošnem potrjuje interpretacijo s krovnimi vmesnimi luskami, le da je njihovo število manjše; med Stranami in Tisovcem verjetno ni nobene, vzhodno od Tisovca pa ena ali dve. V tem članku to vprašanje ni toliko pomembno, zato so vmesne luske vključene v Hrušiški pokrov.

Velika polegla nanoška čelna antiklinala (Limanowski, 1910; Buser, 1967; Placer, 1981) je bila z ostalim delom Hrušiškega pokrova v postnarivnem obdobju regionalno nagubana, tedaj sta nastali Nanoška antiklinala in Hrušiška sinklinala.

Na sliki 6 so podani glavni strukturni elementi Hrušiškega pokrova. Polegla krovna antiklinala je določena z lego osne ravnine, ki ločuje inverzne in normalne plasti in vpada generalno proti severu. Osi Nanoške antiklinale in Hrušiške sinklinale toneta proti severozahodu.

Hrušiško sinklinalo seka dislokacija, ki jo je Buser poimenoval Predjamski prelom; po stratigrafskih kriterijih ga je povlekel mimo Predjame in ga proti severozahodu povezal s prelomom po dolini Bele, nato s prelomom mimo Predmeje in naprej s prelomom Avče-Dol. Jugovzhodno od Predjame ga je podaljšal v Snežniško hribovje (Buser, 1976), na OGK (Buser et al., 1967) pa tega preloma JV od Predjame ni vrisal. Na lidarju je razvidno, da se glavna prelomna ploskev, ki poteka po dolini Bele, nadaljuje v smeri ESE proti Belskemu, kjer močno premakne narivnico Hrušiškega pokrova. Prelom, ki poteka mimo Predjacriteria. Buser drew the fault trace along Predjama and connected it in the NW direction with a fault along the Bela valley, further due NW with a fault passing Predmeja, and still further with the Avče - Dol fault. Southeast of Predjama, Buser (1976) extended the fault into the Snežnik hills, but this fault segment is not yet drawn on the Buser's geological map (Buser et. al., 1967). It is clear from the lidar image that the main fault plane from the Bela valley continues due ESE toward Belsko, where it considerably offsets the Hrušica Nappe thrust plane. The fault passing Predjama is only a secondary fault (branch) detached from the main fault plane. We suggest therefore, naming the Bela fault that fault that runs along the Bela valley and passes Belsko, while the splay (secondary fault) passing Predjama (30/75) should retain the name Predjama fault. The latter dies out due SE within a relatively short distance, much like the other Bela fault's secondary branches (splays). There are many secondary faults leaning on the Bela fault, and all host geomorphologically responsive sinkholes: the Črnjavska dolina fault hosts a Prepovedanci sinkhole, the Predjama fault, and the Bukovje fault (Čar & Šebela, 2001). Apart from the aforementioned right lateral strike-slip secondary faults, other N-NW trending sub-vertical faults with subsided NW blocks are also important. They too lean on the Bela fault, but only the Roček fault (70/80) among them has been named (after the Roček hot spring).

The multiphase evolution of the Bela fault and both sets of described secondary faults leaning on it (the ones with a strike-slip, as well as those of normal character, is reflected in various geomorphologic effects. Significant vertical offsets are obvious along the normal faults (*e.g.*, Roček fault), while no vertical offsets are observed along the strike-slip faults. However, discussing the genesis of these fault systems is not the purpose of this article.

We propose the name Predmeja fault for the northern part of the Predjama fault (Buser, 1976), as the fault segment between Predmeja and Col reflects the highest geomorphic response.

A NNE–SSW (roughly 20°) trending system of subvertical fractures stands out over the entire Hrušica Nappe area. Due to the dextral strike-slip motion of the Bela fault these fractures are sigmoidally bent and trend in the SW–NE (roughly 40°) direction in their most deformed part.

The Reševnik fault (210/60) is exposed just behind the Hrušica Nappe Thrust Front above Razdrto. Its principal and parallel secondary fault planes later adopted the role of gravitationally generated slip planes. The Reševnik fault is me je le sekundarni odcep omenjene glavne prelomne ploskve. Zato predlagamo, da se prelom, ki poteka po dolini Bele in gre na Belsko imenuje Belski prelom, Predjamski prelom pa naj se imenuje le sekundarni krak, ki poteka mimo Predjame (30/75) in proti jugovzhodu, tako kot drugi sekundarni prelomi Belskega preloma, kmalu zamre. Sekundarnih krakov, ki se naslanjajo na Belski prelom je več, ob vseh so nastali geomorfološko odzivni ponori. To so Črnjavski prelom (Črnjavska dolina), ob katerem je nastal ponor na Prepovedancih, Predjamski prelom in Bukovski prelom (Čar & Šebela, 2001) mimo Bukovja. Poleg omenjenih sekundarnih desnozmičnih prelomov so pomembni še subvertikalni prelomi v smeri NNW-SSE, ob katerih je severovzhodno krilo ugreznjeno. Tudi ti se naslanjajo na Belski prelom; od teh je poimenovan le Ročkov prelom (70/80).

Belski prelom z obema snopoma sekundarnih prelomov, zmičnih in subvertikalnih z vertikalno komponento premika, kaže na večfazni razvoj z različnimi geomorfološkimi učinki. Ob prelomih zmičnega snopa ni v reliefu vertikalnih skokov, ob prelomih tipa Ročkov prelom, pa je opazna izdatna stopnja v reliefu. Geneza teh sistemov ni predmet tega članka.

Za segment Buserjevega Predjamskega preloma med Predmejo in Colom (Buser, 1976) predlagamo, da se preimenuje v Predmejski prelom, ker je ta odsek na celotni trasi geomorfološko najbolj odziven.

Na celotnem območju Hrušiške krovne enote izstopa sistem regionalnih subvertikalnih razpok v smeri SSW-NNE (okoli 20°). Te so zaradi desnega zmika ob Belskem prelomu v smeri WNW-ESE regionalno sigmoidalno usločene, tako da imajo v najbolj zasukanem delu smer SW-NE (okoli 40°).

V boku Hruškega pokrova je takoj za njegovim čelom nad Razdrtim viden Reševniški prelom (210/60), katerega glavna in vzporedne prelomne ploskve so pozneje prevzele vlogo gravitacijskih drsnih ploskev. Reševniški prelom je viden le v jugovzhodnem pobočju Nanosa, na površju proti severozahodu pa še ni bil sleden.

Pobočni zdrsi so prisotni povsod, kjer so karbonati na flišu ekstremno dvignjeni nad krajino. Na slikah 6 in 8 so razdeljeni na tiste pod čelom nariva (Rebrnice) in na tiste pod jugovzhodnim pobočjem Nanosa pod »Ubeljsko«, Votlo in Rjavo steno. Ime »Ubeljska stena« ne obstaja v geografski ali ljudski terminologiji, uvedli smo ga iz praktičnih razlogov in zajema strmo pobočje med Razdrtim in Votlo steno.

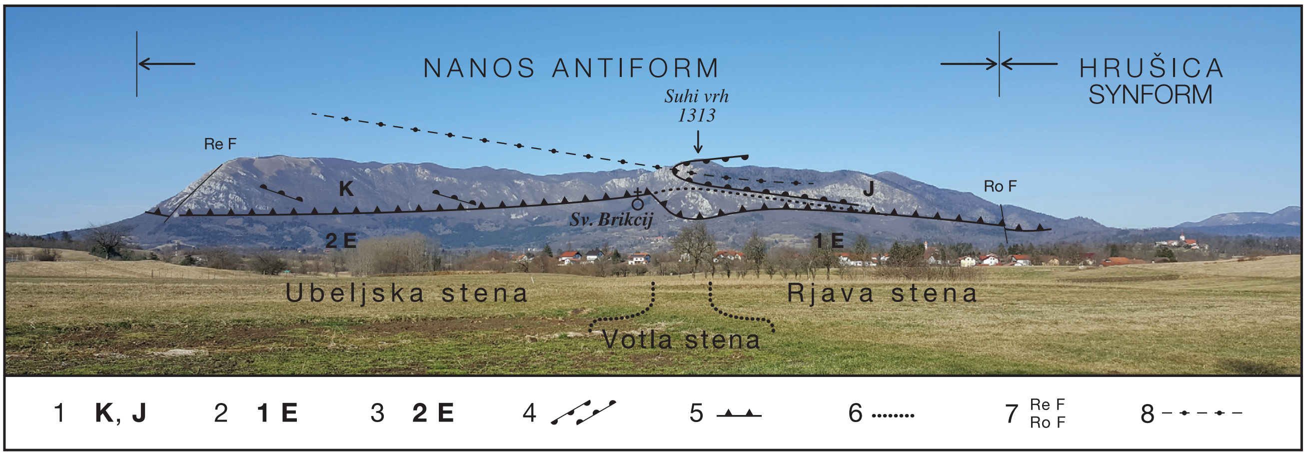

Fig. 7. Panoramic photography of the SE slope of Mt. Nanos and transverse geological cross-section of the Hrušica Nappe front part.
Sl. 7. Panorama jugovzhodnega pobočja Nanosa in prečni geološki profil čelnega dela Hrušiškega pokrova.
1 Hrušica Nappe / Hrušiški pokrov: J – Jurassic carbonates / jurski karbonati, K – Cretaceous carbonates / kredni karbonati
2 1E – Eocene flysch of the Snežnik Nappe / eocenski fliš Snežniškega pokrova
3 2E – Eocene flysch of the External Dinaric Imbricated Belt / eocenski fliš Zunanjedinarskega naluskanega pasu
4 Bedding: normal, inverse / plasti: normalne, inverzne
5 Hrušica Nappe boundary / meja Hrušiškega pokrova
6 Hrušica Nappe boundary projection in the Ubeljska stena cross-section / projekcija meje Hrušiškega pokrova v ravnini profila Ubeljske stene
7 Normal fault / normalni prelom: ReF – Reševnik fault / Reševniški prelom, RoF – Roček fault / Ročkov prelom
8 Axial plane of the recumbent frontal anticline / osna ravnina polegle krovne antiklinale

only observable on the SE slope of Mt. Nanos and has not yet been mapped due NW.

Landslides are present wherever carbonates lying on flysch are uplifted high above the surrounding landscape. Landslides are divided into those beneath the thrust front (Rebrnice) and those on the SE slope of Mt. Nanos (beneath the Ubeljska stena, Votla stena and Rjava stena) (Figs. 6 and 8). An “Ubeljska stena” toponym does not exist in geographical or other terminology. We introduced the term for practical purposes in order to refer to the steep slope between Razdrto and Votla stena.

The structure of the Hrušica Nappe front exposed on the SE slope of Mt. Nanos between Razdrto and Roček spring (Fig. 8) is presented in the panoramic photo (Fig. 7). Geologic cross-sections are constructed across and parallel to the view in Figure 7. The most important part of the geological structure there is a recumbent anticline reconstructed from its visible core in the Votla stena, just beneath Suhi vrh. The inverse strata are present from the Ubeljska stena, across Votla and Rjava stena. Its axial plane rises towards the thrust front and should lean on the thrust plane in the opposite direction. However, this point (where the recumbent fold’s axial plane meets the thrust plane) is not determinable due to scarce structural data on the geological map (Buser et al., 1967). An inverse limb more than 4 km long is surprising.

Zgradba čelnega in začelnega dela krove enote Hrušiškega pokrova je vidna v jugovzhodnem pobočju Nanosa med Razdrtim in izvirom Roček (sl. 8). Predstavljena je na panoramskem posnetku na katerem je skiciran strukturni profil (sl. 7). Tu je najpomembnejši element strukture rekonstruirana polegla krovna antiklinala, ki je izvedena iz njenega vidnega jedra v Votli steni tik pod Suhim vrhom. Inverzne plasti se raztezajo preko Ubeljske, Votle in Rjave stene. Osna ravnina polegle antiklinale se proti čelu pokrova dviguje, v nasprotno smer pa bi se morala naslanjati na narivno ploskev, vendar te točke ni mogoče določiti zaradi skopih strukturnih podatkov na OGK, list Postojna (Buser et al., 1967). V profilu preseneča izdatna dolžina inverznega krila, ki presega 4 kilometre.

Narivna ploskev v profilu na sliki 7 je določena po morfoloških znakih v pobočju, kjer poteka pod pregibom med strmo karbonatno steno v krovnini in flišnim pobočjem v talnini, ki je položnejše in prekrito s pobočnim gruščem in plazovi. Razen nad Sv. Brikcijem ni fliša videti nikjer. V steni nad Razdrtim je videti Reševniški prelom, kjer se narivna ploskev od 750 m dvigne za nekaj deset metrov na 800 m, proti Sv. Brikciju pa se vedno bolj strmo dviga do 1000 m. Pod Votlo steno se spusti do višine 850 m nad Stranami, od koder se polagoma spušča do Ročkovega preloma, kjer doseže višino okoli 770 m. Na drugi strani pre-

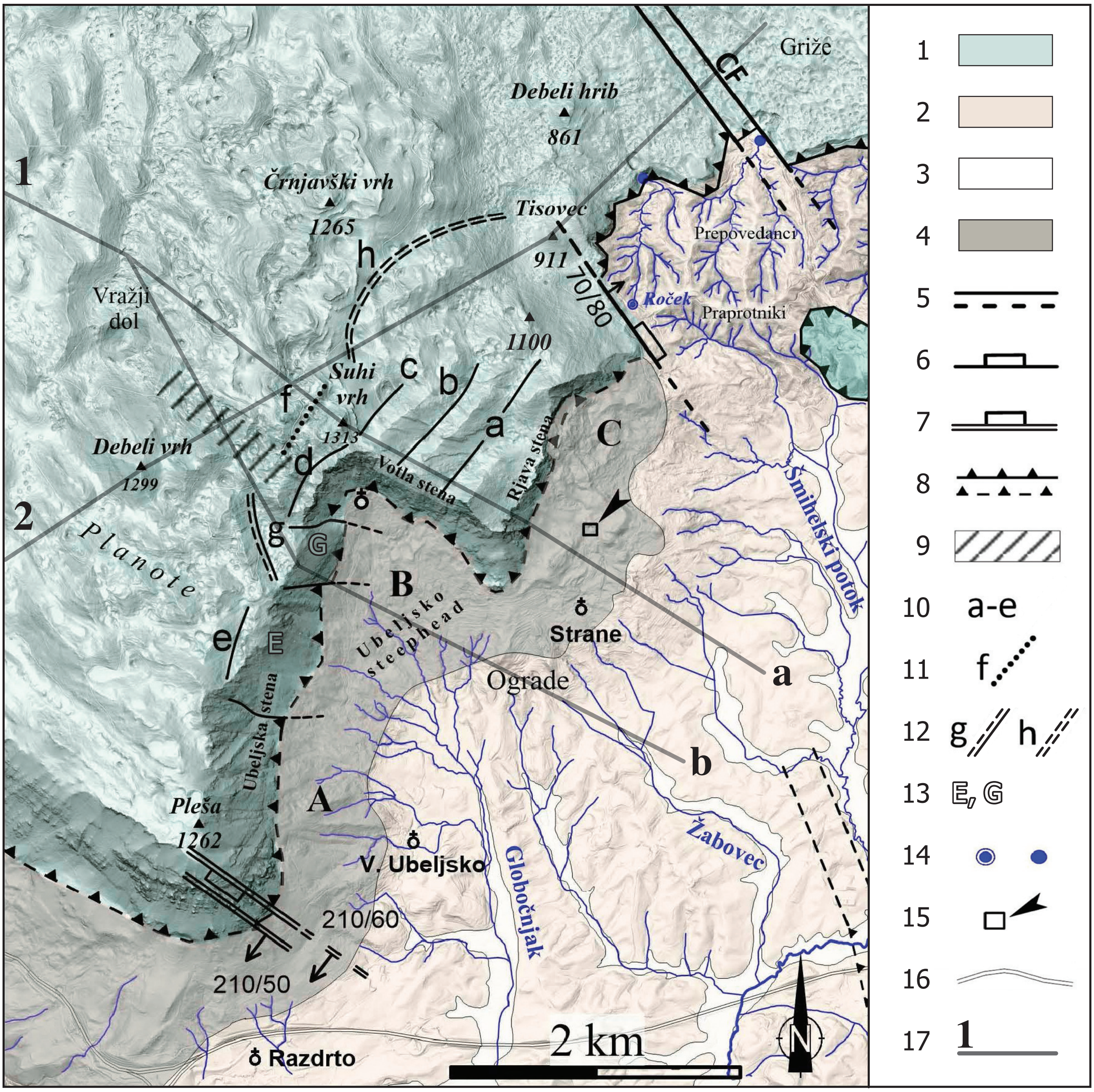

Fig. 8. Geological - geomorphological sketch of the SE part of Mt. Nanos.

Sl. 8. Geološko - geomorfološka skica jugovzhodnega dela Nanosa.

1 Mesozoic carbonates / mezozojski karbonati

2 Eocene flysch / eocenski fliš

3 Alluvium / aluvij

4 Landslide areas / plazišča: Rebrnice, A – »Ubeljska stena«, B – Votla stena, C – Rjava stena

5 Strike-slip fault / zmični prelom: CF – Črnjavska dolina fault / Črnjavski prelom

6 Normal fault / normalni prelom: RoF – Roček fault 70/80 / Ročkov prelom 70/80

7 Normal fault with hereditary gravitational slide / normalni prelom z nasledstvenim gravitacijskim zdrsom: ReF – Reševnik fault 210/60 / Reševniški prelom 210/60

8 Nappe boundary / meja pokrova

9 Tectonized zone within the recumbent frontal anticline core / tektonizirana cona v jedru prevrnjene krovne antiklinale

10 Shear razdol / strižni razdol: a, b, c, d, e

11 Divergent razdol / razmični razdol: f

12 Marginal trench / robni jarek: g – probable / verjetni, h – inferred / domnevni

13 Gravitational block / gravitacijski blok: E, G

14 Spring, sinkhole / izvir, ponor

15 Gravel pit, reversely rotated bedding (Fig. 10) / občasni kop gramoza, povratno rotirane plasti (sl. 10)

16 Motorway / avtocesta

17 Position of geological cross-sections 1a, 1b (Fig. 11) and 2 (Fig. 16) / lega profilov 1a, 1b (sl. 11) in 2 (sl. 16)

The thrust plane in the cross section in Figure 7 is defined by the morphologic features on the slope that appear a few metres below the inflection point, between a steep carbonate slope belonging to the hanging wall and a more gradual flysch footwall slope covered by the slope scree and landslides. Flysch is exposed only above Sv. Brikcij (St. Brictius). The Hrušica Nappe thrust plane is located at 750 m a.s.l. in the thrust front above Razdrto. On the other side of the Reševnik fault it rises to 800 m a.s.l. and rises ever more steeply up to 1000 m a.s.l. at Sv. Brikcij. Beneath the Votla stena the thrust plane drops down to 850 m a.s.l. above Strane and descends down to 770 m a.s.l. at the Roček Fault. Across the fault, it drops to 730 m a.s.l. and gradually descends down to the lowest point (on this section) at 500 m a.s.l. at Predjama. The cross-section geometry is distorted, as the Rjava stena and Ubeljska stena don't lie on the same plane, but lie closer to the observer for a distance roughly the length of the Votla stena (about 1500 m) (Fig. 6). An inferred course of the Hrušica Nappe thrust plane in an extension of the Ubeljska stena is presented as a dotted line in Figure 7 and illustrates the apex of the convex bulge beneath Suhi vrh (1313 m a.s.l.), the highest geographic point in the area (of Mt. Nanos). However, the bulge and the highest peak do not coincide with the axis of the Nanos anticline. An explanation of this phenomena would go beyond the aim of this paper; however, let us summarize by stating that both the bulge and the Nanos anticline arose simultaneously, and that the reason for this peculiarity lies in the internal structure of the Hrušica Nappe. Here we are confronted by two different structural features formed in the same folding phase. The (convex) bulge in the flysch base has an anticlinal form, hence the Nanos flysch antiform. Not only is the flysch in the base cambered, but the entire nappe, so we can generally refer to this feature as the Nanos antiform.

The Nanos antiform, recumbent Nanos anticline and Hrušica syncline reflect the regional importance of the post-thrusting folding. A Hrušica synform can be deduced from the existence of the Nanos antiform, but unfortunately, we cannot directly prove it, as the Hrušica Nappe thrust plane isn't exposed in the NE block of the Idrija fault. We do, however, find a hint (in the form of circumstantial evidence) in the post-thrust Trnovo Nappe structure that the Hrušica thrust plane, at some depth, continues also to the NE. The Križna gora synform structure at the SE margin of Trnovo Nappe north of Srednja gora (1275 m a.s.l.) (Fig. 6) formed in the core of the Hrušica syncline and continues under the central part of the Trnovski gozd

loma naglo preskoči na okoli 730 m in se potem polagoma spušča do Predjame, kjer leži nekaj pod 500 m. Tu je najbolj spuščena na tem odseku meje Hrušiškega pokrova. Prerez narivne ploskve je popačen, ker Rjava stena ne leži v ravnini Ubeljske stene, temveč je za dolžino Votle stene, okoli 1500 m, pomaknjena proti opazovalcu (sl. 6). Lega narivne ploskve v namišljenem podaljšanem prerezu Ubeljske stene je narisana pikčasto (sl. 7) in lepo nakazuje vrh konveksne izbokline. Ta se nahaja pod Suhim vrhom (1313 m), ki je najvišja točka Nanosa in se ne pokriva z osjo Nanoške antiklinale. Gre za strukturno posebnost katere razlaga presega okvir tega članka, za sedaj pa je dovolj če vemo, da sta obe izbočeni strukturi nastali istočasno in da tiči izvor anomalije v notranji zgradbi krovne enote. Pred seboj imamo dva različna strukturna objekta, ki pa sta nastala v isti fazi gubanja. Konveksna izboklina flišne podlage ima obliko antiforme in jo imenujemo nanoška flišna antiforma. Izbočen ni samo fliš v podlagi temveč tudi narivna enota, zato govorimo v splošnem o nanoški antiformi.

Regionalni pomen postnarivnega gubanja Hrušiškega pokrova se kaže v obstoju nanoške antiforme, Nanoške antiklinale in Hrušiške sinklinale. Iz obstoja nanoške antiforme sklepamo tudi na obstoj hrušiške sinforme, ki pa je ne moremo neposredno dokazati, ker na severovzhodni strani Idrijskega preloma narivnica Hrušiškega pokrova nikjer ne izdanja. Da se gubanje narivne ploskve nadaljuje v globini verjetno tudi proti severovzhodu, obstaja posredni namig v postnarivni zgradbi Trnovskega pokrova. V jedru Hrušiške sinklinale je razvita sinformna struktura Križne gore, ki leži na skrajnem JV robu Trnovskega pokrova, severno od Srednje gore (1275 m) (sl. 6). Sinforma se nadaljuje pod osrednji del Trnovskega gozda proti severozahodu (Placer & Čar, 1974), proti severovzhodu se previje v antiformno strukturo Idrijskega tektonskega polokna, ta v sinformno strukturo Idrijsko-Žirovskega ozemlja in ta v antiformno strukturo Poljansko-Vrhniških nizov. Omenjene sinforme in antiforme imajo dinarsko smer. Lega sinformne strukture Križne gore v osi Hrušiške sinklinale pomeni, da sta nastali v isti fazi gubanja.

due NW (Placer & Čar, 1974). To the NE it is cambered in an antiform structure of the Idrija tectonic half-window, and the Idrija tectonic half-window transits into the Žiri - Idrija synform which continues into the Poljane - Vrhnika hills antiform further to the northeast. These synforms share a NW (Dinaric) trend. The position of the Križna gora synform on the axis of the Hrušica syncline means that they both formed in the same folding phase.

Structure of the southwestern part of Mt. Nanos

Two unusual relief structures, the result of gravitational processes, surprise on the SE slope of Mt. Nanos, the steephead valley closed by the Ubeljska and Votla stena called the Ubeljsko steephead, and geological structure of the block behind the Votla and Rjava stena called the Suhi vrh gravitational structure. There, other classical slope features are present, as well in the Rebrnice slope and in the landslide areas (zones) named after the cliffs above them – the Ubeljska stena landslide area, the Votla stena landslide area, and the Rjava stena landslide area (Fig. 8).

Zgradba jugovzhodnega dela Nanosa

V jugozahodnem pobočju Nanosa presenečata dve neobičajni reliefni strukturi, ki sta posledici gravitacijskih procesov, prva je zatrep, ki ga zapirata Ubeljska in Votla stena, imenujemo ga ubeljski zatrep, druga je zgradba bloka v zaledju Votle in Rjave stene, imenujemo jo gravitacijska struktura Suhega vrha. Poleg tega so tu tudi klasični pobočni pojavi na plazišču Rebrnice in na plaziščih, ki jih poimenujemo po stenah nad njimi; plazišče Ubeljska stena, plazišče Votla stena in plazišče Rjava stena (sl. 8).

Plazišče Rebrnice se nahaja pod jugozahodnim pobočjem Nanosa, vendar prispeva poznavanje razmer na tem prostoru pomemben delež k razumevanju zgradbe celotnega območja. Za Rebrnice so značilni strukturni, rotacijski in zemeljski planarni plazovi ter podori, kot tudi (blatno) drobirsko plazenje in tečenje (Popit, 2016). Pomemben nasledstveni dejavnik nestabilnosti je tu Reševniški prelom (sl. 9), za katerega domnevamo, da je njegova prelomna ploskev v sedanjem stadiju denudacije čela

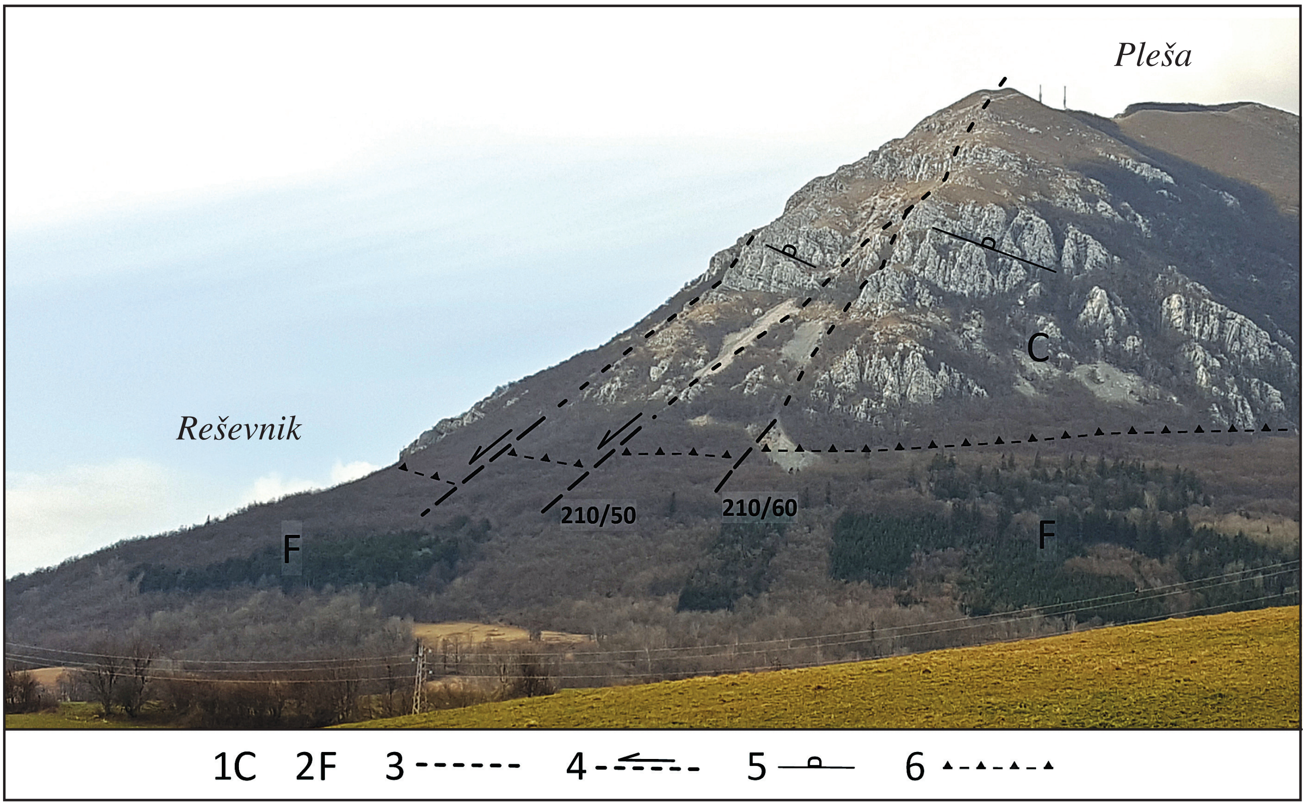

Fig. 9. Gravitational slide along the fault planes in the Reševnik fault zone. Hrušica Nappe front above Razdrto village.
Sl. 9. Gravitacijski zdrs po prelomnih ploskvah v coni Reševniškega preloma. Čelo Hrušiškega pokrova nad Razdrtim.
1 C – Hrušica Nappe carbonates / karbonati Hrušiškega pokrova
2 F – Flysch of the External Dinaric Imbricated Belt / fliš Zunanjedinarskega naluskanega pasu
3 Main fault plane 210/60 / glavna prelomna ploskev 210/60
4 Parallel fault plane 210/50 and other hereditary gravitational rupture planes / vzporedna prelomna ploskev 210/50 in ostale kot nasledstvene gravitacijske zdrsne ploskve
5 Inverse bedding / inverzne plasti
6 Hrušica Nappe boundary / meja Hrušiškega pokrova

Fig. 10. Reversely rotated bedding of the rotational landslide in the gravel pit in the Rjava stena landslide area (Figs. 8 and 11, 1a).
Sl. 10. Povratno zasukane plasti rotacijskega plazu v občasnem kopu gramoza na plazišču Rjava stena (sl. 8 in 11, 1a).

The Rebrnice landslide area is situated beneath the SW slope of Mt. Nanos, and its revealed structure contributes significantly to our understanding of the structure of the entire area. Structural and rotational landslides, translational earth slumps, rockfalls, as well as debris flows (Popit, 2016) are characteristic features of the Rebrnice. The Reševnik fault (Fig. 9) is an important hereditary factor of slope instability there, and it is inferred that its fault plane took over the role of the gravitational slip plane in the present denudation stage of the Hrušica Nappe Thrust Front. (The arguments for the interpretation are provided further into the text herein.) Slope scree and minor rockfalls prevail on the surface of the Ubeljska stena and Votla stena landslide areas. More important, however, is the Rjava stena landslide area, where large block slides and rockfalls prevail in the northern part, and rotational landslides in the southern part, respectively. A rotated dip (335/20) in the displaced material of a fossil rotational rubble slide above the village of Strane is presented in Figure 10. Popit (2017) found a similar rotated bedding in the Rebrnice area. There is an active landslide in the central part of the Strane village itself, but the landslide mechanism has not yet been investigated.

Let us take a look at the longitudinal cross-sections 1a and 1b (Fig. 11) before we describe the gravitational structure of Mt. Suhi vrh. The thrust plane is constructed according to the flysch outcrops

Hrušiškega pokrova, prevzela vlogo gravitacijske zdrsne ploskve. Argumenti za tako interpretacijo bodo podani kasneje. V plaziščih Ubeljska stena in Votla stena na površju prevladujejo pobočni grušč in manjši skalni podori. Pomembnejše pa je plazišče Rjava stena, kjer v severnem delu prevladujejo veliki blokovni zdrsi in podori, v južnem delu pa rotacijski plazovi. Za ilustracijo je na sliki 10 prikazan povratni vpad plasti (335/20) fosilnega gruščnatega rotacijskega plazu nad vasjo Strane. Podobne povratne vpade plasti litificiranih meliščnih zaplat ugotavlja Popit (2017) v zaledju plazov Šumljak na območju Rebrnic. V sami vasi Strane pa obstoja delujoči plaz, ki zajema osrednji del naselja. Mehanizem tega plazu ni raziskan.

Preden opišemo gravitacijsko strukturo Suhega vrha, si moramo ogledati vzdolžna profila Nanosa 1a in 1b na sliki 11. V profilu 1a je narivna ploskev konstruirana po izdankih fliša nad Sv. Brikcijem, ki stoji na višini 960 m, fliš pod Suhim vrhom torej presega višino 1000 m in se nato spušča proti dnu Rjave stene, kjer dosega višino okoli 850 m. Pri interpretaciji profila so bili odločilni trije elementi zgradbe, na prvem mestu je dejstvo, da v strukturi Votle stene ni videti stopničastega zaporedja normalnih prelomov ali velikih gravitacijskih drsnih ploskev, ki bi pojasnjevale nastanek dolin a, b in c (sl. 8), na drugem mestu je podatek, da ležijo omenjene

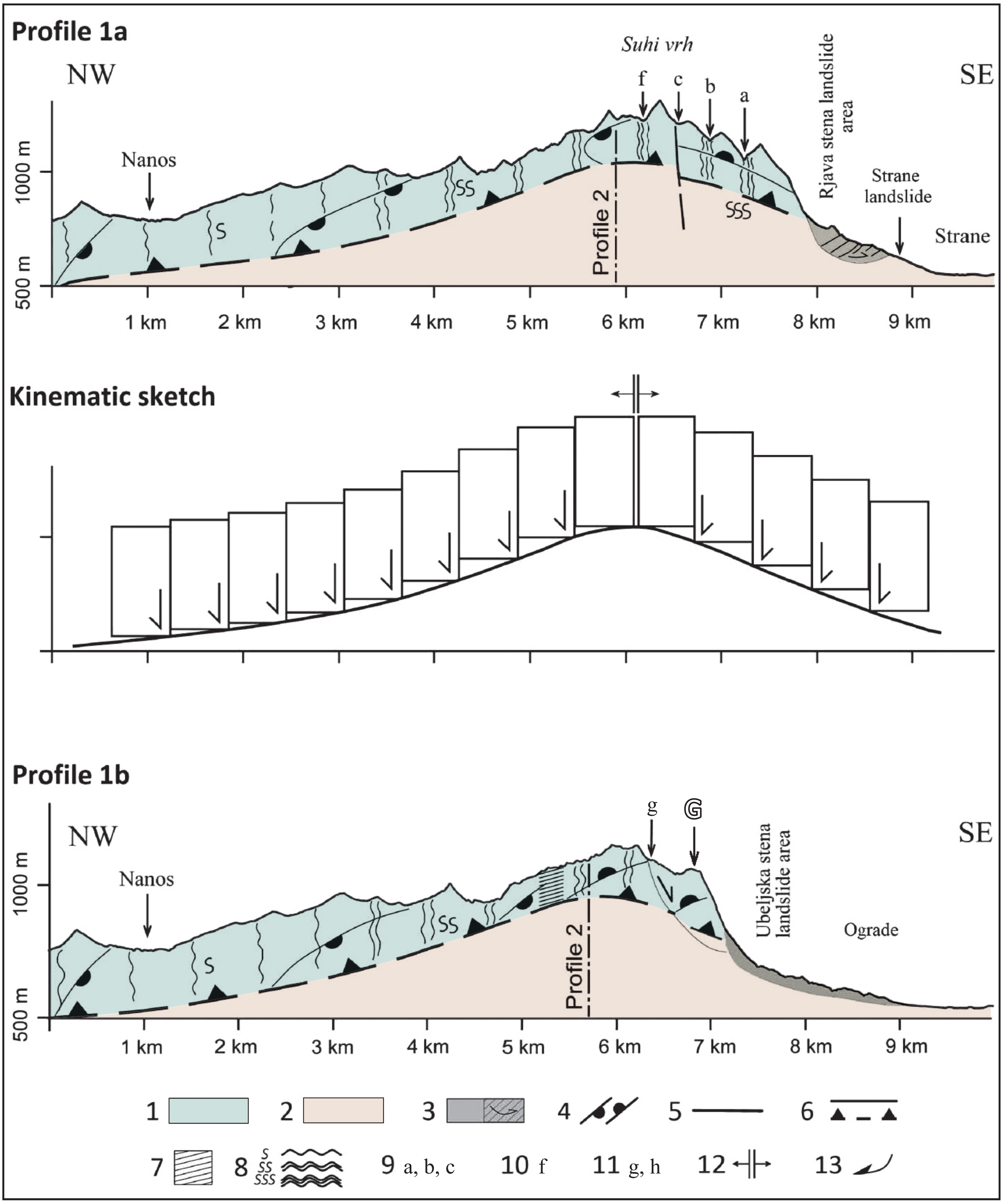

Fig. 11. Longitudinal structural cross-sections of the Mt. Nanos and a kinematic sketch. Profile 1a: Nanos (village) – Mt. Suhi vrh (1313 m) – Rjava stena – Strane (village). Profile 1b: Nanos (village) – »Ubeljska stena« – Ograde (near village Strane). Kinematic sketch of differential offsets of the carbonate micro and macrolithons along regional sub-vertical fractures (strike angle 20° - 40°) above the convexly cambered (bent) thrust plane in the Nanos antiform.

Sl. 11. Vzdolžna strukturna profila Nanosa in kinematska skica. Profil 1a: Nanos – Suhi vrh (1313 m) – Rjava stena – Strane. Profil 1b: Nanos – »Ubeljska stena« – Ograde pri Stranah. Kinematska skica diferencialnih premikov karbonatnih mikro in makrolitonov ob regionalnih subvertikalnih razpokah (od 20° do 40°) nad konveksno usločeno krovno narivno ploskvijo nanoške antiforme.

1 Mesozoic carbonates / mezozojski karbonati
2 Eocene flysch / eocenski fliš
3 Slope scree, rotational landslide / pobočni grušč, rotacijski plaz
4 Bedding: normal, inverse / plasti: normalne, inverzne
5 Fault: RoF – Roček fault, ReF – Reševnik fault / prelom: RoF – Ročkov prelom, ReF – Reševniški prelom
6 Hrušica Nappe thrust plane / narivna ploskev Hrušiškega pokrova
7 Tectonized zone in the core of the recumbent frontal anticline / tektonizirana cona v jedru polegle krovne antiklinale
8 Regional subvertical fractures with 20° - 40° strike angle: s – fracture lines without geomorphological response: ss – fractural furrows: sss – razdols / regionalne subvertikalne razpoke smeri 20° do 40°: s – razpoklinske linije s slabim geomorfološkim odzivom: ss – razpoklinske linije z močnejšim geomorfološkim odzivom: sss – razdoli
9 Shear razdol / strižni razdol: a, b, c
10 Divergent razdol /razmični razdol: f
11 Marginal trench / robni jarek: g – probable / verjetni, h – inferred / domnevni
12 Divergence area / območje razmikanja
13 Hypothetical gravitational heredital slide along the Reševnik fault in the Rebrnice slope / hipotetični gravitacijski nasledstveni zdrs po Reševniškem prelomu na Rebrnicah

above Sv. Bikcij (St. Brictius) (960 m a.s.l.) in the 1a cross-section. The flysch beneath Mt Suhi vrh is therefore higher than 1000 m a.s.l. and descends towards the base of the Rjava stena, where it is found at approx. 850 m a.s.l. Three structural elements are decisive for the cross-section interpretation. The first is the fact that there is no succession of step-like normal faults in the Votla stena structure, nor any large gravitational slip planes to explain the formation of the a, b and c valleys in Figure 8. The second lies in the fact that these valleys are parallel to the regional NNE – SSW-oriented subvertical fractures rotated in a NW - SE direction; and finally, the fact that the geomorphological responsiveness of this regional fracture system is consistent with the thrust plane morphology, which takes the shape of a convex bulge called the Nanos antiform. The fractures' geomorphologic responsiveness to the thrust plane morphology is reflected in the Lidar-derived image as individual furrows and more or less obvious strings of dolines (the **s** fracture lines) that deviate from other doline strings, like those formed along the bedding traces (Fig. 11). The geomorphic response to these fractures is stronger, but less obvious in the area where the Hrušica Nappe thrust plane is steeper, between the village of Nanos and Suhi vrh (1313 m a.s.l.). The geomorphologic response to the bedding of the Lower Cretaceous limestones in the form of step-like valleys is stronger there and thus prevails. The only interruption of individual ridges between these asymmetric valleys seems to represent a geomorphologic response to the NNE - SSW oriented fractures (the **ss** lines) there (Fig. 11). In the block above the Rjava stena, however, relatively deep, straight symmetric valleys are formed (the **sss** lines). For the latter, a new term razdol is proposed here. The abbreviated Slovene terms razpoka (Slovene term for fracture) and dol = dolina (valley) are combined into the proposed term razdol. Only razdols have a characteristic shape in the Mt. Nanos area, while more or less

doline v smeri sistema regionalnih subvertikalnih razpok SSW-NNE, ki so tu rotirane v smer SW-NE, in nazadnje dejstvo, da je geomorfološka odzivnost omenjenega sistema regionalnih razpok usklajena z morfologijo narivne ploskve, ki ima obliko konveksne izbokline imenovane nanoška antiforma. Geomorfološka odzivnost teh razpok na morfologijo narivne ploskve se kaže tako, da se na širšem območju zaselka Nanos razpoke na lidarju vidne kot posamezne brazde in bolj ali manj očitni nizi vrtač (razpoklinske linije s), ki po usmerjenosti odstopajo od ostalih, npr. razvitih vzdolž plastnatosti (sl. 11). Na območju, kjer je Hrušiška narivna ploskev strmejša, med zaselkom Nanos in Suhim vrhom (1313 m) je geomorfološki odziv teh razpok močneje izražen vendar slabše viden, ker je zakrit z veliko močnejšim geomorfološkim odzivom na plastnatost (medplastni zdrsi) spodnjekrednih apnencev v smeri NNW, zato se odraža le kot prekinitev grebenov asimetričnih dolin vzporednih plastnatosti (linije - ss) (sl. 11). V bloku nad Rjavo steno pa se odziv na te razpoke kaže kot simetrične razpoklinsko-korozijske doline (sss) za katere uvajamo novo ime, ki združuje termina razpoka (skrajšano raz) in dolina (skrajšano dol) v nov termin razdol. Na območju Nanosa imajo vzorčno geomorfološko obliko le razdoli, medtem ko so bolj ali manj razviti razpoklinski nizi vrtač slabše vidni in neprimerni za temeljno predstavitev.

Profil 1b kaže razmere v zaledju Ubeljske stene, kjer poteka preko zdrselega bloka G (sl. 8). Razlaga temelji na interpretaciji senčenega modela reliefa izdelanega iz lidarskih podatkov (eVode, 2016).

developed doline strings along other fracture systems are less pronounced and hence not suitable for comprehensive presentation.

The geological cross-section 1b across a gravitationally slided G block (Fig. 8) illustrates the geological structure behind the Ubeljska stena. The explanation is based on the interpretation of a shaded relief model constructed from lidar images (eVode, 2016).

A comparison of the two cross sections (1a and 1b) shows they are identical, except for the missing carbonate cover in the 1b cross-section that is still present in the 1a cross-section behind the Votla and Rjava stena. The missing carbonate cover E of Ubeljska stena gradually disintegrated into slided and collapsed blocks and corroded relatively quickly due to the presence of water.

A simplified kinematic sketch illustrating the relations between the convex shape of the flysch basement beneath the thrust fault and the structural blocks (macrolithons) in the carbonate hanging block is given in Fig. 11. Offsets in the rigid media

Na podlagi primerjave med profiloma 1a in 1b je moč ugotoviti, da sta identična, razlika je le v tem, da v drugem profilu ni več karbonatnega pokrova, ki še obstaja v zaledju Votle in Rjave stene. Tu je postopoma razpadel v plazišče in zaradi prisotnosti vode hitreje korodiral.

Na sliki 11 je pridana poenostavljena kinematska skica, ki ponazarja odnos med konveksno obliko flišne podlage pod narivno ploskvijo in bloki v karbonatni krovni enoti. Premiki v trdnem mediju so se sproščali na več načinov, ali z zdrsi po posameznih razpokah med mikrolitoni, po snopih razpok med makrolitoni in redkeje po eni zbirni razpoki, ki je postala prelom in prevzela vlogo snopa med makrolitoni. Premiki ob razpokah so povzročili tektonizacijo kamnine zaradi česar je postala korozijsko oslabljena. Razdalja med snopi razpok in zbirnimi razpokami je pogosto sistemska, ker je povezana z različnimi mehanskimi in prostorskimi pogoji, zato je tudi razdalja med razdoli pogosto enaka (sl. 12).

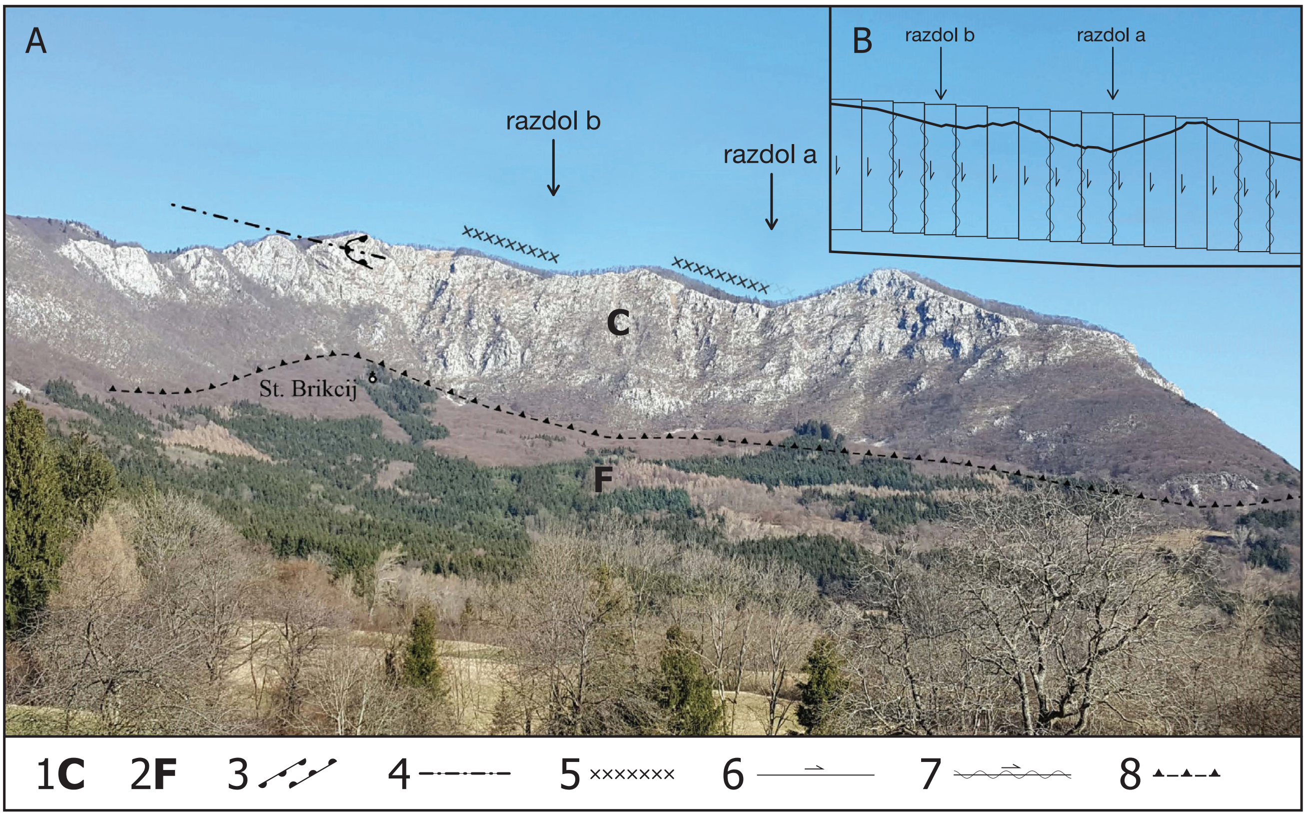

Fig. 12. A. Panoramic view of the Votla stena, B. Kinematic sketch.
Sl. 12. A. Panorama Votle stene, B. Kinematska skica.

1 C – Hrušica Nappe carbonates / karbonati Hrušiškega pokrova
2 F – Flysch of the Snežnik Nappe / fliš Snežniškega pokrova
3 Bedding: normal, inverse / plasti: normalne, inverzne
4 Axial plane of the recumbent frontal anticline / osna ravnina polegle krovne antiklinale
5 Area of intense differential offsets along regional fractures / območje intenzivnejših diferencialnih premikov po regionalnih razpokah
6 Direction of the regional fractures along regional fractures / smer diferencialnih premikov po regionalnih razpokah
7 Direction of intense differential movements along fractures / razpoke z intenzivnejšim diferencialnim premikom
8 Hrušica Nappe boundary / meja Hrušiškega pokrova

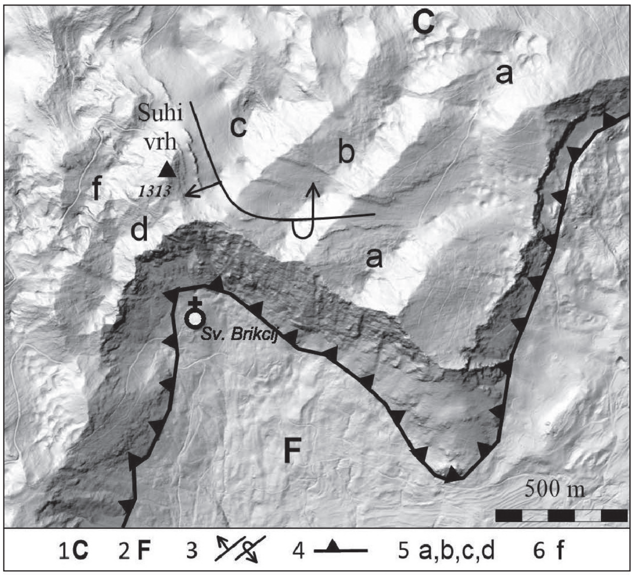

Fig. 13. Razdols morphology.
Sl. 13. Morfologija razdolov.
1 C – Hrušica Nappe carbonates / karbonati Hrušiškega pokrova
2 F – Flysch of the Snežnik Nappe / fliš Snežniškega pokrova
3 Bedding: normal, inverse / plasti: normalne, inverzne
4 Nappe boundary / meja pokrova
5 Shear razdol / strižni razdol: a, b, c, d
6 Divergent razol / razmični razdol: f

(limestone) are realized in several ways – either by slips along individual fractures between microlithons, along fracture sheafs between macrolithons, or less frequently along one collective (cumulative) fracture that became a fault and took over the fracture sheaf role between the macrolithons. The offsets along fractures caused a tectonization of the rock and consequently accelerated corrosion and hence

Na panoramskem posnetku Votle stene (sl. 12) je na levi videti jedro polegle gube, od koder se inverzne plasti vlečejo povprek cele stene, nato razdola a in b, subvertikalne razpoke in snop reaktiviranih razpok v severozahodnem pobočju vsakega od obeh razdolov.

Razdoli a, b in c so nastali nad jugovzhodnim pobočjem nanoške antiforme, mehanizem nastanka je lepo viden pri razdolih a in b. Njihova smer je enaka smeri razpok in so zaradi tega sorazmerno ravni (sl. 13), v ozkem dnu razdola pa je običajno niz ponorov (sl. 14). Pred seboj imamo strižno razpoklinsko-korozivno dolino ali strižni razdol.

Drugačna je morfološka podoba razdola f, ki se nahaja na vrhu nanoške antiforme (sl. 11, 1a); tu se niso toliko uveljavili gravitacijski diferencialni zdrsi temveč razmikanje in kot posledica ugrezanje makrolitonov, podobno kot v primeru ugrezanja temena antiklinale. Temu ustreza tudi morfologija tega razdola; njegovo dno je ravno in predstavlja površino ugreznjenega makrolitona, po nastanku enak malemu tektonskemu jarku. Razdol, ki je nastal z ugrezanjem makrolitona (strukturnega bloka) imenujemo razmično razpoklinsko-korozivna dolina ali razmični razdol (sl. 15).

Na sliki 8 je prikazana razporeditev razdolov a, b, c, d in e, ki so nastali v razpoklinskih sistemih po diferencialnih strižnih premikih in razdol f, ki je razmičnega (divergentnega) nastanka. Poleg tega obstajata še dve, dolini podobni

Fig. 14. Shear razdol a. A valley formed in a course of successive shear offsets in a fracture system, enhanced by corrosion.
Sl. 14. Strižni razdol a. Razpoklinsko-korozivna dolina nastala pri strižnih sukcesivnih premikih po razpoklinskem sistemu.

weakened the rock between offset macrolithons. The distance between the fracture sheafs and collective fractures is often systemic, as it is related to various mechanical and spatial conditions, and thus frequently equidistant from each other (Fig. 12).

The core of a recumbent fold with its inverse strata along the entire wall, together with two razdols are visible in the Votla stena panoramic photograph (Fig. 12), along with the subvertical fractures and finally a sheaf of tectonized fractures on the NW slope of both razdols.

Razdols a, b and c were formed above the SW slope of the Nanos antiform, and the formation mechanism is obvious in the a and b razdols, as their orientation is parallel to the fractures which is why they are relatively straight (Fig. 13) and usually host a string of sinkholes along the narrow bottom (Fig. 14). This type of razdol formed along either a single (leading) or multiple shear fractures, hence the term shear razdol.

The morphology of razdol f is somewhat different (Fig. 11, 1a), as it was formed on the crest of the Nanos antiform. Divergent offsets and the consequential subsidence of the macrolithons prevail in this type of razdol, much like a crestal collapse or a miniature tectonic graben. The base of the shear razdol is therefore flat, as it represents the subsided microlithon upper surface. This type of razdol is referred to as a divergent razdol (Fig. 15).

A disposition of the a, b, c, d, and e shear razdols formed in the fracture systems by subsidence along the shears between the microlithons and the divergent razdol f is presented in Figure 8. Features similar to valleys h and g formed outside the regional (NNE - SSW) fracture system exhibit signs of mass movement. The h valley's circular shape resembles a valley between a head scarp with a shear plane in the hinterland and the reverse slope of the rotated slump blocks. The structural block south-east of the inferred head scarp (h) is 50 to 100 m lower from the block that lies to the north-west and characteristically deformed. The bedding geometry changes several times across the presumably slumped block resembling multiple rotated slump blocks, while north-west of the inferred head the scarp bedding is uniform. In the case of the g valley, a gravitational offset of the G block is evident from its protruding position. The first case (g) is inferred, the other (h) is probable. Not only the G block protrudes, but the E block also protrudes from the Ubeljska stena scarp. It seems that differential offsets along the fracture system in which the e valley formed took place first, and later a more pronounced gravitational offset proceeded along one of the fractures or the fracture sheaf (Fig. 8).

Fig. 15. Divergent razdol f. A valley formed due to divergent offsets in a fracture system enhanced by corrosion. A flat valley bottom and steep side walls suggest subsidence of the intermediate block (macrolithon).

Sl. 15. Razmični razdol f. Razpoklinsko-krozivna dolina nastala zaradi razpiranja po razpoklinskem sistemu. Ravno dno in bočne stene nakazujejo, da se je vmesni blok (makroliton) ugreznil.

tvorbi h in g, ki kažeta na gravitacijska zdrsa izven regionalnega sistema razpok (NNE - SSW), v prvem primeru kaže na to njena polkrožna oblika, ki domnevno predstavlja robni jarek in v zaledju drsno ploskev rotacijskega plazu. Blok jugovzhodno od domnevnega robnega jarka h leži okoli 50 do 100 m nižje od tistega na severozahodu poleg tega je jugovzhodni blok značilno prizadet, tu se lega plasti večkrat spremeni, kar kaže na obstoj različnih manjših blokov, medtem ko imajo plasti severozahodno od tod enotno smer. V primeru domnevnega robnega jarka g je zdrs nakazan z izstopajočo lego bloka G. Prvi primer (g) je domneven, drugi (h) pa verjeten. Poleg bloka G izstopa tudi blok E, kjer izgleda, da je prišlo najprej do diferencialnih premikov po sistemu razpok po katerih je nastal razdol e, Razdols d and e and a trench (valley) g beneath the head scarp are remnants of the gravitational structures, much like those behind the Rjava and Votla stena. Geological conditions in the Ubeljsko steephead were identical to those behind the Rjava and Votla stena before the carbonate cover disappeared due to gravitational, corrosive and denudational processes, which were the same as those observed at the Rjava stena landslide area.

Gravitational phenomena comprising a to f razdols and both g and h marginal trenches belong to the Suhi vrh gravitational structure. Razdols aren’t formed due to classical slope processes, but as part of processes related to gravity.

Let us look at transverse cross-section 2 in Fig. 16 in order to complete the image of the structure of the SE part of Mt. Nanos. The thrust plane position is taken from the 1a and 1b cross-sections; however, difficulties arise in the interpretation – related primarily to its dip rather than elevation above the village of Žvanuti. There is no (karstic) spring to drain the karstic water from Mt. Nanos between Razdrto and Vipava. This fact is formally supported by the 45/20 thrust plane dip in the outcrop at 540 m a.s.l. in the roadcut of the 4th serpentine (from above) of the road to Mt. Nanos, about 3 km NW of cross-section 2. No other relevant data exists on the area between the described outcrop and Razdrto. The absence of karstic (there are springs and streamlets on the SW slope of Mt. Nanos, but these only drain the meteoric water from the slope scree) springs on the SW slope of Mt. Nanos does not correspond to the Nanos antiform beneath Suhi vrh (1313 m a.s.l.); as a result, the only available solution lies in the existence of the 210/60 Reševnik fault above Razdrto (Figs. 8 and 9). The subsided SW block makes it a seemingly normal fault.

pozneje pa tudi do močnejšega gravitacijskega zdrsa po eni od razpok ali snopu razpok (sl. 8).

Razdola d in e ter »robni jarek« g so ostanki gravitacijskih struktur, ki so enake tistim v bloku za Votlo in Rjavo steno. Pred nastankom Ubeljskega zatrepa so tu obstajale enake razmere na celotni površini zatrepa, karbonatni pokrov je tu izginil zaradi gravitacijskih, korozivnih in denudacijskih procesov, ki so bili taki kot jih danes opazujemo na plazišču Rjava stena.

Gravitacijske strukture, ki zajemajo razdole od a do f in oba »robna jarka« g in h pripadajo gravitacijski strukturi Suhega vrha. Razdoli niso nastali zaradi klasičnih pobočnih procesov, gre pa za pojave, ki so povezani z gravitacijo.

Da bi zaokrožili predstavo o zgradbi jugovzhodnega dela Nanosa, si oglejmo še prečni profil 2 na sl. 16, Lega krovne narivne ploskve je povzeta po profilih 1a in 1b, težave pa nastopijo pri interpretaciji njene lege nad Žvanuti na območju Rebrnic. Vprašljiva ni njena višinska kota temveč vpad; v čelu Hrušiškega pokrova od Razdrtega do izvira Vipave ni nikjer izvira, ki bi odvajal kraško vodo iz Nanosa, formalno je ta podatek podprt z vpadom narivne ploskve v golici na četrti serpentini nanoške ceste od zgoraj navzdol, ki znaša 45/20 in se nahaja okoli 3 km severozahodno od profila 2. Od omenjene golice do Razdrtega ni ustreznega podatka. Odsotnost kraških izvirov se ne ujema z antiformo pod Suhim vrhom, v pobočju Rebnic so namreč le potočki, ki odvajajo meteorno vodo. V tem trenutku vidimo rešitev problema v obstoju Reševniškega preloma 210/60 nad Razdrtim (sl. 8 in 9), ob katerem je jugozahodno krilo spuščeno, zaradi česar daje videz normalnega preloma. Vendar ponujajo razmere na območju Razdrtega tudi drugačno razlago, zato postavljamo domnevo,

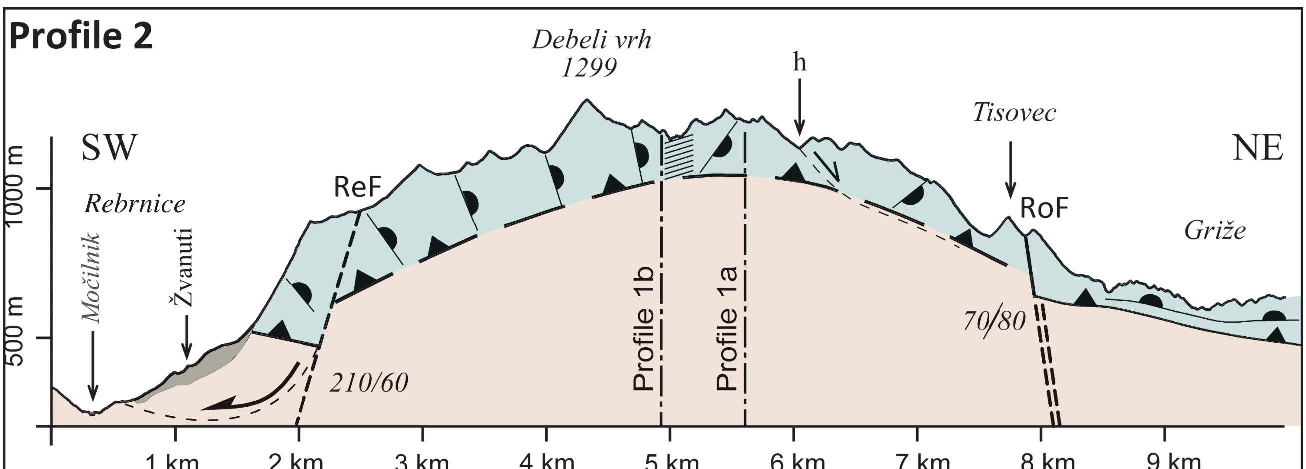

Fig. 16. Transverse structural cross-section 2: Žvanuti – Debeli vrh – Tisovec – Griže. Key in Fig. 11.

Sl. 16. Prečni strukturni profil 2: Žvanuti – Debeli vrh – Tisovec – Griže. Legenda na sl. 11.

However, the geological conditions of the Razdrto area offer an alternative explanation, in which the Reševnik fault planes took over the rupture surface role in the sub-recent erosional-denudational environment. This assumption is supported by a 210/50 fault plane within the Reševnik fault zone. According to the spatial criterion this fault plane could act as a rupture surface of a large Reševnik fossil rotational landslide superimposed by the recent Razdrto translational landslide (Placer, 2006). The Reševnik rotational landslide is confirmed by the reversely tilted flysch beds.

As the Reševnik fault has not been mapped and followed on the surface due NW, only a hypothetical solution is provided in cross-section 2 (Fig. 16). Here, the Reševnik fault is only extrapolated some 3.5 km due NW. A normal fault could not have caused a backtilting of the thrust plane, but only a rotational landslide could have done so. Only specifically targeted research could provide the answer as to whether one or more fossil gravitational phenomena occurred in the Rebrnice slope.

A Nanos antiform

Knowledge of the Hrušica thrust plane morphology is important in order to gain an understanding of the structural, geomorphologic, and hydrologic issues of the area considered here and in the wider area as well. The interpretation of its morphology – structural map of the Nanos antiform (Fig. 17) – is based on the course of its boundaries and structural cross-sections (1a, 1b and 2).

The internal structure of the structural block behind the Votla and Rjava stena is reflected in the Votla stena structure (cross-section 1a in Figs. 11 and 12). It has been established that the Hrušica Nappe thrust plane inclination towards the Postojna basin (SE) is not a consequence of rotational or translational mass movements. It is a differential uplift of the Nanos antiform that triggered differential offsets along the discontinuous SW - NE (SSW - NNE) fracture system. The interpretation is reliable only near the nappe boundary. Beneath the carbonate nappe, the interpretation is based on the coincidence of the anomaly apex and Mt. Suhi vrh (1313 m a.s.l.), the highest peak of Mt. Nanos. Based on this coincidence, it is inferred that the most uplifted parts of Mt. Nanos between Mt. Suhi vrh (1313 m a.s.l.) and Mt. Debeli hrib (1209 m a.s.l.) along the 330° course may be related to this deformation as well. This trend is subtly predented with the Nanos antiform longitudinal axis trend seen in Figure 16.

The isolines course in the Rebrnice slope is based on the cross-section 2 interpretation (Fig. 16). Construction of the 700 m, 800 m and the 900 m isolines

da je prelomna ploskev tega preloma v subrecentnih erozijsko-denudacijskih pogojih postala ploskev gravitacijskega zdrsa. To domnevo utemeljujemo s prelomno ploskvijo znotraj cone Reševniškega preloma 210/50, ki bi po prostorskem kriteriju lahko bila nosilka velikega fosilnega rotacijskega plazu Reševnik na katerem leži recentni planarni plaz Razdrto (Placer, 2006). Na rotacijski plaz Reševnik kažejo povratno zasukane flišne plasti.

Reševniški prelom ni bil kartiran in sleden na površju proti severozahodu, zato je mogoče podati le hipotetično rešitev, kot je prikazana v profilu 2 (sl. 16). Tu je Reševniški prelom ekstrapoliran okoli 3,5 km proti severozahodu, normalni premik ob prelomu ne bi mogel zasukati narivne ploskve v nasprotno smer, to se je lahko dogodilo le zaradi fosilnega rotacijskega plazu. Ali obstoja na Rebrnicah eden ali več fosilnih gravitacijskih pojavov, ni mogoče ugotoviti brez usmerjene raziskave.

Nanoška antiforma

Poznavanje morfologije narivne ploskve Hrušiškega pokrova je pomembno za razumevanje strukturnih, geomorfoloških in hidroloških vprašanj obravnavanega in širšega prostora. Interpretacija morfologije narivne ploskve sloni na poteku meje pokrova in na strukturnih profilih 1a, 1b in 2, rezultat je strukturna karta nanoške flišne antiforme (sl. 17).

Notranja zgradba strukturnega bloka za Votlo in Rjavo steno se kaže v zgradbi Votle stene (profil 1a na sl. 11 in 12). Ugotovljeno je, da vpad narivne ploskve proti Postojnski kotlini ni posledica rotacijskega ali drugačnega plazenja, temveč usločenja nanoške antiforme, kar je povzročilo nastanek diferencialnih premikov po diskontinuitetah razpoklinskega sistema SW-NE (SSW--NNE). Interpretacija je zanesljivejša le blizu meje pokrova, od tu pa je razdeljena na del pod karbonatnim pokrovom in na del nad sedanjim površjem zahodnega dela Postojnske kotline. Interpretacija poteka narivnice pod karbonatnim pokrovom temelji na sovpadanju vrha anomalije in Suhega vrha (1313 m), ki je najvišji vrh Nanosa. Na podlagi tega sklepamo, da so najvišji deli Nanosa proti Debelemu hribu (1209 m), v smeri 330°, lahko povezani s to deformacijo. Ta smer je rahlo nakazana z obliko antiforme. Potek izolinij na Rebrnicah sloni na interpretaciji profila 2 (sl. 16).

Izolinije 900, 800 in 700 nad zahodnim delom Postojnske kotline sledijo razmeram na območju Votle in Rjave stene, kjer vpadajo proti kotlini.

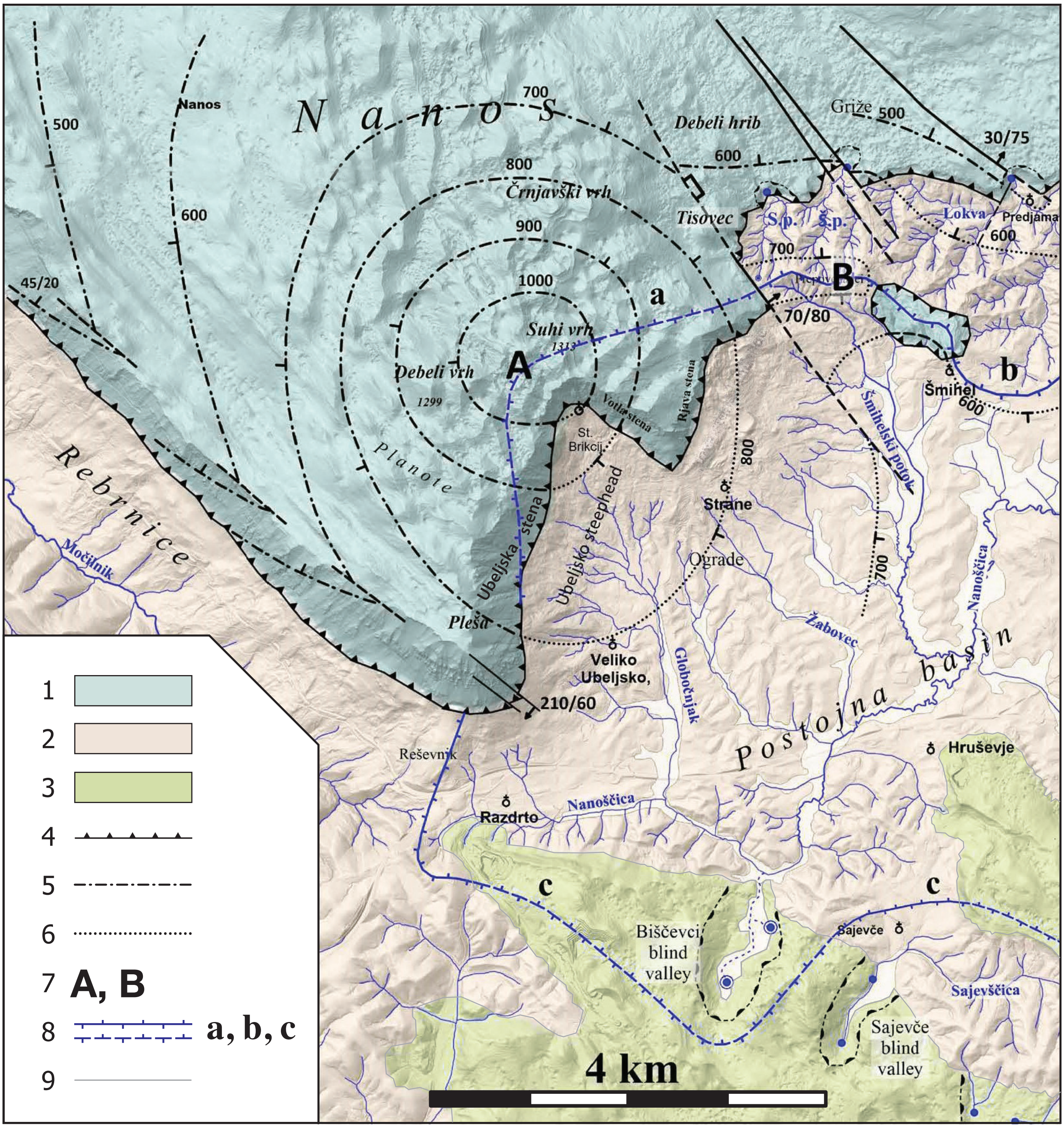

Fig. 17. Structural sketch of the Nanos antiform.
Sl. 17. Strukturna skica nanoške antiforme.

1 Mesozoic carbonates of the Hrušica Nappe / mezozojski karbonati Hrušiškega pokrova
2 Eocene flysch of the External Dinaric Imbricated Belt and of the Snežnik Nappe / eocenski fliš Zunanjedinarskega naluskanega pasu in Snežniškega pokrova
3 Mezozoic and Paleogene carbonates of the External Dinaric Imbricated Belt / mezozojski in paleogenski karbonati Zunanjedinarskega naluskanega pasu
4 Hrušica Nappe boundary / meja Hrušiškega pokrova
5 Thrust plane isoline beneath the nappe / izolinija narivne ploskve pod krovno enoto
6 Thrust plane isoline above the surface / izolinija narivne ploskve nad sedanjim površjem
7 Nanos antiform / nanoška antiforma: A – antiform apex (St. Brictius ridge) / vrh antiforme (hrbet Sv. Brikcija), B – Šmihel ridge / šmihelski hrbet
8 Current Adriatic - Black Sea watershed divide / sedanja razvodnica med jadranskim in črnomorskim povodjem: a – section under the Hrušica Nappe / odsek pod Hrušiškim pokrovom, b – section in the Šmihel (village) area / odsek na območju Šmihela, c – section east of Razdrto (village) / odsek vzhodno od Razdrtega
9 Geological boundary / geološka meja

above the western part of the Postojna basin follows the conditions in the Votla and Rjava stena, where the thrust plane dips towards the basin. In the Šmihel area NE of the Roček fault (70/80) the interpretation is based on the distribution of ponors (sinkholes) W of Predjama and the Šmihel (tectonic) klippe. The thrust plane lies partly below and partly above the 600 m isoline, while the 700 m isoline definitively appears near the ridge between Prepovedanci and Praprotniki, just above the 700 m a.s.l. The described features indicate the existence of a ridge – here called the Šmihel ridge – as part of the Nanos antiform (Fig. 17, B).

When introducing the term Šmihel ridge we must also name the main part of the Nanos antiform for purposes of clearer communication, which is called the Sv. Brikcij ridge or Bric's ridge (Fig. 17, A). The Nanos antiform determines the Adriatic - Black Sea watershed divide in the western part of the Postojna basin (Fig. 17, 8a, 8b). The watershed divide course in the southern part of the Postojna basin east of the village of Razdrto was established as a result of deformations younger than the Nanos antiform S and SE of the Hrušica Nappe (Fig. 17, 8c).

Relief and hydrographic network evolution

The formation and degradation (erosion) of both ridges in the Nanos antiform had a fundamental impact on the morphology of the hydrographic network in the western part of the Postojna basin (Fig. 17). The oldest landforms that are still recognizable arose when the Hrušica Nappe still covered the western part of the Postojna basin and its southern boundary extended to the Razdrto - Hruševje line. Meteoric water was drained vertically through a fractured and karstified limestone nappe to reach a southward-tilted thrust plane. The water formed carstic caves just above the impermeable flysch basement and flowed due south. The springs were aligned along the nappe boundary between Razdrto and Hruševje. After a short course over flysch the water carved two blind valleys due south, the Biščevci and Sajevče valleys. The surface above the blind valleys stands at 650 to 700 m a.s.l., and the valley bottoms out at about 550 m a.s.l. or 20 m above today's Nanoščica Creek valley. The Biščevci blind valley is 1500 m long and up to 500 m wide. The valley bottom is covered by fluvial deposits several meters thick of flysch provenance. Today, the Biščevci valley is a relict blind valley, as the hydrological conditions south-eastward in the karst have changed radically. After rainfall, the water springs from the Biščevci valley and flows due north as a heavy stream into the Nanoščica. When

Na območju Šmihela na severovzhodni strani Ročkovega preloma (70/80), sloni interpretacija na podatkih meje pokrova v pasu ponikalnic in Šmihelske tektonske krpe. Ta leži nekaj pod in nekaj nad izohipso 600, izohipsa 700 pa vsekakor poteka okoli grebena med Prepovedanci in Praprotniki, ki je nekaj višji od 700 m. To kaže na obstoj hrbta, ki je del nanoške antiforme. Imenujemo ga šmihelski hrbet (sl. 17, B).

Ob uvedbi termina šmihelski hrbet je zaradi lažjega sporazumevanja potrebno poimenovati tudi glavni del nanoške antiforme (sl. 17, A), imenujemo ga hrbet Sv. Brikcija ali bricov hrbet. Razvodnico med jadranskim in črnomorskim povodjem v zahodnem delu Postojnske kotline določa nanoška antiforma (sl. 17, 8a, 8b). Potek razvodnice na jugu kotline, od Razdrtega proti vzhodu, pa se je oblikoval zaradi deformacij ozemlja južno in jugozahodno od pokrova. Te so mlajše od nanoške antiforme (sl. 17, 8c).

Razvoj reliefa in hidrografske mreže

Nastanek in razgradnja obeh hrbtov nanoške flišne antiforme sta vplivali na današnjo oblikovanost hidrografske mreže in reliefa v zahodnem delu Postojnske kotline (sl. 17). Najstarejše danes še zaznavne reliefne oblike so nastale, ko je rob Hrušiškega pokrova v zahodnem delu kotline segal še več kilometrov južneje, nekako do črte Razdrto - Hruševje. Padavinska voda je skozi razpokan in zakrasel apnenčasti pokrov vertikalno odtekala do nagnjene narivne ploskve. Tik nad njo je v apnencih oblikovala jame, ter nad nepropustno flišno podlago odtekala proti jugu. Izviri so bili razporejeni ob robu pokrova na črti med Razdrtim in Hruševjem. Izvirna in površinska voda s fliša je nato po kratkem toku po flišu oblikovala dve proti jugu usmerjeni slepi dolini, Biščevce in Sajevško dolino. Dolini sta vrezani v površje, ki je na višinah med 650 in 750 m. Dna slepih dolin sta na nadmorski višini okrog 550 m, oziroma 20 m nad sedanjo dolino Nanoščice. Slepa dolina Biščevci je dolga 1500 m in do 500 m široka. Dno doline pokrivajo več m debele plasti fluvialnih sedimentov, ki jih je vanjo naplavila ponikalnica s fliša. Danes so Biščevci reliktna slepa dolina, saj so se hidrološke razmere v krasu jugozahodno od tod povsem spremenile. V dolini po dežju izvira voda, ki teče proti severu in se kot močan potok izliva v Nanoščico, ob nizkem vodostaju pa se voda skozi apnenec kraško preceja proti Sajevški slepi dolini. Sajevško slepo dolino je po dimenzijah sodeč oblikovala večja voda, verjetno Šmihelski potok. Danes pa v njej ponika le water levels are low, however, it seeps through the karstified limestone towards the Sajevče blind valley. In view of its size, the Sajevče valley must have been formed by a relatively large stream, probably the Šmihel creek. Today, however, only a small streamlet drains the surface water from the flysch and sinks into the valley. The streamlet sinks in the cave of Markov spodmol, part of the Vodna jama v Lozi water cave that stretches 6 km.

The Biščevci and Sajevče blind valleys are the largest blind valleys in the Postojna basin. Their position suggests the primal drainage direction of the western part of the Postojna basin due south. According to their size and shape the southward directed stream courses with a low gradient in the karstic part lasted a relatively long time. The levelled Slavenski ravnik and a preserved unroofed cave there at 600 m a.s.l. also support this interpretation.

The Hrušica Nappe southern front withdrew northward rather quickly due to rockfalls and landslides, and underground drainage contributed greatly to the withdrawal as well. The carbonate cover was undermined and disintegrated rather quickly, as karstic caves were formed along the thrust plane and underground rivers eroded the flysch in the base. Heavily disintegrated and karstified limestone cover there accelerated karstic denudation, as denudation is far more effective in the fractured and tectonized limestone, rockfalls and slope screes. The underground drainage pattern formed along the thrust plane was reproduced down into the flysch and established the courses of the present Globočnjak, Žabovec and Šmihel creek valleys due south.

Only a very small amount of water is drained from the carbonate cover into the Ubeljsko steephead, hence the indistinct fluvial relief and far slower degradation of the thrust margin above. The Hrušica Nappe margin within the Bric's ridge already lies north of its highest part. The surficial watershed divide runs between the Nanoščica creek tributaries and the streams that flow due north and sink under the nappe margin west of Predjama; the creeks are as follows: Stranske ponikve (S.p. in Fig. 17), Šmihelske ponikve creek (*Š.p.* in Fig. 17), and Lokva, all part of the Vipava River catchment area. The elevations of their sinkholes, as determined by the thrust plane are: 608 m a.s.l, 600 m a.s.l., and 462 m a.s.l., respectively. The formation of the valleys was also influenced by the shape and inclination of the thrust plane. The fluvial relief is more pronounced here because it is younger, due to the steeper thrust plane, and the high gradient in the karst.

majhen potok, ki krajevno zbira vodo na flišu. Potok ponika v jami Markov spodmol, ki je del 6 km dolge Vodne jame v Lozi.

To sta največji slepi dolini v Postojnski kotlini. Kažeta na prvotno smer odtekanja zahodnega dela kotline proti jugu. Po velikosti ter obliki dolin je trajal odtok v to smer dolgo časa, gradient v krasu pa je bil majhen. O tem priča uravnava Slavenskega ravnika južno od tod in v njem ohranjena 3 km dolga brezstropa jama na višini okrog 600 m.

Južni rob Hrušiškega pokrova se je zaradi podorov in plazov relativno hitro umikal proti severu. K umikanju je močno prispevala podzemna drenaža. Ob narivni ploskvi so se oblikovale jame, jamske reke pa so erodirale fliš v podlagi. To je spodjedalo in destabiliziralo karbonatni pokrov, ki se je zaradi tega hitreje podiral, pospeševalo pa je tudi kraško denudacijo, ki je veliko hitrejša na pretrtih in porušenih apnencih, podorih in meliščih. Vzorec jamske podzemne drenaže, ki se je oblikovala ob narivni ploskvi pa se je reproduciral navzdol v flišne kamnine in zasnoval potek današnjih dolin Globočjaka, Žabovca in Šmihelskega potoka proti jugu.

Ker sega Ubeljski zatrep skoraj do najvišjega dela bricovega hrbta nanoške antiforme, se danes proti njemu ob narivni ploskvi izceja le malo vode iz apnencev. Zato je fluvialni relief na pobočjih neizrazit, upočasnilo pa se je tudi rušenje apnenčastega narivnega roba.

Rob hrušiškega nariva v območju šmihelskega hrbta leži že severno od njegovega najvišjega dela. Tu poteka površinska razvodnica med pritoki Nanoščice in potoki, ki tečejo proti severu in ponikajo pod robom nariva zahodno od Predjame. To so potoki Stranske ponikve (oznaka S.p. na sl. 17), Šmihelske ponikve in Lokva, ki pripadajo povodju Vipave. Višine ponorov, ki jih določa narivna ploskev, so 608 m, 600 m in 462 m. Tudi na oblikovanje dolin potokov je vplivala oblika in pa vpad narivne ploskve. Fluvialni relief je tu bolj izrazit zaradi manjše starosti, večjega naklona narivnice in velikega gradienta v krasu.

Nastajanje obeh hrbtov nanoške flišne antiforme je potekalo sočasno z oblikovanjem reliefa v zahodnem delu Postojnske kotline. Po tektonskem dvigu območja slepih dolin Biščevci in Sajevške doline, se je Nanoščica preusmerila proti vzhodu v ponorno cono pri Postojnski jami, kjer so ponori na višini 510 m. Odtok proti severu ji je preprečil šmihelski hrbet, ki ima smer zahod-vzhod.

Both ridges in the Nanos antiform formed simultaneously with the formation of the relief in the western part of the Postojna basin. After the tectonic uplift of the Biščevci and Sajevče blind valleys area the Nanoščica creek shifted its course to the west into a ponor (sinkhole) zone at Postojnska jama cave at 510 m a.s.l. as the E - W trending Šmihel ridge restrained its course due north.

The three-dimensional elevation model of the Nanos southeastern slope in Figure 18 is somewhat distorted, nevertheless the geomorphologic features are still well expressed. Ubeljsko steephead in the first plan is bounded by the Ubeljska stena and Votla stena. Razdols a and b are well exposed parallel to the Rjava stena, behind the Votla stena. The difference between the landslide area below the Ubeljska stena and Votla stena covered by the slope scree differ significantly from the landslide area below the Rjava stena composed of multiple slided rotational blocks.

Šmihel ridge, hosting the Black Sea – Adriatic watershed is visible in the north-eastern corner of the elevation model. Streams on its northern

Tridimenzionalni višinski model jugovzhodnega pobočja Nanosa na sliki 18 je nekoliko popačen, vendar so geomorfološke značilnosti lepo vidne. V ospredju izstopa Ubeljski zatrep, ki ga zapirata Ubeljska in Votla stena. Za Votlo steno in vzporedno z Rjavo steno, sta lepo vidna razdola a in b. Opazna je razlika med plaziščem pod Ubeljsko in Votlo steno, na katerem je pretežno pobočni grušč in plaziščem pod Rjavo steno, ki ga sestavlja več rotacijskih blokovnih zdrsov.

V severnem kotu modela je viden šmihelski hrbet po katerem teče razvodnica med jadranskim in črnomorskim povodjem. Potoki na njegovi severni strani ponikajo pod Hrušiški pokrov, kar je pogojeno s hrušiško sinformo, nasprotno pa ni v območju nanoške antiforme nobenega ponora, tu vse vode odtekajo stran od njenega vrha, ki se nahaja za dnom Ubeljskega zatrepa. Popačenje modela je krivo, da ta značilnost ni opazna.

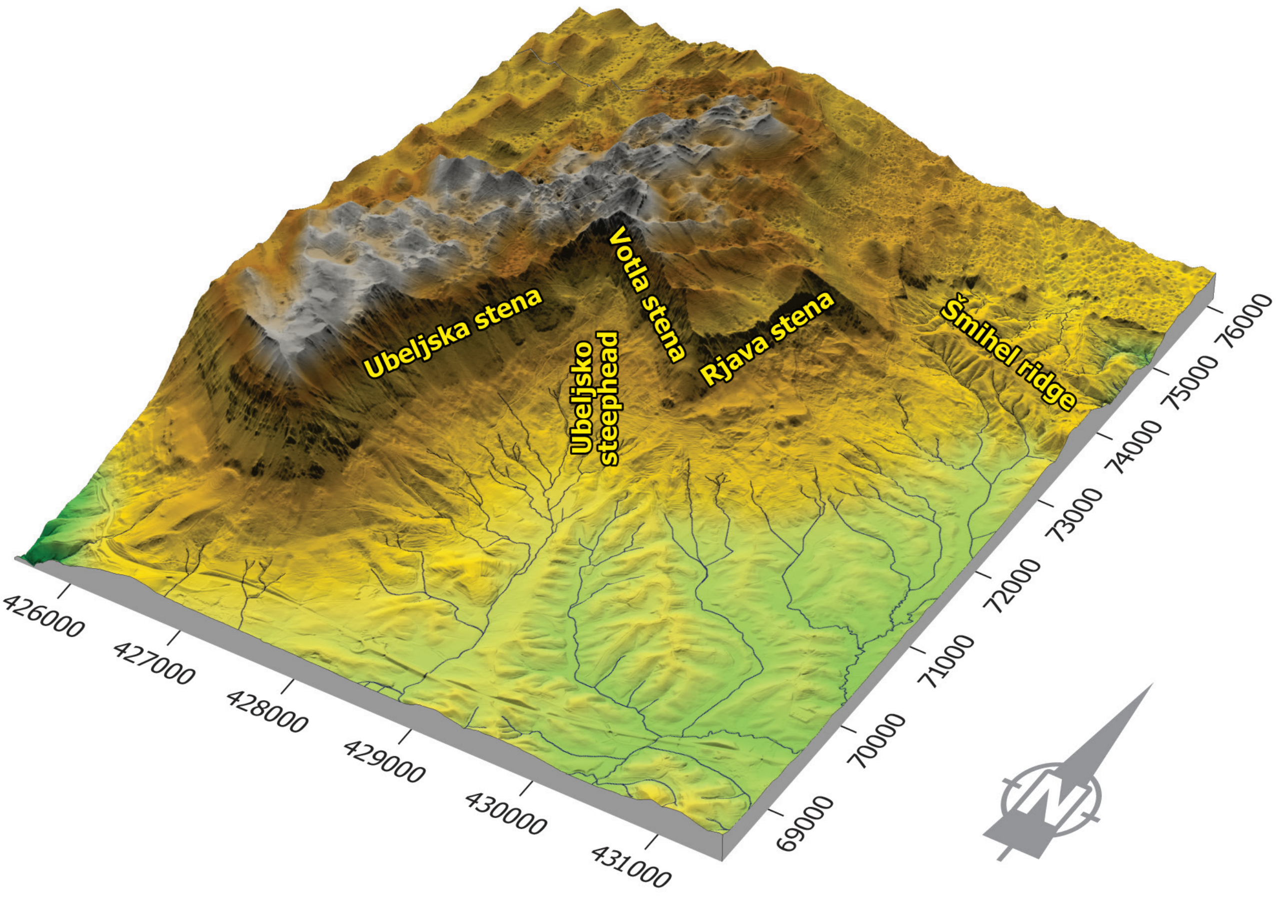

Fig. 18. Three-dimensional view on the southeastern part of Mt. Nanos and of the eastern part of the Postojna basin.
Sl. 18. Tridimenzionalni pogled na jugovzhodno pobočje Nanosa in vzhodni del Postojnske kotline.

side are sinking under the Hrušica thrust due to Hrušica synform and there is no sinkhole in the Nanos antiform area and all the waters run away from its summit behind the base of the Ubeljsko steephead. The described morphologic feature is obscured by the distortion of the elevation model.

Conclusion

Gravitational phenomena along the SE margin of Mt. Nanos are understood as the degradation of the lateral Hrušica Nappe boundary and its retreat due NE and N. The Suhi vrh gravitational zone in the southeastern flank of the Hrušica Nappe (Fig. 1, b) differs in its mechanism from the landslides in the zone of large gravitational phenomena in the Trnovo Nappe south-eastern block (Fig. 1, a), and the Trnovo and Hrušica Nappe Thrust Fronts (Fig. 1).

The Suhi vrh gravitational area (Fig. 1, b) formed due to an antiform uplift in the frontal part of the Hrušica Nappe and its flysch basement with it. Differential gravitational offsets along a system of sub-vertical regional fractures of the SSW - NNE trend manifested as a result of this antiform uplift. These offset kinematics correspond to the internal rotation of blocks and differ from the classical gravitational mass movements in the landslide areas beneath the Ubeljska, Votla and Rjava stena.

The Ubeljsko steephead was formed due to the degradation of the Suhi vrh gravitational structures by classical rockfalls, landslides and denudational processes. A similar scenario takes place in the preserved part of the Suhi vrh structure behind the Votla and Rjava stena, where mass movements undermine the Rjava stena cliff. Here, the denudational process started later, as the nappe thrust front retreats due NE.

The formation of the differential offsets described in the Nanos antiform (Fig. 11) is inhibited in the Črni školj and Mali Modrasovec area (Fig. 1, a; Fig. 2) despite a well-developed system of regional subvertical NNE - SSW trending fractures, as the bulge of a flysch antiform behind the Trnovo Nappe Thrust Front is barely noticeable. Only classical mass movement types are present there. From the regional point of view it is important, however, that the antiform considered here lies NW of the Nanos antiform, so we can conclude that it represents its structural continuation or its distant spatial repetition. At this point it is reasonable to introduce the term "Čaven antiform" in order to distinguish it from the Nanos antiform.

Large fossil rotational landslides in the Snežnik Nappe Thrust Front, the inferred landslide at Petelinje mlake (Fig. 1, c) and the confirmed Ilirska

Sklep

Gravitacijske pojave ob jugovzhodnem robu Nanosa in Hrušice razumemo kot rušenje bočne meje Hrušiškega pokrova in njeno pomikanje proti severovzhodu in severu. Gravitacijsko območje Suhega vrha v jugovzhodnem boku Hrušiškega pokrova (sl. 1, b) se po mehanizmu razlikuje od pobočnih zdrsov v pasu velikih gravitacijskih pojavov v jugovzhodnem boku Trnovskega pokrova (sl. 1, a) ter v čelih Trnovskega, Hrušiškega in Snežniškega pokrova (sl. 1).

Gravitacijsko območje Suhega vrha (sl. 1, b) je nastalo zaradi dviga antiforme v čelnem delu Hrušiškega pokrova in s tem tudi njene flišne podlage. Posledica tega so bili gravitacijski diferencialni premiki po sistemu subvertikalnih regionalnih razpok SSW-NNE. Kinematika teh premikov ustreza interni rotaciji in se razlikuje od mehanizma klasičnih pobočnih gravitacijskih pojavov v plaziščih pod Ubeljsko, Votlo in Rjavo steno.

Ubeljski zatrep je nastal zaradi razpada gravitacijskih struktur Suhega vrha na območju zatrepa, ki so jih degradirali klasični pobočni zdrsi in denudacijski procesi. Podobno usodo doživlja ohranjena gravitacijska struktura Suhega vrha za Votlo in Rjavo steno, ki ju izpodjedajo pobočni zdrsi plazišča Rjava stena. Proces denudacije se je tu pričel pozneje, ker se čelni rob Hrušiškega pokrova generalno umika proti severovzhodu.

Na območju Črnega školja in Malega Modrasovca (sl. 1, a; sl. 2) je izboklina flišne antiforme v čelnem delu in začelju Trnovskega pokrova komaj opazna, zato tu ni pogojev za nastanek diferencialnih premikov kot smo jih opisali v primeru nanoške antiforme (sl. 11), čeprav je tudi tu lepo razvit sistem regionalnih subvertikalnih razpok SSW-NNE. Obstajajo le klasični pobočni zdrsi plazišča Črni školj. V regionalnem smislu pa je pomembno, da leži obravnavana antiforma severozahodno od nanoške antiforme, zato je mogoče sklepati, da predstavlja njeno strukturno nadaljevanje ali pa prostorsko odmaknjeno ponovitev. Zaradi razlikovanja je smiselno uvesti pojem čavenska antiforma.

Velika rotacijska fosilna plazova v čelu Snežniškega pokrova; domnevni Petelinje mlake (sl. 1, c) in dokazani Ilirska Bistrica (sl. 1, d), kažeta na drugačne pogoje postnarivnega deformiranja kot v Hrušiškem in Trnovskem pokrovu.

Skupna značilnost vseh štirih izjemnih gravitacijskih pojavov je, da so povezani z deformacijami istrskega potisnega območja, ki so nastale po fazi dinarskega narivanja. Potisno območje

Bistrica landslide (Fig. 1, d) indicate conditions of post-thrust deformation different from those in the Hrušica and Trnovo Nappes. A common feature of all four exceptional gravitational phenomena is their causal link to the deformations of the Istra Pushed Area that occurred after the Dinaric thrust phase. The Istra Pushed Area is a consequence of the Adriatic Microplate (Adria) movement towards the Dinarides – in our case, the movement of Istra and the offshore (and sea bed) of the Trieste Gulf. The Istran block is moving more intensely than the neighbouring Adria blocks SE of Istra. The process started in the Middle Miocene, and its activity (also recent) is manifested in many different ways.

Differences in the types of gravitational phenomena in the Hrušica and Trnovo Nappes Thrust Fronts on the one hand, and the Snežnik Nappe on the other, are also reflected in the type of post-thrust deformation typical across the entire Istra Pushed Area, with particular differences in geomorphologic development. These will be presented in a following article, while this article serves as a basis for a discussion of these differences.

je nasledek premikanja Jadranske mikroplošče (Adria) proti Dinaridom, v našem primeru premikanje Istre in podmorja Tržaškega zaliva. Ta blok se premika intenzivneje od sosednjih blokov Adrie jugovzhodno od Istre. Proces se je pričel v srednjem miocenu, njegova aktivnost pa se kaže na različne načine še danes.

Razlike med tipom gravitacijskih pojavov v območju čelnega dela Trnovskega in Hrušiškega pokrova na eni in Snežniškega pokrova na drugi strani, se odražajo tudi v tipu postnarivnih deformacij na celotnem ozemlju istrskega potisnega območja. Temu ustrezajo razlike v geomorfološkem razvoju, ki bodo opisane v drugem članku. Ta članek je osnova za razpravo o teh razlikah.

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Late Carboniferous biota from the Ljubija iron mine area, Bosnia and Herzegovina

Poznokarbonska biota z območja rudnika železa Ljubija v Bosni in Hercegovini

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Ključne besede: zgornji karbon, pennsylvanij, alge, foraminifere, konodonti, olistoliti, Sansko-unski paleozoik

Abstract

The Olistostrome member of the Sana-Una Paleozoic complex of the Ljubija ore mine in Bosnia and Herzegovina contains limestone fragments of pebble to block size that have been examined paleontologically. The recovered conodont fauna of the first sample is characterized by the species *Declinognathodus lateralis, Idiognathoides sulcatus sulcatus* and *Idiognathodus* sp. confirming its mid-Bashkirian age. This report is the first on the occurrence of these taxa in the area. The second sample with chaetetid demosponges yields an abundant diversified microbiota consisting of cyanobacteria, algae and foraminifera. Chlorophyts are marked by the common siphonoclad occurrence of *Donezella lutugini* and *D. lunaensis*, whereas rhodophyts include rare representatives of *Stacheia*, *Stacheoides*, *Pseudoungdarella* and *Masloviporidium*. The presence of *Asphaltinella horowitzi* and *Aphralysia carbonaria* of unclear taxonomic position is also documented. Pseudostaffellids, eostaffellids and other foraminifera, mostly endothyrids are present. The examined associations of fossils point to the Bashkirian age of the primary rock that originated in a very shallow habitat most probably linked to a high-energy reef environment.

Izvleček

Olistostromski člen v Sansko-unskem paleozojskem kompleksu rudnika Ljubija v Bosni in Hercegovini vsebuje apnenčaste prodnike in bloke, ki so bili paleontološko raziskani. Konodontno favno prvega vzorca označujejo *Declinognathodus lateralis, Idiognathoides sulcatus sulcatus* in *Idiognathodus* sp., ki dokazujejo njegovo srednjebaškirijsko starost. To je prvo poročilo o pojavu teh taksonov na tem območju. Drugi vzorec s hetetidno demospongijo vsebuje bogato in raznoliko mikrobioto, ki jo sestavljajo cianobakterije, alge in foraminifere. Med klorofiti so pogoste sifonoklade *Donezella lutugini* in *D. lunaensis*, med rodofiti pa so redki predstavniki *Stacheia, Stacheoides, Pseudoungdarella* in *Masloviporidium*. Dokumentirana je tudi prisotnost *Asphaltinella horowitzi* in *Aphralysia carbonaria* z nejasnim taksonomskim položajem. Foraminifere zastopajo psevdostafelide, eostafelide in manjše foraminifere, večinoma endotiride. Raziskana združba kaže na baškirijsko starost izvorne kamnine, ki je nastala v zelo plitkem habitatu, verjetno povezanim z visokoenergijskim grebenskim okoljem.

Introduction

The Ljubija siderite ore field is located around 200 km northwest of Sarajevo (Fig. 1), in Bosnia and Herzegovina, and belongs to the Sana-Una Paleozoic complex (Hrvatović, 2006). Together with the Mid-Bosnian Schist Mountains, the Paleozoic strata of eastern and southeastern Bosnia represents the Paleozoic complexes of the Dinarides in Bosnia and Herzegovina that are not genetically related to the Mesozoic-Paleogene evolution of the Tethys (Hrvatović, 2006). The boundaries of the Sana-Una Paleozoic complex are defined based on an unclear contact with younger strata (northeastern and southwestern boundary), and in parts where tectonic elements are not expressed, the boundaries are set based on topographic criteria (Jurić, 1971). In the northwest, the Sana Paleozoic complex is separated from the Banija by the Una River, and in other parts it is limited by the Mesozoic strata; to the south is the front of the Sana Nappe, to the east the border of the Jurassic and Cretaceous formations, and to the north the inner ophiolite zone of Kozara. The area features interesting geological phenomenon due to the well known and potentially exploited deposits of iron and other raw minerals.

The first studies of the Sana Paleozoic complex commenced with the investigation of Austrian geologists (e. g. Mojsisovics et al., 1880) and later the iron ores near Ljubija were part of detailed examinations of Katzer (1910, 1921, 1926). The new evidences were obtained interpreting the Carboniferous sediments as turbidite deposits that contained mineralized limestone olistoliths. The entire Carboniferous sequence has been severely hydrothermaly influenced (Stefanovska, 1990). Later, these Carboniferous sediments were genetically considered as typical flysch deposits where a significant amount of limestone olistoliths occur (Grubić et al., 2000).

Katzer (1926) was the first who considered the Paleozoic formations of the wider area of Ljubija to be Late Carboniferous in age and his view has been accepted by later researchers (Simić, 1940; Heritsch, 1940; Crnolatac, 1949; Noeth, 1952). However, paleontologic evidence for the Early Carboniferous age of the limestone in the Sana-Una Paleozoic complex was provided by Kostić-Podgorska (1955) based on the coral fauna. Data on fossils found in the Sana-Una Paleozoic complex were successfully systematized by Jurić (1971). The faunas obtained in the olistoliths evidenced the Devonian, Early and Late Carboniferous and according to Grubić et al. (2000) the age of the Olistostrome member is assigned to the topmost Early to Late Carboniferous.

An important study on siderite-barite-polysulfide deposits of the Middle Dinarides, considering the Ljubija ore region, was published by Palinkaš (1990). In the last decades the research concept has been severely based on the metallogeny of this ore region. More recent geochemical examinations of the Ljubija mines resulted in interpretation that ore origin is hydrothermal-metasomatic and that the mineralization is of Permian age (Strmić-Palinkaš et al., 2009; Garašić & Jurković, 2012; Palinkaš et al., 2016). More recent data on the geology and metallogeny of the Ljubija ore region are presented in the works of Grubić et al. (2015) and Milošević et al. (2017).

Conodonts have demonstrated their value for biostratigraphy and they are one of the leading microfossil groups in the interpretation of the biostratigraphy of Paleozoic and Triassic marine strata. As they have proven their practical value as parastratigraphic fossils, the main goal of our study is to examine conodont faunas from the Ljubija area. The conodonts of the Sana-Una Paleozoic strata are scarce. During the mapping of the Geological map of SFRY 1: 100,000 they were identified and described at two locations sites (Jurić, 1975). The tentaculite finds at Blagaj already determined in the field the pre-Carboniferous age of the limestones, and based on lithological analogy with the Devonian limestones of Družetić in western Serbia, a Devonian age was assumed, which was confirmed by the conodont examination (Spasov & Filipović, 1966). The conodont fauna from the Blagaj limestone is characterized by the presence of representatives of the genus *Palmatolepis*, which first appears in the Late Devonian. The list of the identified taxa includes: *Palmatolepis glabra glabra*, *P. minuta*, *P. subperlobata*, *Polygnathus glabra glabra*, *Po. nodosocostata nodosocostata* that are ranged in the interval of the Famennian *crepida-rhomboidea* zones (Spasov & Filipović, 1966).

Another locality is a site south of Prijedor. A conodont fauna of a smaller limestone block, was discovered in a road-cut Ljubija - Sanski Most, about 2 km south of th Adamuša opencast mine. Dark grey limestone contains a rich brachiopod and cephalopod fauna (Stojanović-Kuzenko, 1967); the conodont fauna recovered from this block yields *Gnathodus bilineatus* and *Lochriea commutata commutata* (Spasov & Filipović, 1966). This site was recollected by Ramovš (1990) who added to these listed conodont taxa also *L. mononodosa* and *L. nodosa* that enabled this fauna to be re-assigned to the *nodosa* Zone (Visean, Early Carboniferous).

The purpose of this study is to examine conodont fauna of newly collected samples from the Ljubija mine area, as well as to provide additional data from another sample with a demosponge specimen obtained in a carbonate olistolith from the Adamuša site. The latter sample yields rich algal and foraminiferal associations that are also documented herein. The biostratigraphic and paleogeographic significance of the determined taxa is also provided.

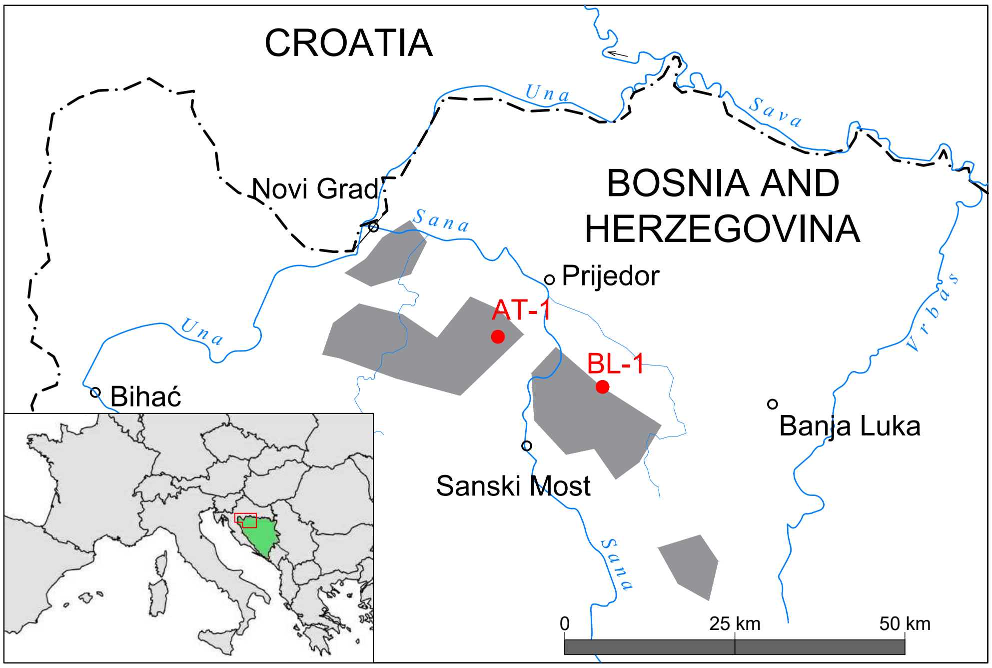

Fig. 1. Index maps with the location of the Ljubija ore mine. **(a)** Map of NW Bosnia and Herzegovina with marked areas of the Sana-Una Paleozoic complex (gray). Red dots indicate the position of the examined samples. **(b)** Geographic position of the area shown in Figure 1a; area of Bosnia and Herzegovina marked in green.

Materials and methods

For micropaleontologic study the conodont sample AT-1 (Fig. 1) was collected (by BJ and TKJ) in the Adamuša opencast mine in 2019 during the field trip of the Congress of geologists in Bosnia and Herzegovina. The collecting of this bed was repeated as this sample proved to be productive for conodonts, and thus an additional quantity of the rock was provided in 2020 (by AM). The coordinates of the sample AT-1 are: 44° 54' 34'' E; 16° 36' 18'' N. For this study we added information about the sample with a demospongia specimen that was collected in 1974 near the location of the conodont sample AT-1, a locality that is today already flooded; the specimen is housed in the Paleontological collection of Jurkovšek, Dol pri Ljubljani under the inventory number BJ 49. Another sample (BL-1) for conodonts was collected in the locality Blatnjak (coordinates 44° 50' 43'' E; 16° 48' 04'' N) that turned out to be devoid of microfauna.

The sample AT-1 with a total rock weight of 6 kg was processed for conodonts. A standard technique for processing conodont samples with the use of diluted acetic acid (5-8 %) was applied and followed by heavy liquid separation. The laboratory preparation was carried out at the Geological Survey of Slovenia, Ljubljana where the residue is also stored in the micropaleontological collection and inventoried under the repository number GeoZS 6219 and 6220. The illustrated conodont elements presented in this paper were photographed by the JEOL JSM 6490LV Scanning Electron Microscope at the Geological Survey of Slovenia.

A total of 11 petrographic thin sections have been made from the host rock from the sample with demospongia (sample BJ). Three thin sections were stained by Alizaren Red S and K-ferricyanide. All thin sections were photographed with magnifications ×12.5, ×25 and ×50. All 11 thin sections were used also for the study of the foraminifera and algae. Foraminifera occur in all of the studied thin sections.

Geological setting

The Sana-Una Paleozoic complex is located east of the Una River. It extends over the area from Novi Grad through Prijedor to Sanski Most, Budimlić Japra, Ključ and Mrkonjić Grad where the most widespread strata belong to the Javorik flysch formation (Fig. 2).

The Ljubija deposits are set in its Carboniferous part belonging to the Javorik flysch formation where the majority of the mineral resources are emplaced within the Olistostrome member. The Javorik flysch formation is well exposed in the Adamuša and Tomašica opencast mines that is, accoring to Grubić et al. (2015), composed of three members, i.e., the Pre-flysch and Lower flysch, Olistostrome member and Upper flysch (Fig. 2).

The basal unit of the Javorik flysch formation is the Pre-flysch and Lower flysch member consisting of dark argillaceous schists with alternation of medium-grain sandstone. It is well studied in the Adamuša opencast mine, in a core of large anticline structure. This member was probably formed in a deeper marine environment (Grubić et al., 2015).

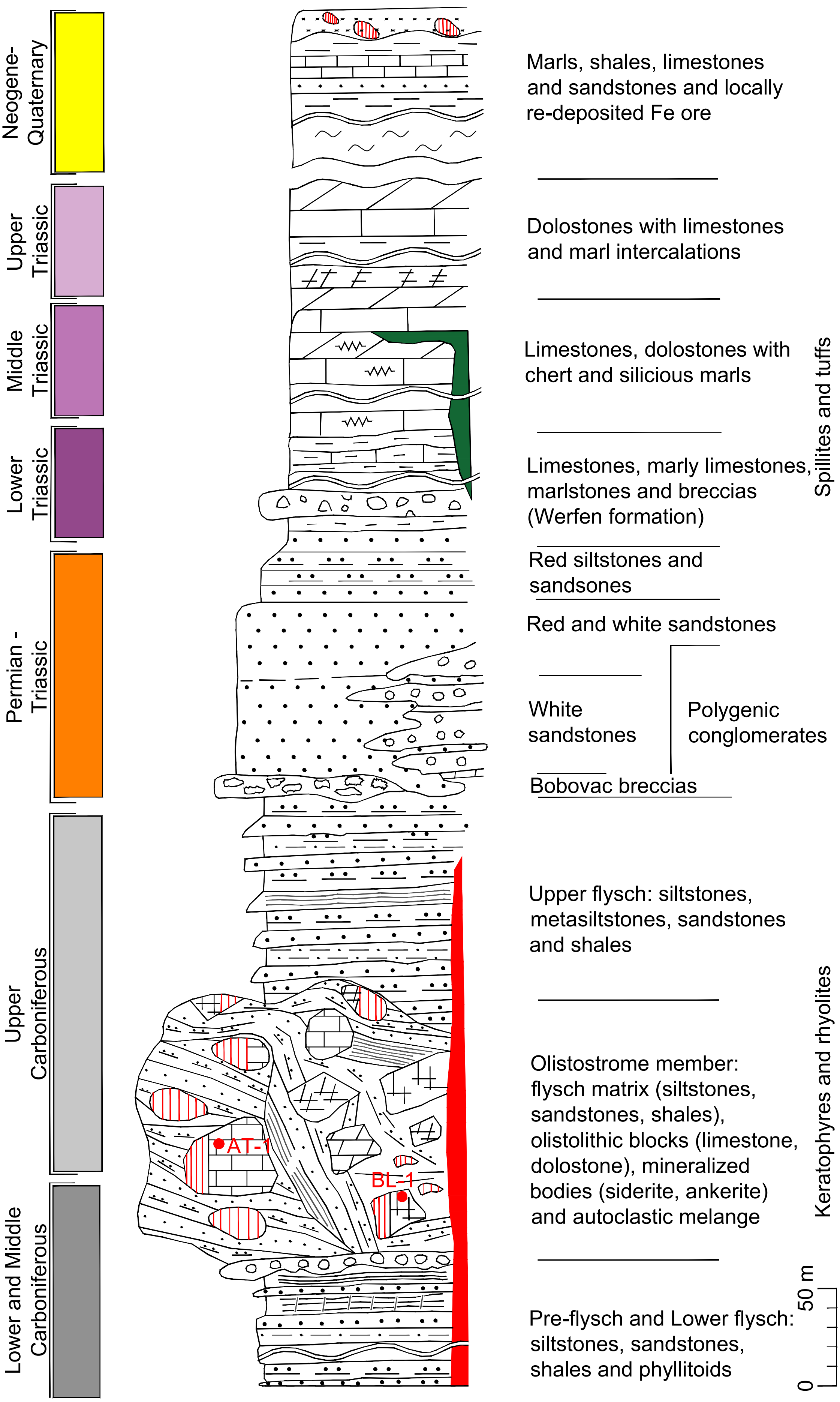

Fig. 2. Schematic lithostratigraphic column of the Sana-Una Paleozoic complex (modified after Grubić et al., 2015).

The Pre-fysch and Lower flysch member is overlain with the deposits of Olistostrome member. The thickness of this member varies between 100 to 300 m. It consists of flysch matrix with embedded carbonate olistoliths - boulders and blocks and their mineralized parts. The mineralized bodies are represented by siderite and ankerite. Carbonate fragments and blocks or boulders of the Olistostrome member include black micrite, dark grey organogenic sparite (rich in fossils), dolomitic limestone and dolostone, ankeritic limestone and ankerite. Within the Olistostrome member some authors distinguished more units, i.e. a Siderite-limonite member, and Wild flysch and Middle flysch (Grubić & Protić, 2003; Garašić & Jurković, 2012). The Olistostrome member was formed under deep-water conditions (Grubić & Protić, 2003) found in the core of the Sana antiform. The studied samples originate from this unit.

The youngest member of the Javorik flysch formation is the Upper Flysch member that is also the most widespread member of the Sana-Una Paleozoic complex. It is well exposed in the Tomašica opencast where it attains thickness of 70 m. It is mainly formed of sandstone-siltstone flysch. Due to Mn oxides and hydroxides particularly, its lower part is black in colour (Grubić & Protić, 2003).

The Permian-Triassic clastic formation appears in discontinuously exposed zones in the north and south limb of the Sana antiform and south from the Sana Nappe. Its maximum thickness is estimated to 150 m. According to Grubić and Protić (2003), five members can be distinguished: a) Bobovica breccia, b) white sandstone, c) white and red sandstone, d) polygenous conglomerate and e) red sandstone and siltstone. Also present are porous dolomite (of a rauhwacke-type), and siderite veins, up to 40 cm long in some places.

The colourful Werfen strata are overlain by limestone and dolomite, covered by a Ladinian volcanogenic-sedimentary porphyrite-chert formation. Among the younger sedimentary rocks, only lacustrine Neogene - Quaternary deposits are present.

The tectonic history of this area is very complex as it was a consequence of Hercynian, Cimmerian and Alpine deformation phases. Hercynian events left their signatures only in the Javorik flysch formation, in the form of folds whose B-axes have an azimuth of 10 to 40°. The dispersion of the B-axis is a consequence of Alpine refolding (Grubić & Protić, 2003).

Results

Microfacies

The microfabric of the rock sample BL-1 with chaetetid demosponge is irregular, peloidal bioclastic grainstone to packstone. In one of the thin-sections also biosparite micro-breccia (rudstone) is present.

Bioclasts and peloids (algal and microbial) predominate. Intraclasts and pellets also occur. Bioclasts are represented by algae, cyanobacteria and foraminifera are most common. Many echinoderm (mostly crinoid) fragments also occur together with rare thin bivalve shells, small gastropods and ostracods. Very rare are fragments of brachiopods. Intraclasts contain bioclasts and pelmicrite. Echinoderm fragments are up to 1 cm, most of them, and also other bioclasts, exhibit abraded margins with replacements by micrite.

The rock is crosscut with several thin white calcite veins and a few thicker ones. It exhibits weak to strong irregular stylolitization.

Foraminifera

Foraminifera in the BJ 49 sample belong to groups of pseudostaffellids, eostaffellids and smaller foraminifera, mostly endothyrids. Determination on a species level is hindered because of the lack of oriented sections. In the studied material, several specimens of the genus *Pseudostaffella* are found, which in general can be assigned to the *Pseudostaffella* ex gr. *antiqua* (Dutkevitch) species group (Rauser-Chernousova et al., 1951). By the position of the coiling axes and the character of the chomata, the specimens are identified as *Pseudostaffella antiqua* (Dutkevitch), *Ps. grandis* Schlykova, *Ps.* cf. *posterior* Safonova, and ?*Ps.* cf. *proozawai* Kireeva (Pl. 1, Figs. a-e). In general, these forms are slightly smaller in size compared to those common in the Russian Platform and in the Urals (Grozdilova & Lebedeva, 1950; Rauser-Chernousova et al., 1951).

Among forms assigned to the genus *Eostaffella*, the following species are identified: *Eostaffella pseudostruvei chomatifera* Kireeva, *E. parastruvei chusovensis* Kireeva, and *E.* cf. *parastruvei chusovensis* Kireeva (Pl. 1, Figs. f-i). The genus *Plectostaffella* is represented by *Plectostaffella varvariensis* (Brazhnikova & Potievskaya), *P.* ex gr. *bogdanovkensis* Reitlinger; *P.* cf. *irregularia* (Reitlinger); *P. ovoideaformis* (Reitlinger) (Pl. 1, Figs. j-n). Also present is the genus *Semistaffella* with the species *S. variabilis* (Reitlinger), *S. primitiva* (Reitlinger),

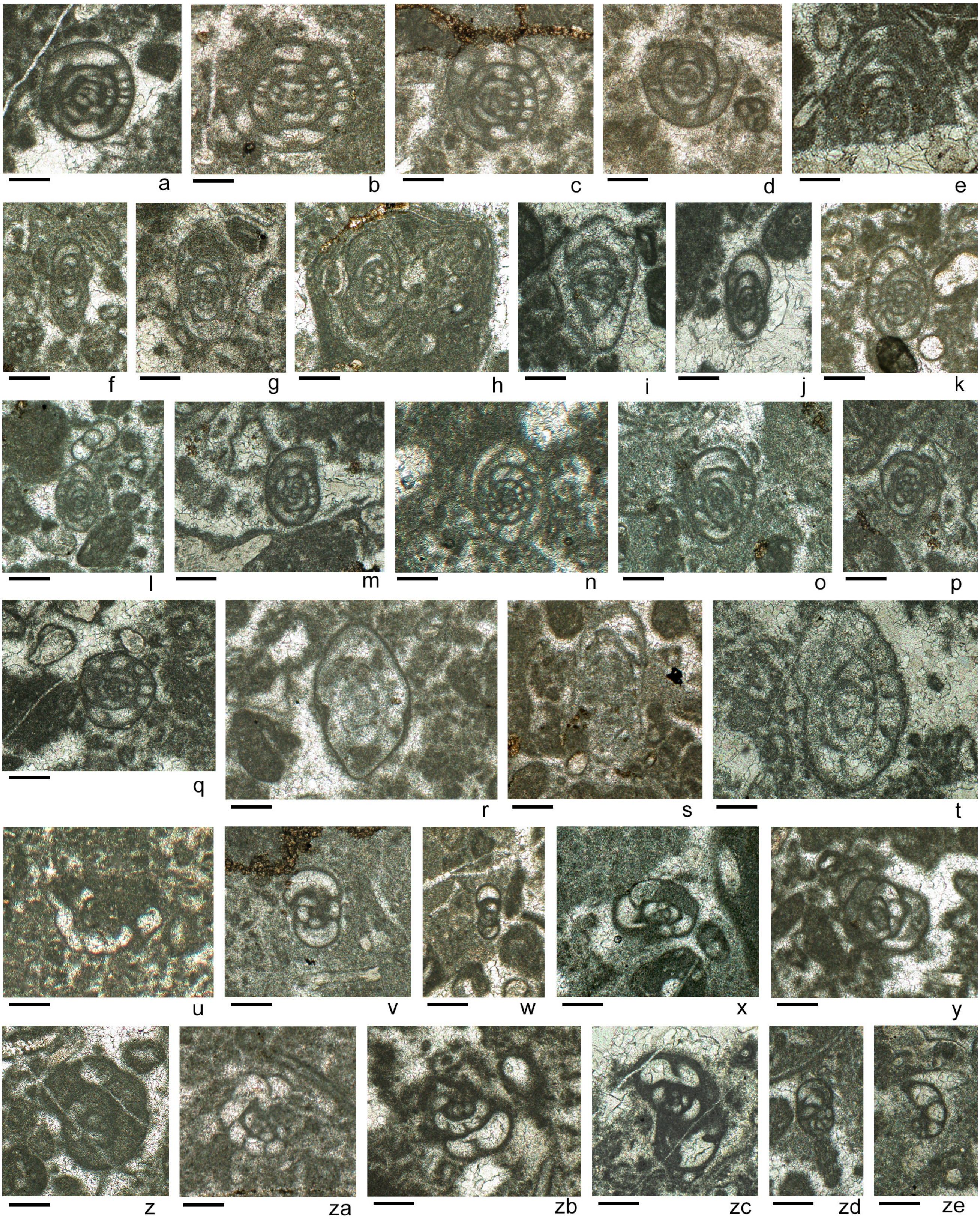

Plate 1. Fusulinoidean and smaller foraminifera from Ljubija, sample BJ 49. Scale bar is 200 microns.

(a): *Pseudostaffella antiqua* (Dutkevitch), (b, c): *Pseudostaffella grandis* Schlykova, (d): *Pseudostaffella* cf. *posterior* Safonova, (e): ?*Pseudostaffella* cf. *proozawai* Kireeva, (f): *Eostaffella pseudostruvei chomatifera* Kireeva, (g): *Eostaffella parastruvei chusovensis* Kireeva, (h): *Eostaffella* cf. *parastruvei chusovensis* Kireeva, (i): *Eostaffella* sp., (j): *Plectostaffella varvariensis* (Brazhnikova & Potievskaya), (k): *Plectostaffella* ex gr. *bogdanovkensis* Reitlinger (l): *Plectostaffella ovoideaformis* (Reitlinger), (m): *Plectostaffella* cf. *irregularia* (Reitlinger), (n): *Plectostaffella* sp., (o): *Semistaffella variabilis* (Reitlinger), (p): *Semistaffella primitiva* (Reitlinger), (q): *Semistaffella minor* (Rauser-Chernousova), (r): *Parastaffella* cf. *struvei* (Möller), (s): *Parastaffella* cf. *poststruvei* Rauser-Chernousova, (t): *Parastaffella* sp., (u): ?*Endothyra* sp., (v): *Endothyra bradyi simplex* Reitlinger, (w, x): *Endothyra* sp. (*E.* ex gr. *bradyi* Mikhailov), (y): *Endothyra mutabilis* Reitlinger, (z): *Endothyra* cf. *mosquensis* Reitlinger, (za): *Endothyra bradyi compressa* Reitlinger, (zb): *Endothyra* sp. (*E.* cf. *mosquensis* Reitlinger), (zc): *Planoendothyra* ex gr. *spirilliniformis* (Brazhnikova & Potievskaya), (zd): *Biseriella minima* (Reitlinger), (ze): *Biseriella* ex gr. *moderata* (Reitlinger).

and *S. minor* (Rauser-Chernousova) (Pl. 1, Figs. o–q). A few lenticular forms with acute margins belong to *Parastaffella* cf. *struvei* (Möller) and *P.* cf. *poststruvei* Rauser-Chernousova (Pl. 1, Figs. r–t).

Endothyrids are represented in significant amounts. The species *Endothyra* ex gr. *bradyi* Mikhailov, *E. bradyi compressa* Reitlinger, *E. mutabilis* Reitlinger, *E.* cf. *mosquensis* Reitlinger, and *Planoendothyra* ex gr. *spirilliniformis* (Brazhnikova & Potievskaya) were recognized (Pl. 1, Figs. u–zc).

Accompanied foraminifera, occuring in small amounts are Globivalvulinidae (*Biseriella minima* (Reitlinger) and *B.* ex gr. *moderata* (Reitlinger) (Pl. 1, Figs. zd, ze), Bradyinidae (*Bradyina* ex gr. *nautiliformis* Möller and ?*B. pseudonautiliformis* Reitlinger) (Pl. 2, Figs. a–c), Palaeotextularioidea (*Koskinobigenerina aljutovica* (Reitlinger); *Koskinotextularia posteximium* (Reitlinger), *Deckerellina* cf. *mirabilis* Reitlinger (Pl. 2, Figs. d–g) and *Neoarchaediscus postrugosus* (Reitlinger) (Pl. 2, Fig. h), *Tuberitina bulbacea* Galloway & Harlton (Pl. 2, Fig. i), ?*Tolypammina* ex gr. *complicata* Reitlinger (Pl. 2, Fig. j), *Postmonotaxinoides* cf. *horridus* (Lipina) (Pl. 2, Fig. k), and *Pseudoglomospira* cf. *elegans* (Lipina) (Pl. 2, Fig. l).

In the International Stratigraphic Scale (Aretz et al., 2020), the base of the Bashkirian Stage (base of the Pennsylvanian) is marked by the appearance of the conodont *Declinognathodus noduliferus*. This level correlates with the base of the ammonoid *Homoceras* Zone and the base of foraminiferal *Plectostaffella bogdanovkensis* Zone. The *P. bogdanovkensis* Zone is traced in the Urals (Kulagina, 2014), in the Caspian Region (Zaytseva & Klenina, 2008), and in Middle Tien-Shan (Dzhenchuraeva et al., 2013).

The appearance of the species *Pseudostaffella antiqua* (Dutkevitch) is a noticeable level in the evolution of fusulinids corresponding to the middle part of the lower Bashkirian (the base of the Akavasian Regional Substage in Urals or Severokeltmenian Regional Substage of the Russian Platform) and is distinguished as the rapid diversification of pseudostaffellids (Kulagina & Gorozhanina, 2019). The represented species of the genera *Eostaffella*, *Plectostaffella* and *Semistaffella* are characteristic of the lower Bashkirian. The species *Plectostaffella varvariensis* (Brazhnikova & Potievskaya) is known from the top of the Serpukhovian. *P. bogdanovkensis* is a zonal marker of the Serpukhovian/Bashkirian boundary of the East European Platform and the Urals. The genus *Semistaffella* appears slightly higher. There are transitional forms between them as well as between *Semistaffella* and primitive *Pseudostaffella*.

During the Early Carboniferous, the genera and species of the Ozawainellidae and Staffellidae were common in shallow carbonate shelves and in basins of nearly all regions of the world (BouDagher-Fadel, 2008). The diversity of the fusulinids and their related forms increased at the Serpukhovian-Bashkirian boundary. Foraminiferal provinces have been clearly distinguished already since late Famennian (Lipina, 1973) with three different provinces becoming recognizable: the East European Basin that are characterized by an abundance of *Eostaffella* and *Bradyina*; the Tethyan Realm, where the palaeotextulariids were abundant; and the North American Realm, where *Bradyina* did not appear before the Bashkirian.

During the Late Carboniferous (Bashkirian to Gzhelian), the endothyrids, staffellids and bradyinids may have colonized their habitats within or in adjoining high-energy environments (Dingle et al., 1993; Della Porta et al., 2005). The endothyrids were common in low- and high-energy settings. Their exclusion from lagoonal environments with a restricted circulation and variable salinity suggests that these forms preferred open-marine environments (Della Porta et al., 2005). The lenticular staffellids are abundant in higher energy, reef facies, whereas the subspherical forms were common in the quieter, back reef facies (Dingle et al., 1993), in the shallowest setting and in paleoenvironments characterized by abnormally high temperatures and salinity. The Bradyinidae were probably epiphytes and *Bradyina* is interpreted as a shallow-water taxon adapted to life in current-swept environments (Gallagher, 1998; Gallagher & Somerville, 2003; BouDagher-Fadel, 2008).

Cyanobacteria and algae

The remains of cyanobacteria are very common in the studied thin sections (Pl. 2, Figs. m–o). They are similar to the remains of filament-forming and coccoid bacteria described by Mamet & Preat (2010) from Bashkirian foraminifer zones 20 and 21 of Arctic Alaska. Besides the remains of *Girvanella* sp. (Pl. 3, Fig. d) also *Stipulella fascicularis* Maslov (Pl. 2, Figs. r–s) is identified. This species was described from the Lower Carboniferous of the Moscow Basin (Maslov, 1956). It is distributed in the Kizelian Regional Substage of the upper Tournaisian and the upper part of

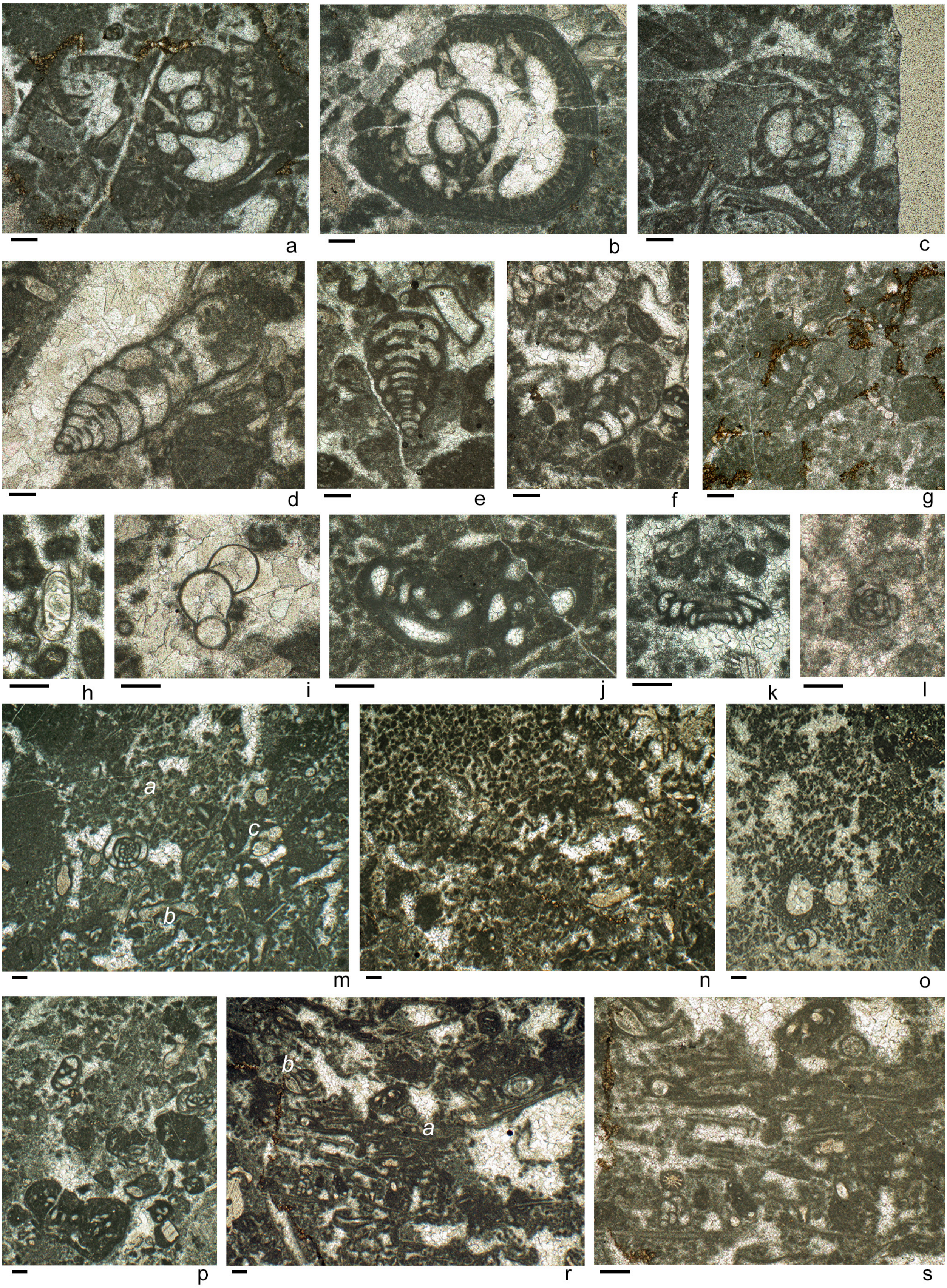

Plate 2. Smaller foraminifera and cyanobacteria from Ljubija, sample BJ 49. Scale bar is 200 microns.

(a-c): *Bradyina* ex gr. *nautiliformis* Möller (?*B. pseudonautiliformis* Reitlinger), (d): *Koskinobigenerina aljutovica* (Reitlinger), (e): Koskinobigeneriidae, (f): *Koskinotextularia posteximium* (Reitlinger), (g): *Deckerellina* cf. *mirabilis* Reitlinger, (h): *Neoarchaediscus postrugosus* (Reitlinger), (i): *Tuberitina bulbacea* Galloway & Harlton, (j): ?*Tolypammina* ex gr. *complicata* Reitlinger, (k): *Postmonotaxinoides* cf. *horridus* (Lipina), (l): *Pseudoglomospira* cf. *elegans* (Lipina), (m): *a* – Filament-forming and cocoid cyanobacteria, *b* – *Donezella* sp., *c* – *Anthracoporellopsis* sp., (n, o): Filament-forming and cocoid cyanobacteria, (p): Oncolites with *Tolypammina fortis* Reitlinger, (r): *a* – *Stipulella fascicularis* Maslov, *b* – *Donezella* sp., (s) *Stipulella fascicularis* Maslov.

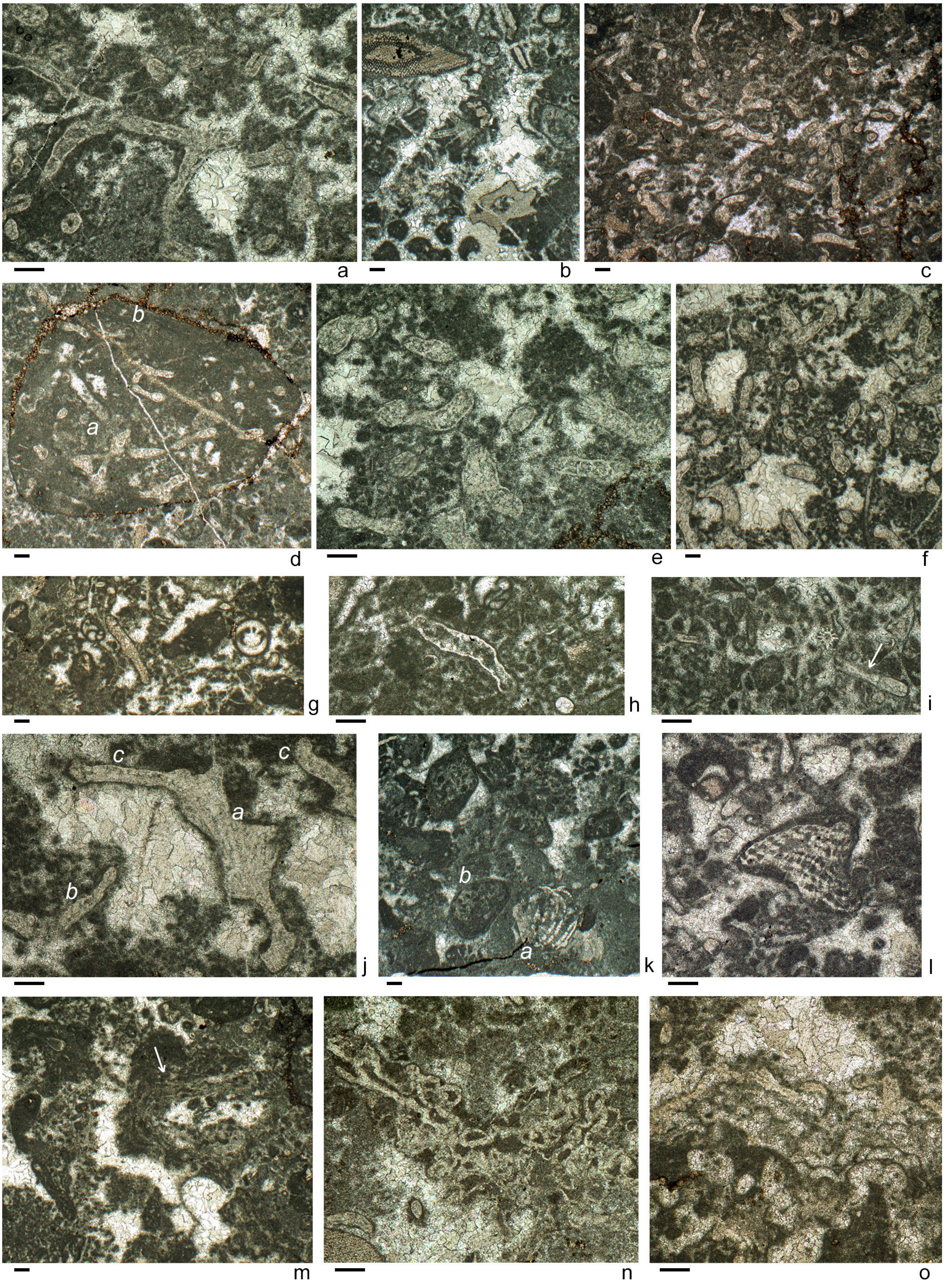

Plate 3. Green and red algae and problematica from Ljubija, sample BJ 49. Scale bar is 200 microns.

(a, b, c): *Donezella lutugini* Maslov, (d): *a* – *Donezella lutugini* Maslov, *b* – *Girvanella* sp., (e, f): *Donezella lunaensis* Racz, (g): *Dvinella* cf. *bifurcata* Maslov & Kulik, (h): *Proninella enigmatica* Mamet & Roux, (i): *Anthracoporellopsis* cf. *machaevii* Maslov, (j): *a* – *Pseudoungdarella* sp. (?*P.* cf. *linearis* R. Ivanova), *b* – *Praedonezella* cf. *cespeformis* Kulik, *c* – ?*Donezella* sp., (k): *a* - *Stacheia* cf. *marginulinoides* Brady, *b* – *Stacheoides* cf. *meandriformis* Mamet & Rundloff, (l): *Masloviporidium delicata* (Berchenko), (m): *Stachaeoides* sp., (n): *Asphaltinella horowitzi* Mamet & Roux, (o): *Aphralysia carbonaria* Garwood.

the Serpukhovian Stage of the Urals (Ivanova, 2013), in the Zapaltyubian Regional Substage of the Serpukhovian Stage of the Donets Basin (Berchenko, 1983), and the Visean and Namurian of the Paleo-Tethys (Mamet & Roux, 1983). Forms similar in morphology, described as *Ortonellopsis laxa* Vachard & Cozar were found in the upper Visean - lower Serpukhovian of Montagne Noire, France (Vachard et al., 2016).

Rare algae also occur in thin sections, however of poor preservation. Chlorophyta, represented mainly by Siphonocladales, and also including representatives of the genera *Donezella*, *Dvinella*, *Proninella*, *Exvotarisella*, *Anthracoporellopsis* are distinguished by a relative diversity. *Donezella* is more common with two species: *Donezella lutugini* Maslov (Pl. 3, Figs. a-d) and *D. lunaensis* Racz (Pl. 3, Figs. e-f). Both species are characteristic of the Bashkirian and are distributed up to the Asselian Stage of the Lower Permian in Arctic Canada (Mamet et al., 1987), northern Spain (Mamet & Villa, 2004), northwestern Serbia (Pajić & Fillipović, 1995) and in Urals, Donets Basin and Tajikistan (Ivanova, 2013). Fragments of *Dvinella* cf. *bifurcata* Maslov & Kulik (Pl. 3, Fig. g), *Proninella enigmatica* Mamet & Roux (Pl. 3, Fig. h) and *Anthracoporellopsis* cf. *machaevii* Maslov (Pl. 3, Fig. i) thalli were identified. The species *Dvinella bifurcata* is known from the Middle Carboniferous of the Urals and the East European Platform, from the Bashkirian of northwestern Serbia (Pajić & Fillipović, 1995), and in northern Greenland it occurs in the Moscovian Stage (Mamet & Stemmerik, 2000). *Proninella enigmatica* is described from the upper Visean of North America (Mamet & Roux, 1978). In the Urals, it was reported from the Tournaisian, upper Visean and Bashkirian (Ivanova, 2013). *Anthracoporellopsis machaevii* is described from the Middle Carboniferous of the Donets Basin (Maslov, 1956). In Western Europe, it is found in Visean deposits. The stratigraphic range of this species in the Urals is from the upper Visean to the Lower Permian (Ivanova, 2013). In the Moscow Basin it is found in the upper Visean (Gibshman & Alekseev, 2017).

The studied material also contains two species of Chlorophyta of unclear taxonomic position: *Asphaltinella horowitzi* Mamet & Roux and *Aphralysia carbonaria* Garwood (Pl. 3, Figs. n-o). The first species is described from the Visean of Canada, southwestern Alberta (Petryk & Mamet, 1972) and is especially abundant in the Serpukhovian. It occurs in the upper Visean of the Moscow Basin (Gibshman & Alekseev, 2017), and in the Bashkirian of the Urals (Ivanova, 2013). The species *Aphralysia carbonaria* is widespread in the Dinantian of England and is known from the upper Serpukhovian of the Donets Basin (Berchenko, 1983).

Rhodophyta include sporadic isolated representatives of the genera *Stacheia*, *Stacheoides*, *Pseudoungdarella*, and *Masloviporidium* (Pl. 3, Figs. j-l) The species *Stacheia marginulinoides* Brady is distributed in the upper Visean and Serpukhovian of the Paleo-Tethys (Mamet & Roux, 1983) and from the Serpukhovian-Bashkirian boundary strata of Alaska (Mamet & Preat, 2010). On the western slope of the South Urals, it was found in the Bashkirian strata. *Stacheoides meandriformis* Mamet & Rundloff is a cosmopolitan species and is known from the Visean of France, Belgium, Morocco, USA, from the Upper Carboniferous of the Canadian Arctic Archipelago, the Permian of Turkey, and the Serpukhovian Stage ranging from the Lower to Upper Carboniferous of the Urals (Ivanova, 2013). The species *Masloviporidium delicata* (Berchenko) is described from the Serpukhovian Stage of the Donets Basin (Berchenko, 1982). Its geographic distribution is in North Africa (Algeria) and North America where it was assigned to the uppermost Serpukhovian and Bashkirian stages (foraminiferal zones 20 and 21) (Groves & Mamet, 1985). In the Urals, it is known from the upper Visean to the Bashkirian Stage (Ivanova, 2013). The species *Pseudoungdarella linearis* Ivanova occurs in the Serpukhovian, Bashkirian and Moscovian of the Urals (Ivanova, 2013).

Thus, the algoflora in the studied block is represented by forms of wide stratigraphic range and geographic distribution. The most important species among them are *Donezella lutugini* and *D.* cf. *lunaensis*, which were bioherm-formers and rock-formers in the Bashkirian Stage (Ivanova, 2013; Rodriguez-Castro et al., 2020).

Demospongia

A specimen of *Chaetetes*, a hyper-calcified demosponge was collected in the Adamuša opencast mine (Fig. 3). The demosponge fossil (isometric 5-6 cm large skeleton) occurs in a single clast together with coarse matrix and large crinoidal ossicles. Its surface reveals a skeleton consisting of closely connected tubules (diameter 0.3-0.7 mm) with indicated radial growth direction. Chaetetids were previously classified as extinct corals, bryozoans, algae, stromatoporoids and sclero-

Fig. 3. *Chaetetes* sp. Adamuša, sample BJ 49. Scale bar 10 mm.

sponges (West, 2011). They grew in very shallow water and formed expansive biostromes (Stanton et al., 2016). The fossil record of chaetetids is known worldwide and they are common in strata ranging from the Ordovician through Jurassic (West, 2011). The species *Chaetetes radians* that was first described from the Carboniferous of the Moscow Basin (Fischer, 1837) has been already reported from the Ljubija mine area, i.e., in the Jakarina Kosa locality, near Adamuša where it was collected from Carboniferous strata (Kostić-Podgorska, 1959, 1965).

Conodonts

Despite moderate preservation, five conodont elements can be identified from the sample AT-1 (Fig. 4) at the genus and even species level, which allow dating of the source rock with sufficient accuracy (Fig. 5).

The most important specimen is a right P1 element without a free blade, but it has slightly curved nodular carina to the rostral margin whose nodes are fused with the nodes of rostral parapet. These characters are indicative for the species *Declinognathodus lateralis* (Higgins & Bouckaert) described from the Namurian (Alportian and Kinderscoutian) in Belgium. The species is widely distributed in the lower and middle Bashkirian strata of Great Britain (Higgins, 1975), Donets Basin, Ukraine (Nemyrovska, 1999), South Urals, Russia (Kulagina et al., 2014; Nikolaeva et al., 2017), and South China (Hu et al., 2018). In South China, *D. lateralis* spans in the middle Bashkirian, with its first occurrence (FO) is in the lower part of the *Idiognathoides sinuatus* Zone, and its lower occurrence (LO) is in the middle part of the "*Streptognathodus*" *expansus* M1 Zone (Hu et al., 2019), but in the South Urals it first appears in the lowermost Bashkirian and its FO coincides with the base of the *D. noduliferus* Zone (Kulagina et al., 2014).

Three specimens, which are also uncomplete right P1 elements, possess two narrow nodose parapets separated by relatively deep median trough. They belong to the subspecies *Idiognathoides sulcatus sulcatus* (Higgins & Bouckaert) that was established on left elements only, but

Fig. 4. Outcrop at the Adamuša iron deposit where the limestone sample AT-1 was collected.

Higgins (1975) illustrated also right elements for this subspecies which are very similar to the ones from Ljubija. This subspecies occurs in the Bashkirian being described from the ammonoid R1-G2 genozones of Belgium (Higgins & Bouckaert, 1968) and Great Britain (Higgins, 1975), but in South China and the South Urals, Russia, it is found in much younger strata reaching the Bashkirian/Moscovian boundary and even in the lower Moscovian (Kulagina et al., 2001; Hu et al., 2019).

The third conodont morphotype is broken P1 element, without ventral part of the free blade and most of dorsal platform. However, the platform is very wide with no recognized trough. This element belongs to the genus *Idiognathodus* without any doubts, but the species identification is not possible, therefore the element is assigned to *Idiognathodus* sp. only.

The FO of the genus *Idiognathodus* is very important datum plane in the conodont zonations: *I. primulus* marks the Marsdenian (R2 Genozone) of England (Higgins, 1975) and the mid-Bashkirian *Idiognathodus primulus* Zone of South China (Hu et al., 2019). However, in the type Bashkirian sections of the South Urals the three *Idiognathodus* species (*I. sinuosus* Ellison & Graves; *I. delicatus* Gunnell and *I. primitivus* (Nemirovskaya & Alekseev)) occur in the middle Bashkirian interval, at the base of the Askynbashian Substage (Kulagina et al., 2001).

The joint presence of the species *Declinognathodus lateralis, Idiognathoides sulcatus sulcatus* and *Idiognathodus* sp. confirms a mid-Bashkirian age of the source rocks, which is the Askynbashian and lower Arkhangelskian substages in the Russian stratigraphic nomenclature (Alekseev, 2008).

A strange character of the Ljubija conodont assemblage is the absence of *Idiognathoides corrugatus* (Harris & Hollingsworth) and *Id. sinuatus* Harris & Hollingsworth, two ubiquitous Bashkirian and early Moscovian species, that might be explained by very lower count of the extracted conodont elements (only five). The assemblage belongs to the outer shelf and slope *Declinognathodus*-*Idiognathoides* biofacies (Davis & Webster, 1985).

In the Spanish Pyreneans, the assemblage of the *Idiognathodus* Zone is similar to the one from Ljubija that is present in the Quinto-Real area in the upper part of the Baserdi Member of the Olazar Formation, in the siliciclastic Kulm-type unit interpreted as Kinderscoutian-Marsdenian in age (Sanz-López & Blanco-Ferrera, 2012).

A joint occurrence of several species of *Idiognathodus* and *Declinognathodus lateralis* is known also in the Namurian C (G1 Zone) limestone bands M, N and P in the Lublin Basin, Poland (Skompski, 1996). In the Donets Basin the FO of *Idiognathodus sinuosus* is in the Limestone F11, upper part of the Mandrykian Regional Substage, middle Bashkirian, where it occurs together with *D. lateralis* (Nemyrovska, 1999, 2017). If the Ljubija area has a relation to the North Gondwana Realm, very similar conodont assemblage including *D. lateralis* and *Idiognathodus* is reported from the Bechar Basin, Algeria, from marine inner shelf of the Hassi Kerama Formation of the middle Bashkirian age (Weyant, 1985).

Bashkirian conodonts are not common in Great Britain and Western Europe, where they are known only from England (Higgins, 1975), Belgium (Higgins & Bouckaert, 1968), Germany (Meischner, 1970) and Poland (Skompski, 1996). In these countries, conodonts of this age occur only in marine horizons inside of coal-bearing terrestrial sequences, but they are widely distributed in marine carbonate successions of the French and Spanish Pyreneans as well in the Cantabrian Mountains of North Spain.

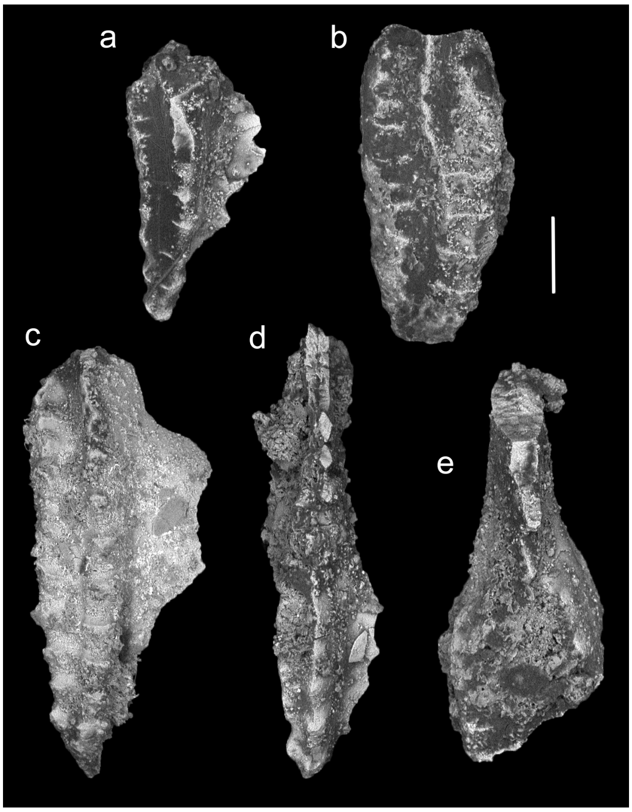

Fig. 5. Conodonts from Ljubija, sample AT-1 (GeoZS 6220). Scale bar is 100 microns.

(a, c, d) *Idiognathoides sulcatus sulcatus* Higgins & Bouckaert, (b) *Declinognathodus lateralis* (Higgins & Bouckaert), (e) *Idiognathodus* sp.

Conclusions

Biota obtained from limestone samples of the Olistostrome member of the Adamuša site in the Ljubija area in western Bosnia and Herzegovina have been examined. The limestone sample AT-1 is marked by the joint presence of *Declinognathodus lateralis, Idiognathoides sulcatus sulcatus* and *Idiognathodus* sp. confirming the mid-Bashkirian age of the primary rocks. This report is the first of the listed conodont taxa in the area. The Ljubija conodont assemblage is similar to the *Declinognathodus-Idiognathoides* biofacies of the outer shelf and slope. On the other hand, it can also be compared to an equivalent conodont assemblage of marine inner shelf in Algeria.

The chaetetid demospongia (from sample BJ) is associated with a prolific microbiota consisting of cyanobacteria, algae and foraminifera. Microfacies of the rock is peloidal bioclastic grainstone to packstone. Cyanobacteria are common and exhibit great similarity to the known Bashkirian filament-forming and coccoid bacteria remains. Chlorophyta are dominated by Siphonocladales of relative diversity, among which are common *Donezella lutugini* and *D.* cf. *lunaensis* that are characteristic of the Bashkirian. Rhodophyta include sporadic isolated representatives of the genera *Stacheia*, *Stacheoides*, *Pseudoungdarella* and *Masloviporidium*. The biota also contains two species of unclear taxonomic position, *Asphaltinella horowitzi* and *Aphralysia carbonaria*. Foraminiferal assemblage consists of pseudostaffellids, eostaffellids and smaller foraminifera, mostly endothyrids. The presence of the foraminiferal species *Pseudostaffella antiqua* points to the Bashkirian age. The association of the endothyrids, staffellids and bradyinids indicates their primary habitat was linked to a high-energy reef environment that is confirmed by the presence of *Donezella* siphonoclads, which formed bioherms during the Bashkirian.

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Ocena količinske ranljivosti podzemne vode na podnebno spremembo v Sloveniji

Assessment of groundwater quantitative vulnerability to climate change in Slovenia

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Key words: groundwater, climate change, exposure, sensitivity, adaptivity, vulnerability

Izvleček

Ocena potencialnega vpliva podnebne spremembe na napajanje vodonosnikov in razpoložljivost podzemnih vodnih virov je tudi za Slovenijo pomembno izhodišče načrtovanja prilagajanja za zmanjševanje vplivov, predvsem na območjih, kjer je stopnja njene izkoriščenosti največja, sposobnost prilagajanja pa najmanjša. Količinsko ranljivost podzemne vode na podnebno spremembo v Sloveniji smo ocenili preko kazalnika potencialnega vpliva in kazalnika prilagoditvene sposobosti za vsa telesa podzemnih voda v Sloveniji. Povišano količinsko ranljivost podzemne vode v Sloveniji izkazuje le okoli 9 % ozemlja države. Največjo količinsko ranljivost smo ugotovili v plitvih aluvialnih vodnih telesih podzemnih voda v severovzhodnem delu države, kjer pričakovane letne količinske spremembe napajanja vodonosnikov zaradi podnebne spremembe do sredine tega stoletja predstavljajo več kot četrtino sedanjega povprečnega letnega odvzema podzemne vode.

Abstract

Assessment of the potential impact of climate change on groundwater recharge and availability of groundwater resources is as essential in Slovenia as it is elsewhere. Adaptive planning is of immense importance when aiming for reduction of negative impacts, even more so in areas with the highest groundwater exploitation levels and the lowest adaptive capacity. We have assessed quantitative groundwater vulnerability to climate change through potential impact and adaptive capacity indicators for all groundwater bodies in Slovenia. High and moderatly high quantitative groundwater vulnerability can be observed in merely 9 % of Slovenian territory. The highest quantitative vulnerability was accounted to shallow alluvial groundwater bodies in the northeastern part of the country, where the annual change in groundwater recharge due to climate change until the middle of this century is expected to represent more than a quarter of the current average annual groundwater extraction.

Uvod

S potrebo po oceni potencialnih vplivov podnebne spremembe na količinsko obnavljanje podzemne vode v Sloveniji so se soočili že avtorji prvega nacionalnega poročila okvirne konvencije Združenih narodov o spremembi podnebja (Kajfež-Bogataj et al., 1999; Paradiž & Kranjc, 2002). Na podlagi rezultatov vseh takratnih nacionalnih poročil in ostalih študij, med katerimi so srednjeevropske raziskave napovedovale tudi polovično zmanjšanje poletnega napajanja vodonosnikov (Eckhardt & Ulbrich, 2003), v sredozemskem prostoru pa celo preko 70 % (Döll & Flörke, 2005), je *Medvladni panel za podnebne spremembe* nekaj let kasneje podal okvir za potrebo po ocenjevanju ranljivosti človeka in ekosistemov na podnebne spremembe ter ranljivost opredelil kot oceno potencialnih vplivov podnebne spremembe in sposobnosti prilagajanja sistemov (IPCC, 2007). Ranljivosti podzemne vode na podnebno spremembo so se za območje Slovenije dotaknile različne regionalne študije (Döll, 2009; Nistor et al., 2016; Nistor, 2019) in severovzhodni del Slovenije z najmanjšo količino padavin v državi ocenile kot območje srednjega razreda ranljivosti, katerega površina pa naj bi se po predvidevanjih za ta del Panonskega bazena do leta 2050 nekoliko povečala. Tudi kompleksna regionalna ocena vpliva podnebne spremembe na napajanje vodonosnikov v jugovzhodni Evropi, ki so jo izdelali raziskovalci projekta *Climate Change and Impact on Water Supply »CC-WaterS«* (Čenčur Curk et al., 2014), območje podzemnih voda Slovenije ocenjuje kot nizko do največ srednje ranljivo na podnebno spremembo z verjetnostjo za povečanje njene količinske ranljivosti v naslednjih desetletjih.

Rezultati dosedanjih regionalnih študij omogočajo grobo oceno izpostavljenosti in količinske ranljivosti podzemnih voda na podnebno spremembo v Sloveniji, vendar pa njihova merila oz. prostorske ločljivosti rezultatov niso omogočale podrobnejših razmislekov o potrebi po lokalnih prilagoditvenih ukrepih oz. ukrepih po posameznih telesih podzemnih voda v Sloveniji. Na celotnem območju Slovenije je prvo oceno vpliva podnebne spremembe na napajanje vodonosnikov omogočila uporaba regionalnega modela vodne bilance GROWA-SI v okviru priprave »*Načrta upravljanja voda 2016–2021*« (Andjelov et al., 2016; MOP, 2016) in kasneje s spremenjenimi podnebnimi scenariji še v projektu »*Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja*« (Dolinar, 2018). V okviru priprav strokovnih izhodišč za nadaljnje načrtovanje upravljanja podzemnih voda smo rezultate dosedanjih modelskih simulacij letnih vodnih bilanc in poznavanja hidrogeoloških lastnosti vodonosnikov preko pristopa razvrščanja in tehtanja parametrov (Hölbling et al., 2018) ocenili izpostavljenost in občutljivost sistema ter ob uporabi indeksa vodne revščine (Liu et al., 2019) ocenili tudi prilagoditveno sposobnost teles podzemnih voda na podnebno spremembo v Sloveniji.

Podatki in metode

Za potrebe ocenjevanja stanja in upravljanja podzemnih voda je območje Slovenije razdeljeno na 21 teles podzemne vode z zelo raznoliko hidrogeološko zgradbo in hidravlično prepustnostjo ter posledično zelo različno izkoristljivostjo podzemne vode (sl. 1), ocenjeno in regionalizirano po metodologiji za opredelitev vodnih teles podzemnih (Prestor et al., 2006). Izkoristljivost, določena na podlagi lastnosti vodonosnikov in njihove členitve po priporočilih IAH (Struckmeier & Margat, 1995), je najmanjša v vodnih telesih s prevladujočimi manjšimi vodonosniki in lokalnimi omejenimi vodnimi viri, največja pa v aluvialnih vodnih telesih z medzrnsko poroznostjo in razmeroma visokim koeficienti prepustnosti v razponu od $1{\cdot}10^{-4}$ do $1{\cdot}10^{-3}$ m/s (Prestor et al., 2006). Pet ravninskih aluvialnih vodnih teles na okoli 10 % območja Slovenije po podatkih iz evidence vodnih povračil skupno zagotavlja 85.500.000 m^3 vode letno (46 % vse odvzete podzemne vode v Sloveniji) in predstavljajo količinsko najbolj obremenjene vodonosnike v Sloveniji. Stopnja izkoriščenosti podzemnih voda, razmerje med odvzeto in razpoložljivo količino, je na posameznih najbolj obremenjenih delih aluvialnih vodnih teles izrazito večja, kot se ocenjuje na celotnih vodnih telesih. V nekaterih vodonosnikih se količina črpanja pri srednih nizkovodnih razmerah že približuje polovici vseh razpoložljivih podzemnih vodnih virov (Uhan & Andjelov, 2019).

Pregled metodologije ocenjevanja ranljivosti podzemne vode na podnebno spremembo po svetu odkriva velike razlike in ob tem razmeroma slabo primerljivost in zanesljivost rezultatov dosedanjih raziskav s tega področja. Vzroki so predvsem v nekritični uporabi različnih kazalnikov, scenarijev in konceptov vrednotenja v različnih časovnih in prostorskih skalah. Zaradi tega raziskovalci izpostavljajo potrebo po predhodnih analizah kazalnikov, tako s področja okolja kot tudi s področja človekovih aktivnosti v širšem socialnem in ekonomskem okviru ter potrebo po uporabi enotne konceptualne sheme »izpostavljenost – občutljivost – prilagoditvena sposobnost« (Schröter et al., 2004; IPCC, 2007; Aslam et al., 2018). Ob tem konceptualnem izhodišču smo za oceno ranljivosti podzemnih voda na podnebno spremembo po posameznih telesih podzemnih voda v Sloveniji uporabili kombiniran model ocene potencialnega vpliva in prilagoditvene sposobnosti, kot je bila predlagana v projektu »CCWaters« (Čenčur Curk et al., 2014). Ocena potencialnih vplivov oz. izpostavljenosti in občutljivosti temelji na pristopu »AQUICLIM« (Hölbling et al., 2018), za oceno prilagoditvene sposobnosti sistema pa smo po shemi kazalnikov »gonilne sile – obremenitev – stanje – vpliv – odziv« (DPSIR) za podzemne vode izračunali indeks vodne revščine (WPI) (Liu et al., 2019) (sl. 2).

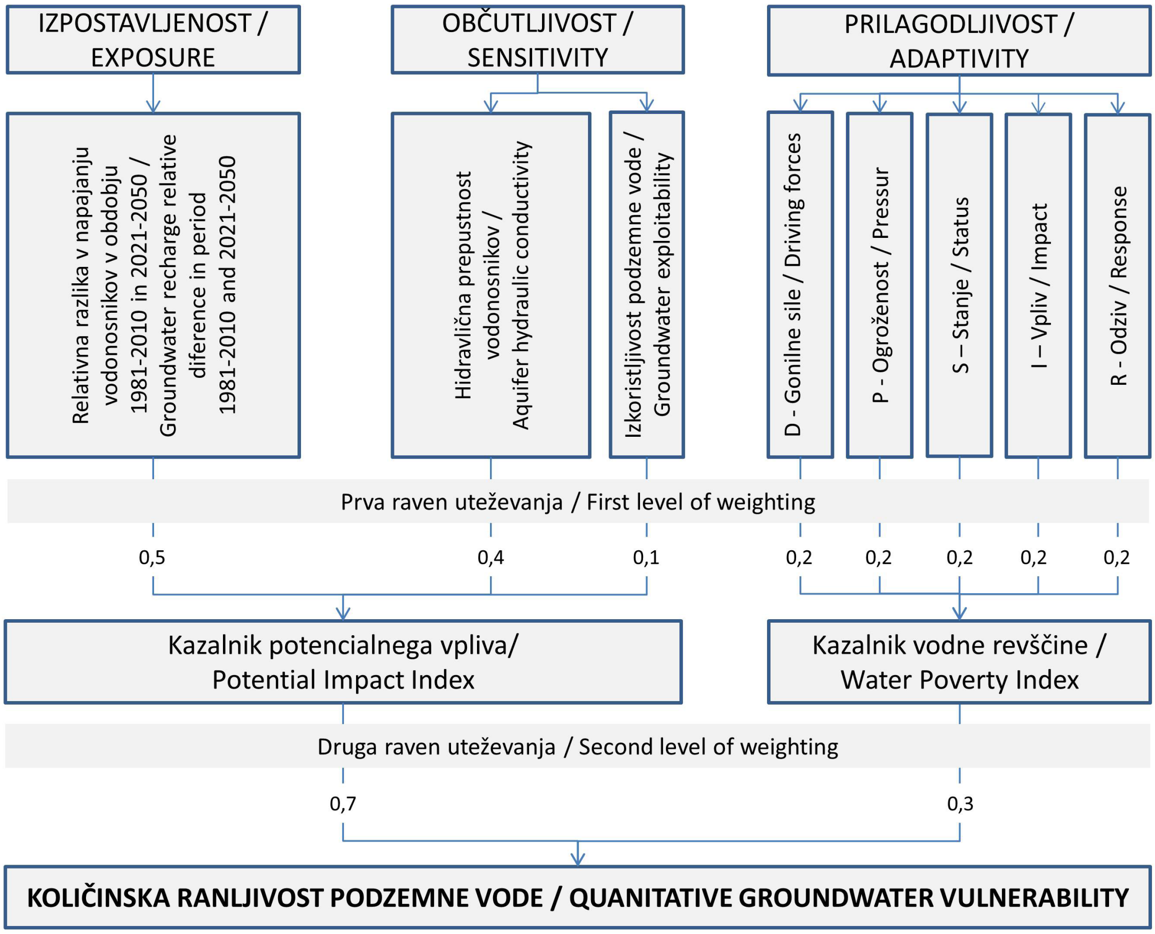
Potencialni vplivi podnebne spremembe na podzemne vode

Za oceno izpostavljenosti in občutljivosti podzemnih voda na podnebno spremembo so v Nemčiji razvili pristop »AQUICLIM« in ga preizkusili tudi na številnih pilotnih območjih v projektu GeoERA - TACTIC »*Tools for assessment of climate change Impact on groundwater and adaptation strategies*« (Hinsby et al., 2020). Pristop »AQUICLIM« je enostavna metoda razvrščanja in

Sl. 1. Hidrogeološke lastnosti teles podzemnih voda v Sloveniji po podatkih Geološkega zavoda Slovenije (Prestor et al., 2006)
Fig. 1. Hydrogeological characteristics of groundwater bodies in Slovenia after Geological Survey of Slovenia (Prestor et al., 2006)

tehtanja hidrogeoloških parametrov izpostavljenosti (napajanje vodonosnikov) in občutljivosti (hidravlična prepustnost kamnin in izkoristljivost podzemne vode) z namenom ocene potencialnega vpliva podnebne spremembe na podzemne vode (sl. 2). Nedvomno bi oceno občutljivosti lahko izboljšali še z upoštevanjem transmisivnosti, vendar so podatki o debelinah vodonosnikov po posameznih vodnih telesih skopi in podani v velikih razponih. Predstavljena ocena vplivov podnebne spremembe na podzemne vode v Sloveniji zato sledi mednarodno že preizkušenemu pristopu »AQUICLIM«.

Za oceno izpostavljenosti smo uporabili podatke o napajanju oz. relativni razliki pri napajanju plitvih vodonosnikov v referenčnem vodno-bilančnem obdobju 1981-2010 in simuliranem napajanju v obdobju 2021-2050 Agencije Republike Slovenije za okolje. Napajanje vodonosnikov je bilo ocenjeno z empiričnim regionalnim vodnobilančnim modelom GROWA-SI, ki konceptualno kombinira distribuirane meteorološke podatke z distribuiranimi hidrološkimi in drugimi fizično-geografskimi parametri za izračun elementov vodne bilance v prostoru (Andjelov et al., 2016). Za vodnobilančno modeliranje so bili na Agen-



Sl. 2. Shema ocenjevanja količinske ranljivosti podzemne vode na podnebno spremembo v Sloveniji (prilagojeno po Hölbling et al., 2018, Liu et al., 2019 in Čenčur Curk et al., 2014)

Fig. 2. Scheme for quantitative groundwater vulnerability assessment to climate change in Slovenia (adapted after Hölbling et al., 2018, Liu et al., 2019 and Čenčur Curk et al., 2014)

ciji Republike Slovenije za okolje uporabljeni scenariji, kot so jih razvili v evropskem projektu ENSEMBLES (van der Linden & Mitchell, 2009), kasneje pa nadgradili na Agenciji RS za okolje (Dolinar, 2018).

Ocena občutljivosti pa je temeljila na podatkih o hidravlični prepustnosti vodonosnikov ter izkoristljivosti podzemnih voda, pridobljenih iz hidrogeološke podatkovne zbirke Geološkega zavoda Slovenije. V pristopu »AQUICLIM« (Hölbling et al., 2018) predpostavljajo višjo količinsko ranljivost območja vodonosnikov z bolj prepustnimi kamninami ter območjih vodonosnikov z večjo izdatnostjo. Ob tem predpostavljamo, da bodo pričakovani učinki časovnega spreminjanja v količinskem obnavljanju in razpoložljivosti podzemne vode zaradi počasnejšega pretakanja in napajanja zasičenega dela vodonosnika v manj prepustnih kamninah manjši. Interpretiranje rezultatov pa mora kritično slediti tovrstnim predpostavkam in metodološkim poenostavitvam, ki so za pregledne regionalne študije kompleksnih procesov pogosto neizbežne. Za izračun kazalnika potencialnega vpliva smo podatke o relativni razliki v napajanju, prepustnosti vodonosnikov in izkoristljivosti podzemne vode, ob upoštevanju pozitivnega ali negativnega vpliva spremenljivke, normalizirali z metodo Min-Max in utežili v razmerju 0,5 : 0,4 : 0,1, kot je bilo priporočeno in preizkušeno v pristopu »AQUICLIM« (Hölbling et al., 2018; Damm et al., 2018).

Na podlagi podatkov regionalnega vodno-bilančnega modela GROWA-SI (Andjelov et al., 2016) in »Nacionalne baze hidrogeoloških podatkov za opredelitev vodnih teles podzemnih voda« (Prestor et al., 2006) je bil po shemi »AQUICLIM« (Hölbling et al., 2018; Damm et al., 2018) s prilagojenimi parametri (sl. 2) izračunan indeks potencialnega vpliva za vsa vodna telesa podzemnih voda v Sloveniji. Indeks (vi) je za vsako prostorsko enoto seštevek zmnožkov uteži parametra j (w_j) in vrednosti razvrstitvenega razreda i znotraj parametra j (x_{ji}) (Enačba 1):

$$vi = \sum_{j=1}^{3} w_j \cdot x_{ji} \quad (1)$$

Sposobnost prilagajanja na podnebno spremembo

Za integralno oceno sposobnosti prilagajanja sistema na podnebno spremembo smo uporabili kazalnik vodne revščine WPI (*ang. Water Poverty Index*). Kazalnik WPI je široko uporabljeno interdisciplinarno ocenjevalno orodje, ki upošteva ključna vprašanja v zvezi z vodnimi viri in združuje fizične, socialne in ekonomske informacije (Sullivan, 2002). Kazalnika WPI smo za podzemne vode območja celotne Slovenije izračunali preko petdelne modelske sheme DPSIR (D – gonilne sile, P – obremenitve, S – stanje, I – vplivi, R – odzivi) (Smeets & Weterings, 1999), ki vrednoti skupne učinke odnosov med okoljem oz. podzemno vodo in človekovimi aktivnostmi v širšem socialnem in ekonomskem okviru (Liu et al., 2019). Izračun kazalnika, ki ga v primeru študije območja Slovenije označujemo z gWPI (DPSIR), temelji na letnih podatkih petnajstih spremenljivk za obdobje 2007-2017 iz podatkovnih zbirk Statističnega urada Republike Slovenije (SURS), Direkcije Republike Slovenije za vode (DRSV), Agencije Republike Slovenije za okolje (ARSO), Nacionalnega inštituta za javno zdravje (NIJZ) in Kmetijskega inštituta Slovenije (KIS) (Tabela 1). Podatke vsake posamezne spremenljivke smo z metodo normaliziranja Min-Max linearno transformirali v vrednosti glede na pozitivni ali negativni vpliv spremenljivke na kazalnik gWPI (DPSIR). Uteževanje posameznih normaliziranih spremenljivk za izračun kazalnika gWPI (DPSIR) je v tej raziskavi temeljilo na uporabi metode analitičnega hierarhičnega procesa AHP (Saaty, 1980; Goepel, 2013) in entropijske metode uteževanja EWM (Diakoulaki et al., 1995). Na tak način smo razmeroma subjektivno ekspertno presojo po metodi večparametrskega odločanja AHP (DPSIR) korigirali z objektivnejšo entropijsko metodo EWM, ki temelji na analizi merjenih podatkov (Li & Zhang, 2017; Liu et al., 2019).

V okviru analitičnega hierarhičnega procesa AHP se hierarhijo kriterijev opiše z matrikami ekspertnih primerjav njihove pomembnosti ob uporabi devetstopenjske lestvice relativne pomembnosti (Saaty, 1980), iz konsistentne matrike parnih primerjav pa se izračuna elemente normiranih lastnih vektorjev, ki predstavljajo uteži. Zaradi zmanjšanja subjektivnosti ekspertnega presojanja v procesu AHP smo upoštevali priporočilo korekcije uteži z entropijsko metodo uteževanja EWM (Shannon, 1948). Po tej metodi se podatke x_{ij} iz matrike m × n standardizira v p_{ij} (Enačba 2) in iz njih izračuna entropija E_i (Enačba 3) in utež w_i (Enačbe 4):

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \qquad (2)$$

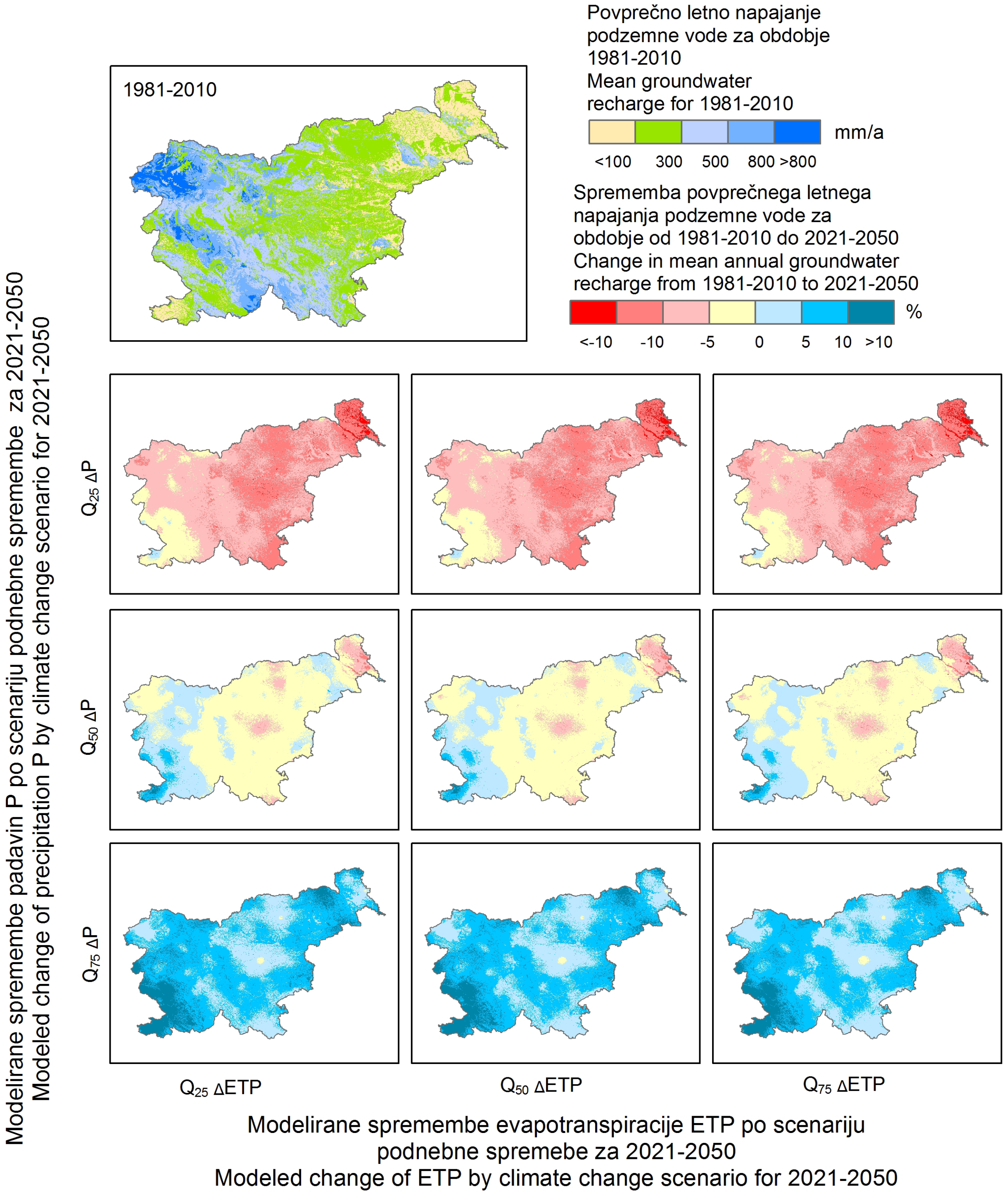
$$E_i = -\frac{\sum_{j=1}^{n} p_{ij} \cdot \ln p_{ij}}{\ln n} \qquad (3)$$

$$w_i = \frac{1 - E_i}{\sum_{i=1}^{m}(1 - E_i)} \qquad (4)$$

Rezultati in razprava

Analiza meteoroloških podatkov o podnebju v Sloveniji v obdobju 1961-2010, je ugotovila zvišanje povprečne letne temperature zraka za 1,7 °C in zmanjšanje povprečnih letnih padavin do 20 % (Vertačnik & Bertalanič, 2017). Sprememba podnebja tega 50-letnega obdobja je vplivala tudi na vodni krog z zmanjšanjem obnovljivih količin podzemnih voda. Primerjava modelskih rezultatov povprečnega letnega napajanja med obdobjema 1971-2000 in 1981-2010 je pokazala zmanjšanje letnega napajanja plitvih vodonosnikov za 15 mm oz. odstopanje za okoli -5 % (Andjelov et al., 2014).

Rezultati podnebnih modelskih simulacij do konca 21. stoletja za Slovenijo sicer predvidevajo znatno povečanje povprečne letne višine padavin (Dolinar, 2018), vendar pa kratkoročnejše simulacije z vodnobilančnim modelom GROWA-SI (Andjelov et al., 2016) po različnih kombinacijah podnebnih in emisijskih scenarijev iz evropskega projekta ENSEMBLES (van der Linden & Mitchell, 2009) predvidevajo manjša odstopanja. Za pripravo scenarijev za območje Slovenije so na Agenciji Republike Slovenije za okolje uporabili 18 modelskih izračunov iz projekta ENSEMBLES in iz njih ocenili vrednosti 25. in 75. percentila ter mediano vseh modelskih izračunov višine padavin in temperature zraka, posredno pa tudi evapotranspiracije. Kombinacije višine padavin in potencialne evapotranspiracije 25. percentila, mediane in 75. percentila za obdobje 2021–2050 so bile uporabljene kot vhodne informacije v modelu GROWA-SI, ki je omogočil simulacijo devetih kombinacij napajanja podzemne vode (sl. 3). Na podlagi teh modelskih simulacij lahko v prihodnem obdobju 2021-2050 pričakujemo, da se bodo povprečne letne obnovljive količine podzemne vode na območju celotne Slovenije, glede na dolgoletno povprečje 1981-2010, spremenile v razponu od -8,7 do +6,5 %, povprečno za okoli -1 %.

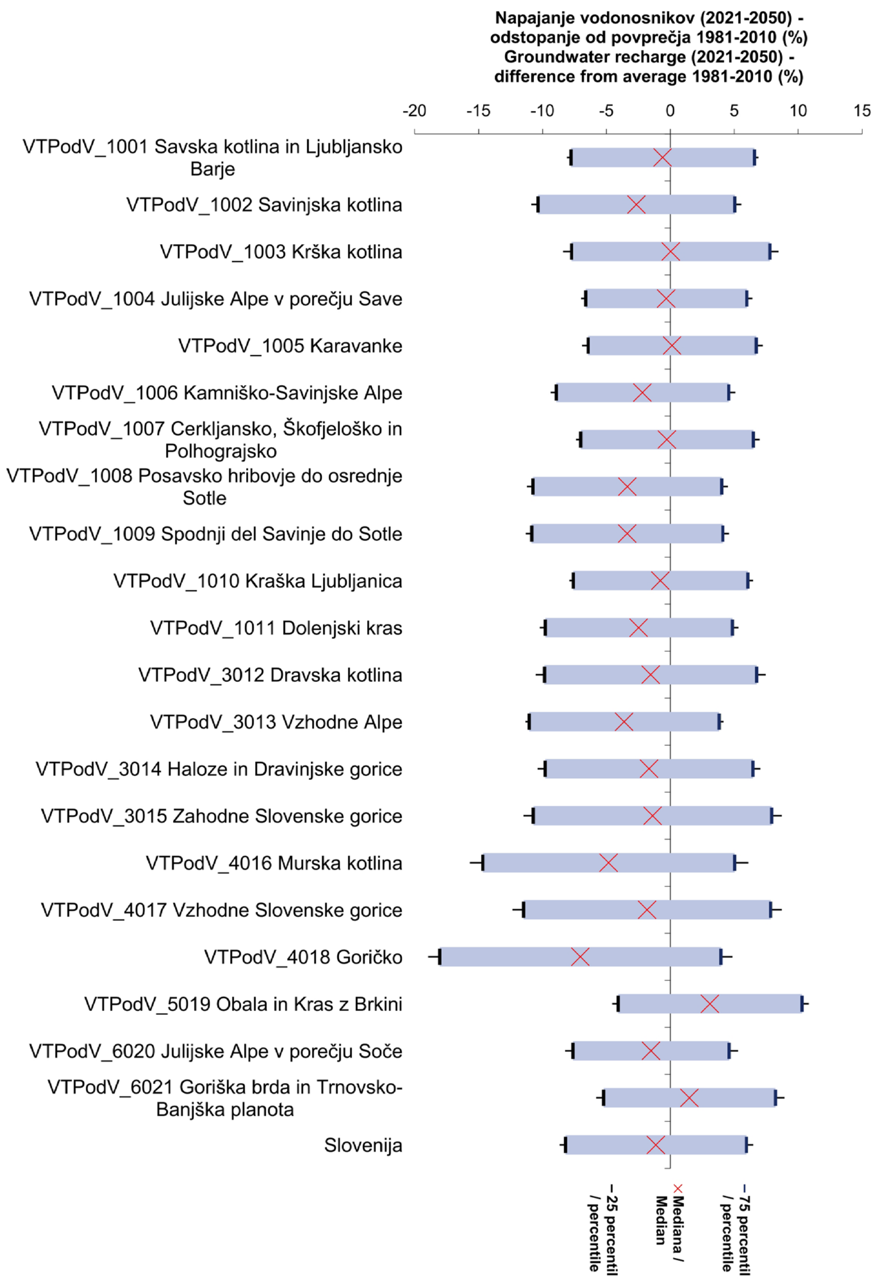


Sl. 3. Odstopanje v napajanju podzemnih voda, modelirano z regionalnim vodnobilančnim modelom GROWA-SI ob uporabi 25. percentila, mediane in 75. percentila padavin in potencialne evapotranspiracije iz ansambelskih napovedi podnebne spremembe za obdobje 2021-2051 (Andjelov et al., 2016).

Fig. 3. Deviation in groundwater recharge by GROWA-SI regional water balance model, applying the 25th, mediana and 75th percentile of precipitation and potential evapotranspiration of climate change model ensemble for the period 2021-2050 (Andjelov et al., 2016).

Največje potencialne vplive pričakovane podnebne spremembe na napajanje plitvih vodonosnikov lahko po simulaciji do leta 2050 pričakujemo v severovzhodni Sloveniji, povprečno -4,8 % v VTPodV_4016 Murska kotlina in -7 % v VTPodV_4018 Goričko (sl. 3, 4). Omenjeni vodni telesi pa tudi po uteženju z normaliziranima hidrogeološkima spremenljivkama hidravlične prepustnosti vodonosnika in izkoristljivostjo podzemne vode izstopata kot območji z največjim potencialnim vplivom podnebne spremembe na napajanje podzemne vode, ki se izražajo z najnižjim vrednostmi vsote uteženih normaliziranih vrednosti.

Drugi del ocenjevalnega postopka količinske ranljivosti podzemne vode na podnebno spremembo odkriva stopnjo prilagoditvene sposobnosti sistema, ocenjene preko petdelne sheme DPSIR z izbranimi petnajstimi parametri. Uteži posameznega parametra odražajo vpliv na skupni kazalnik prilagoditvene sposobnosti, izraženim s kazalnikom vodne revščine gWPI (DPSIR). Višja vrednost uteži govori o večji povezanosti parametra s skupnim kazalnikom. V sklopu gonilnih sil (D) je v analitičnem hierarhičnem procesu ocenjevanja ob upoštevanju entropije največjo težo dobil parameter količine porabljene vode iz javnega vodovoda na prebivalca (P2), v sklopih obremenitev (P) in stanja (S) pa problematika nitratnega onesnaženja podzemnih voda (P3 in S3), kateri se v sklopu vplivov (I) pridružuje še problematika izpostavljenosti prebivalcev s preseženimi vsebnostmi pesticidov v pitni vodi (I3). V sklopu odzivov (R) pa so vrednosti uteži najvišje pri parameteru višine investicij v upravljanje odpadnih voda (R3), celo višje od parametra vodne produktivnosti (R1), ki podaja razmerje med bruto domačim proizvodom in količino vode, dobavljene iz javnega vodovoda (Tabela 1). Učinki povečanja investicij v upravljanje odpadnih voda bi lahko pomembno vplivali na količine onesnažene vode oz. odtis sive podzemne vode (Uhan & Andjelov, 2019) in bi marsikje lahko celo presegli pričakovane učinke podnebne spremembe na njeno količinsko stanje.



Sl. 4. Statistika predvidenih sprememb v napajanju podzemnih vodnih teles v Sloveniji med obdobjema 1981-2010 in 2021-2050.

Fig. 4. Statistics of predicted changes in recharge of groundwater bodies in Slovenia between the period 1981-2010 and 2021-2050.

Tabela 1. Uteži izbranih DPSIR kazalnikov, ocenjene z analitičnim hierarhičnim procesom AHP in entropijsko metodo uteževanja EWM.

Table 1. Weights of selected DPSIR indicators, assessed with Analytic hierarchy process AHP and Entropy weight method EWM.

Sklopi modela DPSIR / DPSIR model components	**DPSIR kazalniki / DPSIR indicators**	**Vir podatkov / Data sources**	**AHPw**	**EWMw**	**Iw**
D: GONILNA SILA / D: DRIVING FORCE	D1: Skupni prirast prebivalstva / D1: Growth rate of population	SURS	0,221	0,238	0,229
	D2: Porabljene vode iz javnega vodovoda na prebivalca / D2: Water consumption from public water supply per capita	SURS	0,319	0,381	0,420
	D3: Rast bruto družbenega proizvoda (BDP) na prebivalca / D3: Gross domestic product (GDP) growth rate per capita	SURS	0,460	0,381	0,269
P: OBREMENITEV / P: PRESSURE	P1: Količina načrpane podzemne vode za javno oskrbo / P1: Groundwater withdrawal quantities for public supply	SURS	0,387	0,355	0,371
	P2: Izpust neprečiščene odpadne vode / P2: Untreated wastewater discharge	SURS	0,169	0,318	0,244
	P3: Bilančni presežki dušika v kmetijstvu / P3: Nitrogen bilance surplus in agriculture	KIS (KOS)	0,443	0,326	0,385
S: STANJE / S: STATE	S1: Količina razpoložljive podzemne vode / S1: Available groundwater quantities	ARSO	0,327	0,344	0,336
	S2: Količinski stres podzemne vode / S2: Quantitative groundwater stress	ARSO	0,260	0,333	0,296
	S3: Stopnja nitratne onesnaženosti podzemne vode / S3: Groundwater nitrate pollution level	ARSO	0,413	0,323	0,368
I: VPLIV / I: IMPACT	I1: Zniževanje gladine podzemne vode / I1: Groundwater table decline	ARSO	0,249	0,378	0,313
	I2: Prebivalci s preseženimi nitrati v pitni vodi / I2: Inhabitants with exceeded nitrates in drinking water	NIJZ (KOS)	0,157	0,319	0,238
	I3: Prebivalci s preseženimi pesticidi v pitni vodi / I3: Inhabitants with exceeded pesticides in drinking water	NIJZ (KOS)	0,594	0,304	0,449
R: ODZIV / R: RESPONSE	R1: Vodna produktivnost / R1: Water productivity	SURS	0,349	0,339	0,344
	R2: Investicije za varstvo okolja / R2: Environmental protection investments	SURS	0,168	0,330	0,249
	R3: Investicije za upravljanje odpadnih voda / R3: Investments for waste water management	SURS	0,484	0,331	0,407

Opombe / Notes:
SURS – Statistični urad Republike Slovenije / Statistical Office of the Republic od Slovenia
DRSV – Direkcija Republike Slovenije za vode / Slovenian Water Agency
ARSO – Agencija Republike Slovenije za okolje / Slovenian Environmental Agency
KIS – Kmetijski inštitut Slovenije / Agricultural Institute of Slovenia
NIJZ – Nacionalni inštitut za javno zdravje / National institute of Public Health Slovenia
KOS – kazalci okolja Slovenije / Environmental indicator of Slovenia
AHPw – utež analitičnega hierarhičnega procesa / Weight of Analytic hierarchy process
EWMw – utež entropijske metode uteževanja / Weight of Entropy weight method
Iw = (AHPw+EWMw)/2 - skupna utež / Integrated weight

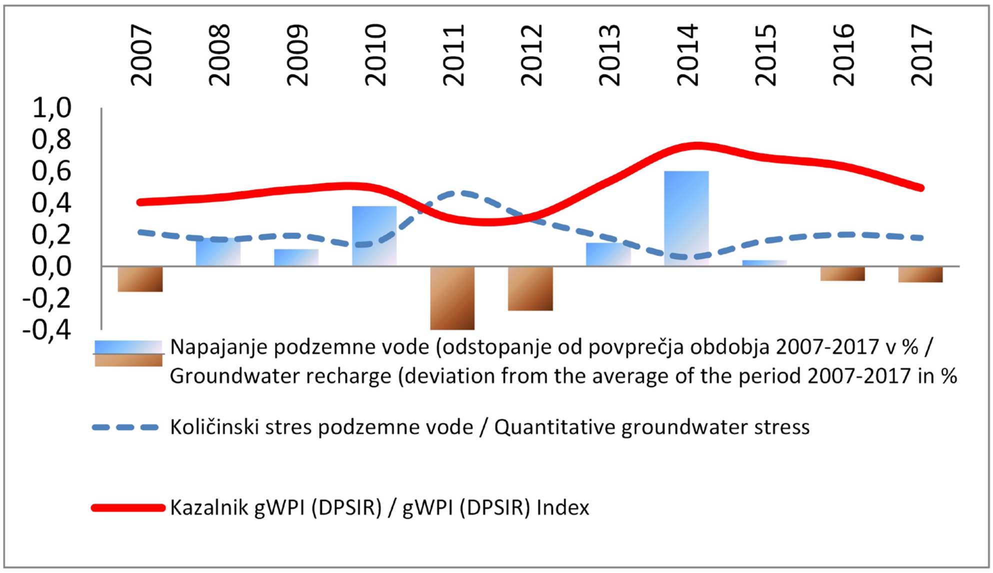
Tabela 2. Kazalnik gWPI po sklopih modela DPSIR za podzemne vode Slovenije v obdobju 2007-2017.

Table 2. gWPI index for DPSIR model components for groundwater in Slovenia in the period 2007-2017.

LETO / YEAR	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
D	0,26	0,17	0,24	0,47	0,46	0,45	0,61	0,62	0,67	0,79	0,78
P	0,40	0,63	0,53	0,58	0,38	0,39	0,46	0,86	0,83	0,76	0,17
S	0,55	0,69	0,68	0,82	0,07	0,16	0,69	1,00	0,68	0,59	0,60
I	0,59	0,45	0,42	0,28	0,48	0,30	0,62	0,78	0,78	0,94	0,86
R	0,22	0,22	0,55	0,31	0,11	0,25	0,29	0,52	0,47	0,08	0,06
gWPI (DPSIR)	**0,40**	**0,43**	**0,49**	**0,49**	**0,30**	**0,31**	**0,53**	**0,76**	**0,69**	**0,63**	**0,49**

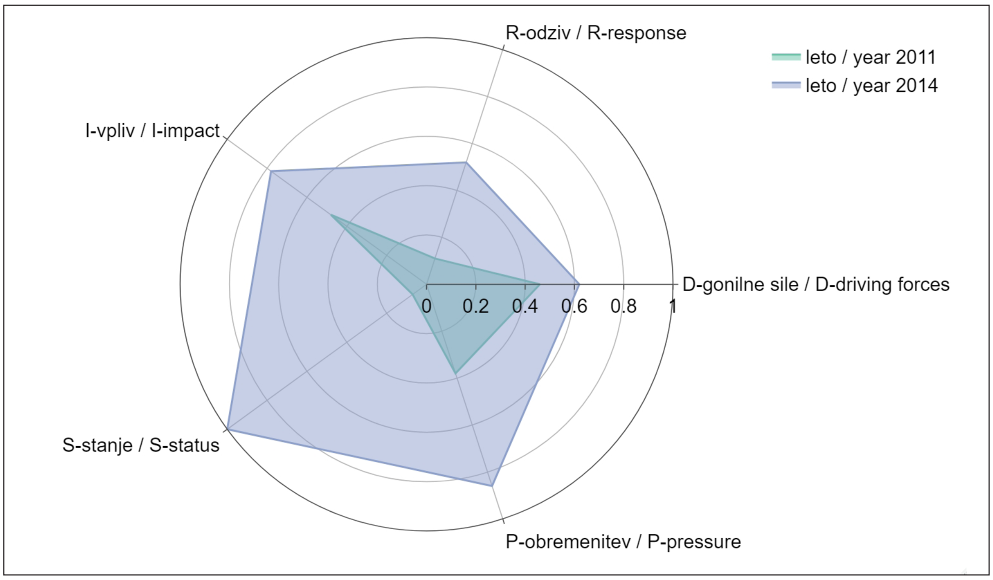
Ocena kazalnika vodne revščine (gWPI) je bila za potrebe ocene prilagoditvene sposobnosti sistema izdelana na standardiziranih podatkovnih nizih parametrov sheme DPSIR za obdobje 2007-2017 po metodi utežene vsote. Zmanjševanje vrednosti gWPI (DPSIR) od 1 proti 0 govori o slabšanju razmer in vse večjem tveganju za pomanjkanje podzemne vode. Vrednost gWPI (DPSIR) je bila v obravnavanem obdobju v razponu od 0,30 do 0,76, s povprečjem 0,50 (Tabela 2, sl. 5). K velikemu razponu največ prispevata parametra, ki opisujeta odziv (R) in stanje (S).

Najnižje vrednosti je kazalnik gWPI (DPSIR) dosegel v letu 2011, ko je bilo napajanje podzemne vode v Sloveniji 40 % pod povprečjem obdobja 1981-2010, najvišje vrednosti pa leta 2014, ko je bilo napajanje v Sloveniji 60 % nad omenjenim primerjalnim obdobnim povprečjem. V hidrološko sušnem letu 2011 se je stanje (S) podzemnih voda, predvsem zaradi manjšega napajanja,



Sl. 5. Napajanje podzemne vode, količinski stres in vrednost kazalnika gWPI (DPSIR) podzemne vode v Slovenijo v obdobju 2007-2017.

Fig. 5. Groundwater recharge, quantitative stress and gWPI (DPSIR) values for groundwaters in Slovenia in the period 2007-2017.



Sl. 6. Komponente DPSIR kazalnika gWPI podzemnih voda v Sloveniji v hidrološko sušnem letu 2011 in v hidrološko mokrem letu 2014.

Fig. 6. DPSIR components for groundwaters gWPI index in Slovenia in the hydrological drought year 2011 and in hydrological wet year 2014.

izrazito poslabšalo, ki pa mu ni sledilo povečanje odziva (R), vrednotenega preko izbranih parametrov vodne produktivnosti in višine investicij (sl. 6). Vrednosti kazalnika gWPI (DPSIR) smo zaradi nekaterih podatkovnih vrzeli regionalizirali preko vodnobilančnega modela in kazalnika vodnega stresa (Andjelov et al., 2016; Uhan & Andjelov, 2019), ki je izmed vseh petnajstih DPSIR kazalnikov korelacijsko najtesneje povezan s kazalnikom vodne revščine oz. vodne blaginje. Vpliv slabe prilagoditvene sposobnosti je najizrazitejši na najbolj obremenjenih ravninskih vodonosnikih z medzrnsko poroznostjo (Tabela 3). Povišano količinsko ranljivost podzemne vode v Sloveniji izkazuje le okoli 9 % ozemlja države. V skupino količinsko najbolj ranljivih podzemnih vodnih teles z visoko in srednje visoko ranljivostjo se v Sloveniji uvrščata VTPodV_4016 Murska kotlina in VTPodV_3012 Dravska kotlina, sledita pa VTPodV_1001 Savska kotlina in Ljubljansko Barje ter VTPodV_1002 Savinjska kotlina (Tabela 3, sl. 7).

Predstavljena ocena količinske ranljivosti podzemne vode na podnebno spremembo v Sloveniji temelji na rezultatih modelske vodnobilančne simulacije za obdobje 2021-2050 v letni časovni skali na celotnem območju države (Andjelov et al., 2016). Po tej simulaciji se največja odstopanja pričakuje v severovhodnem in jugozahodnem delu, prav na območjih z najmanj padavinami v državi. Na Goričkem naj bi se napajanje plitvih vodonosnikov zmanjšalo za 7 %, na Obali in Krasu z Brkini pa naj bi se glede na primerjalno obdobje 1981-2010 povečalo za 3,1 %.

Te ocene sicer nekoliko odstopajo od najnovejših predvidevanj, ki za severovzhodni predel Slovenije napovedujejo več padavin in povečanje napajanja (Dolinar, 2018), vendar so blizu ugotovitvam analiz meteoroloških podatkov o zmanjšanju višine padavin v obdobju 2061-2010

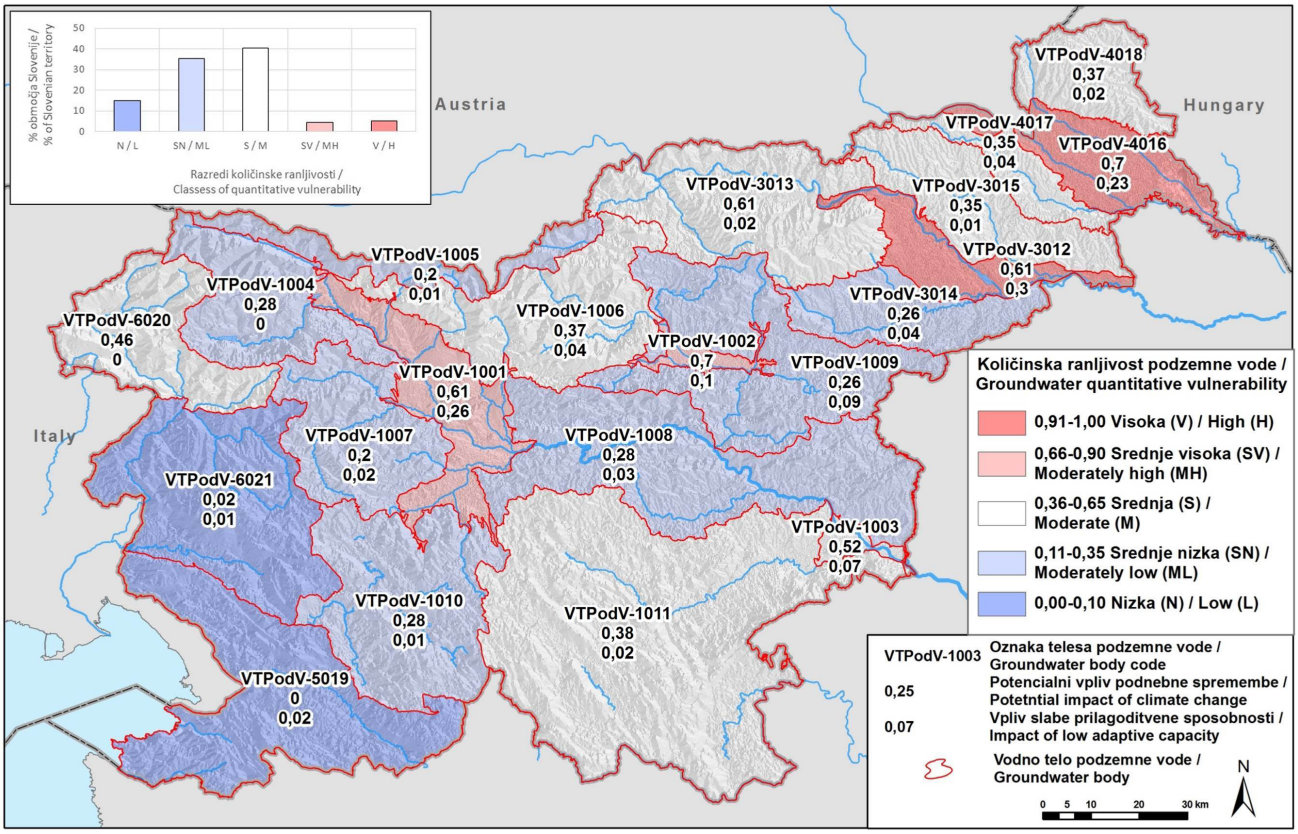
Tabela 3. Normalizirane in utežene vrednosti kazalnikov potencialnega vpliva podnebne spremebe in vpliva slabe prilagoditvene sposobnosti ter vsota uteženih normaliziranih vrednosti, kot skupna ocena količinske ranljivosti podzemne vode na podnebno spremembo teles podzemnih voda v Sloveniji.

Table 3. Weighted normalized values for potential impact of climate change and impact of low adaptive capacity with the sums of weighted normalized values as a groundwater quantitative vulnerability assessment to climate change in Slovenia.

Vodno telo podzemne vode / Groundwater body	**Potencialni vpliv podnebne spremembe / Potential impact of climate change**		**Vpliv slabe prilagoditvene sposobnosti / Impact of low adaptive capacity**		**Količinska ranljivost podzemne vode / Groundwater quantitative vulnerability**
	Normalizirane vrednosti / Normalized values	**Utežene normalizirane vrednosti / Weighted normalized values**	**Normalizirane vrednosti / Normalized values**	**Utežene normalizirane vrednosti / Weighted normalized values**	**Vsota uteženih normaliziranih vrednosti / Sum of weighted normalized values**
		Utež 0,7 / Weight 0,7		**Utež 0,3 / Weight 0,3**	
VTPodV_1001 Savska kotlina in Ljubljansko Barje	0.88	0.61	0.85	0.26	0.87
VTPodV_1002 Savinjska kotlina	1.00	0.70	0.32	0.10	0.80
VTPodV_1003 Krška kotlina	0.75	0.53	0.23	0.07	0.60
VTPodV_1004 Julijske Alpe v porečju Save	0.41	0.28	0.01	0.00	0.29
VTPodV_1005 Karavanke	0.28	0.20	0.02	0.01	0.20
VTPodV_1006 Kamniško-Savinjske Alpe	0.53	0.37	0.13	0.04	0.41
VTPodV_1007 Cerkljansko, Škofjeloško in Polhograjsko hribovje	0.28	0.20	0.06	0.02	0.21
VTPodV_1008 Posavsko hribovje do osrednje Sotle	0.41	0.28	0.11	0.03	0.32
VTPodV_1009 Spodnji del Savinje do Sotle	0.38	0.26	0.29	0.09	0.35
VTPodV_1010 Kraška Ljubljanica	0.41	0.28	0.03	0.01	0.29
VTPodV_1011 Dolenjski kras	0.54	0.38	0.06	0.02	0.39
VTPodV_3012 Dravska kotlina	0.88	0.61	1.00	0.30	0.91
VTPodV_3013 Vzhodne Alpe	0.88	0.61	0.07	0.02	0.63
VTPodV_3014 Haloze in Dravinjske gorice	0.38	0.26	0.15	0.04	0.31
VTPodV_3015 Zahodne Slovenske gorice	0.50	0.35	0.03	0.01	0.36
VTPodV_4016 Murska kotlina	1.00	0.70	0.77	0.23	0.93
VTPodV_4017 Vzhodne Slovenske gorice	0.50	0.35	0.13	0.04	0.39
VTPodV_4018 Goričko	0.53	0.37	0.06	0.02	0.39
VTPodV_5019 Obala in Kras z Brkini	0.00	0.00	0.06	0.02	0.02
VTPodV_6020 Julijske Alpe v porečju Soce	0.66	0.46	0.00	0.00	0.46
VTPodV_6021 Goriška brda in Trnovsko-Banjška planota	0.03	0.02	0.03	0.01	0.03

(Vertačnik & Bertalanič, 2017) in modelskim vodnobilančnim analizam med obdobjema 1971-2000 in 1981-2010, ki so pokazale zmanjšanje letnega napajanja plitvih vodonosnikov za okoli 5 % (Andjelov et al., 2014). Rezultati modelske vodnobilančne simulacije za obdobje 2021-2050 v letni časovni skali na celotnem območju države temeljijo na upoštevanju mediane višine padavin in potencialne evapotranspiracije iz ansambelskih napovedi podnebne spremembe za obdobje 2021-2051 (Andjelov et al., 2016). Rezultate omenjene modeske simulacije prevzema tudi Načrt upravljanja voda v Sloveniji za obdobje 2016-2021 (MOP, 2016).

Za oceno potencialnega vpliva podnebne spremembe na napajanje teles podzemnih voda smo



Sl. 7. Količinska ranljivost podzemne vode na podnebno spremembo v Sloveniji za obdobje 2021–2051.
Fig. 7. Groundwater quantitative vulnerability to climate change in Slovenia for the period 2021–2051.

oceno izpostavljenosti uteženo vrednotili v luči občutljivosti, ki jo v tej analizi predstavljata parametra regionalne ocene hidravlične prepustnosti vodonosnikov in izkoristljivosti podzemne vode. Zaradi razmeroma velike prepustnosti in velike izkoristljivosti se kot najbolj občutljiva območja izkazujejo plitvi aluvialni vodonosniki z medzrnsko poroznostjo, kjer so lahko potencialni vplivi podnebne spremembe na napajanje zaradi teh hidrogeoloških lastnosti vodonosnikov najvišji. Pričakovane količinske spremembe podzemne vode do leta 2050 na teh območjih presegajo količine, ki so potrebne za ohranjanje kopenskih ekosistemov (Janža et al., 2017) in predstavljajo zaznaven delež povprečnega letnega odvzema podzemne vode (Uhan & Andjelov, 2019).

Končna ocena količinske ranljivosti v predstavljeni analizi upošteva tudi prilagoditveno sposobnost sistema, ki je preko petnajstih parametrov sheme DPSIR ocenjena s kazalnikom vodne revščine gWPI. Izbor parametrov DPSIR močno omejuje razpoložljivost podatkov, od katerih se večinoma zbira in prikazuje po prostorskih enotah statističnih regij ali občin in ne po vodnih telesih, ki so osnovne prostorske enote načrtovanja in upravljanja voda. Izbor parametrov o odzivih bi v prihodnje moral vključevati tudi informacije o porabi sredstev sklada za podnebne spremembe in sklada za vode. Vpliv subjektivnosti je v tem delu analize izrazit tudi v analitičnem hierarhičnem procesu ekspertnega presojanja pomena posameznih parametrov za oceno kazalnika vodne revščine, ki smo ga z upoštevanjem entropije podatkov poskušali dodatno zmanjšati, vendar je potrebno biti pri interpretaciji končnih rezultatov dodatno pozoren prav na ta vir negotovosti, ki bo terjal posebno skrb tudi v nadaljnih analizah.

Končna ocena količinske ranljivosti podzemne vode na podnebno spremembo kaže na dve izstopajoči vodni telesi: VTPodV_4016 Murska kotlina in VTPodV_3012 Dravska kotlina. Murska kotlina izstopa že po visoki oceni potencialnega vpliva, medtem ko je Dravska kotlina izstopajoča tudi po slabi prilagoditveni sposobnosti. Klasificiranje kazalnika količinske ranljivosti podzemne vode pokaže, da se v skupino visoke in zelo visoke ranljivosti uvrščajo štiri telesa podzemne vode: poleg VTPodV_4016 Murska kotlina in VTPodV_3012 Dravska kotlina še VTPodV_1001 Savska kotlina in Ljubljansko Barje in VTPodV_1002 Savinjska kotlina, katerih skupna površina ne presega 10 % državnega ozemlja.

Sklep

Sprememba podnebja bo s spremembo temperature zraka in višine padavin nedvomno zaznavno vplivala tudi na vodni krog. Poznavanje količinske ranljivosti podzemne vode so zaradi pomena podzemnih vodnih virov za oskrbo prebivalstva s pitno vodo ene od ključnih izhodišč načrtovanja upravljanja voda. Prvi poskus tovrstne ocene vpliva podnebne spremembe na količino letnega napajanja plitvih vodonosnikov posameznih teles podzemnih voda v Sloveniji ob nekaterih podatkovnih vrzelih odkriva razmeroma veliko prostorsko spremeljivost količinske ranljivosti. S povišano stopnjo količinske ranljivosti izstopajo štiri vodna telesa z okoli 9 % državnega ozemlja, ki zagotavljajo 45 % vodnih količin za oskrbo prebivalstva s pitno vodo. Med temi štirimi telesi je stopnja izkoriščenosti podzemnih voda oz. količinski stres največji v Murski in Dravski kotlini. Pričakovane količinske spremembe do leta 2050 predstavljajo v teh vodnih telesih več kot četrtino povprečnega letnega odvzema podzemne vode. Iz gledišča letne vodne bilance po posameznih vodnih telesih omenjena predvidevanja ne bi smela biti zaskrbljujoča, vendar pa se moramo zavedati velike sezonske spremenljivosti količinskega obnavljanja vodonosnikov, ki lahko občasno in lokalno ogrozi tudi količinsko varnost oskrbe s pitno vodo v državi.

Ob tej prvi oceni količinske ranljivosti teles podzemne vode v Sloveniji je potrebno opozoriti predvsem na dve področji možnih oz. potrebnih izboljšav v nadaljevanju raziskav. Prvo priporočilo je s področja ocene potencialnih vplivov, ki se v tej raziskavi osredotoča le na spremembo letne višine padavin, ne analizira pa spremembe drugih parametrov podnebja, ki bi še lahko vplivali na spremembo napajanja vodonosnikov: intenziteta padavin, višina snežne odeje itd. Čeprav nekatere raziskave na posameznih območjih ne nakazujejo velikega pomena tem spremembam, bi kljub temu veljalo v prihodnje analize količinske ranljivosti vključiti tudi ostale podnebne parametre in jih skupno analizirati v podrobnejši časovni in prostorski skali. Nadaljnje raziskave količinske ranljivosti podzemne vode naj bi bile usmerjene predvsem v podrobnejšo sezonsko analizo obdobja z najmanjšim napajanjem vodonosnikov in največjo potrebo po podzemni vodi. Drugo priporočilo pa se nanaša na oceno prilagoditvene sposobnosti na podnebne spremembe, kjer je nedvomno potrebna sistemska sprememba pri definiranju za upravljanje voda pomembnih parametrov in zbiranju ter obdelovanju podatkov na ravni osnovnih prostorskih enot upravljanja voda (Direktiva 2000/60/ES), na vodnih telesih podzemnih voda in ne na nivoju statističnih regij ali upravnih enot.

Zahvala

Prve ocene izpostavljenosti podzemnih voda na podnebno spremembo v Sloveniji temeljijo na številnih simulacijah regionalnega vodno-bilančnega modela GROWA-SI, ki je rezultat nemško-slovenskega raziskovalnega projekta med Agencijo Republike Slovenije za okolje in Forschungszentrum Jülich. Ključno vlogo pri prenosu tega regionalnega modela v slovenski prostor je imel nemški raziskovalec prof. dr. Frank Wendland. Avtorja članka se za njegovo dolgoletno odlično sodelovanje iskreno zahvaljujeva.

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West Balkan Mineral Register of Primary Raw Materials

Register primarnih mineralnih surovin Zahodnega Balkana

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Ključne besede: primarne mineralne surovine, Zahodni Balkan, register mineralnih surovin, projekt RESEERVE

Abstract

Rational and long-term planning and sustainable mineral resources management is of strategic importance in Europe's efforts to secure the self-supply of mineral raw materials. European mineral data is organized and accessible within the pan-European Minerals Intelligence Network. Most EU countries are part of this network, while the West Balkan region presents a gap in this regard. A common West Balkan mineral register needs to be established in order to close the gap and bring the area closer to the EU market. Including the region into the network would provide new opportunities to local industry and improve mineral management at the national and regional level. In this context, the Geological Survey of Slovenia is working in cooperation with numerous partners and stakeholders in different projects within the framework of European initiatives and programs. We collected and properly organized relevant data on minerals in the region according to the INSPIRE Directive. This paper describes the creation of the West Balkan Mineral Register of primary raw materials, and its content.

Izvleček

Premišljeno in dolgoročno načrtovanje ter trajnostno upravljanje z mineralnimi surovinami je strateškega pomena za surovinsko samooskrbo Evrope. Podatki o evropskih mineralnih surovinah so urejeni in dostopni znotraj vseevropske informacijske mreže o mineralnih surovinah (angl. pan-European Minerals Intelligence Network). Večina držav Evropske unije je že vključenih vanjo, medtem ko predstavlja območje Zahodnega Balkana vrzel v tej mreži. Zato je bilo potrebno izdelati register mineralnih surovin Zahodnega Balkana, ki bo pokril vrzel na tem področju in omenjeno območje približal evropskem trgu. Vključitev regije v informacijsko mrežo bo ustvarila nove priložnosti za lokalno industrijo in hkrati omogočila boljše upravljanje z mineralnimi surovinami tako na nacionalni kot tudi na širši regionalni ravni. S tem namenom izvaja Geološki zavod Slovenije v sodelovanju s številnimi partnerji in deležniki različne projektne aktivnosti v sklopu evropskih pobud in programov. Relevantne podatke o mineralnih surovinah v regiji smo zbrali in primerno uredili v skladu z INSPIRE Direktivo. V članku predstavljamo snovanje Registra primarnih mineralnih surovin Zahodnega Balkana in njegovo vsebino.

Introduction

Europe is aiming to reduce its dependence on imported mineral resources from other continents by increasing its self-supply capacities. One of the most important regions that the European Commission recognizes as a greatpotential contributor to the effort to lower Europe's dependence on imported mineral resources is the South-East Europe (SEE) region and its considerable mineral potential. Southeast Europe, particularly the West Balkans, is rich in primary as well as secondary mineral resources, which are mostly remains of historic or current mining and metallurgical activities. The area has important deposits of copper, lead, zinc, chromium, iron, nickel, and antimony. Furthermore, some explorative geological work is being carried out on new mineral resource deposits (critical raw materials) that are in great demand in Europe. The results of the extensive research work on mineral deposits in the West Balkan are stored in various national archives or have even been lost, which represents a gap in the Europe's existing information system on mineral resources (Fig. 1). Therefore, there was a need for data on primary and secondary mineral deposits in the West Balkans region to be systematically collected, interpreted, and arranged in a single place. In addition, such data should be linked to existing European datasets as publicly accessible data, so as the great potential of mineral reserves in the West Balkans makes it a deserving part of the European mineral information platform.

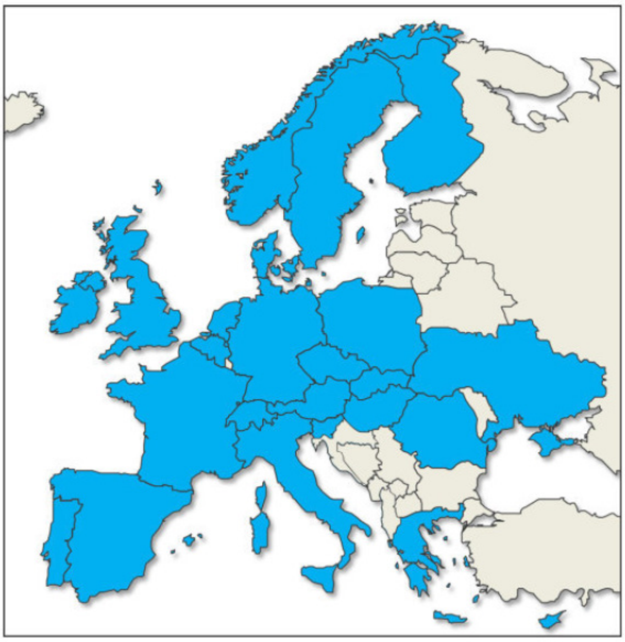


Fig. 1. Data gap (countries in grey) in the Pan European Mineral Intelligence Network (countries in blue) before the RESEERVE project (Archive of the Geological Survey of Slovenia).

Greater collaboration between European and regional partners, as well as with stakeholders is herein of great importance. Owing to the common regional history, knowledge of the local languages, and a good knowledge of the general situation in the area, the Geological Survey of Slovenia can play a significant role in the aforementioned process (Rokavec et al., 2018). Thus, it is intensely involved in the relevant activities and represents a link between EU and West Balkan mineral sector.

Knowledge and Innovation Community (KIC) EIT RawMaterials

The Knowledge and Innovation Community (KIC) EIT RawMaterials was established in 2014 by the European Institute of Innovation and Technology (EIT). EIT RawMaterials has a vision of a European Union where raw materials constitute a major, strategic strength. Its mission is to grow the European raw materials sector and make it more competitive and attractive through radical innovation and guided entrepreneurship. It is the largest and strongest consortium in the mineral raw materials sector worldwide bringing together 317 European partners from 26 countries and represents all three sides of the knowledge triangle: education, research, and industry. The consortium collaborates in finding new, innovative solutions to secure supply and improve the raw materials sector all along its value chain – from exploration, extraction and processing to recycling and reuse. With innovative technological solutions it strives to ensure the highest degree of EU mineral raw material self-sufficiency possible. EIT RawMaterials has a significant impact on European competitiveness and employment by fostering and driving innovation and empowering entrepreneurs, research, and education institutions to move closer to the circular economy model. This results in the introduction of innovative and sustainable products, processes, and services, as well as expert professionals making European society more economically, environmentally, and socially sustainable (Internet 1).

The Geological Survey of Slovenia is strongly connected to the SEE region through the EIT RawMaterials (RM) knowledge and innovation community as its EIT RM "core" partner. Along with acting as a coordinator or partner in different EIT RawMaterials community projects, the Geological Survey of Slovenia is one of the three cofounders of the Regional Center (RC) Adriahub, together with the Slovenian National Building and Civil Engineering Institute and the University of Zagreb, which connects regional raw materials ecosystems with the EIT RawMaterials community (Draksler et al., 2018).

As a member of the EIT community, the Geological Survey of Slovenia has coordinated two projects with the goal of mapping mineral resources in the West Balkan countries, particularly in Albania, Bosnia and Herzegovina, Croatia, North Macedonia, Montenegro, and Serbia (RESEERVE) (Internet 2) and of creating a dedicated public mining/mineral service (MineService) (Internet 3). Until now, these countries were not included in the existing data platforms that provide raw materials potentials data to interested stakeholders (Fig. 1). The main outcome of such activities is the creation of a West Balkan Mineral Register for primary and secondary mineral resources. The register should serve as a starting point to integrate the region into the pan-European Minerals Intelligence Network and bring it closer to the common mineral market.

Data on West Balkan minerals is now part of the European Geological Data Infrastructure (EGDI) portal and the complete Register is available on the RESEERVE project's website (Internet 4). It consists of two parts: the West Balkan Mineral Register of Primary Raw Materials (Internet 5) and the West Balkan Mineral Register of Secondary Raw Materials (Internet 6).

Here we present work within the RESEERVE project to create the West Balkan Mineral Register of Primary Raw Materials (Internet 5) and in so doing, connecting the region to the European Minerals Intelligence Network.

Materials and methods

The aim of creating the West Balkan Mineral Register of primary raw materials is to address one of the major challenges presented in the Raw Materials Initiative (RMI) - II. Pillar: to foster the sustainable supply of raw materials from EU-based sources (European Commission, 2008). This effort should be facilitated and augmented by the mineral potential of the East and Southeast Europe (ESEE) region. Based on strong cooperation with representatives from the selected ESEE countries the following objectives can be established; (1) to identify relevant data providers and examine the quantity, quality, and format of data; (2) to examine existing datasets, extract publicly accessible data, and aggregate specific data when necessary; (3) to present a case study on the harmonisation of existing data with INSPIRE-compliant data (RESEERVE, 2017). The established West Balkan Mineral/Mining community and its Mineral Register should support an array of activities in the ESEE region, especially as a basis for further mineral exploration. These actions will contribute to the integration of the West Balkan region into the pan-European mineral market.

The objectives outlined herein are also aligned with the Europe 2020 Flagship Initiative on Resource Efficiency and the Roadmap to a Resource Efficient Europe (European Commission, 2011), as well as with the INSPIRE Directive establishing an infrastructure for spatial information (Directive 2007/2/EC). They also contribute to EU resource efficiency goals that are aligned with several UN Sustainable Development Goals (United Nations, 2015)

To start building a common raw material register it is essential to determine what data is needed to provide comprehensive information to local Knowledge Triangle Integration (KTI) stakeholders (from industry, education and research institutions) and the relevant authorities as well as to potential international investors. The best way to make information visible worldwide is to prepare in the way they can be available via the internet. Most EU countries (including Slovenia) are already part of the "pan-European Mineral Intelligence Network", whereas most of the SEE region still represents a gap. A first step towards a common register and consequently INSPIRE-aligned data was made with the defining of relevant attributes separated into two sub-tables – for primary and secondary raw materials. This paper focuses on primary raw materials data (Rokavec & Draksler, 2020).

The work required to create common mineral resource datasets was divided into three steps:

1. Study of existing primary raw materials data
2. Selection of competent / relevant attributes
3. Creating a common primary raw materials dataset.

Raw data required for the creation of the register was provided by the relevant responsible institutions from the West Balkan countries: Geological Survey of Slovenia (Slovenia), Croatian Geological Survey (Croatia), Geological Survey of Albania (Albania), Geological Survey of Montenegro (Montenegro), University of Belgrade – Faculty of Mining and Geology (Serbia), Geological Survey of the Federation of Bosnia and Herzegovina (Bosnia and Herzegovina), Macedonian Ecological Society (North Macedonia), and the Geological Survey of the Republic of Srpska (Bosnia and Herzegovina).

In order to study existing primary raw materials data, researchers from SEE national geological surveys captured, evaluated, harmonised, and provided national geologic data, including data on mineral resources, and managed the most relevant mineral datasets. Supplementary, educational and business partners contributed with their needs, experience, and knowledge related to potential investments in the exploitation of primary and secondary mineral resources (Draksler et al., 2018). Finally, the work of Task Partners (TPs), which participated in the project for a specific task, was of particular importance.

Comprehensive mineral data on metals, industrial minerals, and rocks were gathered at the national levels. Publicly accessible data was selected and gaps in existing mineral information were identified. Despite the fact that mineral commodities are in most countries property of the state, some data - such as resources and reserves at individual exploitation site in some countries - is not publicly available. Publicly available data on mineral resources and their deposits are mainly published in mineral yearbooks, professional and scientific articles, expert magazines, websites etc. Datasets differ from country to country due to differences in mineral endowment, level of exploration, data details and the technical (IT) tools in use. Therefore, a comparison of datasets from different countries was performed, and the mineral data validated. A common dataset was established to ensure the comparability of the data provided. A broad set of mineral data from different sites has been included – from active, abandoned, and closed mines to sites where no previous mining activities have taken place, so called "greenfields" (Rokavec & Draksler, 2020).

Construction of the Primary Raw Material (PRM) Register in West Balkan was performed in the following steps:

- Selection of relevant attributes describing raw materials and their deposit as good as possible.
- Comparison of selected attributes with INSPIRE terminology (upon Directive 2007/2/EC).
- Attributes and data mapping to INSPIRE.
- Creation of final common PRM Register.

Attributes selected for the PRM attribute table of datasets were taken from an analysis conducted according to the informational value for stakeholders. Some elementary statistics were compiled according to the Register's PRM attributes.

All attributes in the PRM table were divided as follows (Rokavec & Draksler, 2020):

- Basic data, providing basic information on the deposit
- Technical data, related to technical descriptions of the deposit
- Geological data, describing the basic geology of the deposit

Further on, basic data is divided into:

- Name of mineral deposit
- Municipality of mineral deposit
- X and Y WGS84 (World Geodetic System) coordinates

Technical data is divided into:

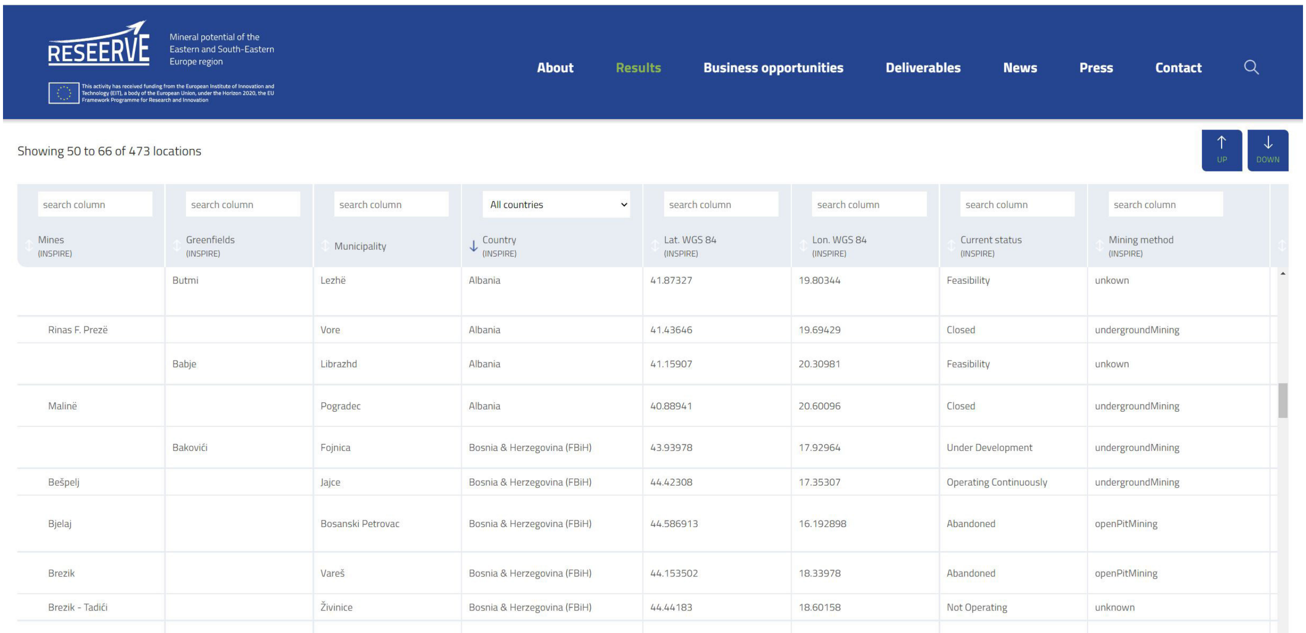
- Current status of mine (abandoned/under maintenance/ operational)
- Mining method (open pit, underground)
- Concessionaire's name
- Mineral reserves (reported in tonnes).

Geological data is divided into:

- Basic geological map at scale 1:100.000
- Type of mineral deposit
- Size of mineral deposit
- Age of mineral deposit
- Host–rock type
- Major, minor, and trace minerals
- Final product made from the mineral.

Results and discussion

The analysis of primary raw material data resulted in 473 PRM sites described by 27 attributes, which were included into the West Balkan Mineral Register of Primary Raw Materials (Internet 5) and presented in an overview table (Fig. 2) and on a map (Fig. 3). Among the PRM sites, there are 248 metal sites and 225 sites of industrial minerals and construction materials. 56 sites or 12 % of all sites are "greenfields".



Mines (INSPIRE)	Greenfields (INSPIRE)	Municipality	Country (INSPIRE)	Lat. WGS 84 (INSPIRE)	Lon. WGS 84 (INSPIRE)	Current status (INSPIRE)	Mining method (INSPIRE)
	Butmi	Lezhë	Albania	41.87327	19.80344	Feasibility	unkown
Rinas F. Prezë		Vore	Albania	41.43646	19.69429	Closed	undergroundMining
	Babje	Librazhd	Albania	41.15907	20.30981	Feasibility	unkown
Malinë		Pogradec	Albania	40.88941	20.60096	Closed	undergroundMining
	Bakovići	Fojnica	Bosnia & Herzegovina (FBiH)	43.93978	17.92964	Under Development	undergroundMining
Bešpelj		Jajce	Bosnia & Herzegovina (FBiH)	44.42308	17.35307	Operating Continuously	undergroundMining
Bjelaj		Bosanski Petrovac	Bosnia & Herzegovina (FBiH)	44.586913	16.192898	Abandoned	openPitMining
Brezik		Vareš	Bosnia & Herzegovina (FBiH)	44.153502	18.33978	Abandoned	openPitMining
Brezik - Tadići		Živinice	Bosnia & Herzegovina (FBiH)	44.44183	18.60158	Not Operating	unknown

Fig. 2. A screen capture of overview table with 473 locations of primary raw materials, as part of the West Balkan Mineral Register of Primary Raw Materials (Internet 5).

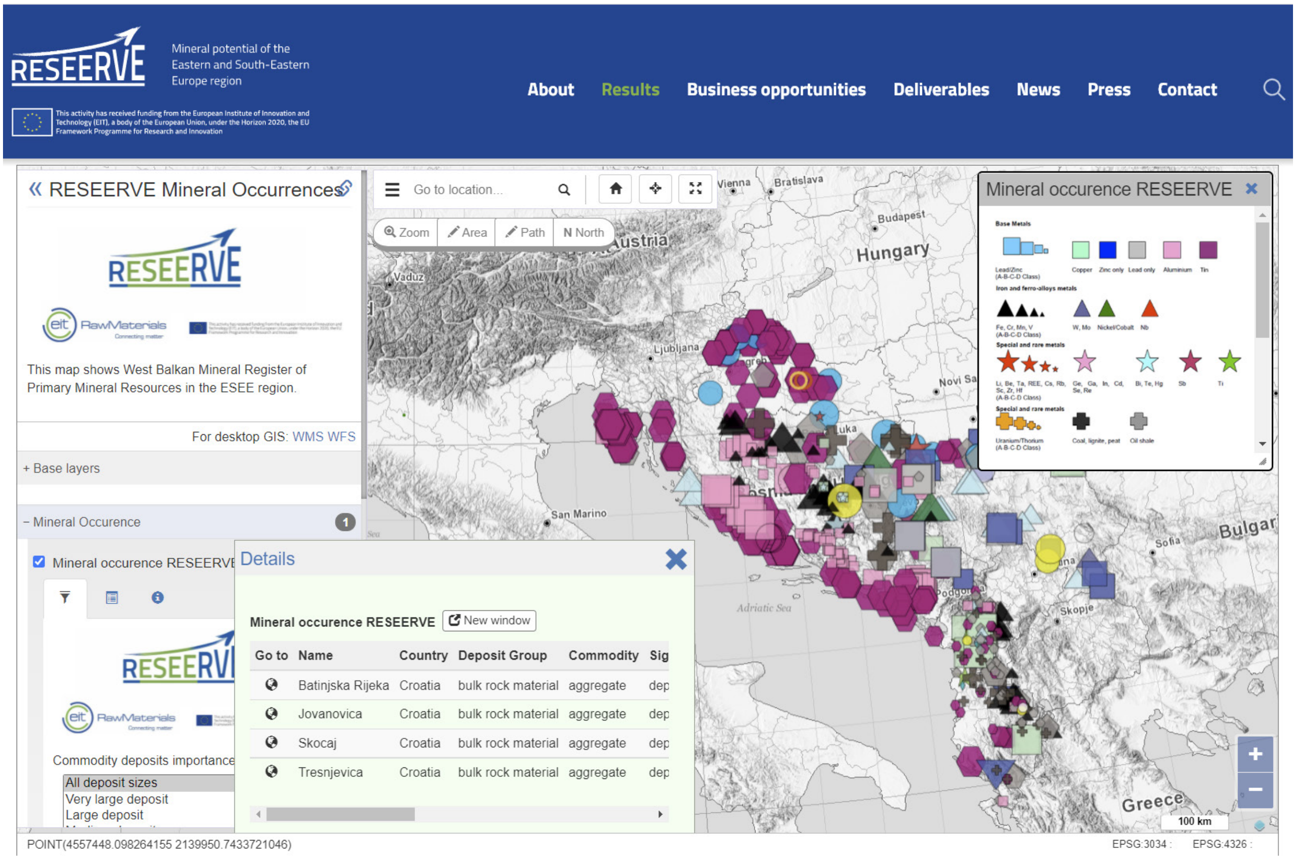


Fig. 3. A screen capture of EGDI map showing the locations of primary raw materials (PRM) with main data, as part of the West Balkan Mineral Register of Primary Raw Materials (Internet 5).

Various mining activities are performed on the remaining 88 % of sites. The site's current status describes the phase of a site's "lifetime". Almost half of the selected sites are in operation. Socio-economic transitions and recent regional wars as well as a lack of proper legislation caused many mines to be abandoned. Very few sites have the status of closed mines, in cases where any closing procedure was applied. 9 % of the selected sites are at the beginning of their "lifetime" cycle in terms of their feasibility status and pending approval.

Mining method is defined by referring to the type of mineral material mined, geological structure, and depth of the ore body. Open pit mining is/was the predominant extraction method at the selected sites, followed by underground mining, and quarrying, which is used for aggregates. In some cases, a combination of different mining methods is employed.

West Balkan PRM data mapped to INSPIRE has been harvested in the European Union Minerals Knowledge Data Platform (EU-MKDP) in the frame of the "Mintell4EU" project (Internet 7). The most interesting data of the sites are therefore visible also on the EGDI portal (Internet 8, Fig. 3). West Balkan mineral information is now accessible and easily shared across Europe and around the world (Rokavec & Draksler, 2020).

Mineral potential of West Balkan

Metal deposits related to the West Balkan Metallogenic Zones

The greatest geotectonic unit of the West Balkan Peninsula are the Dinarides. They are divided into: the External Dinarides (along the Adriatic coast), and the Inner Dinarides (towards the Pannonian basin) (Fig. 4).

Several major mineral metallogenic provinces containing deposits of iron (Fe), copper (Cu), lead (Pb) and zinc (Zn) are known and described from the West Balkan area from West to East: the Dinaric, Vardar, Serbian-Macedonian, and the Carpatho-Balkan zone (Drovenik, 1984; Janković, 1990; Dimitrijević, 1997; Dill et al., 2008; Jelenković et al., 2008; Melcher & Reichl, 2017; Rokavec & Draksler, 2020).

1. The Dinaric Metallogenic Zone covers the western part of Central Serbia, most of BiH territory, southwest Croatia, coastal Montenegro, and part of Albania. Two metallogenic epochs – the late Hercynian and the early Alpine – caused endogenic ore mineralisation.

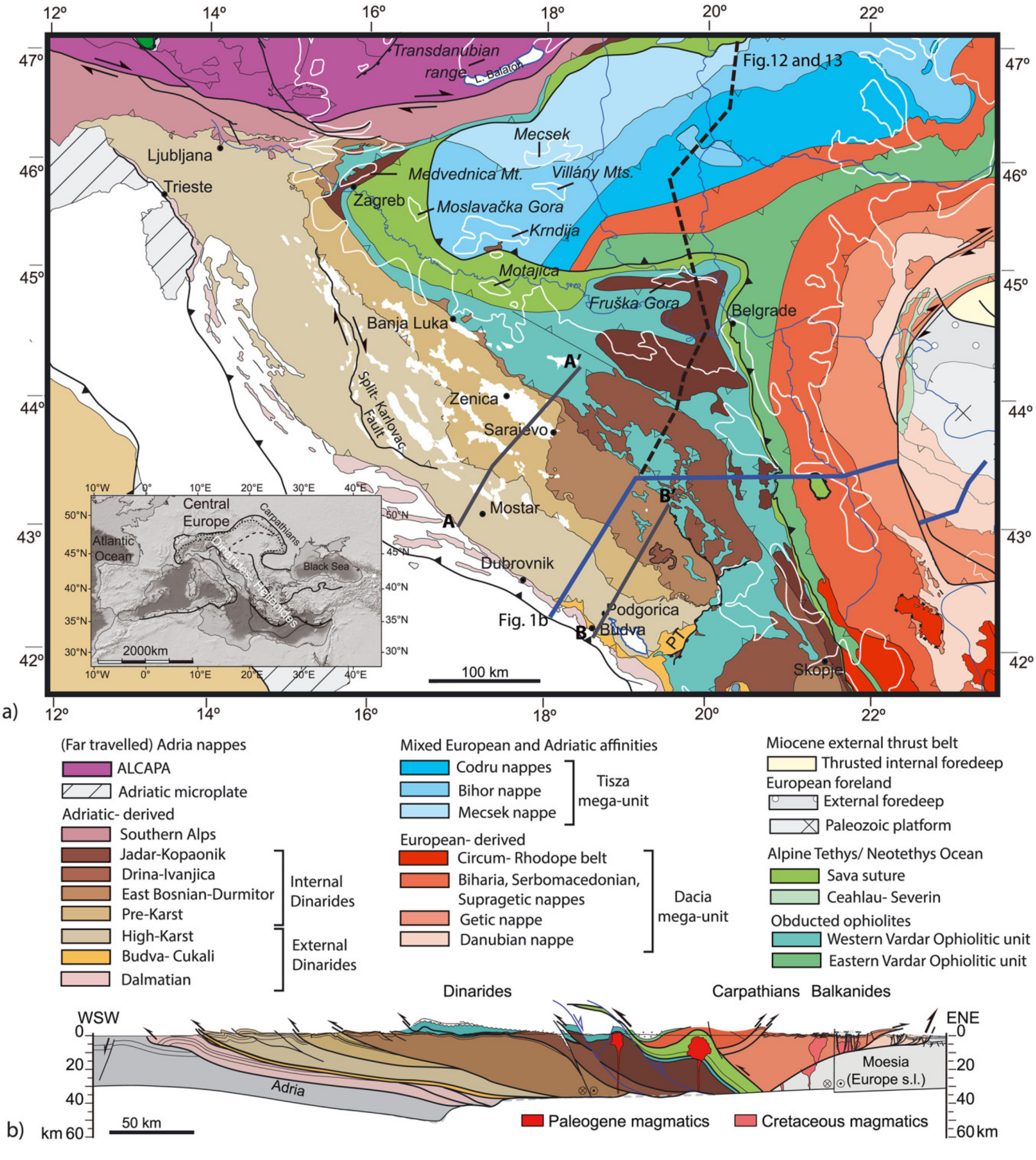


Fig. 4. Geotectonic units in the West Balkans (van Unen et al., 2019 where it was presented compiled and modified after many authors cited therein).

The Bosnia and Hercegovina Dinarides zone is well known for Pb-Zn ores (Veovača, Olovo deposit (Palinkaš et al., 2016), Orti, Rupice (Operta & Hyseni, 2016). While other metal ore deposits are present such as deposits of Fe (e. g. Radovan, Ljubija, Vareš-Smreka (Operta & Hyseni, 2016)) and Cu ores (e. g. Mačkara (Jurković et al, 2010)), and even Sb ore occurs in the Čemernica district (Jurković et al., 1999). The Dinarides in western Central Serbia represent the Zlatibor ore district bearing Fe, while in the Priboj-Tutin Zone and the Polimlje ore district occur Cu deposits (Jelenković et al., 2008). Hydrothermal massive ores of Fe-Cr-Ni sulphides occur in basalts in Albania from the volcano-sedimentary formation of the Middle Triassic - Lower Jurassic ophiolites (Milushi et al, 2012) (Fig. 5).

In the karstic External Dinarides, the most representative mineralisation consists in the form of Fe-bauxite deposits (Šinkovec et al., 1989, Palinkaš et al., 1993, Miko et al., 1999, Radusinović et al., 2017), which extend parallel to the Adriatic coast in Croatia and Montenegro.

2. The Vardar Zone is a belt that lies east of the Dinarides and west of the Serbo-Macedonian Massif. This zone consists of the Srem, Jadar, and Kopaonik blocks separated by ophiolitic fractures (Dimitrijević, 1997). The geological succession of the Vardar Zone consists of small blocks of crystalline schists, Carboniferous Veles Beds, Jurassic ultramafics, Triassic sediments, diabase-chert formations, Jurassic granitoids, Lower and Upper Cretaceous flysch, and Tertiary calc-alkaline volcano-intrusive complexes (Jelenković et al., 2008). The ophiolites of the Vardar Zone consist mainly of Mg-rich peridotite and dunite. Their metallogeny is characterized by major chromite and significant pyritic cupriferous deposits, as well as major magnesite and chrysotile asbestos deposits, locally nickel silicate, and nickeliferous iron deposits.

The Jurassic ophiolites complex (peridotite-pyroxene deposits bearing Cr, Ti, Fe) constitute the main ore mineralisation in the Vardar zone Endogenous ore deposits related to these ophiolitic complexes are mostly Ni-Co-Cu-Fe sulphides, pyritic cupriferous deposits, sporadically magnetite deposits, and minor gold mineralization, but without major chromite deposits (Janković, 1990; Dimitrijević, 1997; Jelenković et al., 2008).

Furthermore, after the previous authors, deposits of hydrothermal massive sulphides of Fe and Cu (particularly important in Albanian basalts) are also present in the Vardar zone unit Ni-Cu mineralisation could be found in Jurassic ultramafic units, as well as the Cr and Ti mineralisation generated during magmatic differentiation.

3. The Serbian-Macedonian Massif spreads North-South along the Great and South Morava valleys in Serbia into western North Macedonia and further into northern Greece (Antić et al., 2016). Metal deposits from the Oligocene-Miocene volcanic intrusive contain ores of Pb and Zn, subordinated of Cu and Sb, accompanied by Au, Ag, As, Ta, Bi and Fe. Hydro-thermal and metasomatic vein type ore deposits are present in the Kopaonik ore region, bearing Pb and Zn and other metals (Ag, Au). Additionally, a Cu porphyry type of deposit is also important in this belt (Fig. 6).

4. The Carpatho-Balkan Arc stretches through Eastern Serbia. The Serbian Carpathians in the northern part is an extension of the Carpathian Range and connects the western parts of the Balkan Mountains (Krstekanić et al., 2020).

Deposits in the Carpatho-Balkanian metallogenic province (eastern Serbian) are often associated with horst-graben structures. These were formed above the subducted oceanic lithosphere under the Eurasian plate and follow the Early Cretaceous closure of a Tethyan branch (Janković, 1990). The most important deposits (Cu, Au, and rare Pb-Zn) are the porphyry copper, skarn type and volcano-hydrothermal (massive-sulphide): Bor deposit, Majdanpek deposit, Veliki Krivelj deposit (Bor metallogenic zone) (Drovenik, 1984) and Ridanj-Krepoljin Zone (Reškovica, Antina Čuka etc.) (Simić et al., 2019).

Fig. 5. Fe-Ni deposit in Albania (Photo: Archive of the Geological Survey of Albania).

Fig. 6. Copper mine in North Macedonia (Photo: Archive of the Geological Survey of Slovenia).

Industrial Minerals and Rocks (including some aggregates)

The West Balkan region has an abundance of aggregates (crushed stones, sand and gravel), although these are only reported from Croatia and Montenegro in the register. Furthermore, bauxite is also abundant in carbonate host rocks throughout the Dinarides (Miko et al., 1999, Radusinović et al., 2017). The bauxite deposits in the register are reported from Croatia, Montenegro, BiH and Albania. In terms of industrial rocks, pure calcite is reported from all countries in the region, while magnesite deposits are reported from BIH and Serbia. Further, dimension stones and different types of clay are also present in the region (Spasovski & Spasovski, 2012; Stolić, 2016; Hajdarević & Babajić, 2018)

Critical Raw Materials

A list of critical raw materials (CRMs) for the EU has been defined by the European Commission (2020). These raw materials are of high importance to the EU economy and their supply is associated with high risk. The most commonly reported CRMs in the West Balkan region are minerals of bauxite, magnesium (Mg), antimony (Sb), and titanium (Ti).

Raw Materials for Electric Vehicle Batteries

Aligned with EU policies and initiatives are relevant regarding battery raw materials (Batteries Directive (2006/66/EC), Strategic Action Plan on Batteries (COM(2019) 176 final), European Battery Alliance (Internet 9), etc.)the register also contains mineral deposits with raw materials used in electric vehicle batteries. All primary minerals for batteries are found in the West Balkan region, except graphite. By providing these raw materials to EU producers of e-vehicle components, the West Balkan represents a great source of support for the EU's transformation into a pro-e-mobility region, and consequently a greener and more sustainable society. There is a high potential for the supply of raw materials to the battery industry in this region.

Conclusion

The European Union aims to become less dependent on imported minerals from other continents. The West Balkan region is recognized by the European Commission as one of the most outstanding potential sources of mineral raw materials.

The Geological Survey of Slovenia, with support from its local partners, took tangible steps in filling the gap in the existing mineral information network through the EIT RM projects. Bringing the West Balkan region into the EU raw materials market also represents another of the project's benefits.

The West Balkan Mineral Register has been created within the RESEERVE project. The mineral data are included in the European information network and thus became publicly accessible and attractive for potential investments in the mineral sector in West Balkans. The Mineral Register provides basic information to reinforce national mineral management and make Europe more mineral self-sufficient, which in turn is crucial for European industry. Data summarized in the Mineral Register will increase the visibility of the most promising mineral sites in the West Balkan region and will serve to increase investments in exploration and potential extraction there. The resulting positive long-term effects will consist in increased innovation in the West Balkan region, the transfer of new technologies, job creation, and will help stem brain-drain in the region.

The complete West Balkan Mineral Register is freely available on the RESEERVE project's website: https://reseerve.eu/results.

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Analiza nihanja gladine podzemne vode na območju plitvih aluvialnih vodonosnikov Pomurja v SV Sloveniji

Groundwater level oscillation analysis in shallow alluvial aquifers in Pomurje, NE Slovenia

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Key words: Groundwater level, alluvial aquifers, cluster analysis, percentile analysis, time series, trend analysis, sequential trend analysis, Pomurje, Slovenia

Izvleček

Sistematično spremljanje gladin podzemne vode na državni ravni v Sloveniji poteka že od leta 1952. Analiza dolgoletnih podatkov gladin podzemne vode nam omogoča ugotavljanje posebnosti in sprememb v nihanju gladine podzemne vode v prostoru in času. V članku z uporabo različnih statističnih analiz značilnih mesečnih gladin podzemne vode ugotavljamo, kaj nam dolgoletni podatkovni nizi nihanja podzemne vode razkrivajo o vodonosnikih vodnega telesa podzemne vode Murska kotlina. Na podlagi rezultatov uporabljenih metod zaključimo, da se v nihanju gladine podzemne vode Pomurja odražajo kompleksni dejavniki, ki imajo mestoma izvor v naravnih vplivih napajanja in praznjenja vodonosnika, mestoma pa v človeških posegih v prostor. Z metodo percentilnih analiz v kombinaciji s clustersko analizo smo določili območja s sorodnim nihanjem gladine podzemne vode, z dolgoročnimi trendi mesečnih gladin podzemne vode pa smo se opredelili do povezave med nihanjem vodnih količin in podnebnimi značilnostmi raziskovanega ozemlja. Poleg naravnih, smo z metodo trendov nihanja gladin podzemne vode, izdvojili nekatera območja z izkazanim antropogenim vplivom na vodno telo podzemne vode.

Abstract

Systematic hydrologic monitoring of groundwater quantity at the national level in Slovenia has been ongoing since 1952. An insight into long-term groundwater level data enables us to delineate parts of aquifers with similar groundwater level oscillation properties as well as to identify changes of those properties in time. We used variety of statistical methods to identify long-term behaviour of groundwater level oscillation of groundwater body (GWB) Murska kotlina. Results showed that fluctuation of groundwater level in time reflect complex set of events that originate in natural or anthropogenic interferences. Using percentile analysis in combination with cluster analysis, we were able to isolate areas with a related groundwater fluctuation. Results of long-term data trends analyses of monthly groundwater level showed the impact of the research area climate on long-term and seasonal groundwater level fluctuation. In addition to natural causes, by performing trend analysis on groundwater level data, we were able identify some human induced interventions into the environment made in the past.

Uvod

»Meriti pomeni vedeti«, je menil že Lord Kelvin (1883). Podatki o gladinah podzemne vode predstavljajo osnovni vir informacije o količinah podzemne vode, hidroloških pritiskih, ki se izvajajo na vodonosnik, in o tem, kako ti pritiski vplivajo na napajanje, uskladiščenje in odtok podzemne vode. Dolgoročne sistematične meritve gladine podzemne vode zagotavljajo osnovne informacije za oceno sprememb vodnih virov v času, za razvoj analitičnih in numeričnih modelov toka podzemne vode, za napoved trendov ter za načrtovanje, vpeljavo in spremljanje učinkovitosti upravljanja z vodami in pripravo programov zaščite podzemne vode (Taylor & Alley, 2001).

Podzemna voda je le del vodnega kroga, katere količina se lahko v času spreminja. Za natančno prepoznavo vzrokov, ki so povzročili spremembe v količinah podzemne vode, so potrebne temeljite lokalne raziskave vodnega okolja. Pred izvedbo natančnih hidrogeoloških raziskav, usmerjenih v zasledovanje ciljev, povezanih z ugotavljanjem količinskega stanja podzemne vode na lokalni ravni, je smiselna predhodna analiza razpoložljivih podatkov časovnih vrst državnega monitoringa količinskega stanja podzemne vode. Državna zbirka hidroloških podatkov nam zaradi dolgega opazovalnega niza meritev na merilnih lokacijah nudi vpogled v razmere v vodonosnikih tako v času kot tudi v prostoru.

Območje Pomurja je bilo zaradi razmeroma nizke globine do podzemne vode med prvimi v državi, kjer je bil vzpostavljen sistematični državni monitoring količin podzemne vode, v letu 1952 se je na Prekmurskem polju opazovalo gladino podzemne vode na 16 lokacijah. Opazovanja so bila ročna vse do leta 1970, ko so se pričela le-ta nadomeščati z limnigrafskimi meritvami, v letu 2000 pa z avtomatskimi podatkovnimi zapisovalci, ki predstavljajo prevladujoč način zapisovanja meritev tudi danes.

Namen raziskav prispevka je bila preveritev, ali nam lahko državna baza merjenih hidroloških in hidrogeoloških podatkov Agencije RS za okolje na območju plitvih aluvialnih vodonosnikov Pomurja, ob uporabi izbranih metodoloških pristopov, nudi vpogled v časovno dinamiko nihanja gladin podzemne vode na posameznih merilnih območjih in ali je ta dinamika primerljiva med merilnimi postajami. Na podlagi analize trendov gladin podzemne vode smo v nadaljevanju želeli preveriti, ali na območju Pomurja prihaja do dolgoročnih sprememb gibanja gladin podzemne vode ter se na podlagi rezultatov skušali opredeliti do vzroka teh sprememb.

Raziskovano območje

Raziskovano območje predstavljajo plitvi kvartarni prodno peščeni vodonosniki ob Muri, ki so zajeti v vodnem telesu podzemne vode (VTPodV) Murska kotlina (Uradni list RS, št. 63/2005). VTPodV Murska kotlina leži v SV delu Slovenije in s svojimi 591 km^2 pripada tektonski enoti Panonskega bazena. Območje tega vodnega telesa zajema celotno prekmursko nižino med Goričkim, Lendavskimi in Slovenskimi goricami. Pod zgornjimi vodonosniki se nahajajo še vodonosniki v terciarnih sedimentih, pod tem pa termalni vodonosniki v globljih terciarnih sedimentih in predterciarni podlagi (Prestor et al., 2005).

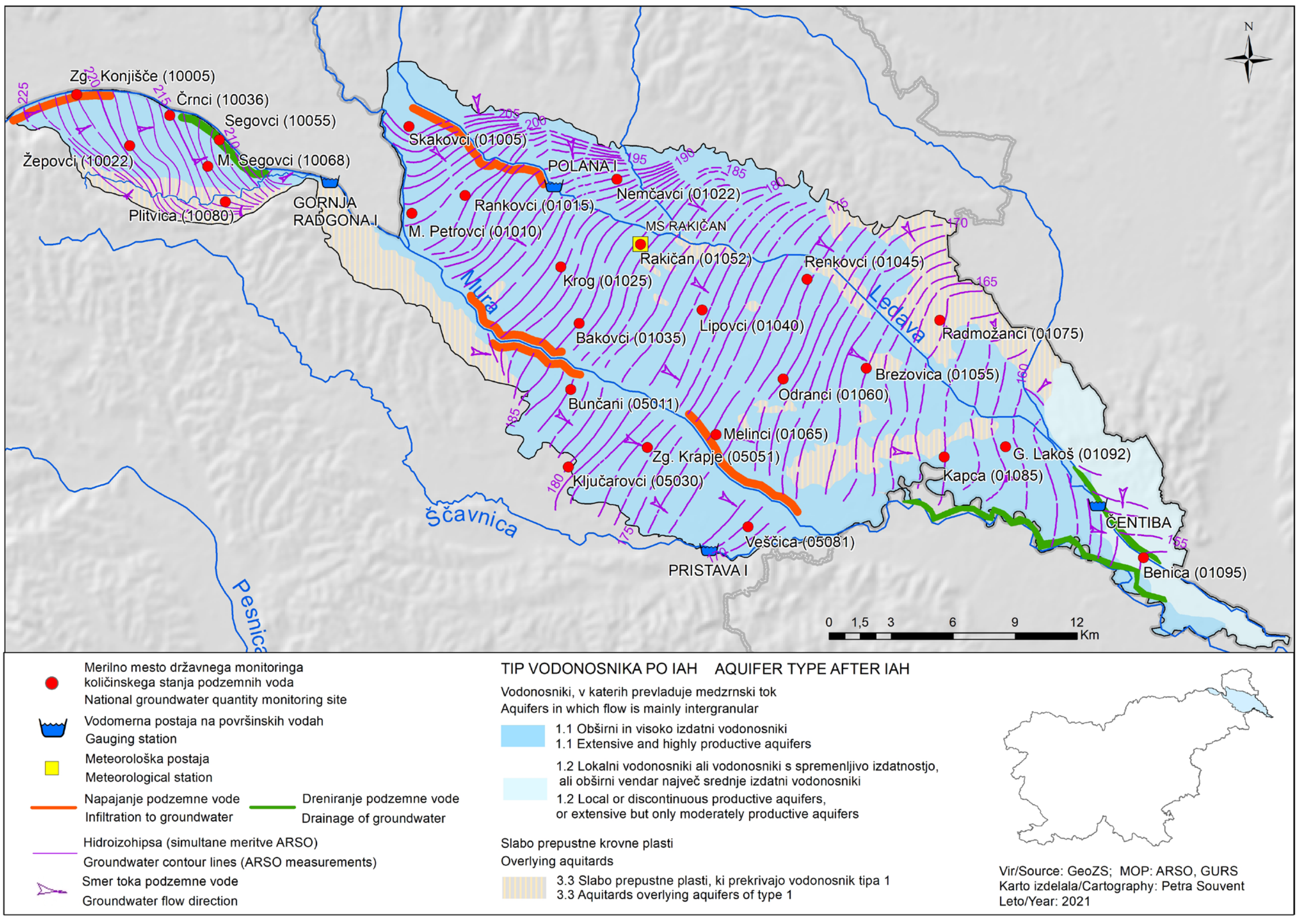
Območje Pomurja je bilo v preteklosti skoraj v celoti zamočvirjeno in gozdnato, prepleteno s številnimi vodotoki, ki so jih v 18. stoletju začeli sistematično regulirati in tako posredno osuševati zemljišča za začetek kmetijstva (Novak, 2009). Večino območja nad vodonosnikom prekrivajo kmetijske površine.

Sistematične hidrogeološke raziskave na območju plitvih vodonosnikov Pomurja segajo v sedemdeseta leta prejšnjega stoletja, ko je bila podana hidrogeološka slika ozemlja, ocenjena prepustnost in izdatnost vodonosnikov ter vodna bilanca (Drobne, 1974). V začetku osemdesetih let so se hidrogeološke raziskave na obravnavanem območju izvajale predvsem z namenom zagotavljanja oskrbe s pitno vodo in raziskav za melioracije Ledave (Drobne, 1983; Meden, 1981). Karta gladin podzemne vode širšega raziskovanega območja je bila izdelana v okviru simultanih meritev na Hidrometeorološkem Zavodu Ljubljana (Savić, 1992). V sklopu nacionalne baze hidrogeoloških podatkov za opredelitev teles podzemne vode v RS je bil izdelan konceptualni model vodnega telesa podzemne vode Murska kotlina (Prestor et al., 2005). Z namenom ureditve celovite oskrbe prebivalstva s pitno vodo in varovanja vodnih virov v Pomurju so bile izvedene obsežne hidrogeološke raziskave in strokovne podlage za območji vodonosnikov Mursko polje in Dolinsko Ravensko (Petauer et al., 2007). Z namenom določanja modelskih izhodiščnih količin podzemne vode na območju vodnega telesa Murska kotlina in oceno medsebojnih vplivov med porabniki podzemne vode je bil za raziskovano ozemlje izdelan stacionarni numerični model toka podzemne vode (Vižintin et al., 2011: Vižintin et al., 2014). Za Apaško polje je bila izdelana analiza vpliva nizkega vodnega stanja reke Mure in podzemnih voda Apaškega polja na količinske in kakovostne parametre črpališča Podgrad (Feguš & Golnar, 2012). S podrobnim hidrogeološkim kartiranjem med Goričkim in Prekmurskim poljem je bila opredeljena karta gladin podzemne vode in določene smeri njenega toka (Koren et al., 2015).

Plitvi vodonosniki obravnavanega vodnega telesa podzemne vode sestavljajo pretežno odprti vodonosniki kvartarne starosti (njeno obrobje pa tudi miocenski, pliocenski in pliokvartarni sedimenti in kamnine), ki so nastali s peščeno prodnimi nanosi reke Mure in njenih pritokov (Plitvica, Kučnica, Ledava s pritoki, Bukovnica, Kobiljski potok, Ščavnica) (Prestor et al., 2005). Glavni vir napajanja podzemne vode so padavine (srednja letna višina padavin obdobja 1981-2010 je 798 mm), dotok površinskih vod z območja Slovenskih in Lendavskih goric, Goričkega ter površinski vodotoki, predvsem reka Mura. Podlago kvartarnega zasipa gradijo pliocenski sedimenti, ki so po svoji sestavi za vodo zelo slabo prepustni.

Vodonosniki so prekriti z različno debelo plastjo gline, melja in peska, ki je ponekod skoraj odnešena, drugod pa preseže debelino 2 m, na severnem robu pa je debelina tudi do 7 m. Ta, v večjem delu plitev pokrov, tanjši od 2 m, je za vodo slabo do zelo slabo prepusten, koeficient prepustnosti teh sedimentov znaša med $1*10^{-6}$ in $1*10^{-8}$ m/s (Petauer et al., 2007). Hidrodinamične značilnosti vodonosnika vplivajo na režim napajanja in praznjenja vodonosnika, kar vpliva tudi na kemijsko stanje podzemne vode, ki se v prostoru spreminja (Gacin, 2015). Koeficient prepustnosti visoke Murske terase na Mursko-Ljutomerskem polju znaša med $1*10^{-5}$ in $1*10^{-3}$ m/s, nizke Murske terase pa med $2*10^{-3}$ in $8*10^{-3}$ m/s. Prepustnost vodonosnika Dolinsko Ravenskega je velikostnega reda $3*10^{-3}$ in se nekoliko spreminja glede na lokacijo (Petauer et al., 2007). Prodni nasip Mure je na severovzhodnem delu debel približno 5 m ter se pravokotno na Muro debeli do 8 m, na meji z Goričkim izklini, na jugovzhodu pa se debelina vodonosnika poveča na preko 11 metrov (Kralj, 1979).

Iz karte gladin podzemne vode izvedene s simultanimi meritvami vodnih gladin v letu 1992 (Savić, 1992) je razvidno, da na severnem in severovzhodnem obrobju vodnega telesa in na jugovzhodnem robu polja na območju dotokov z Lendavskih goric podzemna voda vodonosnika Dolinsko Ravenskega teče v smeri proti jugu oziroma jugovzhodu (sl. 1). Na severnem delu se vodonosnik napaja z Goričkega, vendar so količine glede na prostorsko porazdelitev gladine podzemne vode relativno majhne (Koren et al., 2015). Na podlagi stacionarnega numeričnega modela toka podzemne vode je bil delež dotoka iz zaledja Goričkega in Lendavskih goric ocenjen na 0,26 m^3/s (Vižintin et al., 2014). Primerljiv delež dotoka vode v modelu je bil določen tudi za ob-



Sl. 1. Hidrogeološka karta raziskovanega ozemlja z lokacijami merilnih mest, uporabljenih v analizah. Prostorski podatkovni sloji na karti in njihovi viri: Merilna mesta državnega monitoringa količinskega stanja podzemnih voda, vodomerne postaje na površinskih vodah in meteorološka postaja (MOP-ARSO); napajanje/dreniranje podzemne vode, hidroizohipse in smer toka podzemne vode (MOP-ARSO simultane meritve avgust-september 1992; Savić 1992), tip vodonosnika IAH (GeoZS), kartografska podlaga in rečna mreža (MOP-GURS).

Fig. 1. Hydrogeological map of research area with monitoring sites included in the analyses. Spatial data on the map and their sources: national groundwater quantity monitoring sites, gauging stations and meteorological station (Ministry of the Environment and Spatial Planning-Slovenian Environment Agency); infiltration to/drainage of groundwater, groundwater contour lines and flow direction (Ministry of the Environment and Spatial Planning- Slovenian Environment Agency measurements; Savić, 1992); aquifer type after IAH (Geological Survey of Slovenia); base map and river network (Ministry of the Environment and Spatial Planning-Surveying and Mapping Authority).

močje severozahodnega dela Prekmurskega polja na območju Kučnice. V osrednjem in južnem delu polja prevladuje smer toka podzemne vode od zahoda, severozahoda proti vzhodu, jugovzhodu, skoraj vzporedno s tokom Mure (Savić, 1992). V iztočnem, jugovzhodnem delu vodonosnika med Kapco in Benico podzemna voda konvergira proti vodotokoma Ledave in Mure, v katera se podzemna voda tudi izteka. Na zahodnem robu vodonosnika Mursko-Ljutomerskega polja, na mejnem območju s Slovenskimi goricami, je prevladujoča smer toka podzemne vode od zahoda proti vzhodu. V osrednjem delu polja podzemna voda teče v smeri od severozahoda proti jugovzhodu, vzporedno z reko Muro. To smer zadrži do jugovzhodnega roba polja do meje z Muro in Ščavnico. Tok podzemne vode na Apaškem polju poteka na severnem vtočnem delu v smeri toka reke Mure od zahoda, jugozahoda proti vzhodu, severovzhodu. Podobna smer prevladuje tudi v osrednjem delu polja, na severovzhodnem, iztočnem robu polja pa se tok podzemne vode usmeri od jugozahoda proti severovzhodu. Južni rob vodonosnika napajajo vode iz prispevnega zaledja Slovenskih goric, zaradi česar v tem delu prevladuje smer toka podzemne vode od juga proti severu (sl. 1).

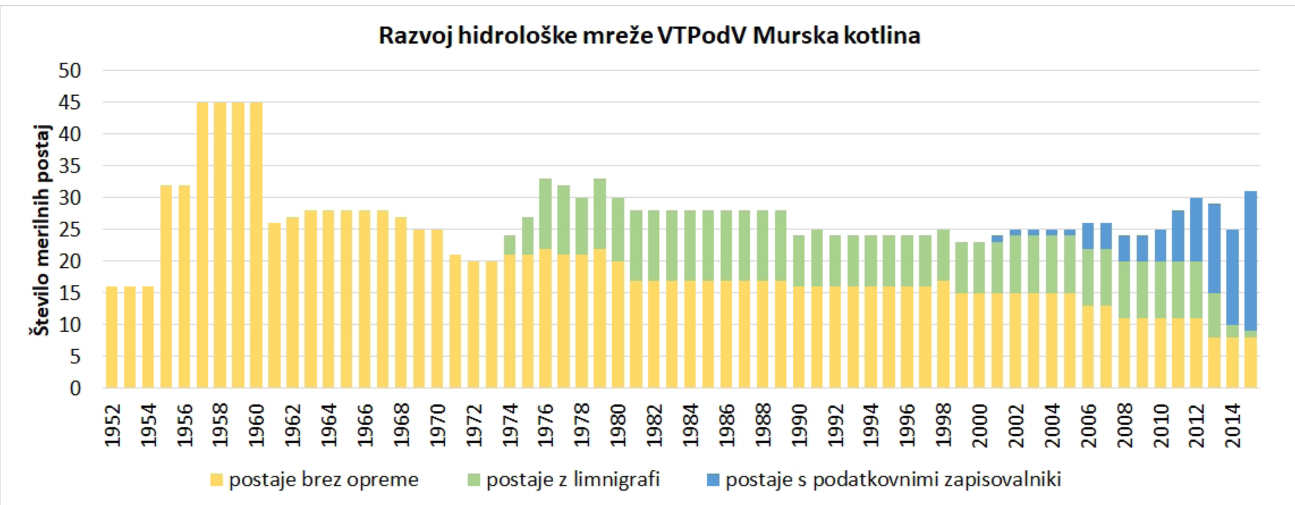
Reka Mura pomembno prispeva h količinskemu stanju podzemne vode na območju VTPodV Murska kotlina. Na pretočni režim reke Mure vpliva taljenje snega iz visokogorskega prispevnega zaledja, zato ima ta reka izrazit višek pretokov v maju in izrazit nižek v januarju. Kljub temu ima Mura v zadnjih desetletjih vse višje tudi jesenske vode (Bat et al., 2008). Mura drenira prodno peščen vodonosnik Prekmurskega polja med Petanjci in Bakovci, med Hrastjem in Babičevim mlinom pri Veržeju ter med Hotizo in Mursko šumo. Mura napaja vodonosnik Prekmurskega polja med Melinci in Dolnjo Bistrico (Vižintin et al., 2011). Ledava napaja vodonosnik Prekmurskega polja med Skakovci in Polano in drenira vodonosnik med Lendavo in Pincami na levem bregu Ledave med reko in Lendavskimi goricami (Vižintin et al., 2011).

Ocena količinskega stanja podzemne vode VTPodV Murska kotlina, izvedena za potrebe načrta upravljanja z vodami, je pokazala, da sodi VTPodV Murska kotlina glede na rabo vode med bolj obremenjena v državi (Andjelov in sod., 2021). Razmerje med povprečnimi letnimi količinami črpanja podzemne vode glede na evidenco vodnih povračil Direkcije RS za vode v obdobju 2014 – 2019 in razpoložljivo količino podzemne vode ocenjeno z regionalnim vodnobilančnim modelom GROWA-SI za obdobje 1991–2020 v tem vodnem telesu znaša okrog 21 % in je tretje najvišje v državi.

Vhodni podatki

Vsi podatki v članku, ki smo jih uporabili v analizah, so iz zbirke javnih podatkov državnega monitoringa, s katerim upravlja Agencija Republike Slovenije za okolje. Državni hidrološki monitoring gladin podzemne vode se izvaja v zgornjih, plitvih aluvialnih vodonosnikih VTPodV Murska kotlina.

Temelji sistematičnega izvajanja hidrološkega monitoringa podzemnih voda v Sloveniji segajo v 50. leta prejšnjega stoletja, ko je bila izdana Odredba o ustanovitvi Uprave hidrometeorološke službe pri tedanji vladi Ljudske Republike Slovenije. S tem so bili postavljeni temelji za hidrološko dejavnost, na katero je vplivalo predvsem



Sl. 2. Razvoj hidrološke mreže na območju VTPodV Murska kotlina.
Fig. 2. Development of groundwater monitoring network on GWB Murska kotlina.

varstvo naselij pred vodnimi ujmami, izraba vodne energije in kompleksno vodno gospodarstvo. Na raziskovanem ozemlju s podatki razpolagamo od leta 1952 dalje, ko je na območju Prekmurskega polja oz. vodonosnika Dolinsko Ravenskega delovalo 16 merilnih postaj. Sprva so bile meritve ročne, opazovalec je enkrat na dan oziroma nekajkrat na teden ali mesec na merilnem traku izmeril ali na števni napravi odčital globino do podzemne vode. Leta 1974 so se ročne meritve pričele dopolnjevati z limnigrafskimi, s čimer se je na papir zvezno izrisoval nivogram, leta 2001 pa so pričeli delovati prvi digitalni podatkovni zapisovalniki (sl. 2). Z uvedbo merjenja gladine podzemne vode z limnigrafi in podatkovnimi zapisovalniki se je informativna vrednost podatkov izboljšala predvsem zaradi povečane frekvence meritev. Natančnost meritev se je s časom mestoma povečevala tudi z izgradnjo namenskih opazovalnih objektov monitoringa stanja podzemne vode, ki se je na območju vodonosnikov Pomurja pričelo leta 2009.

Na Agenciji RS za okolje (v nadaljevanju ARSO) je bil tako v preteklosti kot je tudi danes velik poudarek monitoringa namenjen zagotavljanju kakovosti meritev, kar zagotavlja visoko stopnjo zaupanja v podatke. Za izvajanje državne hidrološke službe in strokovne naloge spremljanja stanja okolja je vzpostavljen in vzdrževan sistem vodenja, ki izpolnjuje zahteve standarda SIST ISO 9001:2000. Kakovost podatkov monitoringa količinskega stanja podzemnih voda se zagotavlja z načrtovanim izborom in vzdrževanjem merilnih mest, z umerjanjem merilne opreme ter z ustrezno strukturo, varovanjem in kontrolo podatkov. Na vseh merilnih mestih državnega monitoringa podzemnih voda se od samega začetka delovanja merilne postaje izvajajo mesečne kontrolne meritve. Potrebna natančnost merjenih veličin je ±0,01 m za globino oz. višino vode in ±1 % merjene vrednosti za hitrost toka površinske vode. Sledijo višje obdelave podatkov, ki vključujejo ekspertni pregled kakovosti posameznih časovnih vrst, pri čemer se oceni in po presoji odstrani ali prilagodi merjene vrednosti, ki so lokalnega značaja in za spremljanje dolgoročnega monitoringa vodnih količin niso relevantne (npr: zatekanje padavinske vode neposredno v opazovalni objekt, lokalno črpanje vode iz opazovalnega objekta za potrebe zalivanja poljščin in podobno). Po končanih osnovnih in višjih obdelavah se podatki verificirajo in arhivirajo v državno zbirko hidroloških podatkov.

Homogenizacija podatkov hidrološkega monitoringa podzemne vode

Od leta 2009 naprej se je državna merilna mreža monitoringa količinskega stanja podzemne vode na območju Pomurja pričela posodabljati na način nadomeščanja starih objektov (vaški vodnjaki) z modernejšimi objekti (namenski piezometri), pri čemer se je na nekaterih območjih v obdelovalnem obdobju analiz v krajšem obdobju istočasno spremljalo nihanje podzemne vode na dveh bližnjih merilnih postajah. V izogib podvajanju rezultatov smo iz izbranih analiz izvzeli podvojene merilne postaje. Da bi ohranili celoten niz meritev gladin podzemne vode nove kot nadomeščene postaje, smo podatke homogenizirali. Ob ugotovljeni dobri linearni korelaciji med staro in novo merilno postajo (korealacijski koeficient R^2>0.95), smo podatke stare merilne postaje prek enačbe linearne regresijske premice prevedli na nivo podatkov nove merilne postaje. Opisana homogenizacija je bila za potrebe tega prispevka izvedena za naslednje pare merilnih postaj: Gornji Lakoš 0271 – Gornji Lakoš Glak-2/14, Zgornje Krapje 0400 – Zgornje Krapje (Kr-2/09), Veščica 0120 – Veščica Ve-2/09, Žepovci 0300 – Žepovci Žep 1/11 in Črnci 0136 – Črnci Črn 1/11 (Tab.1). Nekateri merilni objekti (Apaško polje: Žepovci (10020), Dolinsko Ravensko: Lipovci (01040) in Renkovci (01045)) so v času zelo nizkih vodnih razmer presušili. Za čas presušitev smo na teh merilnih mestih kot višino gladine podzemne vode upoštevali dno merilnega objekta ter na ta način ohranili pomemben del informacije o vodnih razmerah v vodonosniku.

Podatki uporabljeni v analizah prispevka

Za merilne postaje podzemne vode smo analizirali parameter nadmorske višine gladine podzemne vode, za merilne postaje površinske vode pretok vodotoka na izbranem merskem profilu, za meteorološko merilno postajo v Murski Soboti pa vsoto padavin. Osnovni vhodni podatki so bili agregirani na nizke, srednje in visoke (v nadaljevanju: značilne) mesečne gladine podzemne vode, značilne mesečne pretoke vodotokov in mesečno vsoto padavin. V študiji sekvenčnih trendov gladin podzemne vode smo večji pomen kot povprečnim in visokim mesečnim gladinam podzemne vode oziroma pretokom vodotokov posvečali nizkim vodnim količinam. Privzeli smo, da so nizke vodne količine primerni kazalec dinamike toka podzemne vode, saj vsebujejo te časovne vrste določeno stopnjo spomina (Pavlič, 2016). Naključnost visokovodnih dogodkov v hidrologiji je razmeroma velika in zato ti niso enakovreden pokazatelj dolgoročnih značilnosti v nihanju količin podzemne vode nizkim količinam podzemne vode.

V letu 2015 se je globino do podzemne vode na območju vodonosnikov vodnega telesa VTPodV Murska kotlina spremljalo ročno na 8. merilnih postajah, na 1 merilni postaji so se hidrološke meritve izvajale na način limnigrafskega zveznega beleženja višin vodnih gladin, na 22 merilnih lokacijah pa so se meritve izvajale na način digitalnih meritev s podatkovnimi zapisovalci podatkov (sl. 2). V prispevku smo clustersko analizo in analizo percentilov izvedli na skupno 25 merilnih mestih, analizi trendov pa na 17 merilnih mestih (Tabela 1). Dolžine izbranih časovnih vrst niso enake (Tabela 1). Iz nabora merilnih

Tabela 1. Merilna mesta državnega hidrološkega monitoringa podzemne vode VTPodV Murska kotlina v letu 2015 uporabljena v analizah.

Table 1. Monitoring sites of national groundwater monitoring network on GWB Murska kotlina in the year 2015, used in analyses.

Vodonosni sistem	Ime merilnega mesta	Šifra merilnega mesta	Pričetek obdelave (leto)	Clusterska analiza	Analiza percentilov	Analiza monotonih trendov	Analiza sekvenčnih trendov
Dolinsko Ravensko	Skakovci 3471	01005	1990	DA	DA		
	Murski Petrovci 3552	01010	1990	DA	DA		
	Rankovci 3370	01015	1968	DA	DA	DA	DA
	Nemčavci 2762	01022	1998	DA	DA		
	Krog 2932	01025	1990	DA	DA		
	Bakovci 2630	01035	1981	DA	DA	DA	DA
	Lipovci 2270	01040	1953	DA	DA	DA	DA
	Renkovci 0850	01045	1953	DA	DA	DA	DA
	Rakičan Rak-2/09	01052	2011	DA	DA		
	Brezovica 0970	01055	1979	DA	DA	DA	DA
	Melinci 2000	01065	1974	DA	DA	DA	DA
	Radmožanci 0411	01075	1979	DA	DA	DA	DA
	Kapca 0473	01085	1991	DA	DA		
	Gornji Lakoš 0271	01090	1981			DA	DA
	Gornji Lakoš Glak-2/14	01092	2015	DA	DA		
	Benica 0111	01095	1990	DA	DA		
Mursko–Ljutomersko polje	Bunčani 0611	05011	1955	DA	DA	DA	DA
	Ključarovci 0540	05030	1955	DA	DA	DA	DA
	Zgornje Krapje 0400	05050	1955			DA	DA
	Zgornje Krapje (Kr-2/09)	05051	2011	DA	DA		
	Veščica 0120	05080	1974			DA	DA
	Veščica Ve-2/09	05081	2011	DA	DA		
Apaško polje	Zgornje Konjišče S-0176	10005	1976	DA	DA	DA	DA
	Žepovci 0300	10020	1975			DA	DA
	Žepovci Žep 1/11	10022	2012	DA	DA		
	Črnci 0163	10035	1981	DA	DA		
	Črnci Črn 1/11	10036	2012	DA	DA	DA	DA
	Segovci 0141	10055	1981	DA	DA	DA	DA
	Mali Segovci MSeg-1/14	10068	2015	DA	DA		
	Plitvica 0090	10080	1981	DA	DA	DA	DA

mest, uporabljenih v analizah monotonih in sekvenčnih trendov, smo izvzeli merilna mesta z naborom podatkom krajšim od 30 let. Iskali smo namreč dolgoročne spremembe v nihanju gladine podzemne vode raziskovanega območja, zaradi česar bi bili lahko rezultati časovnih vrst s krajšim obdobjem merjenja zavajajoči. Za analizo sekvenčnih trendov vodnih količin smo uporabili le časovne vrste s frekvenco meritev vsaj trikrat mesečno, kar predstavlja minimalni nabor vrednosti za izračun značilnih mesečnih vodnih količin.

Poleg merilnih mest hidrološkega monitoringa podzemne vode smo analize trendov izvedli tudi za podatke hidrološkega monitoringa površinskih voda na merskih profilih Mura - Gornja Radgona, Ledava – Čentiba, Ledava - Polana in Ščavnica – Pristava ter za podatke meteorološkega monitoringa v Murski Soboti (Tabela 1, sl. 1).

Metode dela

Nabor uporabljenih metodologij smo izbrali na podlagi zasledovanja cilja raziskovalnega problema. Gre za razmeroma široko znane statistične metode v hidrologiji časovnih vrst (Helsel & Hirsch, 2002; Tallaksen & Van Lanen, 2004). Percentilna analiza gladin podzemne vode predstavlja robustno opisno statistiko za oceno količinskega stanja podzemne vode na dnevni, mesečni ali letni skali (Post, 2013; Tallaksen & Van Lanen, 2004). Analiza razvrščanja časovnih podatkov o višinah gladin podzemne vode v skupine (clusterska analiza) se v zadnjem času pogosto uporablja v začetni fazi hidrogeoloških raziskav z namenom razvrščanja merilnih lokacij v skupine s sorodnim odzivom dela vodonosnika na zunanje vplive napajanja in praznjenja le-tega (Haaf & Barthel, 2018; Naranjo – Fernandez et al., 2020). Analiza trenda oziroma analiza odvisnosti nihanja izbrane spremenljivke po času sodi med uveljavljene statistične metode za ugotavljanje sprememb nihanju vodnih količin (Gibbons, 1994; Helsel & Hirsch, 2002). V novejših raziskavah se analiza trenda pogosto uporablja kot dopolnilna metoda matematičnim modelom toka podzemne vode in vodno bilančnih modelov za ugotavljanje vpliva podnebnih sprememb na količine podzemne vode (Jackson et al., 2015; Green, 2016; Haas & Birk, 2019; Li et al., 2020; Kumar & Singh, 2015). Analize trendov so pogoste tudi v raziskavah, ki se nanašajo na pogostost suš v vodonosnikih in odkrivanje ostalih pritiskov na obnovljive količine podzemne vode (Haas & Birk, 2019; Shamsudduha et al., 2009; Jackson et al., 2015). V Sloveniji smo kot člani Evropske Skupnosti analize trendov pričeli sistematično izvajati z vpeljavo Direktive Evropskega parlamenta in Sveta 2000/60/ES. V primeru dostopnih podatkov o gladini podzemne vode v vodnem telesu podzemne vode se ti podatki uporabljajo za ugotavljanje napredujočega trenda zniževanja gladin od leta 1990 dalje, povzročenega zaradi prevelike rabe podzemne vode (Andjelov et al., 2019, Andjelov et al., 2021). Sekvenčna analiza trendov nihanja gladin podzemne vode se v hidrologiji uporablja predvsem v oceni sezonske spremenljivosti nihanja količinskega stanja podzemne vode (Satish Kumar & Rathnam, 2020; Kumar et al., 2018; Li et al., 2020), pa tudi z namenom ugotavljanja sprememb v trendih nihanja dolgoletnih vodnih količin (Garbrecht & Fernandez, 1994; Bonacci, 2007). Na območju izvirov Vipave so se sekvenčne analize trendov izvajale z namenom karakterizacije odtoka iz prispevnega zaledja izvirov (Pavlič & Brenčič, 2011).

Clusterska analiza

Po metodi razvrščanja v clustre razvrstimo objekte v bolj ali manj homogene skupine na način, da se izrazijo zveze med posameznimi clustri. Če imamo n predmetov in merimo m značilnosti, metoda razvrščanja v clustre izrazi mere podobnosti med vsako dvojico predmetov. Primer izračuna koeficienta podobnosti k_i je Evklidova razdalja d_{ij}. Izračunamo ga po enačbi:

$$d_{ij} = \sqrt{\frac{\sum_{k=1}^{m}(X_{ik} - X_{jk})^2}{m}}$$

X_{ik} pomeni k-to spremenljivko, merjeno na predmetu i in X_{jk} pomeni k-to spremenljivko, merjeno na predmetu j. Matriko n × m naravnih podatkov pred izračunom indeksa razdalje standandiziramo (Zupančič, 2013).

Analiza percentilov

Percentilni rang je standardna statistična metoda, ki daje relativen položaj številčne vrednosti (v našem primeru povprečne mesečne gladine podzemne vode) v primerjavi z vsemi drugimi številčnimi vrednostmi v porazdelitvi. Percentil je vrednost na lestvici od 0 do 100, ki označuje odstotek opazovanj, ki je enak ali pod to vrednostjo. P-ti percentil izračunamo po enačbi:

$$P_j = X_{(n+1)} * j$$

n predstavlja velikost vzorca X_i, j pa del podatkov, ki je manjši ali enak percentilni vrednosti.

V analizi smo uporabili percentilni rang, ki je mesto oziroma položaj izmerjene gladine podzemne vode na odstotni lestvici glede na rezultat, ki ga je ta meritev dosegla pri celotnem naboru meritev, ki ji tudi sama pripada.

Analiza trenda s statistično značilnostjo po Spearmanu

Monotoni trend posamezne analizirane spremenljivke v času smo testirali z uporabo metode neparametričnega Spearmanovega koeficienta korelacije rangov ρ s 95 % intervalom zaupanja. Spearmanov koeficient korelacije rangov je definiran z vsoto razlik rangov *(R)* med odvisno y in neodvisno x spremenljivko, pri čemer n predstavlja število vseh enot (parov rangov), in ga lahko zapišemo kot (Yue et al., 2002):

$$\rho = 1 - \frac{6\sum_{i=1}^{n}(R(x_i) - R(y_i))^2}{n(n^2-1)}$$

Analiza sekvenčnih trendov

Za ugotavljanje strukturnih sprememb znotraj uporabljenih časovnih nizov podatkov smo uporabili programski sistem R za statistične izračune, knjižnico Strucchange (Zeileis et al., 2002).

V časovni vrsti lahko predvidevamo, da obstaja m točk, pri katerih se regresijski koeficient spremeni iz ene stabilne regresije v drugo. Torej obstaja m+1 segmentov, pri katerih so regresijskih koeficienti konstantni in linearno regresijsko enačbo lahko zapišemo kot:

$$y_i = x_i^\intercal\beta_j + u_i \qquad (i = i_{j-1}+1,\dots,i_j, j = 1,\dots,m+1),$$

kjer je j segmentni indeks, $i_{m,n}=\{i_1, \dots, i_m\}$ prispevek nabora točk prevoja ($i_{m,n}$ se imenuje tudi m-particija). Običajno znaša $i_0=0$ in $i_{m+1}=n$.

V praksi je število točk prevoja pogosto neznano, zato se mora oceniti iz podatkov. Model standardne linearne regresije tako primerjamo s podatki, pri čemer se izpelje empirični proces, ki zajame nihanje ali ostankov modela ali pa samih parametrov modela. Znotraj ničelne hipoteze se to ureja s centralnim limitnim izrekom funkcije (Kuan & Hornik, 1995), pri čemer lahko določimo preseganje meje z verjetnostjo α znotraj ničelne hipoteze. Znotraj alternative se normalno nihanje v procesu spremeni, kar predstavlja odstopanje od ničelne hipoteze. V analizi smo za preverjanje konstantnosti regresijskih odvisnosti v času uporabili kombinacijo testov (RE, CUSUM in MOSUM), ki temeljijo na porazdelitvi rekurzivnih in standardnih ostankov najmanjših kvadratov podatkovne osnove. Standardni ostanki najmanjših kvadratov predstavljajo najmanjšo vsoto kvadratov razlik med vrednostmi odvisne spremenljivke od pričakovane vrednosti te spremenljivke glede na linearni regresijski model. Izračun rekurzivnih ostankov linearnega regresijskega modela pa lahko zapišemo kot (Hackl, 2016):

$$W_t = \frac{Y_t - z'_t b_{t-1}}{\sqrt{1+z'_t(Z'_{t-1}Z_{t-i1})^{-1}z_t}}, \text{ t=k+1, … ,T}$$

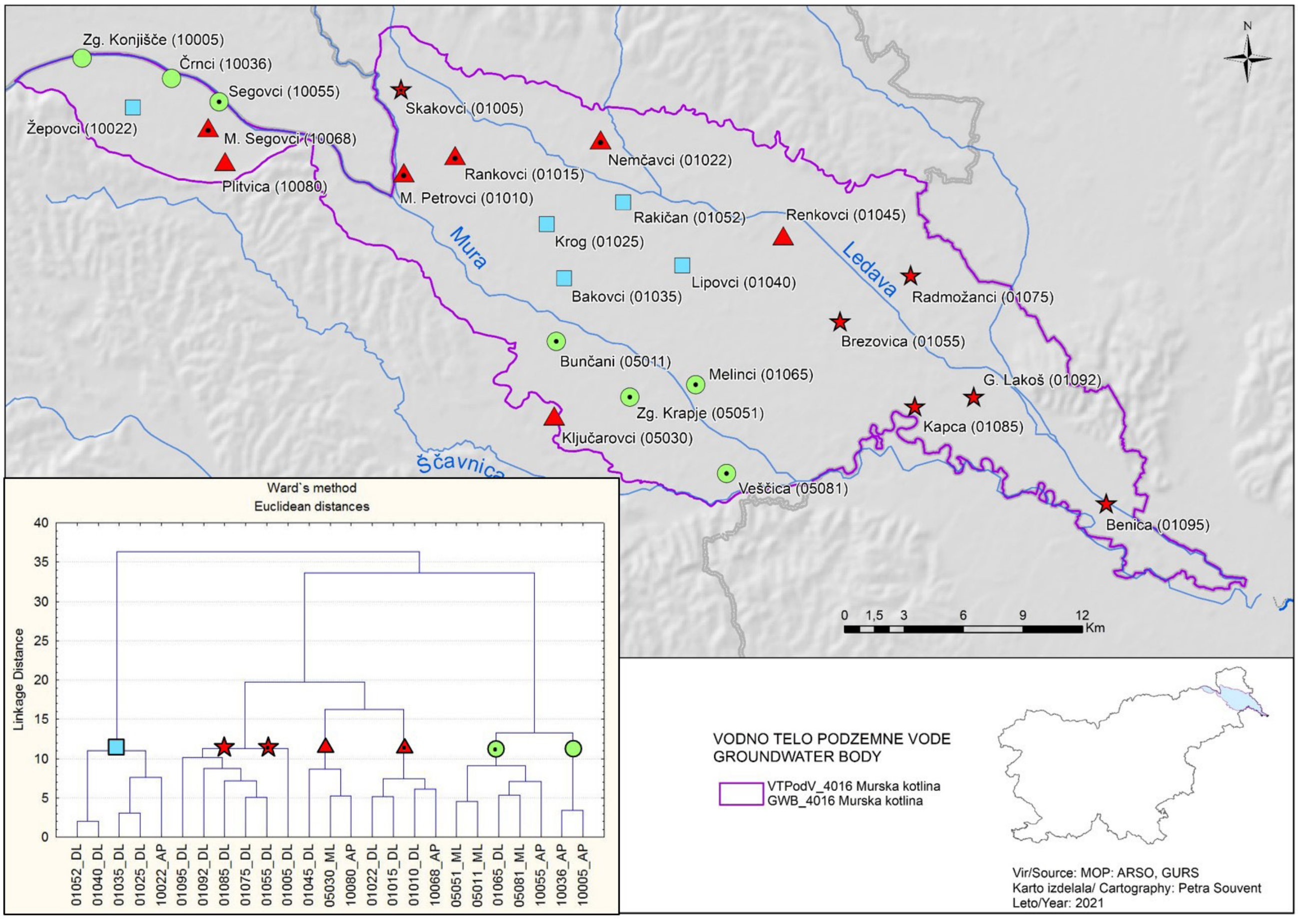
$Z'_{t-1} = (z_1, \dots, z_{t-1})$ in b_{t-1} sta oceni najmanjših kvadratov koeficienta β glede na opazovanja vse do časa *t-1*. V primeru stalnosti parametrov so rekurzivni ostanki neodvisno normalno porazdeljeni s srednjo vrednostjo 0 in varianco σ^2. Če temu ni tako, gre za odstopanje od ničelne hipoteze.

Testiranje konstantnosti regresijskih odvisnosti po principu RE testa temelji na primerjavi rekurzivnih ostankov regresijskih koeficientov z ostanki celotnega vzorca (Ploberger et al., 1989), testa CUSUM in MOSUM pa temeljita na preverjanju konstantnosti regresijskih ostankov le dela vzorca opazovanj in ne celotnega vzorca. Ostanki celotnega vzorca so namreč manj občutljivi na spremembe regresijskih koeficientov kot ostanki le dela podatkov. Test kumulativne vsote ostankov (CUSUM) ugotavlja morebitne spremembe koeficienta β v modelu linearne regresije na način primerjave sekvenčne vsote napovedane standardizirane napake rekurzivnih ostankov z robnim pogojem, ki ga predstavlja 95 % stopnja zaupanja. Statistika CUSUM se oceni za en časovni korak vnaprej. Test ugotavljanja sekvence časovnih vrst z uporabo drseče vsote ostankov (MOSUM) v nasprotju s testom CUSUM ne temelji na izračunu statistik iz ostankov linearnega regresijskega modela do določenega časa ampak na vsoti drsečega povprečja določenega števila ostankov v vnaprej določenem podatkovnem oknu, ki ga premika preko celotnega vzorca opazovanj (Zeileis et al., 2002).

Rezultati

Clusterska analiza

Clustersko analizo smo izvedli s podatki srednjih mesečnih vrednosti gladin podzemne vode, na 25 v letu 2015 delujočih merilnih mestih (sl. 1), razen na merilnem mestu Odranci, ki ga zaradi prekratkega časovnega niza (merilno mesto je začelo delovati marca 2011) nismo vključili v analizo. V analizo vključena merilna mesta smo klasificirali v tri večje skupine (sl. 3): skupina 1 z merilnimi mesti Žepovci (10022),



Sl. 3. Drevo združevanja clusterske analize gladin podzemne vode in prikaz rezultatov na pregledni karti VTPodV Murska kotlina.

Fig. 3. Cluster dendrogram of groudwater levels and the results of the analysis on a map.

Krog (01025), Rakičan (01052), Bakovci (01035) in Lipovci (01040); skupina 2 z merilnimi mesti Zgornje Konjišče (10005), Črnci (10036), Segovci (10055), Melinci (01065), Bunčani (05011), Zgornje Krapje (05051) in Veščica (05081) ter skupina 3 z merilnimi mesti Plitvica (10080), Ključarovci (05030), Nemčavci (01022), Renkovci (01045), Skakovci (01005), Rankovci (01015), Murski Petrovci (01010), Mali Segovci (10068), Brezovica (01055), Radmožanci (01075), Kapca (01085), Gornji Lakoš (01092) in Benica (01095).

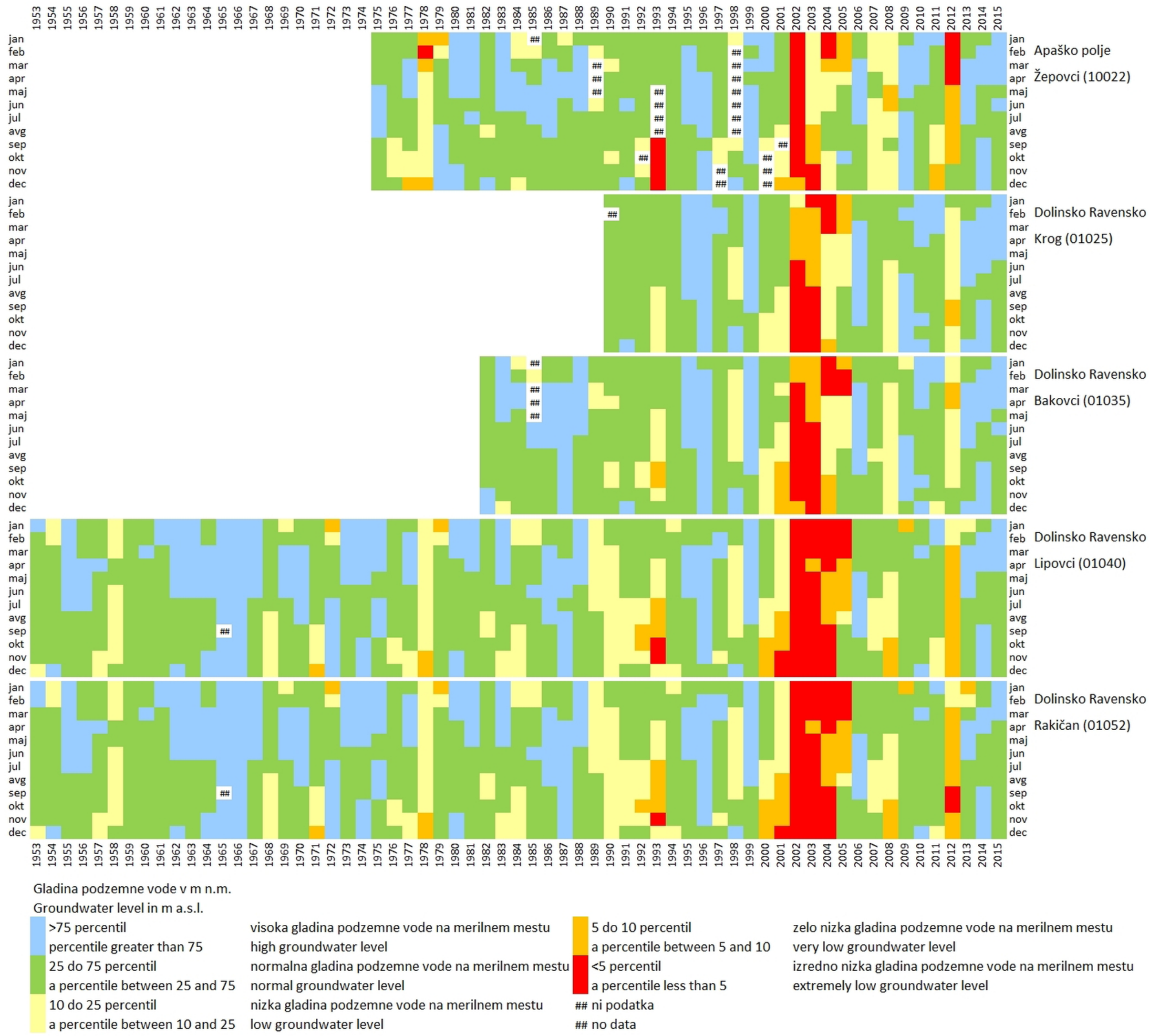
Analiza percentilov

Percentilno analizo smo, kot tudi clustersko analizo, izvedli na 25 merilnih mestih s podatki srednjih mesečnih vrednosti gladin podzemne vode, v celotnem obdobju delovanja postaje. Rezultat analize so mesečni percentilni grafi, ki smo jih glede na podobnost grafov združili v pet skupin merilnih mest (sl. 4 do 8) in sicer:

1. Žepovci (10022), Krog (01025), Bakovci (01035), Lipovci (01040) in Rakičan (01052);
2. Zgornje Konjišče (10005), Črnci (10036), Segovci (10055), Melinci (01065), Bunčani (05011), Zgornje Krapje (05051) in Veščica (05081);
3. Skakovci (01005), Brezovica (01005), Radmožanci (01075), Kapca (01085), Gornji Lakoš (01092) in Benica (01095);
4. Plitvica (10080), Ključarovci (05030) in Renkovci (01045) in
5. Mali Segovci (10068), Murski Petrovci (01010), Rankovci (01015) ter Nemčavci (01022).

Analiza monotonih trendov

Značilne srednje mesečne gladine podzemne vode se v dolgoletnem analiziranem obdobju statistično značilno zvišujejo na merilnih postajah Radmožanci (01075), Veščica (05081) in Segovci (10055) (sl. 1). Statistično značilno se gladine podzemne vode znižujejo na merilnih postajah Renkovci (01045), Lipovci (01040), Zgornje Konjišče (10005), Črnci (10036), Bunčani (05011) in Ključarovci (05030) (sl. 1). Nizke in srednje mesečne vrednosti gladin podzemne vode se statistično značilno znižujejo tudi na merilni lokaciji Melinci (01065), nizke mesečne vrednosti gladin pa še v Gornjem Lakošu (01090). Na merilnih postajah Rankovci (01015), Bakovci (01035), Brezovica (01055), Žepovci (10020), Plitvica (10080) in Zgornje Krapje (05050) (sl. 1) ni bilo ugotovljenega



Sl. 4. Merilna mesta na Apaškem polju ter Dolinsko Ravenskem, kjer je prevladujoče napajanje podzemne vode infiltracija padavin.

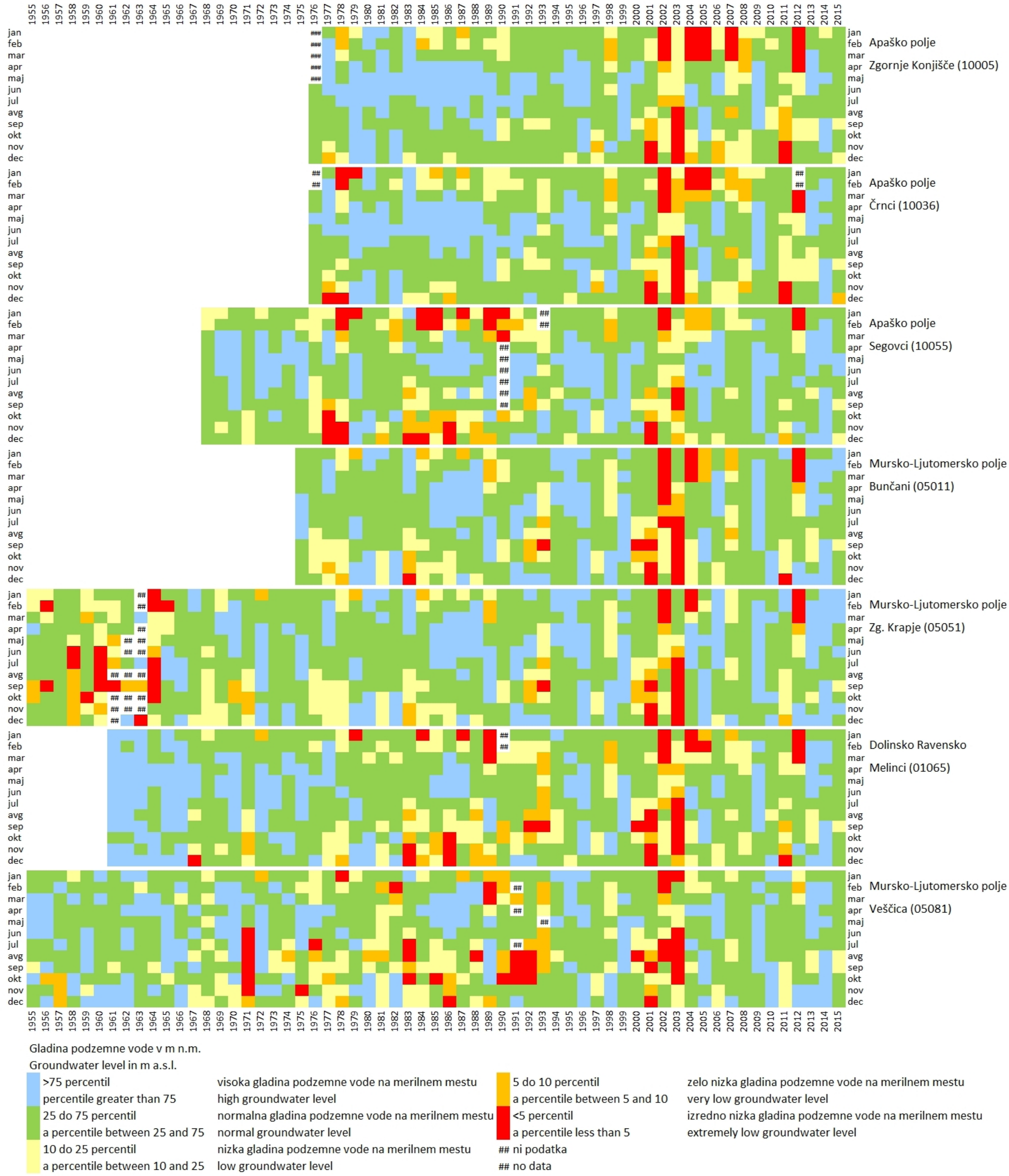
Fig. 4. Monitoring sites with predominant infiltration of precipitation as groundwater recharge.

statistično značilnega trenda v nihanju značilnih mesečnih gladin podzemne vode na stopnji zaupanja 95 %.

Trendi nihanja značilnih mesečnih gladin podzemne vode na merilnih postajah z ugotovljenim trendom zniževanja v dolgoletnem obdelovalnem obdobju po posameznih mesecih kažejo, da se vodna gladina najpogosteje statistično značilno znižuje med marcem in avgustom. Izjemi sta merilni postaji Zgornje Konjišče (10005), kjer se značilne mesečne gladine podzemne vode statistično značilno znižujejo v večini mesecev leta z izjemo januarja in decembra in Ključarovci (05030), kjer je zniževanje nizkih gladin značilno v večini mesecev leta z izjemo oktobra, novembra in decembra. Statistično značilnega monotonega trenda gladin podzemne vode po posameznih mesecih nismo ugotovili na merilnih postajah Rankovci (01015), Bakovci (01035), Brezovica (01055), Žepovci (10020), Plitvica (10080) in Zgornje Krapje (05051) (sl. 1). Statistično značilno zviševanje dolgoletnih nizkih mesečnih gladin je bilo v mesecih med oktobrom in marcem ugotovljeno na merilni postaji Segovci (10055), v septembru, novembru, decembru in januarju pa na merilni postaji Veščica (05080) (sl. 1).

Analiza sekvenčnih trendov

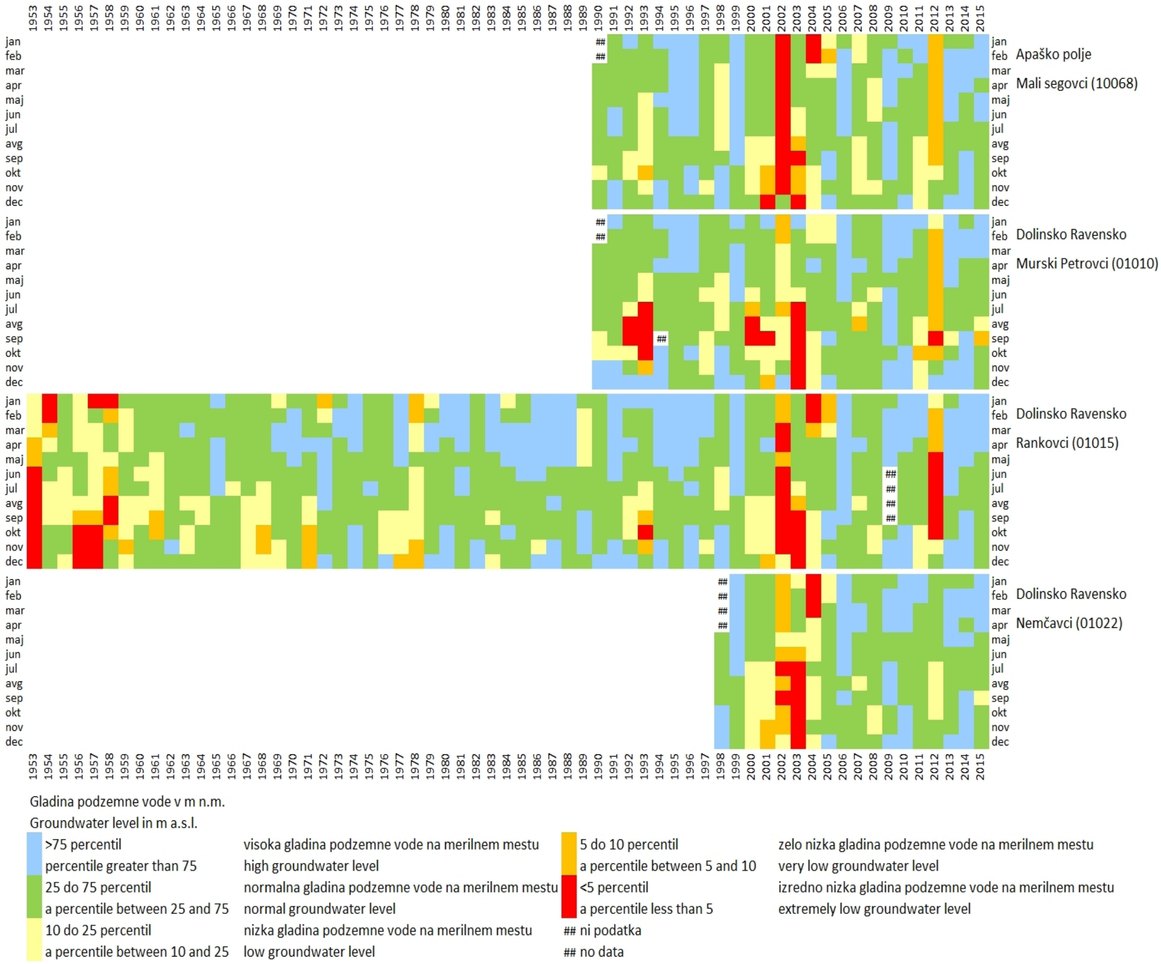
Z analizo sekvenčnih trendov nismo ugotovili trenda oziroma prevoja le-tega za dolgoletne serije podatkov mesečnih vsot padavin v Murski Soboti (obdobje meritev 1950 – 2015). Najmanjše količine mesečne vsote padavin v analiziranem obdobju so bile na tem merilnem mestu izmerje-



Sl. 5. Merilna mesta na območjih vodonosnikov, kjer so gladine pod hidrološkim vplivom režima reke Mure.
Fig. 5. Monitoring sites where groundwater levels are influenced by the Mura river regime.

ne v februarju 1998, januarju 2002 ter januarju 1954, največje vrednosti vsot pa v oktobru 2014, avgustu in v septembru 1972 (arhiv ARSO).

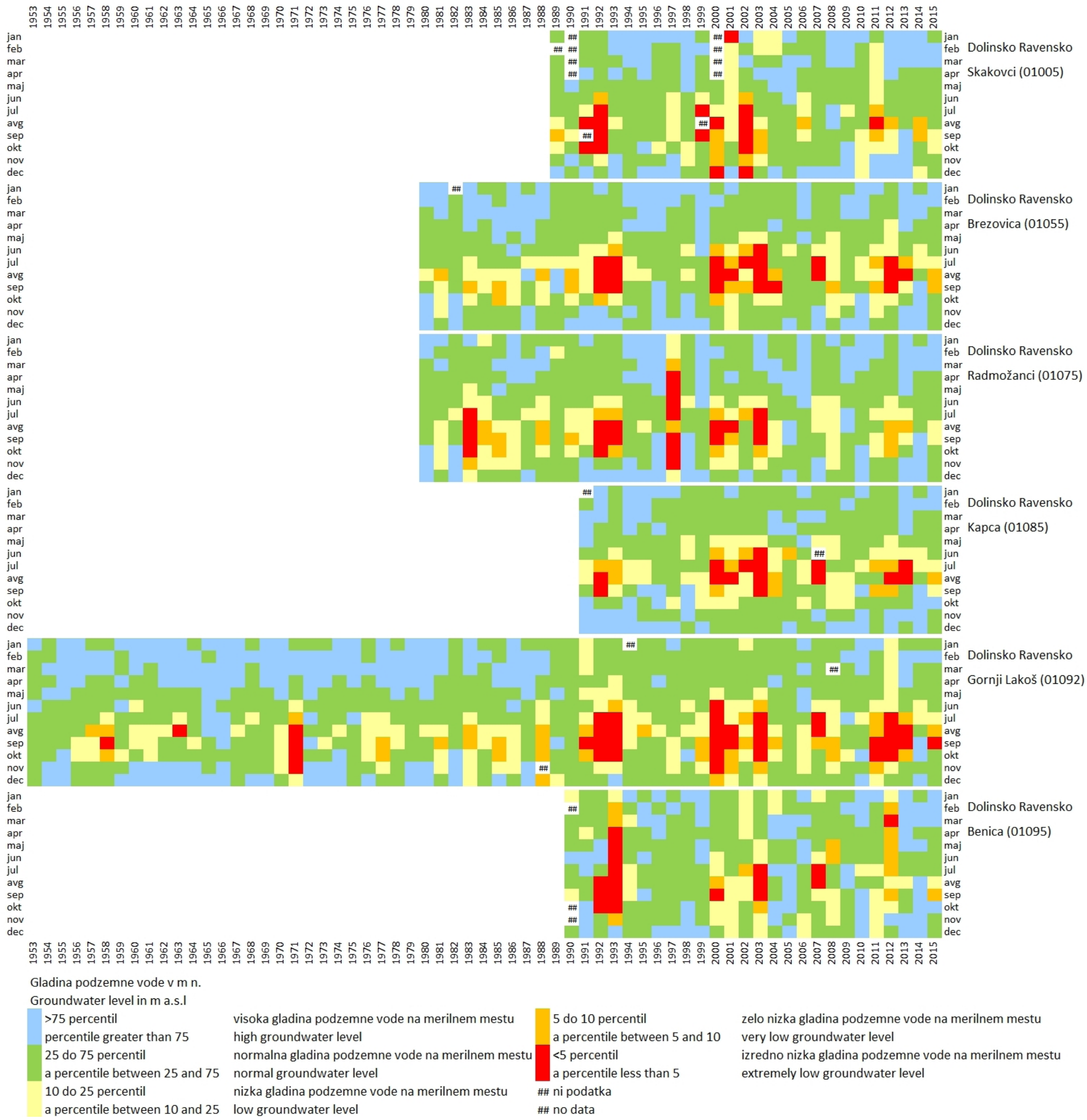
Za dolgoletne pretoke Mure v Gornji Radgoni nismo ugotovili sekvenc v trendu nihanja značilnih mesečnih vrednosti v analiziranem obdobju (Tabela 3). S sekvenčno analizo trendov nizkih mesečnih pretokov Ščavnice v Pristavi smo določili tri sekvence (prevoj novembra 1993 in marca 2000), za srednje in visoke pretoke tega vodotoka pa dve sekvenci v nihanju mesečnih pretokov (Tabela 3). Za nizke pretoke Ledave na merilni postaji v Polani smo določili štiri sekvence s prevoji maja 1970, 1988 in 1999, za nizke pretoke istega vodotoka na merilnem mestu v Čentibi pa tri sekvence s prevoji oktobra 1988 in marca 2000 (Tabela 3, sl. 9). Vse tri sekvence nizkih pretokov Ledave v Polani kažejo na zviševanje vodnih gladin, kar za merilno postajo v Čentibi ne drži (sl. 9).



Sl. 6. Merilna mesta s podobnim režimom nihanja gladine podzemne vode na vtoku in iztoku iz vodonosnika.
Fig. 6. Monitoring sites at inflow or outflow of the aquifer with a similar groundwater level regime.

Tabela 2. Rezultati sekvenčne analize trendov z ugotovljenim nastopom prevoja v nihanju nizkih, srednjih in visokih mesečnih gladin podzemne vode.
Table 2. Sequential trend analysis results with turning points occurrence in trend for low, mean and high monthly groundwater level.

			Nizke mesečne gladine podzemne vode			Srednje mesečne gladine podzemne vode			Visoke mesečne gladine podzemne vode		
Šifra MM	Ime MM	Zač. niza	Prevoj 1	Prevoj 2	Prevoj 3	Prevoj 1	Prevoj 2	Prevoj 3	Prevoj 1	Prevoj 2	Prevoj 3
10036	Črnci	1981	Okt-98	Jul-04		Jun-83	Jun-01		Jul-01		
10005	Zgornje Konjišče	1976	Jun-01			Maj-01			Nov-00		
10020	Žepovci	1975	Jan-00	Jan-05		Jan-00	Feb-05		Jan-00	Feb-05	
10055	Segovci	1981	Jan-98	Jul-03		Nov-00	Dec-05		Okt-00	Nov-05	
10080	Plitvica	1981	Okt-98	Mar-04		Sept-98	Feb-04		Sept-98	Feb-04	
01015	Rankovci	1968	Dec-93	Apr-05		Sep-75	Maj-00		Sep-94	Mar-05	
01045	Renkovci	1953	Maj-67	Okt-94	Mar-05	Maj-67	Okt-94	Mar-05	Apr-67	Okt-94	Feb-05
01035	Bakovci	1981	Dec-93	Jun-02		Nov-93	Feb-04		Nov-93	Feb-04	
01055	Brezovica	1979	Feb-94	Feb-03		Feb-93	Aug-99		Jan-94	Mar-03	
01075	Radmožanci	1979									
01065	Melinci	1974	Maj-93	Okt-03		Maj-93	Okt-03		Okt-89		
01090	Gornji Lakoš	1981	Okt-93	Okt-03		Okt-93	Okt-03		Sept-93	Okt-03	
01040	Lipovci	1953	Jun-67	Jan-95	Apr-05	Jun-67	Jan-95	Apr-05	Jun-67	Jan-95	Apr-05
05080	Veščica	1974	Feb-93			Feb-93			Jan-93		
05050	Zgornje Krapje	1955	Jan-95	Maj-04		Maj-93	Okt-02		Dec-94	Apr-04	
05011	Bunčani	1955	Jun-01			Jun-01			avg-01		
05030	Ključarovci	1955	Dec-94	Apr-04		Jun-88	Apr-00		Sep-94	Jan-04	



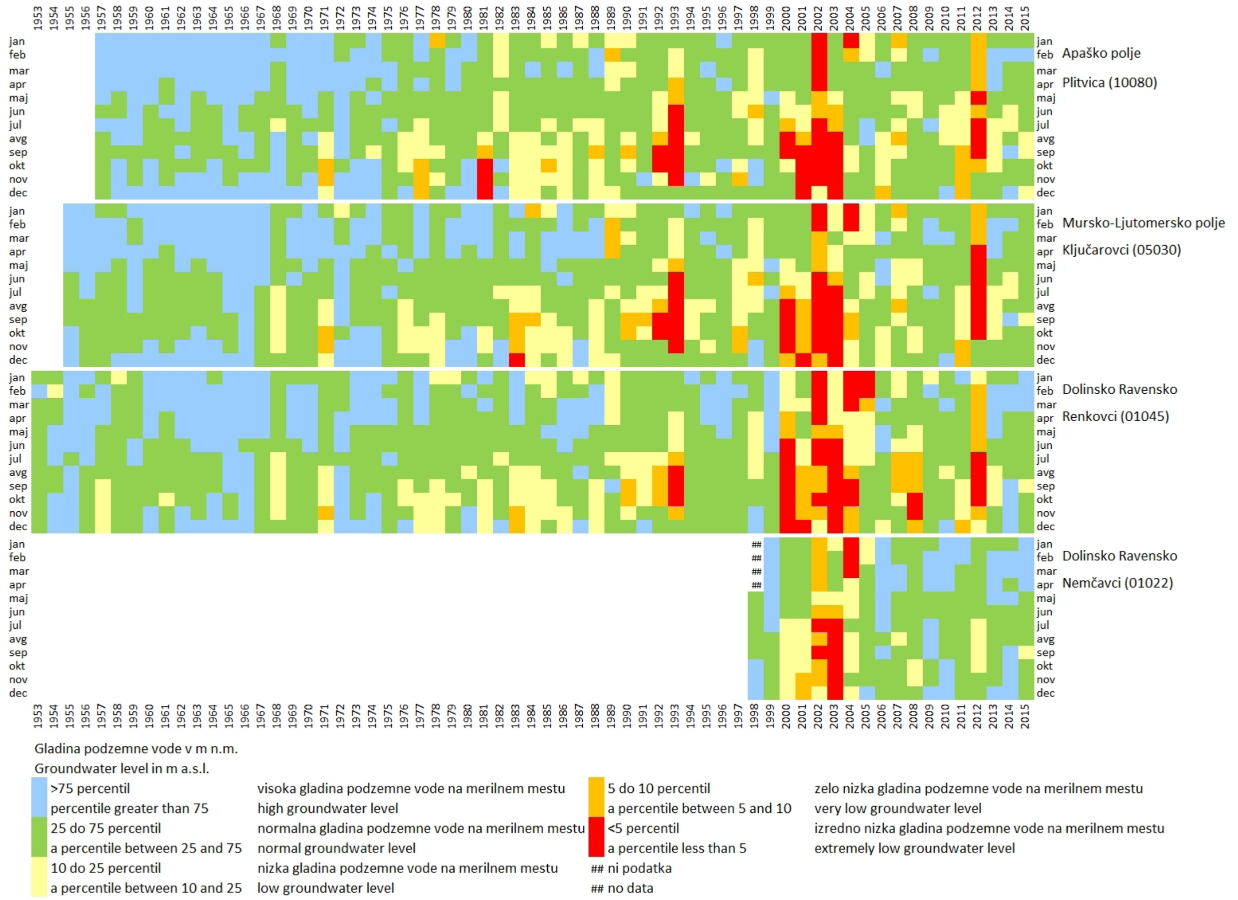
Sl. 7. Merilna mesta s podobnim režimom nihanja gladine podzemne vode z dotoki podzemne vode v vodonosnik iz gričevnatega zaledja.

Fig. 7. Monitoring sites with a similar groundwater level regime, where inflow to the groundwater is from hilly hinterland.

Tabela 3. Rezultati sekvenčne analize trendov z ugotovljenim nastopom prevoja v nihanju nizkih, srednjih in visokih mesečnih pretokov vodotokov.

Table 3. Sequential trend analysis results with turning points occurrence in trend for low, mean and high monthly surface water discharges.

			Nizki mesečni pretoki vodotoka			**Srednji mesečni pretoki vodotoka**			**Visoki mesečni pretoki vodotoka**		
Šifra MM	Ime MM	Zač. niza	Prevoj 1	Prevoj 2	Prevoj 3	Prevoj 1	Prevoj 2	Prevoj 3	Prevoj 1	Prevoj 2	Prevoj 3
1060	Mura-Gornja Radgona	1946									
1140	Ščavnica-Pristava	1975	Nov-93	Mar-00		Mar-00			Jun-99		
1260	Ledava-Čentiba	1969	Okt-88	Mar-00		Okt-88	Mar-00				
1220	Ledava-Polana	1956	Maj-70	Maj-88	Maj-99	Apr-67	Jun-99		Jun-67		

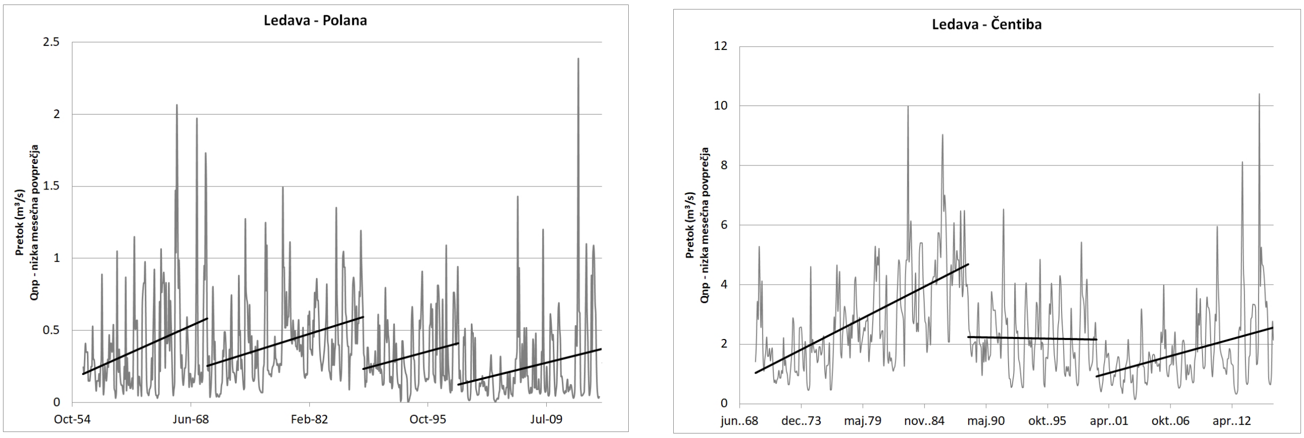


Sl. 8. Merilna mesta, ki se glede na clustersko analizo grupirajo v samostojno podskupino, kažejo pa podobno dinamiko nihanja gladin kot jo spremljamo pri merilnih mestih, kjer prevladuje infiltracija padavin oziroma dotok iz obrobja in vpliv reke.

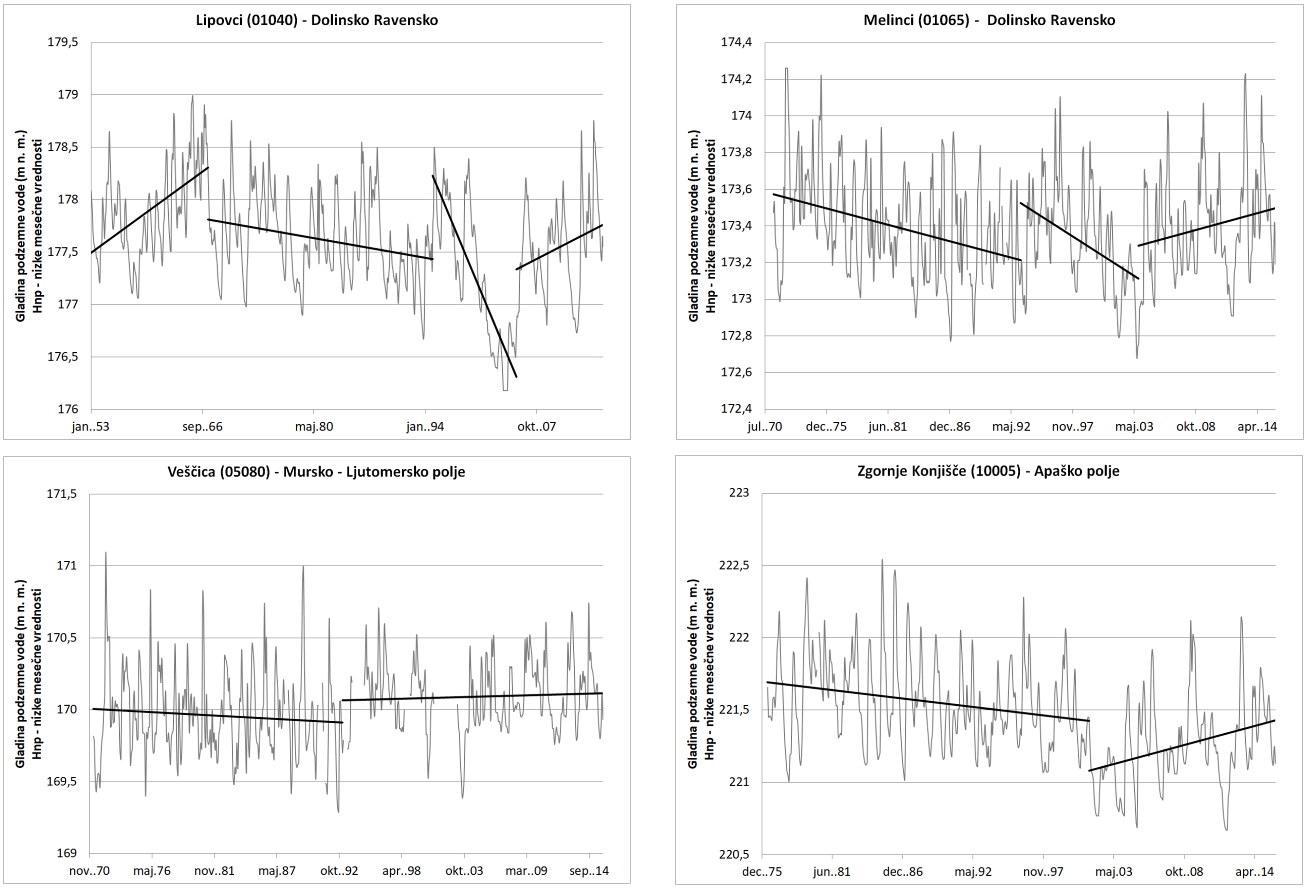
Fig. 8. Monitoring sites which are in the same subgroup according to the hierarchical cluster analysis but show similar groundwater level regime to those monitoring sites where infiltration of precipitation prevail or to those with prevailing inflow to groundwater from hinterland or the river.

S sekvenčno analizo trendov nizkih mesečnih gladin podzemne vode smo določili med 1 in 3 prevojne točke v nihanju vrednosti (Tabela 2, sl. 10 in 11). Prvo prevojno obdobje je bilo značilno za konec pomladi oziroma začetek poletja leta 1967 na merilnih mestih v Renkovcih (01045) in Lipovcih (01040) (sl. 1). Sledilo je obdobje pogostega pojavljanja prevojev v sekvencah gladin podzemne vode med leti 1993 in 1995, ki je na večini merilnih mest nastopilo po daljšemu obdobju brez trenda ali s trendom upadanja podzemne vode (Tabela 2, sl. 11). Temu je sledilo obdobje s prevladujočim trendom zniževanja vodnih gladin do naslednjega izstopajočega obdobja pojavljanja prevojev v sekvencah časovnih vrst, to je med leti 2003 in 2005 (Tabela 2, sl. 11). Značilnost zadnje sekvence posameznih časovnih vrst je trend zviševanja gladin podzemne vode do konca analiziranega obdobja (sl. 10). Izjeme v opisanih rezultatih sekvenčne analize trendov nihanja nizkih mesečnih gladin podzemne vode so bile opredeljene na vseh analiziranih merilnih postajah na območju Apaškega polja (Tabela 1) in v Bunčanih (05011) na Mursko-Ljutomerskem polju (sl. 1). Pri teh merilnih postajah značilnega prevojnega obdobja med leti 1993 in 1995 z opisano metodo nismo ugotovili, prevojno obdobje med leti 2003 in 2005 pa je za razliko od ostalih merilnih mest Pomurja v Črncih (10036), Segovcih (10055) in Plitvici (10080) nastopilo leta 1998, v Žepovcih (10020) januarja 2000, v Zgornjem Konjišču (10005) in Bunčanih (05011) pa junija 2001 (sl. 11). Od rezultatov sekvenčne analize trendov nizkih mesečnih gladin podzemne vode večine merilnih postaj odstopata tudi merilni mesti Veščica (05080), kjer v prvih 21. letih ni bilo določenega prevoja v trendu, in Radmožanci (01075) brez ugotovljenega trenda analizirane časovne vrste (sl. 11).

Razpršenost prevojnih točk srednjih mesečnih gladin podzemne vode v času je v primerjavi z razpršenostjo točk prevoja nizkih mesečnih gladin podzemne vode večja. Prvo obdobje pogostejšega pojava prevojev trendov nastopi med majem in junijem 1967 (Lipovci (01040) in Renkovci (01045)), drugo obdobje med februarjem 1993 in januarjem 1995 (izjeme: Bunčani (05011), Zgornje Konjišče (10005), Žepovci (10020), Segovci

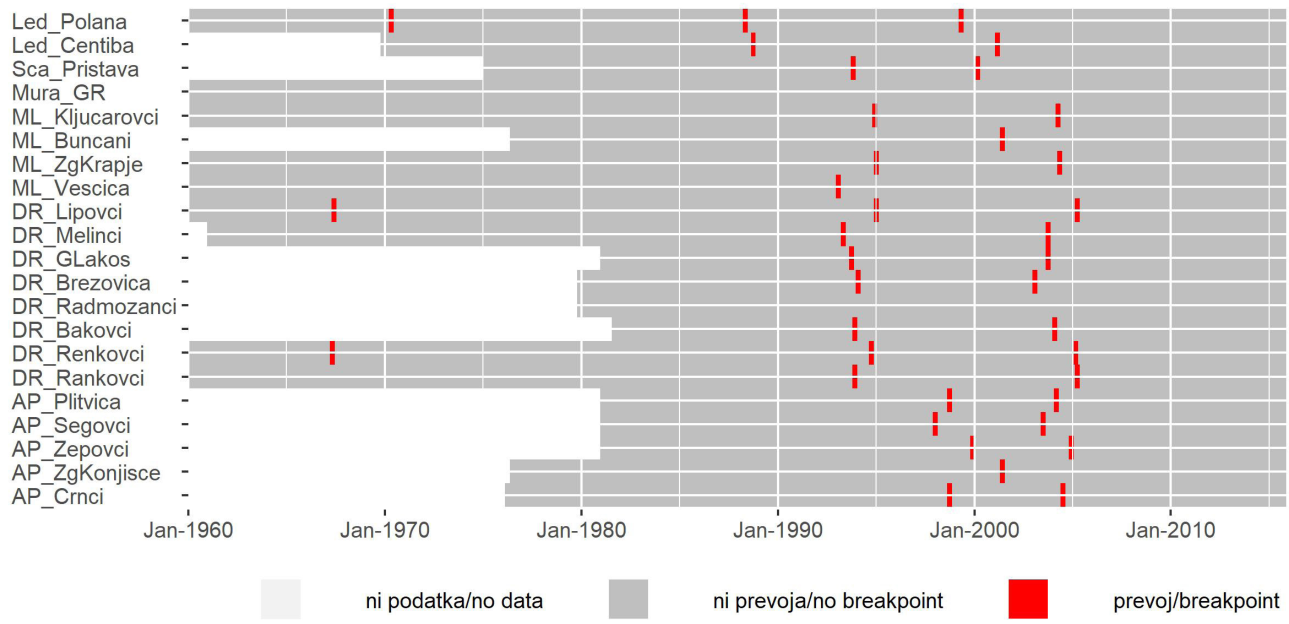


Sl. 9. Rezultati sekvenčne analize trendov nizkih mesečnih pretokov Ledave na merilnem mestu v Polani (levo) in Čentibi (desno).
Fig. 9. Sequential trend analysis results of low monthly discharges of Ledava stream on measuring stations in Polana (left) and in Čentiba (right).

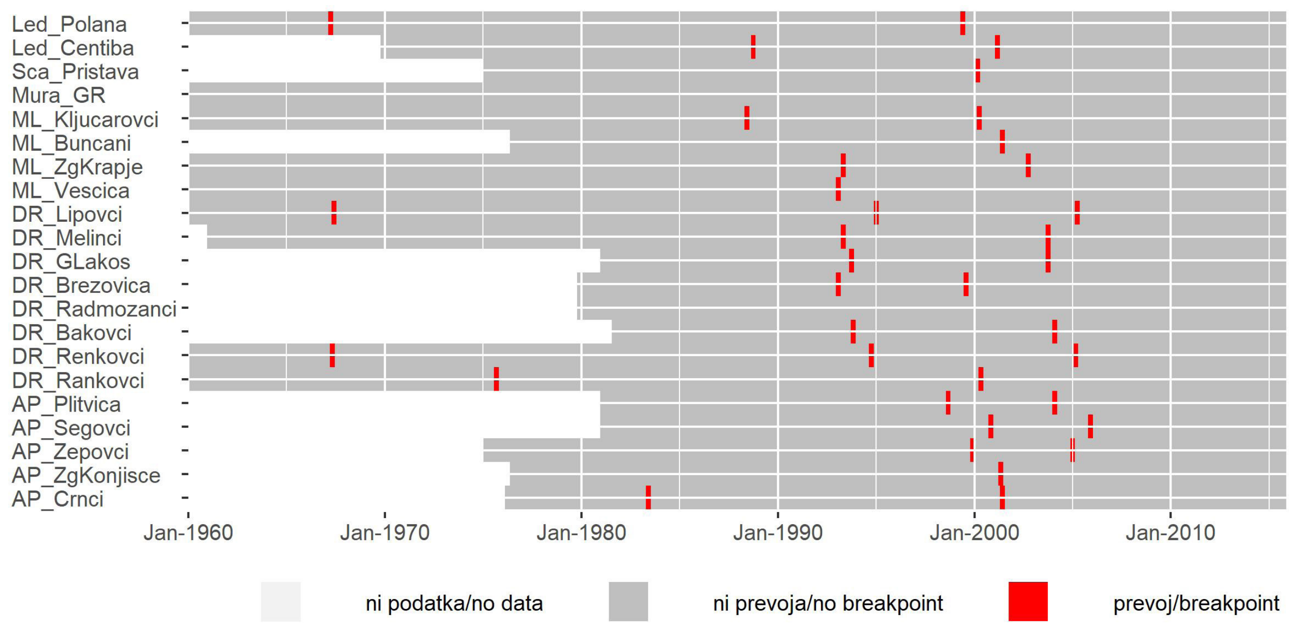


Sl. 10. Rezultati analize sekvenčnih trendov nizkih mesečnih gladin podzemne vode na izbranih merilnih mestih.
Fig. 10. Sequential trend analysis results for low monthly groundwater levels on selected measuring stations.

(10055), Plitvica (10080), Črnci (10036)). Zadnje obdobje s pogostejšimi prevoji trendov smo opredelili z dvema časovnima intervaloma in sicer med avgustom 1999 in junijem 2001 (Ključarovci (05030), Bunčani (01055), Zgornje Krapje (05050), Brezovica (01055), Rankovci (01015), Zgornje Konjišče (10005), Črnci (10036), Segovci (10055)) in med oktobrom 2003 in decembrom 2005 (Žepovci (10020), Segovci (10055), Plitvica (10080), Bakovci (01035), Melinci (01065), Renkovci (01045), Lipovci (01040)). Smeri trendov posameznih segmentov časovnih vrst so sorodni trendom ugotovljenim za nizke mesečne vrednosti (sl. 12). Izrazitejše izjeme v pojavu prevojnih točk srednjih mesečnih gladin podzemne vode smo določili na merilnih postajah Ključarovci (05030) na Mursko-Ljutomerskem polju (junij 1988), Rankovci (01015) (september 1975), Radmožanci (01075) (brez prevoja trenda) na območju vodonosnika Dolinsko - Ravensko in Črnci (10036) na Apaškem polju (prevoj junija 1983).

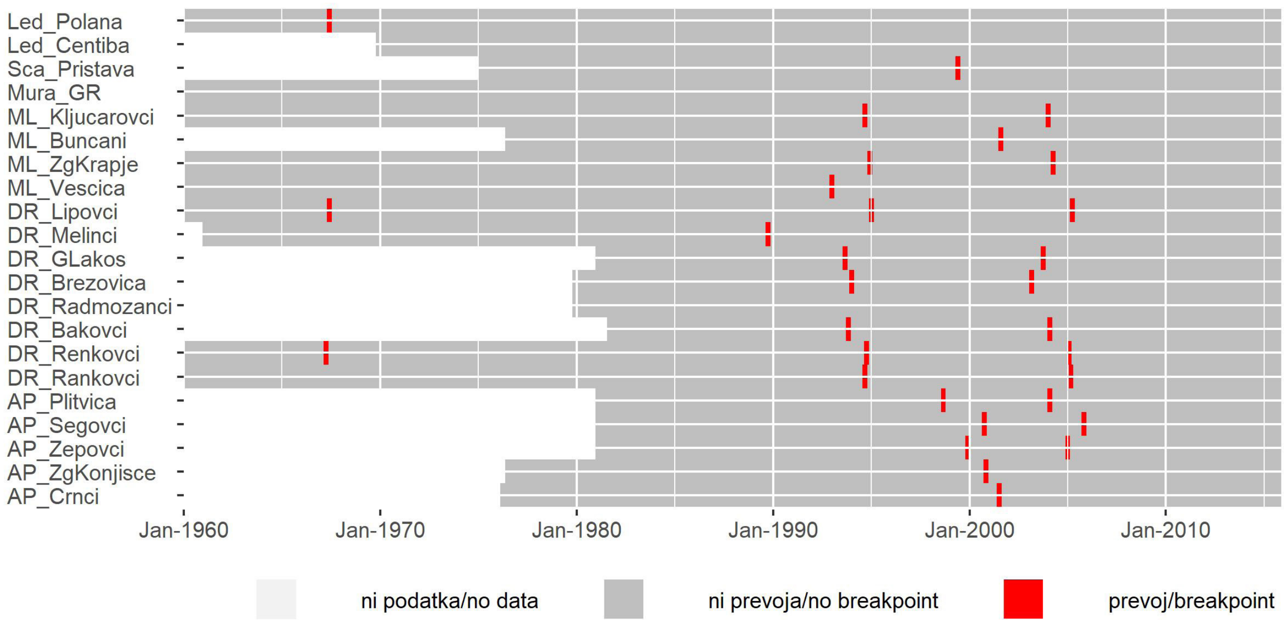


Sl. 11. Rezultati sekvenčne analize trendov nizkih mesečnih gladin podzemne vode/pretokov vodotokov med leti 1960 in 2015
Fig. 11. Sequential trend analysis results for low monthly groundwater levels/river discharges in period from 1960 to 2015.



Sl. 12. Rezultati sekvenčne analize trendov srednjih mesečnih gladin podzemne vode/pretokov vodotokov med leti 1960 in 2015.
Fig. 12. Sequential trend analysis results for mean monthly groundwater levels/river discharges in period from 1960 to 2015.

Rezultati analize sekvenčnih trendov visokih mesečnih vrednosti gladin podzemne vode so primerljivi z rezultati te analize za srednje mesečne vrednosti. Prvo prevojno obdobje med aprilom in junijem 1967 je značilno za Lipovce (01040) in Renkovce (01045) (sl.1), drugo med januarjem 1993 in januarjem 1995 za vse merilne postaje podzemnih voda z izjemo Melincev (01065) (prevoj določen oktobra 1989), Bunčanov (05011) ter vseh analiziranih merilnih mest na Apaškem polju (Tabela 2). Iz zadnjega obdobja pogostega pojavljanja točk prevoja med segmenti visokih mesečnih gladin podzemne vode med novembrom 2000 in aprilom 2005 sta bili izvzeti merilni mesti Veščica (05080) in Melinci (01065) (sl. 13). V Radmožancih (01075) ni bilo ugotovljenega prevoja v nihanju visokih mesečnih vodnih količin.



Sl. 13. Rezultati sekvenčne analize trendov visokih mesečnih gladin podzemne vode/pretokov vodotokov med leti 1960 in 2015.
Fig. 13. Sequential trend analysis results for high monthly groundwater levels/river discharges in period from 1960 to 2015.

Razprava

Iz rezultatov izvedenih analiz značilnih mesečnih gladin podzemne vode na VTPodV Murska kotlina je razvidno, da se v nihanju gladine podzemne vode Pomurja odražajo kompleksni procesi, ki so lahko posledica tako naravnih kot tudi antropogenih vplivov. Ob primerjavi nihanja gladin podzemne vode med posameznimi lokacijami smo lahko z metodami, kot je percentilna analiza v kombinaciji s clustersko analizo, izdvojili območja s sorodnimi značilnostmi nihanja podzemne vode. Z analizo trendov smo prepoznali vzorce sprememb v nihanju podzemne vode skozi čas, katerih vzroke smo v prispevku do določene mere lahko povezali s preteklimi podnebnimi in hidrološkimi dogodki na raziskovanem ozemlju. Vzporednice z nastopom prevojev v sekvencah trendov mesečnih gladin podzemne vode v prispevku med drugim interpretiramo z ugotovitvami analiz standardiziranega padavinskega indeksa (SPI) na merilni postaji Murska Sobota (Dornik, 2016), standardiziranega indeksa pretoka vodotokov (SSI) na območju Pomurja (Zalokar, 2018) in standardiziranega indeksa gladine podzemne vode (SGI) na območju medzrnskih vodonosnikov severovzhodne Slovenije (Draksler et al.,2017; Adrinek & Brenčič, 2019).

Rezultati percentilne analize mesečnih gladin podzemne vode kažejo na več vzorcev nihanja gladine podzemne vode na merilnih mestih VTPodV Murska kotlina, ki jih lahko v grobem vzporejamo z rezultati clusterske analize. Glede na potek gladin podzemne vode (sl. 1, Savić, 1992) in pretekle hidrogeološke raziskave na danem ozemlju (Petauer et al., 2007; Vižintin et al., 2011; Vižintin et al., 2014; Koren et al., 2015), lahko rezultate analiz povežemo s prevladujočimi viri napajanja vodonosnika. Tako smo z omenjenima analizama na obravnavanih merilnih mestih izdvojili območja, kjer:

- je prevladujoče napajanje podzemne vode z infiltracijo padavin: Žepovci (10022) in Mali Segovci (10068) na Apaškem polju; Krog (01025), Bakovci (01035), Lipovci (01040), Rakičan (01052), Murski Petrovci (01010) in Rankovci (01015) na Dolinsko Ravenskem;
- so gladine podzemne vode pod hidrološkim vplivom režima reke Mure (napajanje/dreniranje podzemne vode): Zgornje Konjišče (10005), Črnci (10036) in Segovci (10055) na Apaškem polju; Bunčani (05011), Zgornje Krapje (05051) in Veščica (05081) na Mursko-Ljutomerskem polju; Melinci (01065) na Dolinsko Ravenskem;
- prevladujejo dotoki podzemne vode v vodonosnik iz gričevnatega zaledja: Plitvica (10080) na Apaškem polju, Ključarovci (05030) na Mursko-Ljutomerskem polju in Renkovci (01045) ter Nemčavci (01022) na Dolinsko Ravenskem;
- gre za različne vire napajanja podzemne vode na vtoku oziroma iztoku iz vodonosnikov: Skakovci (01005), Brezovica (01055), Radmožanci (01075), Kapca (01085), Gornji Lakoš (01092) in Benica (01095) na Dolinsko Ravenskem.

Na merilnih mestih: Žepovci (10022), Krog (01025), Bakovci (01035), Lipovci (01040) in Rakičan (01052) (sl. 4), ki jih je združila metoda razvrščanja v skupine (sl. 3), se opazno odraža signal primanjkljaja padavin v letih 2002, 2003 in 2004 (Dornik, 2016). V teh treh letih je na VTPodV Murska kotlina v povprečju padlo za 13 % manj padavin glede na povprečje 1981-2010. Po zelo nizkih oziroma izredno nizkih gladinah podzemne vode mestoma izstopata tudi leti 1993 in 2012. Obdobje primanjkljaja padavin med leti 2002 in 2003 ter v letu 1993 sovpada s pojavom znatno izraženih prevojnih točk nizkih mesečnih gladin podzemne vode, ugotovljenih z s sekvenčno analizo trendov (sl. 12). Za omenjena merilna mesta ocenjujemo prevladujoče napajanje podzemne vode z infiltracijo padavin v vodonosnik.

Gladine na merilnih mestih: Zgornje Konjišče (10005), Črnci (10036), Segovci (10055), Melinci (01065), Bunčani (05011), Zgornje Krapje (05051) in Veščica (05081) odražajo povezavo z režimom nihanja pretočnosti reke Mure. Mura ima s svojim snežnim režimom glavni višek v poletnih mesecih (Bat et al., 2008), kar se odraža tudi na gladinah podzemne vode, ki so v poletnih mesecih višje kot v preostalih mesecih leta (sl. 5).

Vzorec nihanja gladine podzemne vode na merilnih mestih, ki so locirana na vtoku: Skakovci (01005) in iztoku: Brezovica (01005), Radmožanci (01075), Kapca (01085), Gornji Lakoš (01092) in Benica (01095) podzemne vode iz vodonosnika Dolinsko Ravensko, sledi manjšim vodnim količinam v vodonosniku v poletnih mesecih med julijem in septembrom, na nekaterih merilnih mestih tudi v jesenskem obdobju (sl. 6). Signal sušnega obdobja 2002–2004 tukaj ni izrazit.

Merilna mesta na delih vodonosnikov, kjer prevladujejo dotoki podzemne vode iz neposrednega gričevnatega zaledja so: Plitvica (10080), Ključarovci (05030) in Renkovci (01045). Tukaj srednje mesečne gladine v poletnem času večinoma izkazujejo nižja vodna stanja kot v preostalih mesecih v posameznem letu, izstopajo pa tudi sušna obdobja v letih 1993, 2000–2004 in 2012 (sl. 7).

Merilna mesta: Mali Segovci (10068) na iztoku podzemne vode iz Apaškega polja, Murski Petrovci (01010) in Rankovci (01015) na vtoku v vodonosnik Dolinsko Ravensko ter Nemčavci (01022) na severovzhodnem obrobju istega vodonosnika, se glede na clustersko analizo grupirajo v samostojno podskupino (sl. 3). Percentilni diagrami mesečnih gladin teh merilnih mest (sl. 8) kažejo na podobno dinamiko, kot jo spremljamo pri merilnih mestih, kjer prevladuje infiltracija padavin (sl. 4). Percentilni diagram merilnega mesta Nemčavci (01022) kaže tudi podobno dinamiko nihanja gladine podzemne vode kot merilna mesta, ki so v skupini, kjer sklepamo da je glavnina napajanja iz gričevnatih zaledij (sl. 7), kar v primeru Nemčavcev pomeni vpliv dotoka podzemne vode iz Goričkega, ki je bil ugotovljen tudi v hidrogeoloških raziskavah toka podzemne vode med Prekmurskim poljem in Goričkim (Koren et al., 2015).

Analizirane časovne vrste analize monotonih in sekvenčnih trendov nimajo enako dolgega niza meritev, kar je treba upoštevati pri interpretaciji rezultatov in pri primerjavi rezultatov med merilnimi lokacijami. Rezultate smo ovrednotili glede na ugotovljene podnebne značilnosti obdobja preteklih meritev podnebnih parametrov na raziskovanem ozemlju in znane antropogene posege na raziskovanem območju. Podnebne značilnosti preteklega obdobja meritev ne kažejo nujno na podnebno spremenljivost, saj se je za simulacijo vpliva podnebnih sprememb na hidrološke spremenljivke, kot je gladina podzemne vode, potrebno poslužiti modelov, ki temeljijo ali na matematičnih konceptih, kompleksnejših statističnih analizah podatkov ali izračunih zahtevnih fizikalnih procesov, pri čemer je treba upoštevati tudi razlike v prostorskih in časovnih ločljivostih med hidrološkimi in podnebnimi modeli (Jackson et al., 2015).

Rezultati dolgoročnih monotonih trendov nihanja nizkih mesečnih gladin podzemne vode kažejo, da se na 8 od 17 analiziranih merilnih postajah gladine podzemne vode s časom statistično značilno znižujejo, na 3 statistično značilno zvišujejo, na 6 pa ni ugotovljenega statistično značilnega trenda v dolgoročnem nihanju vodnih gladin. Glede na ugotovljene podnebne značilnosti severovzhodnega dela države in ocenjeno spremembo vodne bilance v tem času lahko predvidevamo, da so glavni razlog ugotovljenih trendov zniževanja gladin podzemne vode, ki so izrazitejši med marcem in avgustom, posledica podnebnih značilnosti raziskovanega prostora v dolgoletnem obdobju opazovanj. Analize podnebja vzhodne polovice države v dobi meritev med leti 1962 in 2011 namreč kažejo na zviševanje temperature zraka spomladi in poleti, kar povečuje stopnjo evapotranspiracije in zmanjšuje količino vode, ki odteka v vodonosnike. V dolgoletnem referenčnem obdobju je za severovzhod države ocenjen tudi približno 10 % primanjkljaj padavin v pomladnem in poletnem času (Vertačnik et al., 2018).

Ker podnebnih značilnosti raziskovanega območja v celoti ne moremo povezati z rezultati analize trendov predvidevamo, da na nihanje gladine podzemne vode na območju Pomurja vplivajo tudi drugi, lokalno pogojeni dejavniki, ki so bodisi naravnega bodisi antropogenega izvora. V nadaljevanju podajamo nekaj možnih vplivov na nihanje gladine podzemne vode, ki povzročajo odklon od prevladujočega vzorca rezultatov analize monotonih trendov gladin podzemne vode.

Na gladino merilnega mesta Plitvica (10080) v vodonosniku Apaškega polja, za katero ni bilo ugotovljenega statistično značilnega trenda nihanja vodnih gladin, lokalno vpliva potok Plitvica (Petauer et al., 2007) in dotoki iz gričevnatega zaledja vodonosnika (Savić, 1992), kar lahko povzroča odstopanje od ostalih rezultatov trendov gladin podzemne vode. Merilno območje v Segovcih (10055) v istem vodonosniku, kjer se podzemna voda dolgoročno zvišuje, je pod znatnim vplivom istoimenskega črpališča. Kvaliteta načrpane vode v črpališču Segovci je odvisna od načrpane količine in intenzitete uporabe gnojil in škropiv pri predelavi poljščin na velikih površinah v zaledju vodnega vira. Črpališče ima izdatnost 70 l/s, vendar pri črpanju več kot 14 l/s kvaliteta načrpane vode ne ustreza Pravilniku o pitni vodi, saj vsebnost nitratov v načrpani vodi znatno naraste preko dopustne meje (Petauer et al., 2007), kar je privedlo do omejitve količine črpanja. Dodatni umetni poseg na območju merilne postaje Segovci (10055) je bila izgradnja aktivne zaščite vodnega vira v sklopu projekta Oskrba s pitno vodo Pomurja – sistem C med leti 2013 in 2015, ki obsega 14 črpalno nalivalnih vodnjakov (Kukovec, 2013). V Veščici (05080) na jugu vodonosnika Mursko–Ljutomerskega polja so ugotovljeni monotoni trendi v smeri zviševanja vodnih količin. Globina merilnega objekta se na tej lokaciji nahaja na približno 3 metrih (Arhiv ARSO), kar pomeni, da se meritve izvajajo v zgornjem, slabše prepustnem pokrovu glavnega vodonosnika Mursko-Ljutomerskega polja, katerega globina je na tem območju ocenjena na preko 4 metre (Petauer et al., 2007) in zato ne odražajo nujno hidrogeoloških razmer analiziranega medzrnskega vodonosnika. Posebnost rezultatov analize trendov nihanja gladine podzemne vode po posameznih mesecih na merilni postaji Zgornje Konjišče (10005) na Apaškem polju je, da se gladina podzemne vode statistično značilno znižuje v večini mesecev z izjemo decembra in januarja. Pojav si razlagamo s poglabljanjem dna struge reke Mure v njenem zgornjem toku, zaradi česar se posledično zmanjšuje intenzivnost količine napajanja vodonosnika iz vodotoka (Feguš & Golnar, 2012).

Rezultati analize sekvenčnih trendov na območju VTPodV Murska kotlina kažejo podrobnejšo dinamiko nihanja posamezne uporabljene časovne vrste, ki je z drugimi uporabljenimi metodami ni bilo mogoče ugotoviti v enakem obsegu. Obdobja prevojev v nihanju gladin podzemne vode si v večini primerov lahko razlagamo s podnebnimi značilnostmi raziskovanega območja oziroma s pretočnostjo reke Mure, dveh robnih pogojev napajanja vodonosnikov, ki pomembno vplivata na količinsko stanje podzemne vode v Pomurju (Savić, 1992; Vižintin et al., 2014).

Prvo obdobje prevojev, ki so ga podali rezultati sekvenčne analize trendov nizkih mesečni gladin podzemne vode, je bilo ugotovljeno na merilnih mestih v osrednjem delu vodonosnika Dolinsko Ravensko (Lipovci (01040) in Renkovci (01045)) in je nastopilo med aprilom in junijem 1967. Ugotovljen prevoj v nihanju gladin podzemne vode sovpada z vrednostmi nihanja srednjih in visokih mesečnih pretokov vodotoka Ledave v Pristavi, ne pa tudi istega vodotoka v dolvodni Čentibi. V času prevoja so se gladine podzemne vode na omenjenih merilnih postajah znižale, pretoki Ledave v Polani pa zmanjšali (sl. 9). Prvo prevojno obdobje povezujemo s spremembo v količini obnavljanja podzemne vode v tem času, povezano s spremembo v količini padavin na obravnavanem ozemlju. Z analizo standardiziranega indeksa padavin (SPI) dve oziroma večmesečne (6, 9, 12) akumulacije padavin na merilni postaji Murska Sobota je bilo namreč ugotovljeno, da je bil po padavinsko ugodnemu obdobju med oktobrom 1960 in decembrom 1967 na merilni postaji Murska Sobota zabeležen dvomesečni odklon negativnih vrednosti SPI2 v letu 1968, proti koncu leta 1971 pa tudi negativni odklon vrednosti SPI6, SPI9 in SPI12, ki se je nadaljeval v leto 1972 (Dornik, 2016). Pojav se kaže tudi v rezultatih standardiziranega indeksa pretoka (SSI) na 12 oziroma 24 kumulativni stopnji povprečnega pretoka na merilni postaji Ledava – Polana med leti 1960 in 2016, kjer po obdobju pozitivnih vrednosti indeksa SSI pred letom 1968 nastopi očitnejša sprememba v vodnatosti tega vodotoka (Zalokar, 2018). Primerljivega pojava na merilni postaji Ledava – Čentiba nismo ugotovili zaradi kasnejšega začetka izvajanja meritev na merilni postaji (Tabela. 3).

Drugo obdobje v pogostem prevoju trendov na analiziranih nizih merilnih postaj je nastopilo med februarjem 1993 in januarjem 1995, ko je večmesečno obdobje podpovprečnega napajanja vodonosnikov z infiltracijo padavin prešlo v krajše obdobje nadpovprečnega napajanja (arhiv ARSO). Pojav je bil izražen z izrazitejšim negativnim odklonom standardiziranega padavinskega indeksa (SPI) 6 oziroma 9 mesečne akumulacije padavin na merilni postaji Murska Sobota v letih 1989, 1992 in 1993, v oktobru 1995 pa tudi z negativnim odklonom 1 in 2 mesečne akumulacije padavin na tej merilni postaji (Dornik, 2016). Prav tako je bil pojav izjemno nizkih gladin podzemne vode v tem obdobju ugotovljen tudi z znatnim odklonom standardiziranega indeksa gladin podzemne vode (SGI) v medzrnskih vodonosnikih Dravske in Murske kotline (Draksler et al., 2017, Adrinek & Brenčič, 2019). V VTPodV Murska kotlina se je pojav v sekvencah trendov odrazil skladno s količino napajanja tako, da je bilo obdobje brez trenda ali s trendom zniževanja gladine podzemne pred letom 1993 na večini merilnih mest prekinjeno zaradi dviga podzemne vode, sledilo pa je obdobje s trendom zniževanja vodnih gladin do naslednjega prevojnega obdobja, ki je na večini analiziranih merilnih postaj nastopilo med leti 2003 in 2005. Prevoja trenda med leti 1993 in 1995 ni bilo opredeljenega za merilno območje vodonosnika Apaškega polja in Bunčanov (05011) na območju vodonosnika Mursko–Ljutomerskega polja. Na dinamiko toka podzemne vode na teh merskih območjih izrazito vpliva režim nihanja pretokov reke Mure. Značilnost pretočnosti Mure med leti 1993 in 1995 je bila, da so med majskim viškom leta 1992 in junijskim viškom leta 1995 povprečni mesečni pretoki reke odstopali od značilnega snežno dežnega pretočnega režima reke. Pričakovanih pozno pomladnih viškov zaradi tanjše snežne odeje v visokogorskem zaledju reke v letih 1993 in 1994 ni bilo, pretoki vodotoka so bili v tem času nižji od običajnih. Na drugi strani smo 1992 in 1993 spremljali povišane jesenske pretoke Mure (arhiv ARSO). Na povišano pretočnost Mure v Gornji Radgoni v začetku 90. let kažejo tudi standardizirani indeksi pretokov (SSI), ki za razliko od analiziranih standardiziranih padavinskih indeksov (SPI) v tem obdobju niso izpostavili sušnih dogodkov (Zalokar, 2018).

Tretje prevojno obdobje, ki je bilo izraženo s prevojem sekvenc trendov nizkih mesečnih gladin podzemne vode gladin med februarjem 2003 in aprilom 2005 (sl. 11), lahko povežemo s pojavom ene izmed najizrazitejših meteoroloških in hidroloških suš v zadnjem stoletju. Standardiziran indeks letne vsote padavin (SPI12) je na merilni postaji Murska Sobota v letu 2003 dosegel ekstremno nizko vrednost dolgoletnega referenčnega obdobja (Dornik, 2016), ekstremno nizke vrednosti v obdobju med leti 2003 in 2005 so bile ugotovljene tudi za vse analizirane standardizirane indekse kumulativnega volumna mesečnega pretoka (1, 3, 6, 12, 24) na merilni postaji Mure v Gornji Radgoni (Zalokar, 2018), pa tudi za standardizirane indekse gladin podzemne vode na merilnih postajah Murske in Dravske kotline (Draksler et al., 2017; Adrinek & Brenčič, 2019). Na večini merilnih mest je temu prevojnemu obdobju sledilo obdobje s trendom zviševanja gladin podzemne vode, ki je trajalo do konca obdelovalnega obdobja. Na merilnih mestih Zgornje Konjišče (10005) na Apaškem polju, ter Veščica (05080) in Bunčani (05011) na Mursko–Ljutomerskem polju je bil prevoj trenda ugotovljen nekoliko prej kot na ostalih merilnih postajah, v letih 2000 oziroma 2001 (sl. 11, Tabela 2).

Zaključki

Na podlagi izvedenih raziskav sklenemo, da nam državna zbirka hidroloških podatkov, ob uporabi izbrane metodologije, lahko poda dragocene informacije o značilnostih nihanja podzemne vode in o spremembah teh značilnosti skozi čas. Ugotovili smo, da so za plitve medzrnske vodonosnike Pomurja značilni različni vzorci nihanja podzemne vode, ki smo jih lahko uvrstili v posamezne skupine. Dobljene skupine smo povezali s prevladujočim vplivom napajanja vodonosnikov, pri čemer smo razdvojili območja s prevladujočim napajanjem iz reke Mure od območij s prevladujočim napajanjem z infiltracijo padavin oziroma z dotoki iz gričevnatega zaledja vodonosnika. Dolgi časovni nizi podatkov, ki omogočajo vpogled v dinamiko nihanja gladin podzemne vode skozi čas, na območju plitvih aluvialnih vodonosnikov Pomurja ne kažejo enotne slike, saj smo mestoma ugotovili statistično značilno zniževanje gladin podzemne vode, mestoma statistično značilno zviševanje tega parametra, na nekaterih merilnih mestih pa trend nihanja gladin podzemne vode ni bil izražen. Znotraj posameznih časovnih vrst smo lahko določili sekvence v trendih nihanja gladin in ugotovili, da so nastopi prehoda iz ene v drugo sekvenco trenda med različnimi merilnimi postajami pogosto med seboj časovno primerljivi. Z izbranim metodološkim pristopom smo tako potrdili osnovno raziskovalno vprašanje.

Ugotovili smo, da je območje Pomurja v veliki meri odvisno od podnebnih značilnosti območja, ki se odražajo v količini napajanja vodonosnikov bodisi s prenicanjem padavin, dotoki iz prispevnega zaledja ali z napajanjem iz vodotokov. Vseh trendov v nihanju gladine podzemne vode ni bilo možno povezati s podnebnimi značilnostmi območja, kar je pokazatelj, da na količinsko stanje podzemne vode v VTPodV_Murska kotlina lokalno vplivajo tudi drugi, predvidoma antropogeni posegi v vodno okolje. Del teh posegov smo poskušali pojasniti z dostopnimi navedbami iz literature, del pa je ostal nepojasnjen.

V prihodnje bi bilo podobne analize smiselno izvesti tudi za ostala vodna telesa podzemne vode s prevladujočo medzrnsko poroznostjo, na katerih razpolagamo z dolgimi nizi meritev državne mreže monitoringa podzemnih voda na več lokacijah. Na območju kraških vodonosnikov je uporabljen pristop verjetno omejen zaradi manjšega nabora merilnih mest, saj količinsko stanje podzemne vode v kraških vodonosnikih običajno spremljamo le na območju kraškega izvira, ki predstavlja koncentriran iztok podzemne vode iz celotnega prispevnega zaledja izvira.

Pogoj za uspešno analizo in njeno interpretacijo je dovolj dolg niz meritev na primerni merilni lokaciji s primerno frekvenco meritev. Ocenjujemo, da je za metodo analize dolgoročnih trendov pogoj vsaj 30 letni niz opazovanj s pogostostjo meritev vsaj trikrat mesečno. Pri clusterski analizi in analizi percentilov ocenjujemo, da dobimo zadovoljive rezultate pri vsaj 15 letnem nizu opazovanj. Pomembno pa je, da merilna lokacija odraža najpomembnejše elemente konceptualnega modela dela vodonosnika, ki ga predstavlja. Pogosto se primernost merilne lokacije izkaže šele po večletnem opazovanju gladine podzemne vode, saj šele z daljšim razpoložljivim nizom meritev lahko ovrednotimo značilnosti nihanja podzemne vode. Poleg tega se pogosto sprememba v nihanju podzemne vode zaradi umetnih vplivov na količinsko stanje podzemne vode pokaže šele po določenem odzivnem času od nastopa spremembe.

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Nove knjige - New books

Baltazar HACQUET, 2020: **Oryctographia Carniolica ali Fizikalno zemljepisje vojvodine Kranjske, Istre in deloma sosednjih dežel.**
Knjižnica Jožeta Udoviča Cerknica in Založba Maks Viktor, Ljubljana, 162 str. + lii..

Na ozemljih, kjer so živeli Slovenci, to je na območju nekdanje zgodovinske Kranjske in sosednjih dežel Štajerske, Koroške, Istre in Goriške je bilo v preteklosti napisanih nekaj pomembnih in temeljnih znanstvenih del. Med njimi sta za kulturno in znanstveno zgodovino Slovencev najpomembnejši deli Slava vojvodine Kranjske Janeza Vajkarda Valvasorja in Oryctographia Carniolica Baltazarja Hacqueta. Če smo celoten prevod prve v slovenščino končno dočakali leta 2009 pa je ostajal dolg do Baltazarja Hacqueta odprt. V preteklosti je bilo natisnjenih nekaj prevodov odlomkov, ki pa še zdaleč niso omogočali vpogleda v celoto. Konec leta 2020 smo vendarle dočakali tudi prevod prve knjige Oryctographie Carniolice. Knjigo je iz stare nemščine druge polovice 18. stoletja mojstrsko prevedel Primož Debenjak, ki je pred tem sodeloval tudi pri prevodu Valvasorja. Celoten projekt izdaje prve knjige je izvedel in pripeljal do konca Tomaž Čeč iz založbe Maks Viktor ob sodelovanju Marije Hribar, vodje knjižnice v Cerknici, ki je vodila celoten projekt in tudi poskrbela za finančno podporo Občine Cerknica, brez katere knjiga verjetno ne bi zagledala luči dneva. Pri nastanku knjige so sodelovali še drugi strokovnjaki. V uredniškem odboru in pri izdelavi kazal je sodeloval Valentin Schein. Prevode iz latinščine je prispeval Matej Petrič, spremne študije pa Mihael Brenčič in Andrej Kranjc. Zaradi zahtevnosti so prevod pregledali tudi recenzenti različnih strok. Posebna dodana vrednost knjige je, da je natisnjena kot faksimile, kjer posamezna stran prevoda v slovenščini ustreza strani v originalni izdaji. Verno preslikane in natisnjene so tudi vse grafične vinjete in druge podobe iz originala.

Baltazarja Hacqueta bi lahko označili kot neznanega znanca. Njegova biografija je polna lukenj in protislovnih opisov, začenši z njegovim rojstvom leta 1739 ali 1740. Dvoumnosti in nejasnosti so predvsem značilnost obdobja pred njegovim prihodom v Idrijo leta 1766, kjer je postal ranocelik in pomočnik Giovannija Antonija Scopolija. Prav Idrija je bila tista, ki ga je spodbudila k intenzivnemu znanstveno raziskovalnemu delu in pisanju. Po ukinitvi jezuitskih šol leta 1773 je bil Hacquet premeščen v Ljubljano, kjer je ostal do leta 1787. Tega leta je odšel na novoustanovljeno univerzo v Lvovu v današnji Ukrajini. Ko je bil v Idriji in v Ljubljani je, kolikor mu je dopuščal čas, potoval po širši in daljni okolici. Rezultat tega so bila številna dela; knjige

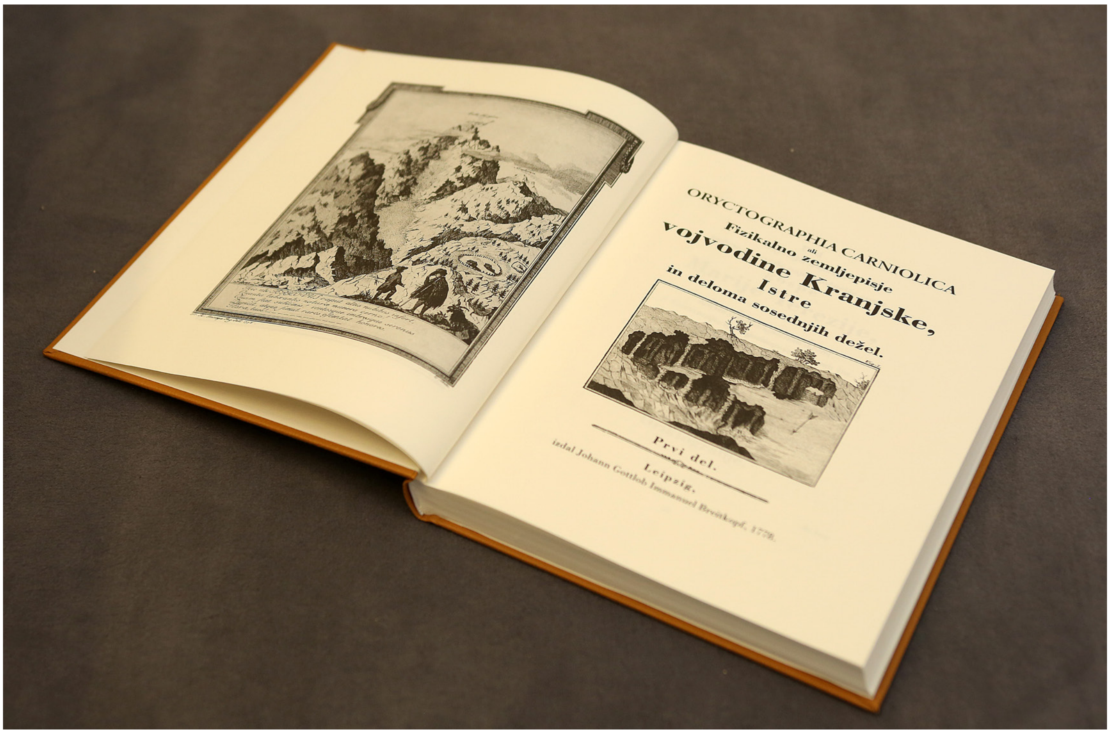


foto: Ljubo Vukelič

in članki. Čeprav bi Hacqueta lahko opredelili kot tipičnega razsvetljenskega polihistorja, ki so ga zanimala mnoga disciplinarna področja, je največjo težo svojih raziskav polagal na montanistične vede, in znotraj tega predvsem na geologijo. S svojimi s potovanji podprtimi raziskavami je nadaljeval tudi kasneje na območju Ukrajine in Poljske. Umrl je leta 1815 na Dunaju. Njegove naravoslovne zbirke so postale del zbirk Jagelonske univerze, najstarejše poljske visokošolske ustanove, njegovih del pa, navkljub kar nekaj podrobnim študijam bibliografije, še vedno ne poznamo v celoti.

Težko je soditi, katero Hacquetovo delo je najpomembnejše. Za območje današnje Slovenije je to vsekakor Oryctographia Carniolica ali Oriktografija Kranjske, ki je od leta 1778 do leta 1789 izšla v štirih zvezkih pri založniku Johannu Gottlobu Breitkopfu v Leipzigu. In sedaj je prva v slovenščino prevedena knjiga pred nami. Toda, navkljub mojstrskemu prevodu nas čaka zahtevno branje. Hacquetov stil pisanja bi z lahkoto opisali kot baročnega, vendar ta ne odraža le duha časa, temveč tudi naravo njegovega dela in raziskav. Njegovi opisi so daleč od zahtev današnje znanosti v kateri veljajo mnogo bolj natančna pravila pisanja. Morda bi lahko njegovo pisanje figurativno označili kot popotnikov tok zavesti. Hacquet potuje po pokrajini, na pot ga vodijo podatki, ki jih je dobil od lokalnih prebivalcev in od drugih intelektualnih popotnikov pred njim, še bolj kot to pa ga vleče radovednost. Potuje sem in tja, po eni dolini navzgor ob toku reke, nato zavije v stransko dolino, pa se čez čas ponovno vrne v kraj, kjer je že bil. Pri tem razmišlja in teoretizira in se sklicuje na reference, ali pa celo izvede kakšen eksperiment. In tako iz strani na stran. Branje, ki utrudi tudi vztrajnega in izkušenega bralca. Vsekakor pa je besedilo, ki je pred nami, izredno dragoceno.

Prevod prve knjige Oriktografije Kranjske nam ponuja vrsto pestrih razgledov po intelektualni pokrajini druge polovice 18. stoletja. To je obdobje, ki je za razvoj geološke znanosti na slovenskem izredno pomembno. Tega dejstva se vse premalo zavedamo, kaže pa se v slabem poznavanju literature tega obdobja. Zaradi rudnika živega srebra v Idriji, posredno pa tudi drugih geoloških in geomorfoloških danosti, je bilo to ozemlje krajši ali daljši čas predmet zanimanja številnih naravoslovno usmerjenih polihistrojev, ki jih je zanimala predvsem geologija. Naštejmo le nekatere najpomembnejše med njimi: Johann Jacob Ferber, Ignaz von Born, Tobias Gruber, Alberto Fortis, Deodat de Dolomieu, Johann Ehrenreich Fichtel in nenazadnje tudi Žiga Zois. Baltazar Hacquet hodi vzporedno s temi intelektualci in je pri tem v svojih opisih najbolj temeljit. Hacquetova metoda je metoda potujočega geologa; potuje v kraje, o katerih so informacije pomanjkljive ali pa se o njih ne ve ničesar. Pri tem zbira podatke in jih zlaga v skladovnico. S tem se kopičijo informacije, ki omogočajo vpogled v naravne danosti ozemlja in pomagajo razumeti prostor, tudi tridimenzionalno, v geološkem pomenu. Hacquet premišljuje o teoretičnih konceptih in o nastanku ozemlja. Pri tem je eklektik. Če smo se v preteklosti spraševali ali je v svojih geoloških interpretacijah plutonist ali neptunist, se nam v prvi knjigi pokaže v drugačni teoretični luči. Hacquet je predvsem pripadnik šole Giovannia Arduina italjanskega geologa in enega prvih stratigrafov, tudi avtorja pojma terciar, ki ga ni mogoče uvrstiti ne v neptunistično in ne v plutonistično paradigmo.

Prevajanje besedila je bilo izredno trd oreh. Vzrok leži v tem, da Hacquet uporablja izraze, ki so v rabi še danes, a nosijo povsem drugačen pomen. Tako na primer pogosto govori o marmorjih in o bazaltih. Pri tem mu prvi predstavljajo katerokoli sedimentno kamnino za katero je mnenja, da bi jo bilo možno uporabiti kot gradbeni kamen ali celo za umetniška dela, bazalt pa mu predstavljajo drobnozrnate ali mikrokristalne kamnine, najpogosteje črne barve. Uporablja tudi veliko formacijskih imen, ki se nikoli niso uveljavila, in jih je danes skoraj nemogoče izslediti. Hacquet je zelo jasno razlikoval dolomit od apnencev, in to v času ko to razlikovanje ni bilo samoumevno. Med seboj loči bituminozni dolomit in »navadni« dolomit. Vendar je pri tem potrebno poudariti, da je zmotno prepričanje, ki je zastopano v delu literature, da je bil prvi, ki je dolomitno kamnino znanstveno opisal. Še pred njim je to v svojih sistematikah mineralov opravil švedski naravoslovec in avtor binarne klasifikacije Carl von Linné.

Knjiga, ki je pred nami je temeljno geološko besedilo, ki od sedaj dalje velja upoštevati v pregledih geološke literature posameznih območij Slovenije. Poleg tega pa nam prevod omogoča mnogo več, nudi nam globok vpogled v nastanek in razvoj geološke znanosti. Razsvetljensko 18. stoletje je formativno obdobje geologije kot samostojne znanstvene discipline. Vabljeni k branju, med tem ko z nestrpnostjo čakamo na prevod druge knjige Oriktografije Kranjske.

Mihael Brenčič

Simon MOZETIČ, Tomislav, MATOZ, Andrej LAPANJE & Nina RMAN, 2020:
Geofiozikalne meritve v vrtinah, Karotažne meritve.
Geološki zavod Slovenije, Ljubljana: 21. str.

Brošura »Geofizikalne meritve v vrtinah« zapolnjuje strokovno vrzel s področja karotažnih meritev. Znastveno-pedagoška literatura s tega področja je prisotna že nekaj časa in omogoča globji vpogled v fizikalne metode meritev v vrtinah. Za strokovno manj podkovanega bralca pa do sedaj na slovenskem jezikovnem področju nismo imeli prave izbire.

Pričujoča brošura bralca najprej seznani s pomenom karotažnih meritev in zgodovino izvajanja le-teh v slovenskem prostoru. V brošuri je v nadaljevanju prikazanih deset metod, ki so bralcu zaradi lažjega razumevanja predstavljene tekstovno in slikovno. Spremljajoča besedila različne metode predstavijo s stališča njihove namembnosti in uporabnosti. Iz besedil so razvidne tudi njihove omejitve in osnovne zahteve po opremljenosti vrtin za izvedbo uspešnih meritev. Slikovno gradivo se skladno dopolnjuje z besedilom, hkrati pa bralcu omogoča osnoven vpogled v pričakovane rezultate meritev. Bralec se tako lahko hitro seznani s posamezno metodo in njeno primernostjo za uporabo pri določenih preiskavah v vrtinah. Bralcu je v precejšno pomoč pregledna tabela, ki različne geofizikalne metode prikazuje skupaj glede na njihovo uporabnost na posameznem področju. Posebej velja avtorjem pohvala za podatke o pričakovanih hitrostih izvajanja posamezne meritve, kar je zelo uporabno tudi za izkušenega strokovnjaka; gre za podatke, ki so mnogokrat spregledani v fazi projektiranja vrtin.

Menim, da bo brošura dobrodošla na vsaki knjižni polici tako tistih, ki se ukvarjajo z vrtalno tehniko, kot tistih, ki bi se radi seznanili z osnovami geofizikalnih meritev v vrtinah.

doc. dr. Goran Vižintin

Bogdan JURKOVŠEK & Tea KOLAR-JURKOVŠEK, 2021:
Fosili Slovenije: pogled v preteklost za razmislek o prihodnosti.
Geološki zavod Slovenije, Ljubljana: 264 str.
(Fossils of Slovenia: looking into the past to reflect in the future. Geological Survey of Slovenia, Ljubljana, 259 p.)

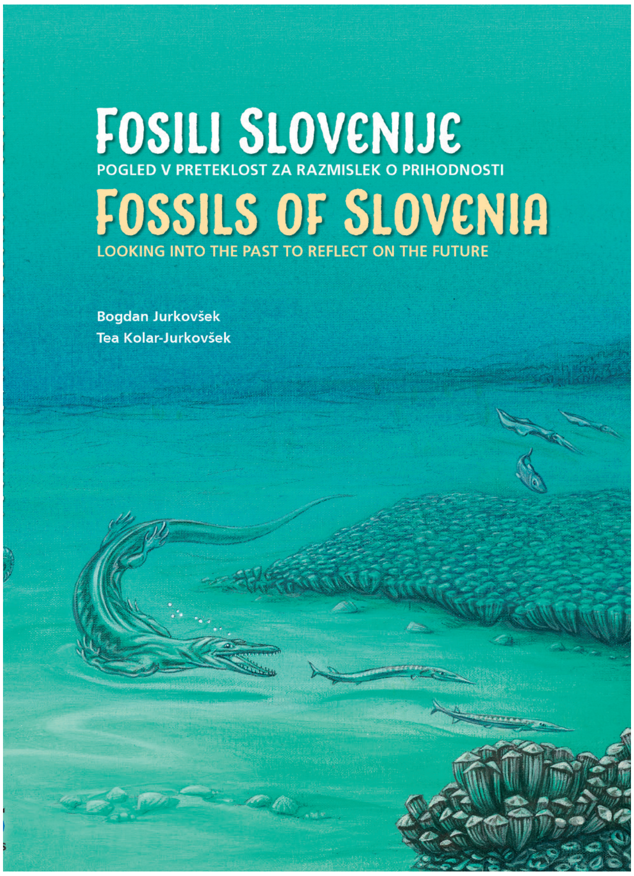
Fosili so kakršni koli ostanki organizmov iz geološke preteklosti. Velik del fosilov najdemo v sedimentnih kamninah, izjemoma pa se ohranijo tudi v metamorfnih. Fosili so izjemno pomembni za določanje relativne starosti kamnin, rekonstrukcije paleo-okolij in življenjskih razmer v geološki preteklosti ter za preučevanje evolucije in ugotavljanje sorodstvenih vezi med skupinami organizmov. S preučevanjem fosilov se ukvarja paleontologija, ki v zadnjih desetletjih doživlja pravi preporod in ob uporabi novih raziskovalnih metod odgovarja na nekatera vprašanja, ki so se dolgo časa zdela bolj v domeni domišljije kot preverljive in dokazljive znanosti.

Območje Slovenije je geološko razmeroma pestro in zanimivo tudi za tiste, ki jih zanimajo fosili – pa naj stoji za tem raziskovalni interes, ali pa zgolj veselje ob iskanju nečesa zanimivega in preživljanje prostega časa v naravi. Fosile lahko pričakujemo skozi skorajda celotno stratigrafsko zaporedje, ki je zastopano pri nas, od masivnih devonskih apnencev na Jezerskem, do neogenskih plitvomorskih apnencev vzhodne Slovenije in celo v pleistocenskih jamskih sedimentih. Zaradi vse te pestrosti in potenciala za nove najdbe zanimanje za fosile med Slovenci verjetno nikoli ne bo izginilo, čeprav zaradi izčrpanosti nekaterih že dalj časa znanih, bolje dostopnih ali nezaščitenih najdišč fosilov, zaraščanja ali opuščanja kmetovanja, ugašanja rudarske dejavnosti, zapiranja manjših kamnolomov in včasih (žal) tudi slabe ozaveščenosti vseh nas, nekatera najdišča fosilov zlagoma tonejo v pozabo.

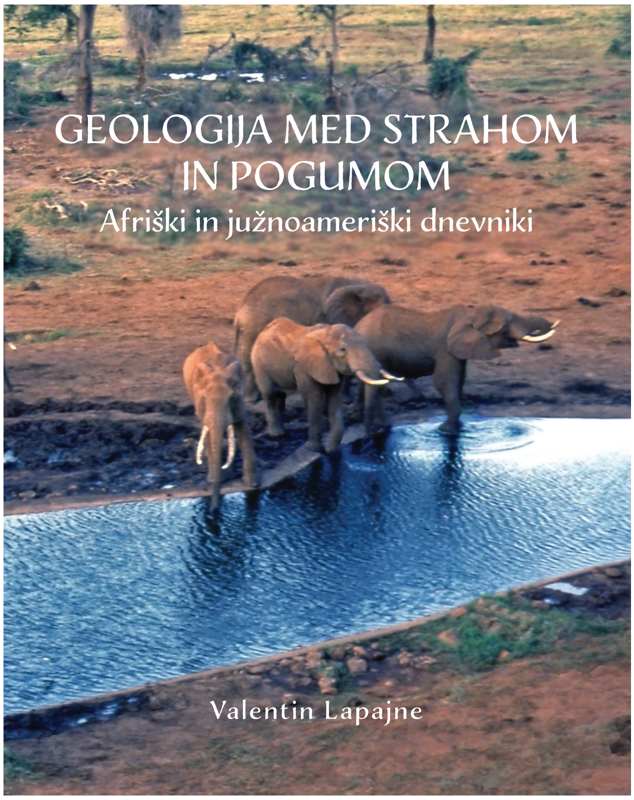
Knjiga »Fosili Slovenije: pogled v preteklost za razmislek o prihodnosti« bo marsikaterega bralca navdušila za področje paleontologije in verjetno marsikoga tudi spodbudila k raziskovanju lastne okolice. Za tiste, ki so s področjem paleontologije že dobro seznanjeni, pa knjiga prinaša osvežen pregled pomembnejših in bolj znanih najdb in najdišč fosilov pri nas ter celosten pregled razvoja biosfere. Slednji zajema najpomembnejše evolucijske dogodke, kot so pojav prvih živih organizmov, kambrijska eksplozija in množično izumrtje ob koncu perma. Avtorja sta pri sestavljanju knjige uporabila bogate izkušnje s področja paleontologije in prirojen občutek za razumljiv in priljuden način pisanja. Knjiga je bogato ilustrirana in opremljena s fotografijami primerkov, ki so bili najdeni v Sloveniji. Pri izboru le-teh sta se avtorja osredotočila na makrofosile, torej na tiste fosile, ki so vidni in določljivi s prostim očesom. Dodane so številne rekonstrukcije paleo-okolij, ki bralcu omogočajo lažjo predstavo o tem, kako je izgledalo površje Zemlje pred desetinami in stotinami milijonov let.

Knjiga je primerna za vse ljubitelje fosilov in naravoslovja nasploh. Zaradi množice referenc, ki so sprotno navedene v tekstu, je tudi nadvse uporabno vodilo za poklicne geologe. Pomembno bo prispevala k izobraževanju novih generacij geologov ter njihovemu razumevanju fosilnih združb in sosledij. Nenazadnje je opisana knjiga tudi spomenik naši naravni dediščini in opomin k vestnemu ohranjanju le te.

Luka Gale



Valentin LAPAJNE, 2021: **Geologija med strahom in pogumom: Afriški in južnoameriški dnevniki**. Geološki zavod Slovenije, Ljubljana: 366 str.



Ob praznovanju 75. obletnice obstoja, je Geološki zavod Slovenije izdal knjigo dolgoletnega sodelavca Valentina Lapajneta z naslovom Geologija med strahom in pogumom: Afriški in južnoameriški dnevniki.

Dnevniški zapisi z odprav, ki so raziskovale različne mineralne surovine v Eritreji in Etiopiji (1963/64), Tanzaniji (1979), Gvajani (1981/82) in Mozambiku (1983), ki jih je izvajal takratni Geološki zavod Ljubljana, nam živo slikajo delo, razmere, vzdušje ter strokovne in moralne izzive geologa na terenu daleč od varnosti in udobja svojega doma. Knjiga predstavlja neprecenljivo pričevanje o pomembnem obdobju geološke stroke v Sloveniji, ko so bili odhodi na večmesečne ali celoletne odprave v Afriko in Južno Ameriko malodane nekaj vsakdanjega, kar je mlajšemu bralcu skoraj nepredstavljivo.

Knjiga obsega 366 strani in vsebuje 130 barvnih fotografij in skic. Napisana je duhovito in iskrivo, z občutnim čustvenim nabojem ter slogom, ki pritegne tudi zahtevnega bralca. Razdeljena je na štiri samostojne vsebinske sklope; vsak od njih v kronološkem zaporedju opisuje posamezno odpravo in njen potek.

Zapisi so bolj kot na podrobno geološko zgradbo raziskovalnih področij osredotočeni na opis dežele, organizacijo terenskega dela, logistiko, naloge terenskega geologa, doživljanja dela, odnose v ekipi ter stike z lokalnim prebivalstvom. Ekipe na terenu so bile ves čas izpostavljanje nevarnostim, predvsem napadom divjih živali kot so kače, levi, bizoni in povodni konji, raziskave pa so pogosto potekale na nemirnih območjih vpletenih v državljansko vojno, kjer je v zraku ves čas visela negotovost zaminirane ceste ali napada gverile. Od tod prihaja tudi motivacija za naslov knjige – vsak član odprave je moral namreč premagati nešteto svojih strahov, da je lahko deloval v takšnih razmerah.

Prvi del, ki opisuje odpravo v Eritrejo in Etiopijo (1963/64), je naslovljen »Cena za kvadratni kilometer džungle«. V njem Valentin zelo dinamično, doživeto in čustveno opisuje prvo srečanje z afriško celino in raziskave osredotočene na železo in mangan. Sledimo lahko opisom dela v ekstremni vročini, neskončnih pohodov skozi džunglo, bližnjega srečanja z izjemno strupeno zeleno mambo, gverilskega napada iz zasede ter poti v peklensko depresijo Danakil, kakor tudi tovarištva v ekipi in pristnih stikov z domačini.

Dnevnik odprave v Tanzanijo (1979) nosi naslov »V deželi ognjenikov«. Postreže nam z opisom raziskav apatitov v karbonatitnih kompleksih, pohoda v divjino Zizija, ki je spominjal na pohode prvih evropskih raziskovalcev Afrike, detajlnim opisom zgradbe Kilimanjara ter čudovito predstavitvijo številnih tanzanijskih nacionalnih parkov. Iz pripovednega toka je že čutiti avtorjevo zrelost in prekaljenost.

V nasprotju s predhodnima dnevnikoma, kjer smo priča selitvam na različna raziskovalna območja, pa je tretji dnevnik z naslovom »Zlatonosni peski Gvajane« nekoliko bolj statičen, saj opisuje detajlne raziskave zlata v rečnih nanosih reke Konawaruk v osrčju Gvajane (1981/82). Kljub temu ni nič manj zanimiv, saj delo na terenu pomeni nenehno reševanje težav in prilagajanje. Ekipa je med nadzorom banka vrtanja ves čas izpostavljena nevarnosti ugriza kač in nepredvidljive reke. V zaključku dnevnika nas Valentin popelje še v ZDA, kjer si je pred odhodom domov privoščil še daljše popotovanje.

Zadnji dnevnik z naslovom »Geologija v vojnih razmerah« opisuje odpravo v Mozambik (1983), ki je raziskovala nahajališča granita, pegmatita in kaolinita v severnem delu države, kjer so potekali spopadi med gverilci in vojsko. Zapisi so zato pogosto polni tesnobe, napetosti in negotovosti, saj so bili kljub vojaškemu spremstvu lahka tarča gverilcev. Zaradi vojnega stanja avtorjeve misli pogosto pobegnejo v otroštvo, ko je kot mlad fantič na Hleviški planini preživel 2. svetovno vojno. Kljub vsemu iz opisov še vedno veje optimizem ter očaranost nad morfologijo, geološko sestavo, prebivalci in sodelavci.

Knjiga je napisana poljudno in razumljivo zato predstavlja prijetno branje tudi za laično javnost, kateri bo približalo tako raznolikost Afrike in Južne Amerike kakor tudi koncept dela terenskega geologa, ki se navkljub digitalizaciji sveta ni dosti spremenil. Poleg tega nas knjiga ves čas opominja, da se naš pogum poraja ravno iz premagovanja naših strahov.

Knjiga je tik pred izidom, njena uradna predstavitev pa je načrtovana v septembru.

Vabljeni k branju teh zanimivih spominov.

Klemen Teran

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 lahko predlagajo **tri recenzente**, uredništvo pa 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.

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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:
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- *Podnaslovi slik in tabel*
- *Tabele, Slike, Table*

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