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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.

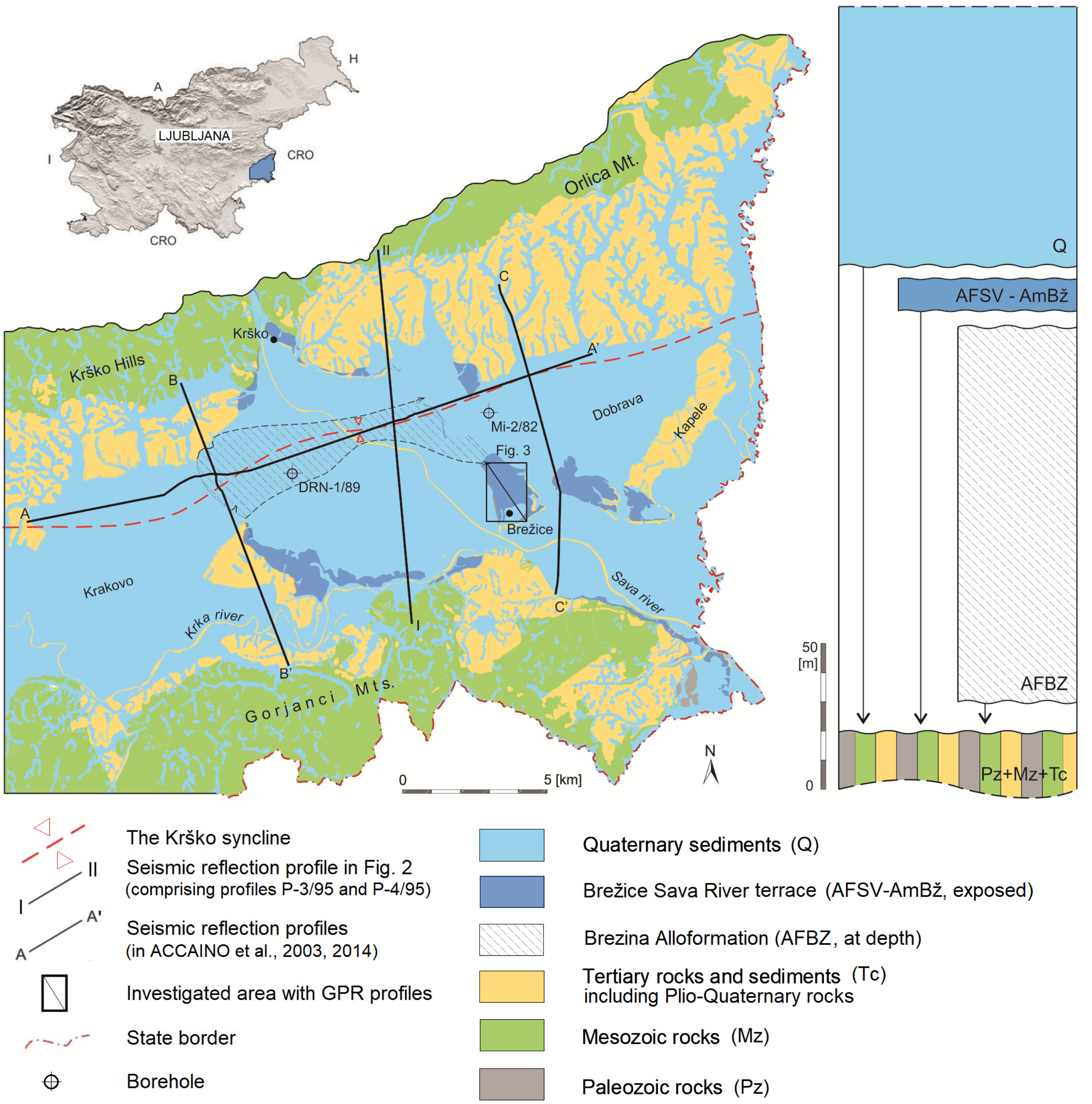


Fig. 1. Simplified geological map of the Krško basin (after Poljak, 2017a) with delineated exposures of the BSRT and a generalized geological column of described lithostratigraphic units showing their maximal thicknesses.

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"

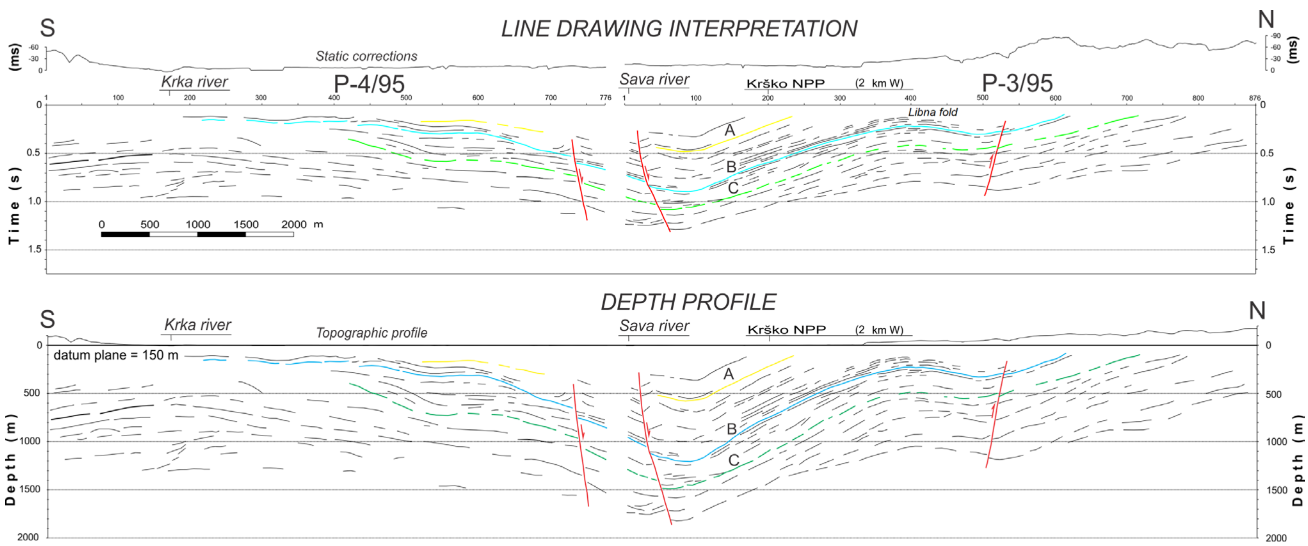


Fig. 2. Line drawing interpretation and depth conversion of the P-3/95 and P-4/95 seismic reflection profiles recorded across the eastern part of the Krško basin (from Gosar, 1998), depicted in Fig. 1 as a merged seismic profile marked I-II. Horizon A – the base Plio-Quaternary unconformity; horizon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

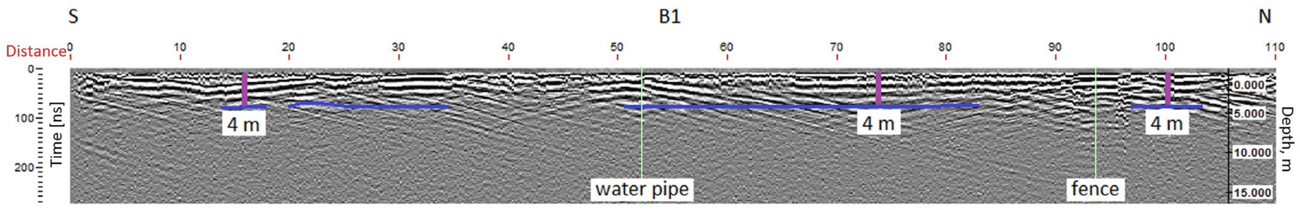


Fig. 4. Calibration GPR profile B1 used to define electromagnetic signal velocity based on measured lower BSRT boundary depth at outcrop (Fig. 3B).

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.

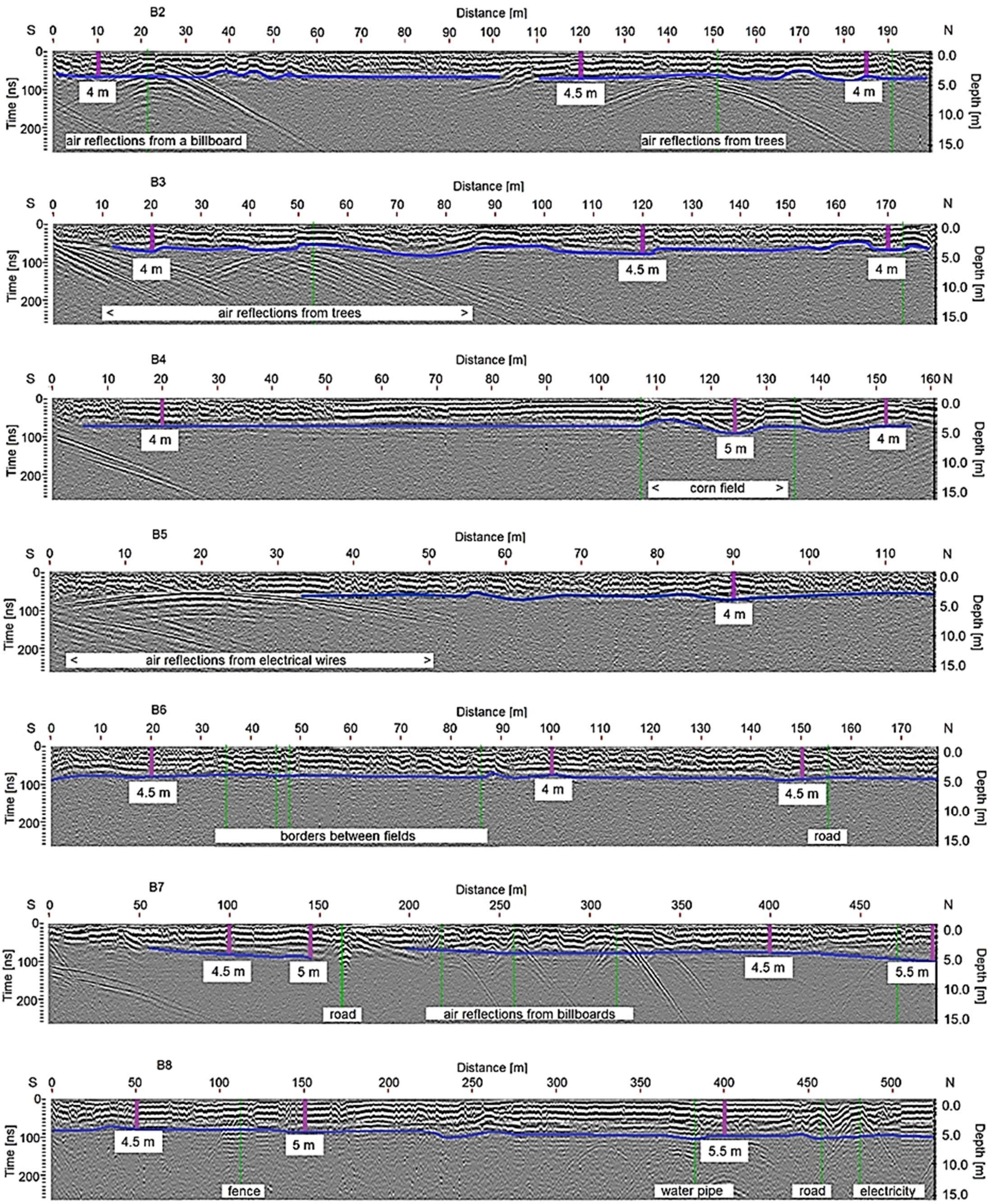


Fig. 5. GPR profiles B2 to B8 with marked BSRT base – boundary between BSRT gravel above and Pannonian marl below (blue line), depths to the BSRT base inferred from GPR profiles (purple lines), and markers (green lines).

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).

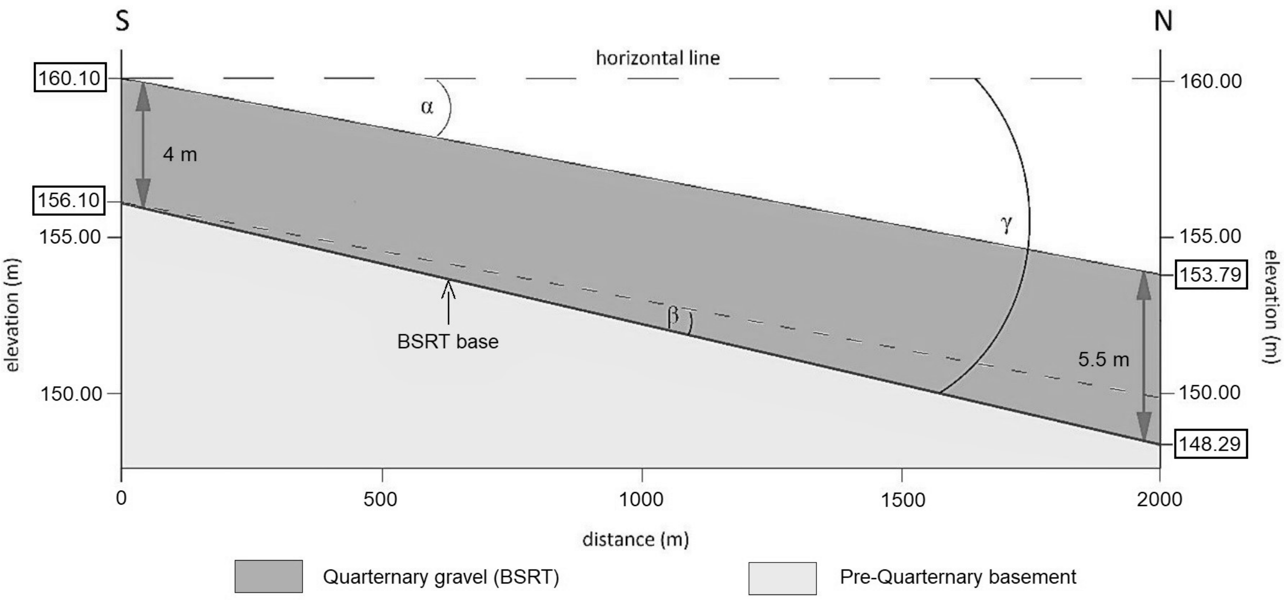


Fig. 6. Interpretation of LiDAR and GPR data showing the surface elevation difference of the present day topography in the area, tilt of the BSRT surface (angle α), the tilt of the surface during sedimentation (angle β) and cumulative northward tilt of the boundary between Quaternary sediments above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