

USE OF GEOMORPHOLOGICAL INDICATORS FOR THE DETECTION OF ACTIVE FAULTS IN SOUTHERN PART OF LJUBLJANA MOOR, SLOVENIA

UPORABA GEOMORFOLOŠKIH INDIKATORJEV ZA DOLOČANJE TEKTONSKO AKTIVNIH PRELOMOV NA JUŽNEMU DELU LJUBLJANSKEGA BARJA

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The Iška alluvial fan extends towards the Ljubljana moor.
Vršaj Iške sega še daleč proti Ljubljanskemu barju.

Use of geomorphological indicators for the detection of active faults in southern part of Ljubljana moor, Slovenia

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ABSTRACT: In order to detect recently tectonically active faults, *Stream Length-gradient* (SL) index and a newly developed method of river gradient analysis were made for three rivers. Two methods were used on the southern part of Ljubljana moor, where rivers cross dextral (right-lateral) faults with Dinaric orientation (NW-SE). Watercourse profiles were analysed first, using a »classic«, well established method of SL index. However, this method didn't yield useful results since almost no variability in SL indexes were observed. Additionally, a second newly developed method pointed on the anomalies, which might correspond to the areas of active surface uplift and subsidence as a consequence of active tectonic movements. We compared determined anomalies with the fault lines plotted on the Basic geological map 1 : 100.000 and with the data of radar measurements of vertical movements by PSInSAR method. In this way five potentially active faults, areas of contraction and areas of extension were determined. The results of this research can be used as complementary information for the construction of tectonic model of Ljubljana field and Ljubljana moor.

KEY WORDS: geomorphology, river gradient, SL index, dinaric faults, Ljubljana moor, Ig

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1 Introduction

Hills and alluvial fans of Borovnišča River, Iška River and several smaller streams (Figure 1) are characteristic for the southern margin of Ljubljana moor. This area belongs to the northern margin of geotectonical unit of Slovenian external Dinarides (Placer 1998; 2008) with typically thick sequence of Mesozoic shallow water carbonate rocks (Otoničar 2007; Jež et al. 2011). Towards northwest these sediments border to deep water basin environments (Šmuc and Čar 2002; Rožič et al. 2009; Gale 2010; Šmuc and Rožič 2010).

The major tectonic structures of regional importance in external Dinarides of Slovenia are so-called dinaric faults with strike parallel to the strike of Dinaric orogen (Vrabec and Fodor 2006). Their recent tectonic activity has been proved by different methods: GPS velocity vectors (2 mm/year contraction of the area in the direction north-south; Weber et al. 2006; 2010), the calculation of long-term horizontal velocity fields (the movements ~1.5 mm/year; Kastelic and Carafa 2012), mapping based on LiDAR (Cunningham et al. 2006; 2007), measurements of tectonic micro deformations (Gosar and Lenart 2010; Gosar 2012) and analysis of spatial distribution of earthquake events (Kastelic et al. 2008).

Among many available methods for proving recent tectonic activity of faults, different morphotectonic analyses are commonly used in world scientific literature. They are based on the analysis of the relation between morphology of the surface and tectonics through the calculation of different morphometric indexes. Among them is *Stream Length-gradient index* (SL index; Hack 1973) has been widely recognised. Such research has not been done yet on the territory of Slovenia.

SL index is used for separation of the areas of different tectonic activity (Viveen et al. 2012), specially for the identification of vertical tectonic movements (Burbank and Anderson 2001; Peters and Van Balen 2007). Underformed river profiles have typical concave shape (figure 2), which is relatively quickly formed due to the erosional processes, speaking from the geological perception of time. SL index is defined in the way to detect the changes in »ideal« river slope profile. Its low values can reflect either active tectonic subsidence of the area (Viveen et al. 2012) or low rock resistance to the river erosion, while high values of SL index can indicate either exalted tectonic uplift of the area or high rock resistance to the erosion (Alipoor et al. 2011).

The purpose of the research is an experimental determination of recent active tectonic movements based on the geomorphological indicators. The study area of southern border of Ljubljana moor is segmented by numerous active strike-slip faults of dinaric orientation that are crossed by three parallel watercourses: Iška, Borovnišča and Želimejščica (figure 1). The area is mostly composed of predominantly Mesozoic carbonates, which are known for resistance to the river erosion. Therefore, in this study almost all anomalies in SL index can be attributed to recent tectonic activity. The study begins with the detection of potentially tectonically active faults by SL index method after Hack (1973). After that, the same was done but by using newly developed adapted method of river gradient analysis. Results were later on interpreted by creating a test model of recent tectonic activity of the area and compared with PSInSAR radar measurements of vertical movements.

2 Materials and methods

The calculation of morphometric indexes has been applied on the digital elevation model (DEM) of 12.5 m resolution (source: The surveying and mapping authority of the Republic of Slovenia) and topographic maps of 1 : 5000 scale. *AutoCAD* and *GS Surfer* computer software were used to determine river profiles and other variables, which were later numerically processed by program *MS Excel*.

The calculation of SL index began with the creation of individual rivers cross-sections. They were later on divided into segments, which can be visually approximated by a straight line. For each observed segment SL index is defined by following equation (Hack 1973):

$$SL = (\Delta H / \Delta L) L, \quad (1)$$

where ΔH represents the difference in elevation for the specific segment, ΔL its length and L the distance from the river spring to the middle of the observed segment (figure 2). The ratio $\Delta H/\Delta L$ defines the gradient of the river bed on the observed segment, which was compared later on with the gradient of the theoretical

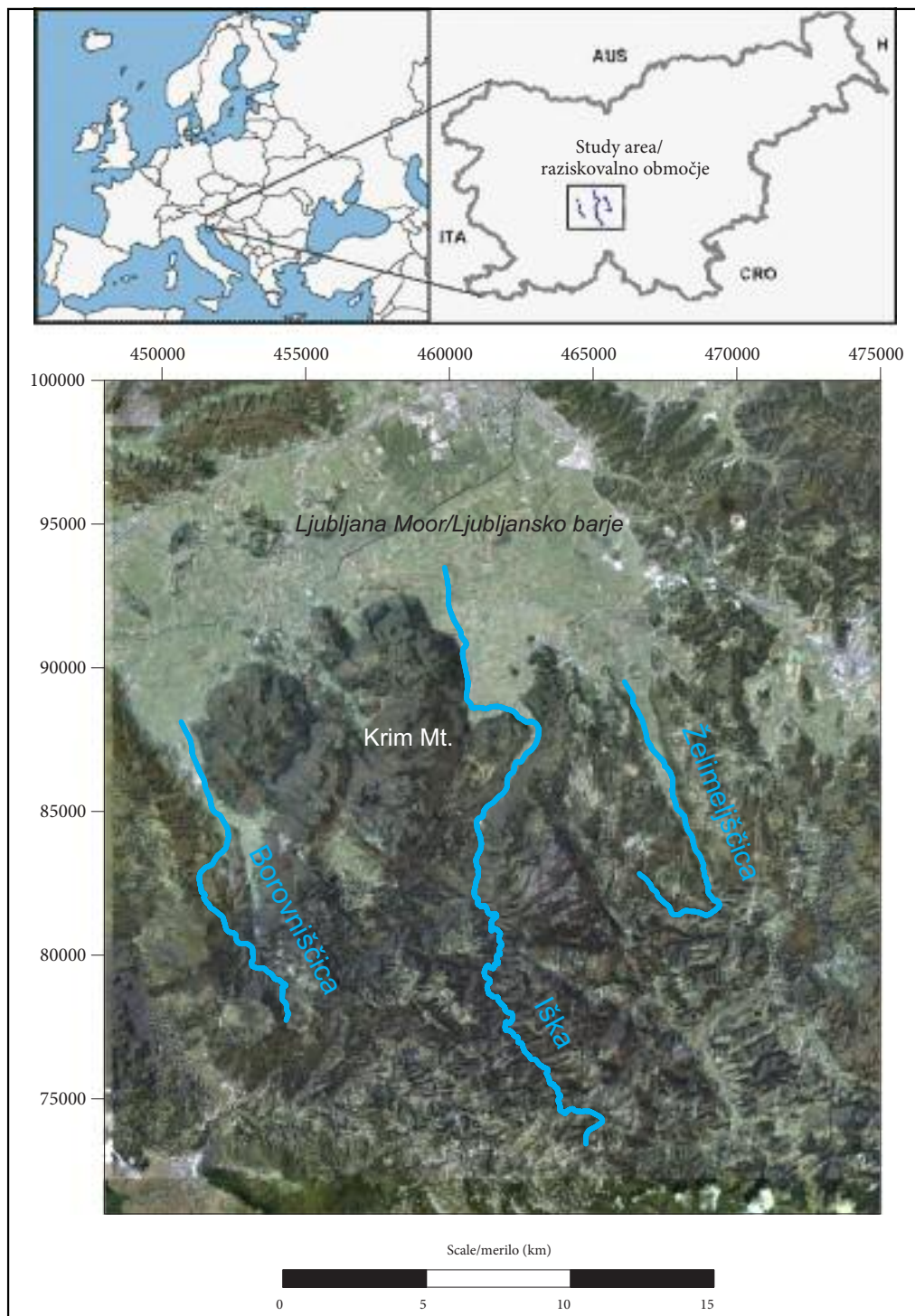


Figure 1: Research area.

»ideal« river, which decreases downwards of the river inversely proportioned to the length L . This is why SL index is normalized by parameter L , which assures constant SL index value on the entire river course, which is especially important for larger and longer rivers.

However, when we analyse only equivalent river cross-sections of smaller dimensions (fewer than 10 km) there is a question if this aforementioned normalisation makes sense and whether it is not an additional source of error. The study of Peters and Van Balen (2007) reveals that in the areas of relatively flat relief SL index does not identify tectonic activity although it is presented. Therefore an improved method of river analysis might be more appropriate. We try to develop one proposal, which was especially constructed to be used in the researched area. The benefit of this method is that it is not sensitive on the normalisation factor L , which can represent an additional source of error and on the other hand the subjective segmentation of river profiles is also avoided completely. Similar method for the analysis of alluvial fan cross-sections was already used by Stepišnik et al. (2007).

The new method, in contrast to the SL index method, assumes an ideal river bed profile as an exponential curve with negative exponent, like it is shown on figure 2 (Hack 1973) and equation 2:

$$H = e^{-kL+n} \quad (2)$$

where H is altitude, L is the distance from the spring towards the river flow and k and n are specific coefficients of the river, derived from the best-fit exponent regression curve to the measured data. By the derivation of both sides equation 3 is obtained:

$$dH = dL e^{-kL} \quad (3)$$

and later on solved by exponent:

$$dH/dL = e^{-kL} \quad (4)$$

From the equation 4 it follows that gradient (dH/dL) of the »ideal« river is also exponentially decreasing with negative exponent from the spring following the watercourse. Further procedure of this method

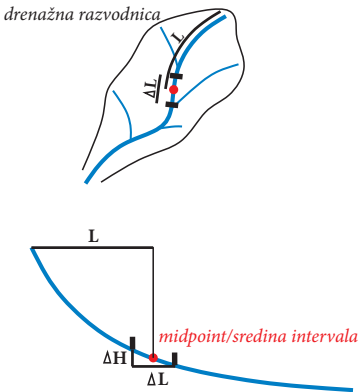
Morphometric index	Formula	Interpretation
<p>STREAM LENGTH-GRADIENT' (SL) INDEX <i>drainage divide/</i> <i>drenažna razvodnica</i></p> 	$SL = \frac{\Delta H}{\Delta L} L$	<p>high values ($> \sim 1500$) when stream flows over / visoke vrednosti ($> \sim 1500$), ko potok teče čez:</p> <ul style="list-style-type: none"> tectonically active uplifts/ območja aktivnih vertikalnih tektonskih premikov areas with high rock resistance/ območja visoko kompetentnih kamnin

Figure 2: The schematic description of commonly used morphotectonic parameter Stream Length-gradient index (Hack 1973).

includes the assessment whether actual river gradient match with the theoretical one or whether there is a significant difference. Large deviations from the ideal homeostatic state might represents a disturbance (lithological or tectonic), where elevated values of dH/dL can mean active tectonic subsidence and contrary, while lower values can mean active tectonic uplift. A criterion for definition of anomalies from »normal« deviations was defined by inclusion of parameter σ (equation 5).

$$dH/dL(\text{border}) = e^{-kL \pm \sigma} \tag{5}$$

Parameter σ is defined as standard deviation of natural logarithm of absolute values of differences between measured river gradient dH/dL and theoretically calculated river gradient, following equations 6 and 7. Equation 6 shows the calculation of standard deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{imax} \left[LnGRAD_i - \frac{\sum_{n=1}^{imax} LnGRAD_n}{imax} \right]^2}{imax - 1}} \tag{6}$$

where $LnGRAD$ is the value of natural logarithm of the absolute value of the difference between measured and expected river bed gradient dH/dL and $imax$ is the number of river gradient measurements. The calculation of $LnGRAD$ values is presented in equation 7:

$$LnGRAD = \ln \left| dH/dL \text{ measured} - dH/dL \text{ expected} \right| \tag{7}$$

Actual procedure begun with precise digitisation of river bed course by using program AutoCAD. DEM in 12,5 m resolution was used for creating gradient (dH/dL) cross section of watercourse by using program GS Surfer. Later on, the calculations of SL indexes, values of parameters k , n and σ and the detection of anomalies were done in program MS Excell. Later on, the locations of calculated anomalies were compared by the data from Basic geological map 1 : 100.000 (OGK). Special attention was put on the comparison of the position of major fault lines and important lithological borders (mainly carbonates – clastic sediments) drawn on OGK and the position of detected anomalies. Authors realised that the scale of used geological map is relatively small comparing to the relief shape extent, but unfortunately more precise geological maps are not available. Nevertheless based on authors' experiences on using OGK, it correctly shows the courses of main faults. Therefore we think that the use of OGK for the purpose of this research is still reasonable.

3 Results

Figure 3 shows the calculated values of SL index on all three watercourses cross-sections. Its value is in interval between 7 and 3425. Values of SL index below 500 are very low and do not mean deviations from the theoretical river slope. Significant deviation can be regarded when SL index values exceed 1500, and values over 3000 indicate extreme deviations from theoretical slope in river profile (Alipoor et al. 2011). Spatial distribution of SL index values along river watercourses of Borovniščica, Iška and Želimeljščica are shown on figure 4. Significantly increased values of SL index are only in the middle flow of Borovniščica, while for Iška and Želimeljščica, the analysis of SL index does not shows any of the potentially tectonically active areas.

Figure 5 shows the principles new method of river gradient analysis on an example of watercourse Borovniščica. Table 1 shows values of parameters k , n and σ for all three watercourses, and figure 6 spatial distribution of detected anomalies, which are separated according to what they show – active tectonic uplift (gradient is lower than expected) or subsidence (gradient is higher than expected) with respect to the homeostatic state. Results show the homogeneous areas of active tectonic uplift, which is expressed especially in the central part of the research area. The areas of an active tectonic subsidence are more common in the southern part of the area and in the transition of the watercourses from the Dinarides to the Ljubljana moor.

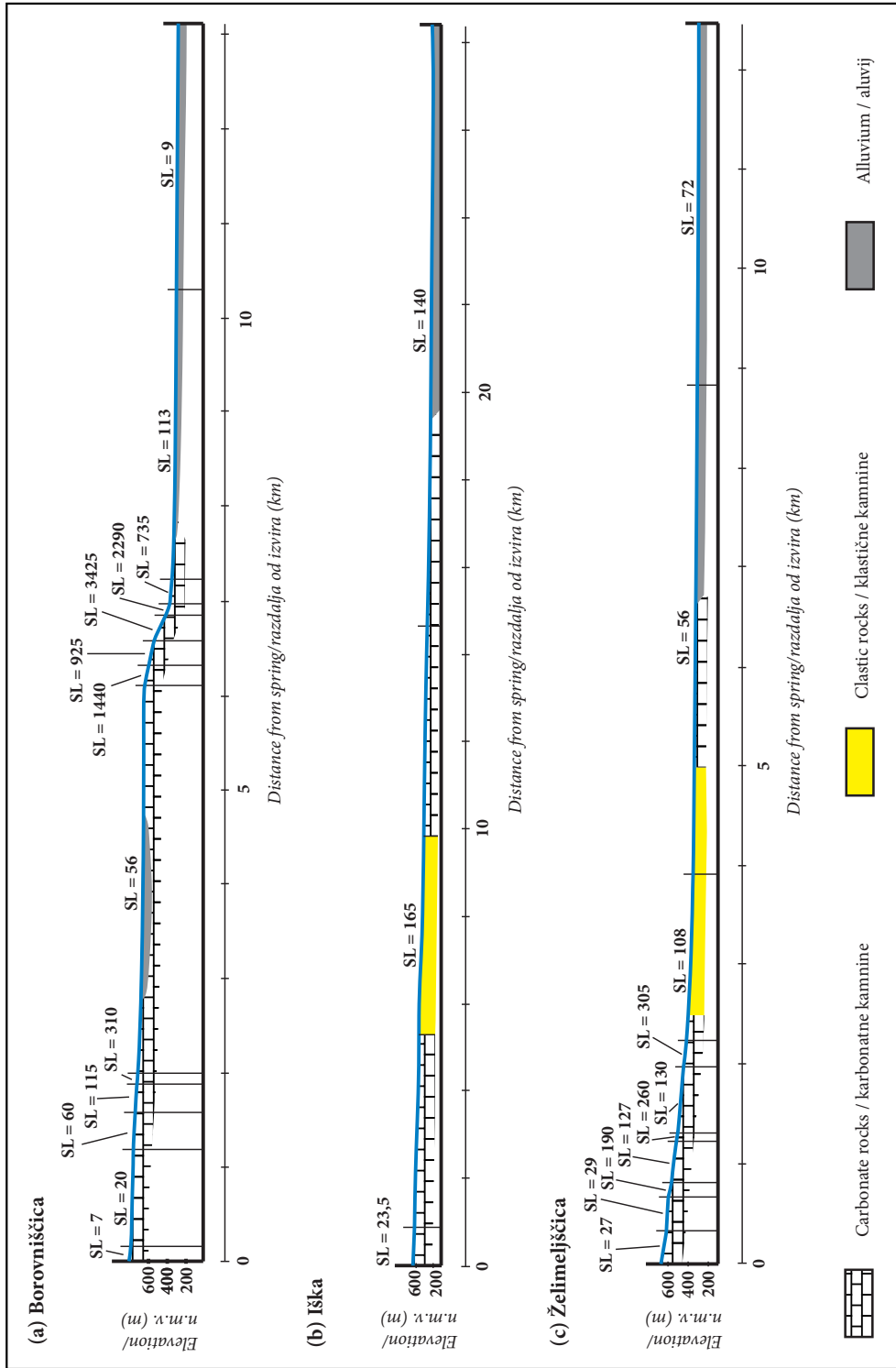


Figure 3: Segmentation and distribution of the calculated values of SL index along analysed river profiles.

Table 1: Values of parameters k , n and σ for all three rivers by using adopted method of river gradient analysis.

River	k	n	σ
Borovniščica	0,000100	2,264	1,326
Iška	0,000074	2,752	1,151
Želmejščica	0,000191	2,402	0,864

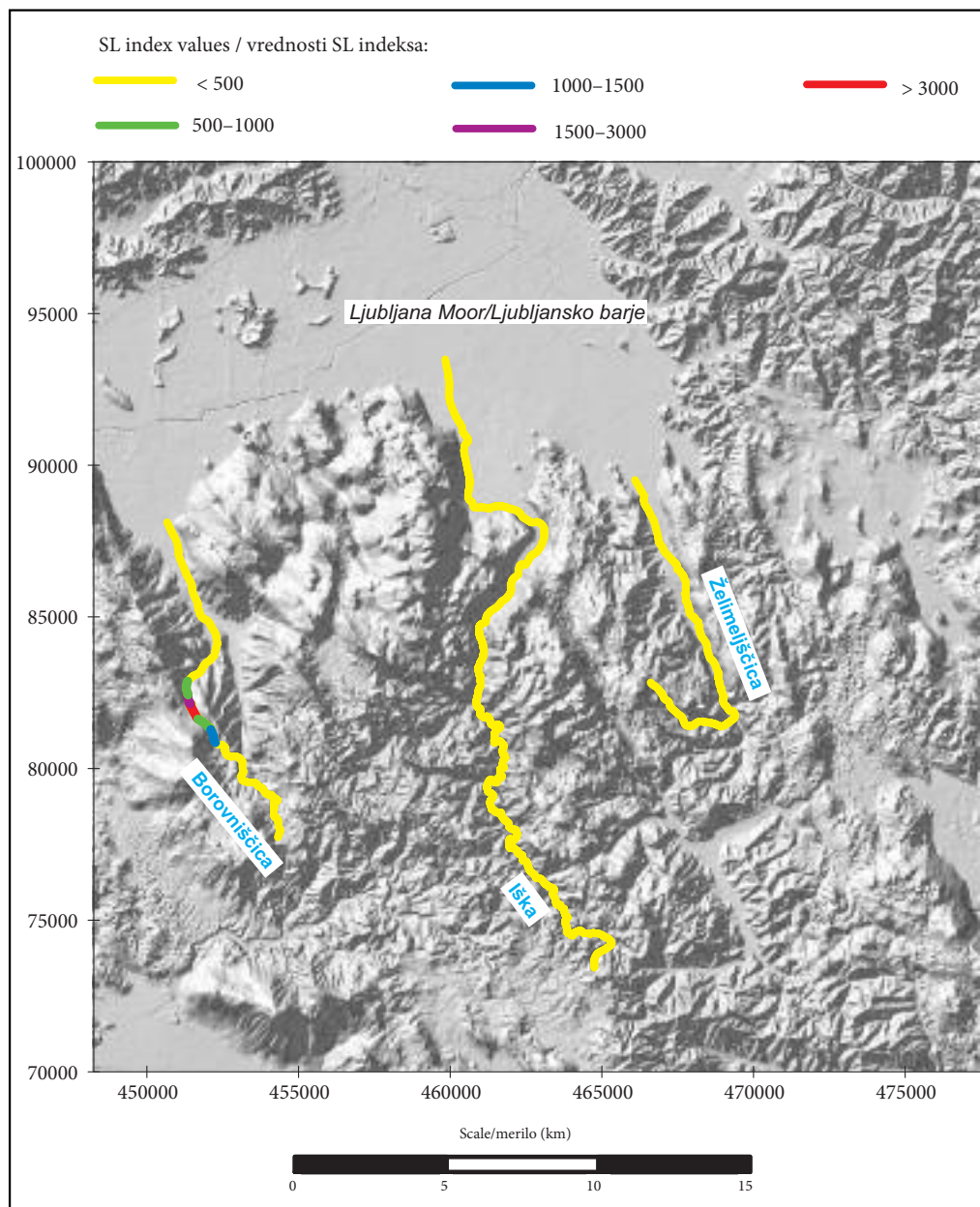


Figure 4: Spatial distribution of SL index values.

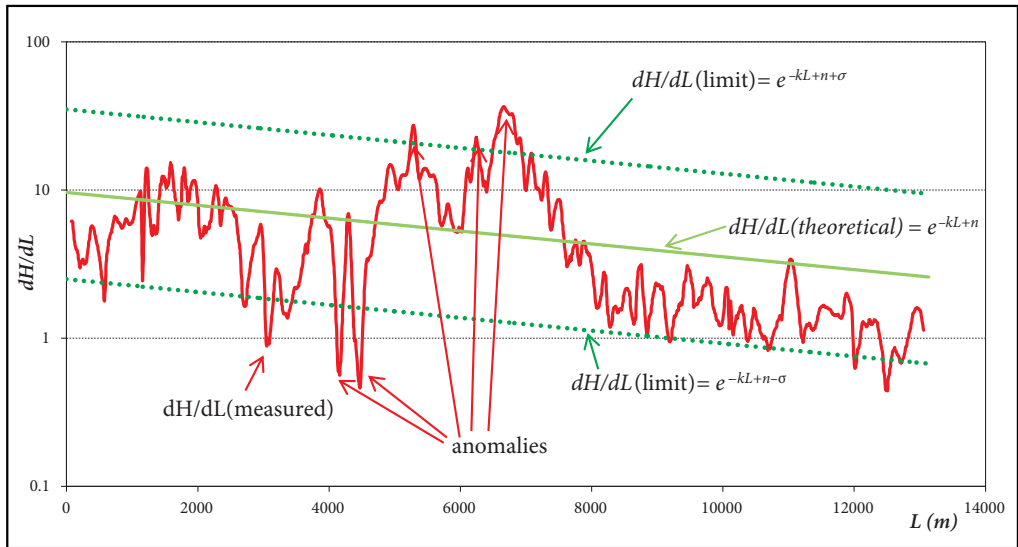


Figure 5: Representation of the river gradient analysis after adapted method on the example of watercourse Borovniščica.

4 Discussion

The interpretation begun with visual extraction of geomorphological expressed active dextral faults in the DEM (Figure 7). Unfortunately the »classical« SL-index method gave very low values of SL index (mostly below 500) over the majority of researched area and generally did not show active tectonics, although it is strongly expressed in relief and supported by constant earthquake activity in the researched area. Therefore for the determination of active faults, different methods are needed, which would expel subjective assessment and other mistakes as much as possible.

The new adopted method gives adequate variability of the results, which enables not only successful correlation with faults on OGK (Buser et al. 1963; 1965), but also the determination of possible new tectonic and geomorphologic structures in the researched area. Figure 7 shows detected anomalies in river cross sections and corresponded strike-slip faults drawn on OGK. A very good match between detected anomalies and tectonic structures is observed.

As an additional corroboration of strike-slip tectonics, the orientations of shear fractures and fault planes on smaller scale (Schmidt net, lower hemisphere) measured on the wider Krim area are presented (Figure 7). Measured orientations coincide with the orientation of major faults on OGK. Obtained results thus pointing towards the direction that indicated tectonical structures on figure 7 are most probably recently active. Lithological changes in the research area cannot satisfactory explain the anomalies, with the only exception of Želimejščica River, where watercourse in the upper parts crosses rocs with very different resistance to erosion (sandstones, as well as conglomerates).

Collected indicators enable the interpretation attempt of recent tectonic activity in the researched area (figure 8). Areas of contraction, areas of extension and possible recently active faults and midpoints of block rotations are included. Local compression appears in narrow NNW-SSE oriented belts. One of the possible explanations is that extensional structures with general orientation north-south are the consequence of local block rotations, which can be formed in pure shear conditions, most probably induced by the nearby Žužemberk fault. The borderline between contraction and tensional areas coincides with faults from OGK (figures 7 and 8). Because the transitions between areas of active uplifts and active subsidence, calculated by the geomorphologic indicators method, are clearly defined, they most probably indicate the change in tectonic activity of the area (uplift/subsidence). Therefore we estimate that the faults, which separate the uplifted areas from subsided ones, are recently the most active faults in the area (figure 8).

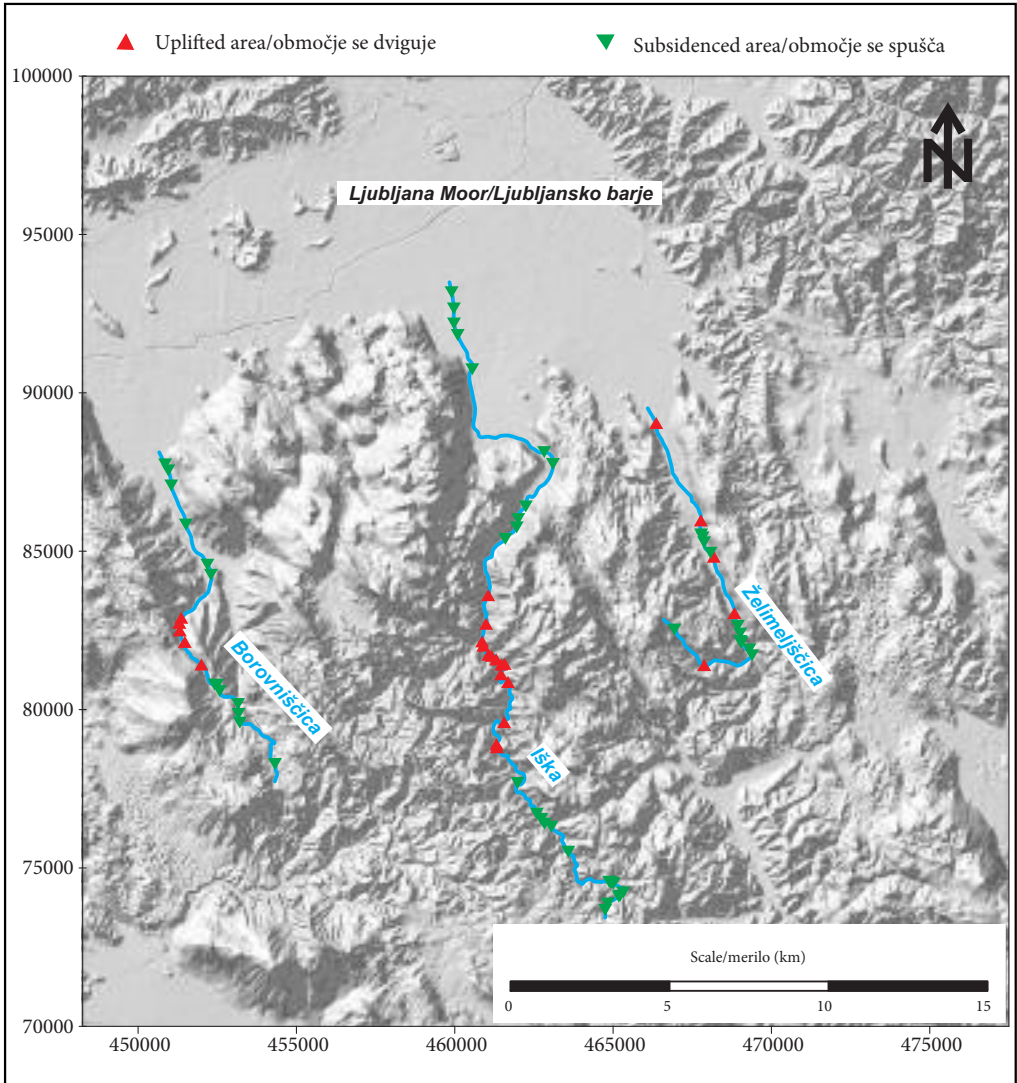


Figure 6: The distribution of areas of an active uplift and active tectonic subsidence along analysed watercourses on river gradient analysis method.

It has to be emphasised that this is the author's interpretation, which should be tested by accurate GPS or SAR radar measurements. Unfortunately the Geological Survey of Slovenia owns radar PSInSAR measurements of surface uplift/subsidence only for small part of the researched area. Results from other studies (Bavec et al., 2008; Sušnik, 2009) also indicates that PSInSAR permanent scatterers on soft moor sediments are not reliable for tectonic interpretation purpose, because the measured terrain subsidence probably reflects the consolidation of soft moor sediments, not active tectonic movements. However, the measurements still indicate particular fit between obtained results and satellite radar measurements, mostly at surface subsidence in the northern part of Iška profile (Figure 9A). Unfortunately this fit is not evident at the transition of Borovniščica to the Ljubljana moor area (Figure 9B) where PSInSAR measurements show active terrain uplift while geomorphologic indicators after adopted method indicate active subsidence. Opposing results on this location can be explained in the way that although the rock mass in this area is uplifting, simultaneously an active extension among rock blocks is presented because of the strike-slip tectonics.

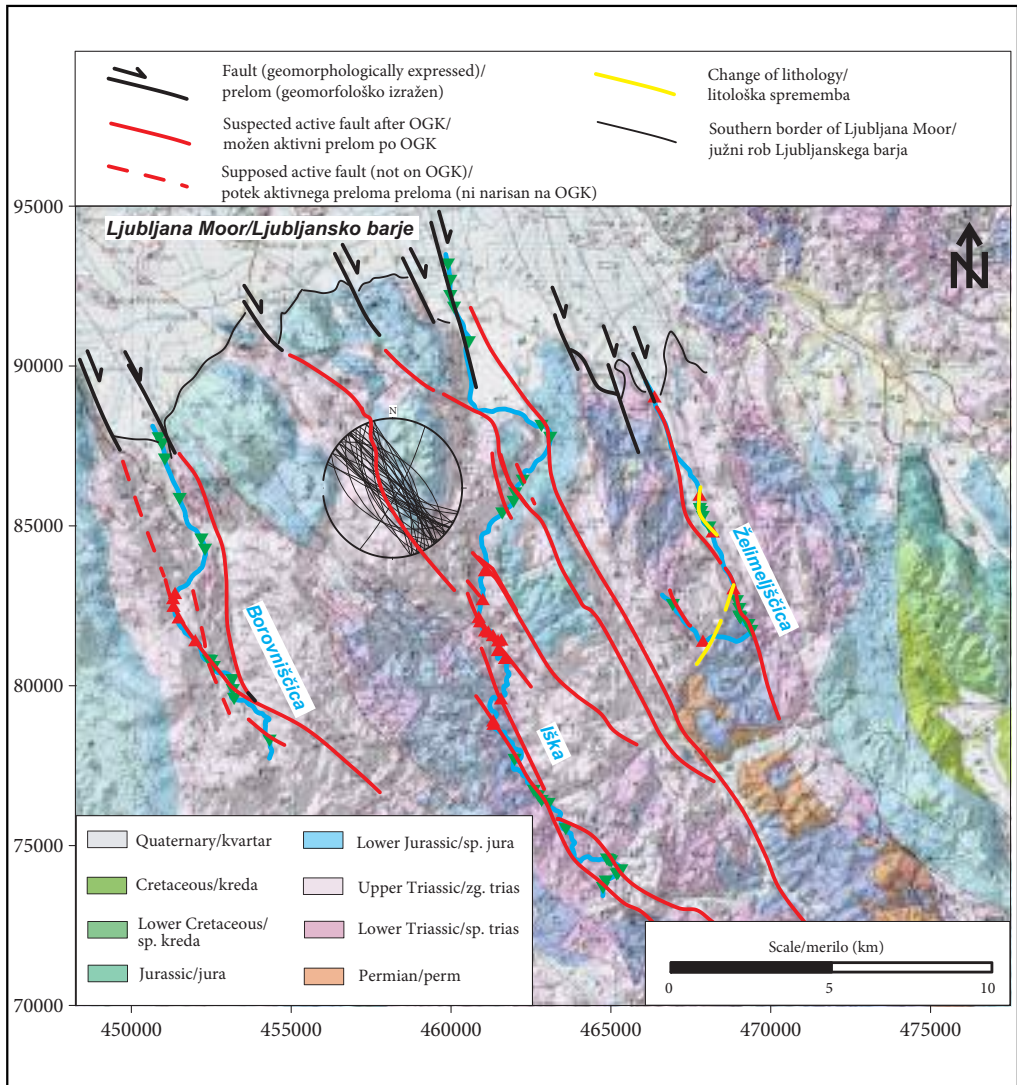


Figure 7: Correlation of the areas of active uplift and subsidence after the method of river gradient analysis with faults of the area after the Basic geological map 1:100.000 (OGK).

Subsequently the area is filled by Borovniščica river sediments. Therefore the area of alluvial sediments can be subsided while the surrounding areas of older consolidated rock masses show an active uplift. Unfortunately permanent scatterers in area B (Figure 9B) are situated on consolidated rocks only. To confirm this interpretation we would need permanent scatterers, which would be situated on Borovniščica river alluvial deposits, but there are no available permanent scatterers for this area.

5 Conclusion

Morphotectonic analysis of river bed slope on southern part of Ljubljana moor was performed using a »classical« method based on calculation of Stream Length-gradient index (SL index). Unfortunately the classic

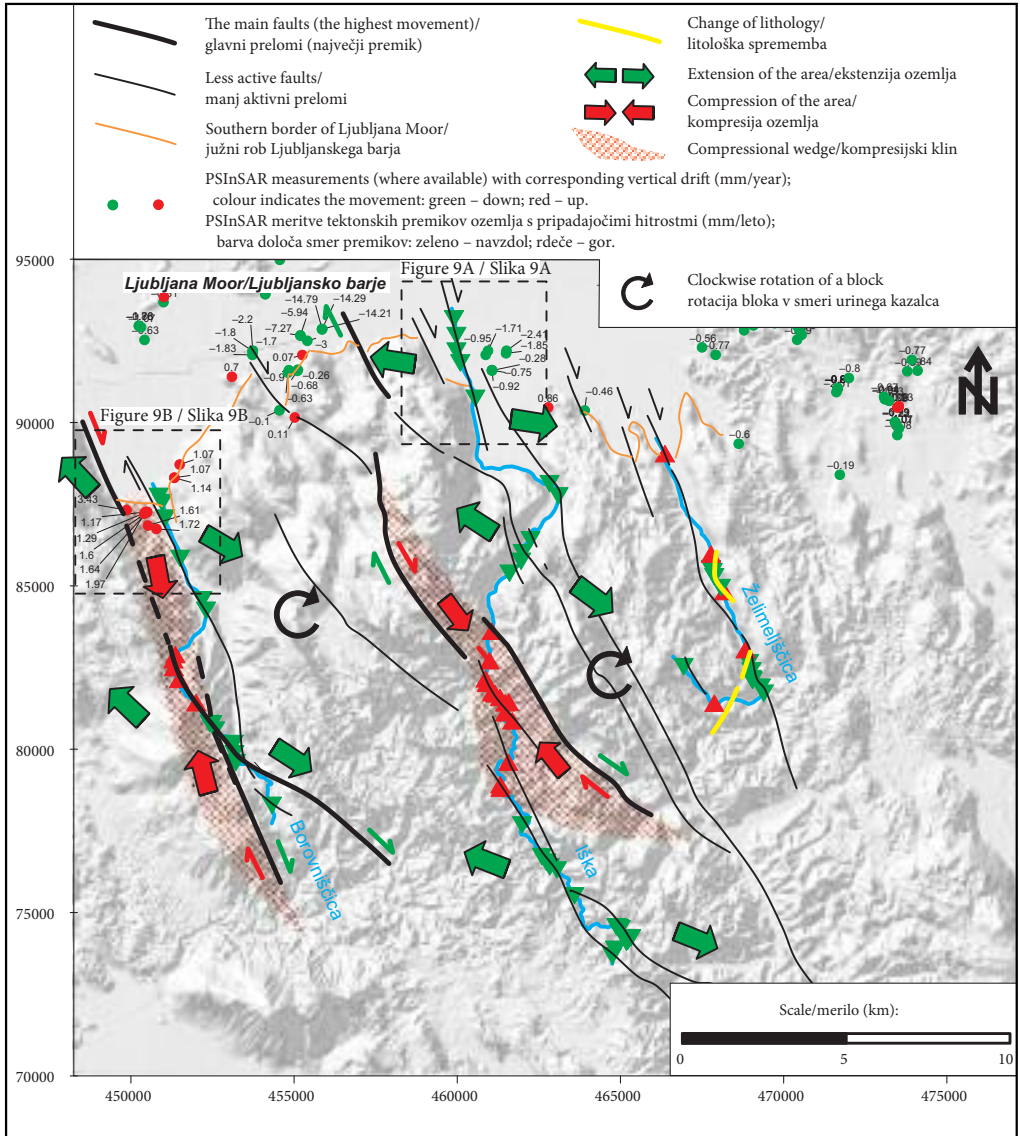


Figure 8: Morphotectonic interpretation of the researched area and available PSInSAR measurements of surface uplift/subsidence. PSInSAR measurements on «soft» moor sediments probably indicate subsidence, which is not related to active tectonic but rather the consolidation of sediments.

method (SL index) did not extract potential tectonically active areas. Therefore the method based on river gradient analysis was developed. This method was able to point out potentially recently active areas, which correspond well to fault areas from OGK, as well as the areas of the largest movements. The possible interpretation of data from OGK, geomorphologically expressed active dextral faults obtained from DEM, measurements of shear structures and fault planes on smaller scale and results from the developed method of river gradient analysis includes narrow areas of contraction (NNW-SE direction), which alternates with wider belts of extension in perpendicular direction. Extensional belts can be explained by the block rotation. Later can be a consequence of the proximity of two faults of regional importance.

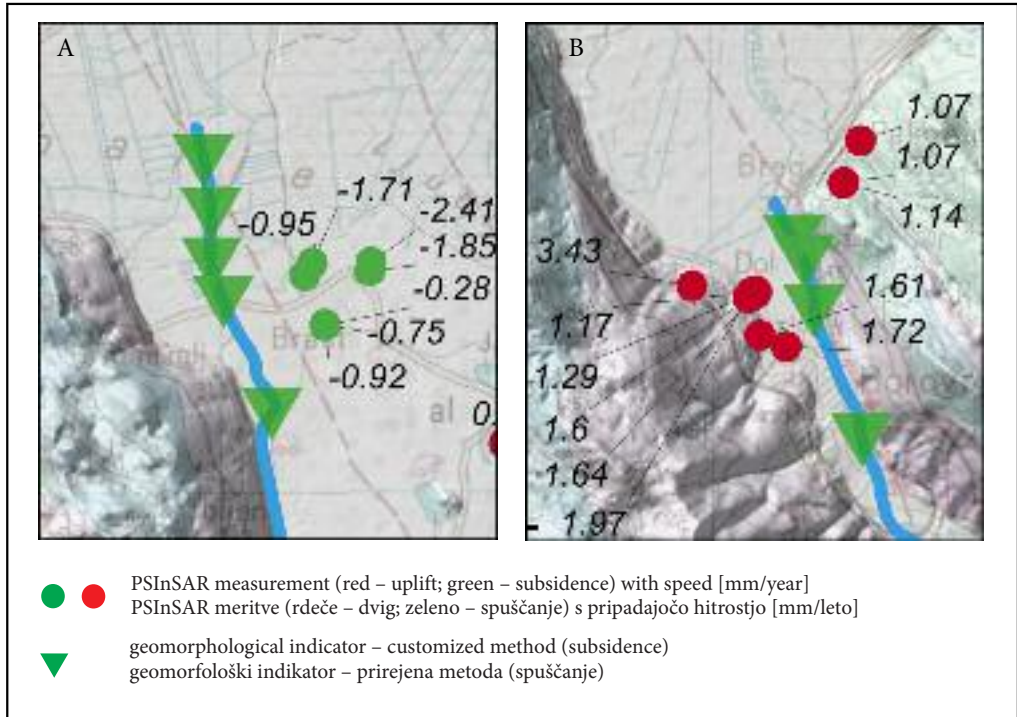


Figure 9: The comparison of measurements of terrain uplift/subsidence based on PSInSAR measurements and geomorphologic indicators after adopted method; section of northern part of Iška river (A) and northern part of Borovniščica river (B). Accurate locations of inserts are showed on figure 8.

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IZVLEČEK: Na podlagi SL indeksa in prirejene metode analize rečnega gradienta so bile analizirane tri reke z namenom ugotovitve recentnih tektonsko aktivnih prelomov. Metodo sva testirala na južnem delu Ljubljanskega barja, kjer reke prečkajo desno zmične dinarsko usmerjene (SZ–JV) prelome. Prereze vodotokov sva najprej analizirala po klasični, v svetovni literaturi vsesplošno uveljavljeni metodi (SL indeks), ki pa ni dala uporabnih rezultatov. Zato sva uporabila prirejeno metodo, ki je omogočila določitev aktivnih območij dvigovanja in spuščanja površja zaradi recentnih tektonskih premikov. Ugotovljene anomalije sva primerjala s podatki Osnovne geološke karte 1 : 100.000 in s podatki radarskih meritev vertikalnih premikov z metodo PSInSAR. Tako sva predpostavila pet potencialno aktivnih prelomov, območja kompresije ter ekstenzije. Rezultati te raziskave so lahko dodaten vir informacij pri izdelavi tektonskega modela Ljubljanskega polja in Ljubljanskega barja.

KLJUČNE BESEDE: geomorfologija, gradient rek, SL indeks, dinarski prelomi, Ljubljansko barje, Ig

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1 Uvod

Za južni rob Ljubljanskega barja je značilen razgiban relief z izrazitimi vršaji Borovniščiце, Iške in Želimeljščice ter številnih manjših potokov (slika 1). Geotektonsko predstavlja območje južno od Ljubljanskega barja severni rob zunanjih Dinaridov Slovenije (Placer 1998; 2008), za katere je značilno debelo zaporedje mezozojskih plitvodvodnih karbonatnih kamnin (Otoničar 2007; Jež in ostali 2011), ki proti severozahodu mejijo na kamnine, ki so se usedale v globljevodnih bazenskih okoljih (Šmuc in Čar 2002; Rožič in ostali 2009; Gale 2010; Šmuc in Rožič 2010).

V zunanjih Dinaridih Slovenije so poglavitne tektonske strukture regionalnega pomena tako imenovani dinarski prelomi, katerih slemenitev je vzporedna slemenitvi Dinarskega gorstva (Vrabcin in Fodor 2006). Recentna aktivnost dinarskih prelomov na območju slovenskih Zunanjih Dinaridov je dokazana z različnimi metodami: GPS vektorji hitrosti (krčenje ozemlja za 2 mm/leto v smeri sever–jug; Weber in ostali 2006; 2010), izračuni dolgoročnih horizontalnih hitrostnih polj (premiki č1,5 mm/leto; Kastelic in Carafa 2012), kartiranjem s pomočjo LiDAR-ja (Cunningham in ostali 2006; 2007), meritvami tektonskih mikro deformacij (Gosar in Lenart 2010; Gosar 2012) ter analizo prostorskih porazdelitev potresnih dogodkov (Kastelic in ostali 2008).

Ena od v svetu uveljavljenih metod za dokazovanje recentne tektonske aktivnosti prelomov je tudi morfotektonska analiza, ki temelji na analizi odnosa med morfologijo površja in tektoniko z izračunom različnih morfometričnih indeksov, med katerimi se pogosto uporablja indeks gradientov rečnih odsekov (ang. *Stream Length-gradient index* – SL indeks; Hack 1973). Za območje Slovenije takšne raziskave do sedaj še niso bile narejene.

Slika 1: Območje raziskovanja.

Glej angleški del prispevka.

SL indeks uporabljamo za ločevanje območij z različno tektonsko aktivnostjo (Viveen in ostali 2012), zlasti za identifikacijo vertikalnih tektonskih premikov (Burbank in Anderson 2001; Peters in Van Balen 2007). Nedefiniran vzdolžni rečni prerez (v nadaljnjem besedilu je smiselno uporabljena besedna zveza »rečni prerez«) ima značilno konkavno obliko (slika 2), ki jo zaradi erozije doseže v geološkem smislu relativno hitro. SL indeks je opredeljen tako, da zazna spremembe naklona »idealnega« rečnega prereza. Njegove nizke vrednosti lahko pomenijo aktivno tektonsko spuščanje območja (Viveen in ostali 2012) ali pa nizko odpornost kamnin na rečno erozijo, visoke vrednosti SL indeksa pa pomenijo hitrejšo tektonsko dvigovanje območja, ali pa kažejo na erozijo bolj odporne kamnine (Alipoor in ostali 2011).

Namen raziskave je določanje recentnih aktivnih tektonskih premikov na podlagi geomorfoloških indikatorjev. Za preizkusno območje sva izbrala južni rob Ljubljanskega barja, ki je razbrzdán s številnimi aktivnimi dinarsko usmerjenimi zmičnimi prelomi, katere sekajo trije vzporedni vodotoki: Iška, Borovniščica in Želimeljščica (slika 1). Ozemlje po večini sestavljajo mezozojske karbonatne kamnine, ki veljajo za dokaj odporne proti rečni eroziji. Zato v tej raziskavi lahko skoraj vse anomalije v SL indeksu na tem območju pripišemo recentni tektonski aktivnosti. Najprej sva poskušala določiti tektonsko aktivne prelome z metodo SL indeksa po Hack-u (1973) in nato tudi z metodo analize rečnega gradienta po modificirani metodi. Rezultate sva interpretirala z izdelavo modela recentne tektonske aktivnosti območja ter jih primerjala z metodo radar-skih meritev vertikalnih premikov PSInSAR.

Slika 2: Opis klasičnega morfotektonskega parametra *Stream Length-gradient* indeks (Hack 1973).

Glej angleški del prispevka.

2 Materiali in metode dela

Temelj za izračun morfometričnih indeksov predstavljata digitalni model višin (DMV) ločljivosti 12,5 m (vir: Geodetska uprava RS) ter topografski zemljevidi v merilu 1 : 5000. S pomočjo uporabe računalniških orodij *AutoCAD* in *GS Surfer* sva pridobila rečne prereze in druge spremenljivke, ki so bile numerično obdelane s programom *MS Excell*.

SL indeks sva izračunala po sledečem postopku. Najprej sva rečne prereze razdelila na intervale, ki jim lahko vizualno prilagodimo premico. Za vsak izbran segment reke sva opredelila SL indeks po formuli (Hack 1973):

$$SL = (\Delta H / \Delta L) L \quad (1)$$

pri čemer je ΔH višinska razlika znotraj obravnavanega segmenta reke, ΔL dolžina obravnavanega segmenta reke in L razdalja od izvira reke do sredine obravnavanega segmenta (slika 2). Razmerje $\Delta H/\Delta L$ opredeljuje naklon dna rečne struge na obravnavanem segmentu reke, ki se glede na teoretično »idealno« reko znižuje po toku reke navzdol obratno sorazmerno z dolžino L . SL indeks je normaliziran s parametrom L , kar pri velikih in dolгих »idealnih« rekah zagotavlja konstantno vrednost SL indeksa po celi dolžini reke.

Pri analizi enakovrednih rečnih prerezov manjših dimenzij (nekaj 10 km) se poraja vprašanje, ali je korekcija naklona z razdaljo od izvira reke smiselna in če morda v tem primeru ni celo dodaten vir napake. Zlasti na območjih, kjer je reliefna razgibanost razmeroma majhna, s SL indeksom pogosto ni mogoče identificirati tektonske aktivnosti, kljub temu da je tam že bila potrjena (npr. Peters in Van Balen 2007). Zato sva rečne prereze analizirala tudi s prirejeno metodo analize gradienta rečnih prerezov. Le-ta je bila izpeljana posebej za uporabo na obravnavanem območju. Njena prednost je, da ni občutljiva na korekcijski faktor L , prav tako pa se povsem izognemo subjektivnemu določanju segmentov na rečnih prerezih. Podobno metodo je pri analizi rečnih vršajev že uporabil Stepišnik s sodelavci (2007).

Prirejena metoda, za razliko od metode SL indeksov, predpostavlja idealen rečni prerez kot eksponentno krivuljo z negativno potenco, podobno, kot je prikazano na sliki 2 (Hack 1973) in enačbi 2:

$$H = e^{-kL+n} \quad (2)$$

pri čemer je H nadmorska višina, L oddaljenost od izvira po toku reke, k in n pa sta specifična koeficienta reke. Slednja dobimo s pomočjo eksponentne regresijske krivulje, ki se kar najbolje prilaga izmerjenim podatkom. Če obe strani enačbe odvedemo, dobimo enačbo 3:

$$dH = dL e^{-kL} \quad (3)$$

in uredimo:

$$dH/dL = e^{-kL} \quad (4)$$

Iz enačbe 4 sledi, da se tudi gradient (dH/dL) »idealne« reke znižuje eksponentno z negativnim eksponentom od izvira navzdol. Nato pri tej modificirani analizi preverimo, ali izmerjeni gradient reke na neki oddaljenosti od izvira sovпада s teoretičnim, ali pa se od njega pomembno razlikuje. Dovolj veliko odstopanje od tega idealnega homeostatskega stanja je motnja (litološka ali tektonska), pri čemer višja vrednost dH/dL od mejne pomeni aktivno tektonsko spuščanje in obratno, dovolj nizka vrednost od mejne pa aktivno tektonsko dvigovanje terena. Določiti je bilo treba tudi kriterij za definicijo mejnih vrednosti z vključitvijo faktorja σ (enačba 5).

$$dH/dL(\text{mejna}) = e^{-kL \pm \sigma} \quad (5)$$

Faktor σ sva definirala kot standardni odklon naravnega logaritma absolutne vrednosti razlike izmerjenih gradientov reke dH/dL od teoretično izračunanih po enačbah 6 in 7. Enačba 6 prikazuje izračun standardnega odklona:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{i \max} \left[\frac{\text{LnGRAD}_i - \frac{\sum_{n=1}^{i \max} \text{LnGRAD}_n}{i \max}}{i \max} \right]^2}{i \max - 1}} \quad (6)$$

pri čemer pomeni $LnGRAD$ vrednost naravnega logaritma absolutne vrednosti razlike med izmerjenim in pričakovanim gradientom rečnega korita dH/dL ter $imax$ število meritev gradienta reke. Enačba 7 prikazuje izračun vrednosti $LnGRAD$:

$$LnGRAD = \ln \left| dH/dL \text{ izmerjeno} - dH/dL \text{ pričakovano} \right| \quad (7).$$

Pri meritvah SL indeksa in pri meritvah po prirejeni metodi sva najprej natančno digitalizirala potek rečnega korita s program *AutoCAD*. Uporabila sva državni DMV ločljivosti 12,5 m ter s programom *GS Surfer* izrisala rečne prereze. Izračun SL indeksov, vrednosti dH/dL , parametrov k , n in σ in primerjavo dobljenih s teoretičnimi vrednostmi sva opravila v programu *MS Excell*. Lego ugotovljenih anomalij sva primerjala z lego poglavitnih prelomnih con iz Osnovne geološke karte 1 : 100.000 (OGK) in lego merodajnih litoloških sprememb med karbonatnimi in klastičnimi kamninami. Avtorja se zavedava, da je merilo uporabljene OGK relativno majhno glede na velikosti reliefnih oblik, vendar natančnejše geološke karte žal niso izdelane oziroma niso dostopne. Kljub vsemu pa OGK regionalnega merila po najinih izkušnjah dovolj dobro nakazuje na potek glavnih prelomov in con, zato misliiva, da je uporaba te karte za namen raziskave vseeno upravičena.

3 Rezultati

Izračunane vrednosti SL indeksa vseh treh vodotokov v prerezih so prikazane na sliki 3 in so v razponu od 7 do 3425. Vrednosti SL indeksa pod 500 veljajo za zelo nizke in ne kažejo odstopanj od teoretičnega naklona reke. Značilno odstopanje od teoretičnega naklona rečnega dna, ki je lahko tudi posledica aktivne tektonike območja, kažejo vrednosti SL indeksa, ki presegajo 1500, vrednosti nad 3000 pa kažejo na ekstremna odstopanja od teoretičnega naklona v prerezu reke (Alipoor in ostali 2011). Prostorska porazdelitev vrednosti SL indeksa vzdolž rečnih prerezov Borovniščice, Iške in Želimeljščice je prikazana na sliki 4. Značilno povišane vrednosti SL indeksa so zgolj v srednjem toku Borovniščice, pri Iški in Želimeljščici analiza SL indeksa ne izloči potencialnih tektonsko aktivnih območij.

Slika 3: Segmentacija in porazdelitev izračunanih vrednosti SL indeksa vzdolž analiziranih profilov rek. Glej angleški del prispevka.

Slika 4: Prostorska porazdelitev vrednosti SL indeksov. Glej angleški del prispevka.

Preglednica 1: Vrednosti parametrov k , n in σ za vse tri reke pri uporabi prirejene metode analize rečnih prerezov.

reka	k	n	σ
Borovniščica	0,000100	2,264	1,326
Iška	0,000074	2,752	1,151
Želimeljščica	0,000191	2,402	0,864

Slika 5 prikazuje uporabo prirejene metode analize rečnega prereza na primeru vodotoka Borovniščica. Preglednica 1 prikazuje vrednosti parametrov k , n in σ za vse tri vodotoke, slika 6 pa prostorsko porazdelitev anomalij, določenih s prirejeno metodo analize gradienta rečnih prerezov. Slednje so ločene glede na to, ali je površje preveč dvignjeno (aktivni tektonski dvig površja) ali pa preveč spuščeno (aktivni tektonski spust površja) glede na homeostazno stanje. Iz slike 6 je razvidno, da lahko pri toku prej omenjenih vodotokov izločimo zelo homogena območja aktivnega tektonskega dvigovanja površja, ki je izrazito predvsem v osrednjem delu obravnavanega območja. Območja aktivnega tektonskega spuščanja, so pogostejša na južnem delu območja in na prehodu vodotokov iz Dinaridov v Ljubljansko barje.

Slika 5: Prikaz analize rečnega gradienta po prirejeni metodi na primeru vodotoka Borovniščica. Glej angleški del prispevka.

Slika 6: Porazdelitev območij aktivnega dvigovanja in aktivnega spuščanja ozemlja vzdolž analiziranih vodotokov po metodi analize rečnega gradienta. Glej angleški del prispevka.

4 Razprava

Za interpretacijo ozemlja sva iz DMV-ja vizualno izločila geomorfološko izražene aktivne desnozmične prelome (slika 7). Nadalje sva z metodo SL indeksa ugotovila, katera so tektonsko aktivna območja (slika 4). Žal je metoda podala izjemno nizke vrednosti SL indeksa (po večini pod 500) in ni pokazala na aktivno tektoniko, čeprav je le-ta reliefno močno izražena, nanjo pa kaže tudi stalna potresna aktivnost na obravnavanem območju. Zato je bilo treba za ugotavljanje aktivnih prelomov uporabiti drugačno metodo, ki v čim večji meri izključuje subjektivne ocene in druge napake.

Slika 7: Korelacija območij aktivnega dvigovanja in spuščanja površja po metodi analize rečnega gradienta s prelomi območja po Osnovni geološki karti 1 : 100.000.

Glej angleški del prispevka.

Prirejena metoda daje zadostno variabilnost rezultatov in omogoča uspešno koreliranje s prelomi na OGK (Buser in ostali 1963; 1965) ter tudi ugotavljanje novih tektonskih in geomorfoloških struktur na obravnavanem ozemlju. Slika 7 prikazuje ugotovljene anomalije v rečnih prerežih ter zmične prelome z OGK, ki bi lahko vplivali nanje. Pri tem vidimo zelo dobro ujemanje med ugotovljenimi anomalijami ter tektonskimi strukturami.

Za dodatno potrditev zmične tektonike podajava tudi smeri strižnih razpok in prelomnih ploskev manjšega merila (Schmidtova mreža, spodnja polobla), ki sva jih izmerila na širšem območju Krma (slika 7). Vidimo, da izmerjene smeri sovpadajo s smerjo nekaterih glavnih prelomov območja po OGK. Prav tako so nakazani prelomi na sliki 7 najverjetneje recentno aktivni, saj litološke spremembe na obravnavnem območju ne morejo zadovoljivo pojasniti teh anomalij. Izjemo predstavlja Želimejščica, ki v zgornjem toku prečka proti rečni eroziji manj odporne klastične kamnine, v osrednjem delu toka pa so konglomerati, ki imajo prav tako drugačno stopnjo odpornosti proti rečni eroziji kot na obravnavanem območju prevladujoče karbonatne kamnine (slika 7).

Slika 8: Morfotektonska razlaga reliefa ter prikazane PSInSAR meritve dvigovanja/spuščanja površja, ki jih ima na razpolago Geološki zavod Slovenije. PSInSAR meritve na »mehkih« barjanskih sedimentih verjetno kažejo na spuščanje, ki ni povezano s tektonskimi procesi, ampak s konsolidacijo teh sedimentov.

Glej angleški del prispevka.

Zbrani indikatorji omogočajo interpretacijo recentne tektonske dejavnosti na obravnavanem območju (slika 8), pri čemer sva ločila območja stiskanja, območja raztezanja, možne recentne aktivne prelome ter možne centre rotacij blokov. Krajevna kompresija se pojavlja v ozkih pasovih v smeri SSZ–JVV. Ena od možnih razlag je, da so tenzijske strukture s splošno orientacijo v smeri sever–jug posledica krajevnih rotacij blokov, ki nastanejo pri razmerah čistega striga, katerih glavni nosilec je najverjetneje bližnji Žužemberški prelom. Meja med območji ekstenzije in območji kompresije sovpada s prelomi z OGK (sliki 7 in 8). Ker so prehodi med območji aktivnega dvigovanja in aktivnega spuščanja, dobljenimi po metodi geomorfoloških indikatorjev, jasno opredeljeni, zelo verjetno odražajo spremembo v tektonski aktivnosti ozemlja (dvigovanje/spuščanje). Zaradi tega ocenjujemo, da so prelomi, ki ločujejo območja dvigovanja od območij spuščanja, recentno najaktivnejši prelomi na obravnavanem ozemlju (slika 8).

Poudariti je treba, da je to razlaga avtorjev, ki bi jo bilo treba preveriti na podlagi natančnih GPS meritev ali pa na podlagi metod SAR radarskih meritev. Na žalost Geološki zavod Slovenije razpolaga z radarskimi PSInSAR meritvami tektonskega dvigovanja/spuščanja površja le za zelo majhne del obravnavanega ozemlja, poleg tega pa so po nekaterih raziskavah PSInSAR sipalci na mehkih barjanskih sedimentih za namene tektonskih interpretacij nezanesljivi, saj je izmerjeni spust terena verjetno odraz konsolidacije »mehkih« barjanskih sedimentov in ne odraz aktivnih tektonskih premikov (Bavec in ostali, 2008; Sušnik, 2009). Vseeno pa te meritve kažejo določeno stopnjo ujemanja med dobljenimi rezultati in satelitskimi radarskimi meritvami, predvsem pri spuščanju ozemlja na območju severnega dela profila Iške (slika 9A). Tega ujemanja žal ne zaznamo v primeru vstopa Borovniščice na območje Ljubljanskega barja (slika 9B), kjer PSInSAR meritve kažejo aktivno dvigovanje terena, geomorfološki indikatorji po prirejani metodi pa aktivno spuščanje. Vendar je moč nasprotno rezultate na tej lokaciji pojasniti s tem, da se območje matičnih kamnin hribovja sicer dviguje, vendar se sočasno zaradi zmičnih sil ustvarja tudi območje aktivnega razpiranja kamninskih blokov. V to območje nato nanaša reka Borovniščica sedimente. Zato se območje aluvialnih

sedimentov lahko tudi spušča, medtem ko se okoliška območja, sestavljena iz sprijetih in starejših kamenin, aktivno dvigujejo. Žal so PSInSAR sipalci na tem območju, za razliko od območja iz slike 9A, le na trdnih kanminah. Za potrditev te interpretacije bi torej potrebovali še sipalce, ki so postavljeni na območje nanosov Borovniščiće.

Slika 9: Primerjava meritev dvigovanja/spuščanja terena na podlagi PSInSAR meritev in geomorfoloških pokazateljev po prirejeni metodi; izsek severnega dela Iške (A) in severnega dela Borovniščiće (B). Natančni lokaciji sta označeni na sliki 8.

Glej angleški del prispevka.

5 Sklep

Za obravnavano območje na južnem delu Ljubljanskega barja je bila narejena morfotektonska analiza naklona rečnega dna po klasični metodi, ki temelji na izračunu indeksa gradientov rečnih odsekov (ang. *Stream Length-gradient* oziroma SL indeksa) ter po na novo razviti in v tem članku prvič predstavljeni metodi analize rečnega gradienta. Klasična metoda (SL indeks) se je na testnem območju izkazala za neprimerno in ni izločila potencialnih tektonsko aktivnih območij, medtem ko sva s prirejeno metodo analize rečnega gradienta lahko določila potencialno recentno tektonsko aktivne prelome, ki zelo dobro sovpadajo s prelomnimi območji na OGK ter glavne prelome območja, ob katerih so premiki največji. Poizkus razlage recentne tektonske aktivnosti, ki zajema podatke iz OGK, geomorfološko izražene strukture na DMV, meritve smeri strižnih razpok in prelomnih ploskev manjšega merila na območju Krima ter rezultatov prirejene metode analize rečnega gradienta, obsega ozka območja kompresije (v smerjo SSZ–JV), ki se izmenjujejo s širšimi pasovi ekstenzije v pravokotni smeri. Pasovi ekstenzije so najverjetneje posledica rotacije blokov, ki nastanejo pri zмикanju dveh glavnih regionalnih prelomov.

6 Zahvala

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7 Literatura

Glej angleški del prispevka.