GEOLOGIJA 59/2, 243-257 Ljubljana 2016

http://dx.doi.org/10.5474/geologija.2016.015

A contribution to better understanding of structural characteristics and tectonic phases of the Boč region, Periadriatic Fault Zone

Prispevek k boljšemu razumevanju strukturnih značilnosti in tektonskih faz območja Boča v coni Periadriatskega preloma

Lea ŽIBRET

Research and Development in the Field of Natural Sciences, Černetova ulica 3A,
SI– 1000 Ljubljana, Slovenia; e-mail: zibret.lea@gmail.com

Prejeto / Received 3. 10. 2016; Sprejeto / Accepted 12. 12. 2016; Objavljeno na spletu / Published online 23. 12. 2016

Key words: structural mapping, fault-slip analysis, palaeostress reconstruction, Periadriatic fault, Lavanttal fault; Donat zone, Pannonian Basin

Ključne besede: strukturno kartiranje, analiza zdrsov ob prelomnih ploskvah, rekonstrukcija paleonapetosti, Periadriatski prelom, Labotski prelom, Donačka cona, Panonski bazen

Abstract

The aim of this study was to determine properties of the tectonic contact between Permian/Mesozoic limestones and less competent Miocene clastites on the northeastern foothill of the Boč Mt. Because fault planes significantly mark the relief, this contact was studied by a detailed structural mapping, which showed that the Boč Mt. is limited by subvertical faults in its northeastern part. To ensure that mapped subvertical contact is compatible with regional geodynamics of the area, additionally paleostress analysis of fault-slip data was performed. Four individual paleostress tensor groups were documented in a wider Boč area and compared by published structural data from the border zone between Alps, Dinarides and Pannonian Basin. The oldest paleostress tensor group (Phase 1) is likely of Lower and Middle Miocene age and indicates SW-NE extension accommodated by W-E to WNW-ESE striking normal faults. Phase 2 can be correlated with Middle to Late Miocene NW-SE to WNW-ESE directed extension accommodated by NNE-SSW striking normal faults. Phase 3 is correlated with Late Miocene W-E directed contraction accommodated by N-S striking sinistral faults and NNE-SSW to NE-SW striking dextral faults. The youngest paleostress tensor group (Phase 4) fits well with Pliocene to Quaternary NNW-SSE to N-S directed contraction accommodated by NW-SE to W-E striking dextral faults and NE-SW striking reverse faults. Since the documented paleostress phases fits well with the geodynamic processes of the Alps-Dinarides-Carpathians territory the subvertical border in the northeastern part of Boč Mt. seems to be an acceptable structural solution. The study is important because the study area is located at interaction zone between two major Alpine fault systems: the Periadriatic and the Lavanttal faults.

Izvleček

Glavni namen raziskave je bil ugotoviti značaj tektonskega kontakta, ki poteka vzdolž severovzhodnega pobočja Boča v coni Periadriatskega in Labotskega preloma. Ker gre za kontakt med permskimi/mezozojskimi apnenci in manj kompetentnimi miocenskimi klastiti, prelomne ploskve, ki predstavljajo kontakt enot, v reliefu značilno izstopajo. Zato je raziskava temeljila na natančnem strukturnem kartiranju območja, ki je pokazalo, da je Boč na severovzhodnem delu omejen s subvertikalnimi prelomi. Rezultati terenskega kartiranja se ujemajo z regionalno geodinamiko območja, ki je bila preverjena s paleonapetostno analizo opazovanih zdrsov ob prelomnih ploskvah. V širši okolici Boča so bile dokumentirane štiri skupine paleonapetostnih tenzorjev, ki so bile nato primerjane z objavljenimi strukturnimi podatki iz prehodnega območja med Alpami, Dinaridi in Panonskim bazenom. Najstarejša faza (Faza 1) je najverjetneje spodnje do srednjemiocenske starosti in odraža ekstenzijo ozemlja v smeri SW-NE, ki jo vidimo na normalnih prelomih s slemenitvijo W-E do WNW-ESE. Fazo 2 lahko primerjamo s srednje do zgornjemiocensko ekstenzijo ozemlja v smeri NW-SE do WNW-ESE, ki se odraža na normalnih prelomih s slemenitvijo NNE-SSW. Faza 3 je primerljiva z zgornjemiocensko kontrakcijo ozemlja v smeri W-E, ki se odraža na levozmičnih prelomih s slemenitvijo N-S in desnozmičnih prelomih s slemenitvijo NNE-SSW do NE-SW. Najmlajša faza (Faza 4) se dobro ujema s pliocensko kvartarno kontrakcijo ozemlja v smeri NNW-SSE do N-S in se odraža na desnozmičnih prelomih s slemenitvijo NW-SE do W-E in reverznih prelomih s slemenitvijo NE-SW. Ker se dokumentirane paleonapetostne faze dobro ujemajo s poznanimi geodinamskimi procesi iz Alpsko-Dinarsko-Karpatskega območja, se subvertikalen kontakt vzdolž severovzhodnega dela Boča zdi sprejemljiva strukturna rešitev. Raziskava je pomembna tudi regionalno, predvsem iz razloga, ker raziskovano območje leži vzdolž con dveh regionalnih alpskih struktur.

Introduction

The study area is situated in the SW part of the Pannonian Basin (NE Slovenia, Fig. 1a), along the NE margin of 978 meters high Boč Mountain that is located within the Periadriatic fault zone (Fig. 1b).

The Boč Mt. is built of Permian and Mesozoic strata. These rocks have South Alpine origin and were only later during Lower Miocene (Mancktelow et al., 2001) transmitted eastward along the dextral Periadriatic fault. Wider Boč area was mapped by experts from the Geological survey of Slovenia (Novak et al., 2010) in 2008 and 2009 because this territory represents a possible source of thermal water springs in Rogaška Slatina (Fig. 2). However, the character of the Miocene/Permian-Mesozoic tectonic contact in the NE Boč region, which is important to evaluate the extension of the Rogaška Slatina aquifer system, could not be identified. On the existing geological map of the Boč Mountain area (Fig. 2; Aničić & Juriša, 1984) this contact is interpreted as a post Middle Miocene subhorizontal thrust of Mesozoic carbonates over Miocene strata (Fig. 2). In more recent structural studies the tectonic evolution of the Boč Mt. is genetically linked with formation of duplex structure within dextral transpressive Donat zone (Fodor et al. 1998; Márton at al., 2002). To answer the question, whether mentioned contact is subhorizontal thrust or subvertical fault, a detailed structural mapping of approximately 4 km^2 wide area on the N foothill of the Boč Mt. (Fig. 2) at the scale of 1 : 5000 was conducted (Žibret, 2009). Kinematic characteristics of the mapped contact were estimated by detailed field investigation of structural elements and paleostress analysis of fault-slip data collected within Upper Triassic, Oligocene-Miocene and Middle Miocene rocks. Documented stress orientations were further compared with available structural data from the border zone between Alps, Dinarides and Pannonian Basin to show its regional kinematic compatibility. Results of this research improved the knowledge base about regional tectonics within the contact zone of South Alpine and Pannonian Basin units.

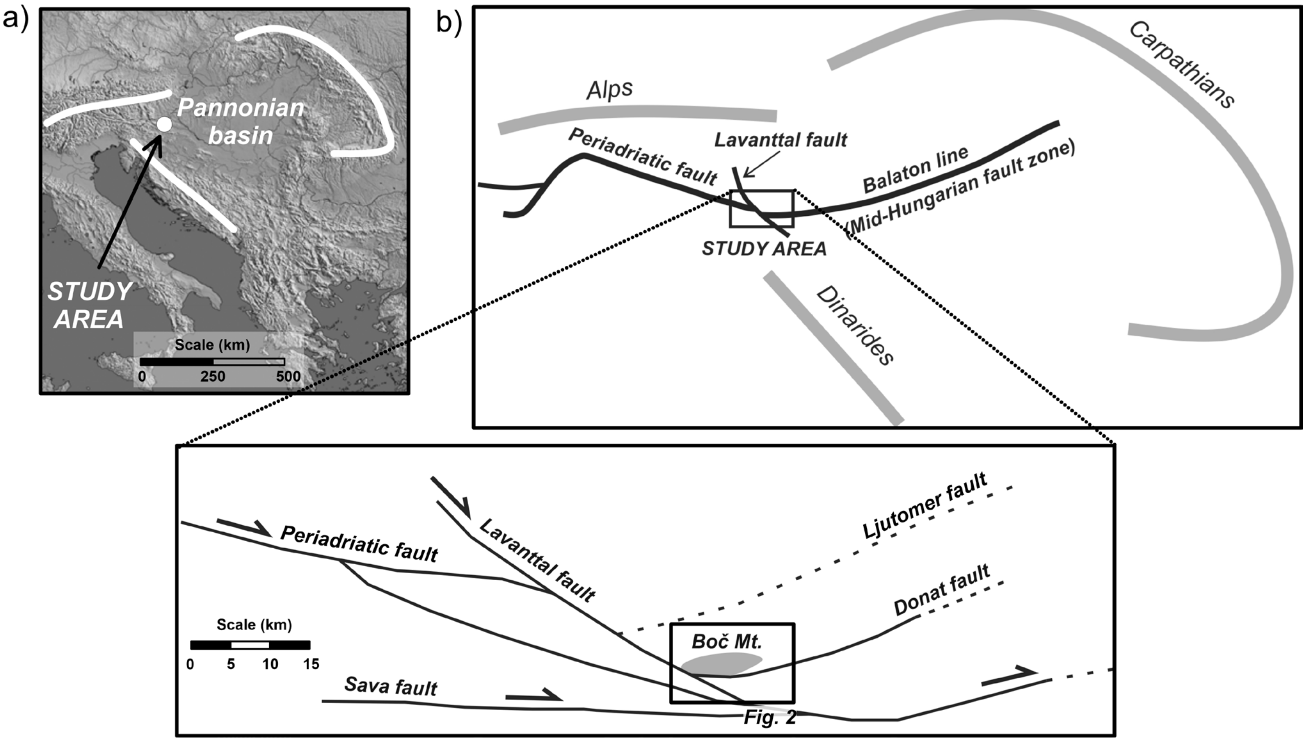

Fig. 1. The location of the study area, Boč Mt. a) in Alps-Dinarides-Carpathians domain; b) in regional tectonic framework with delineated tectonic units and structural domains (after Placer, 1998 and Schmid et al., 2008).

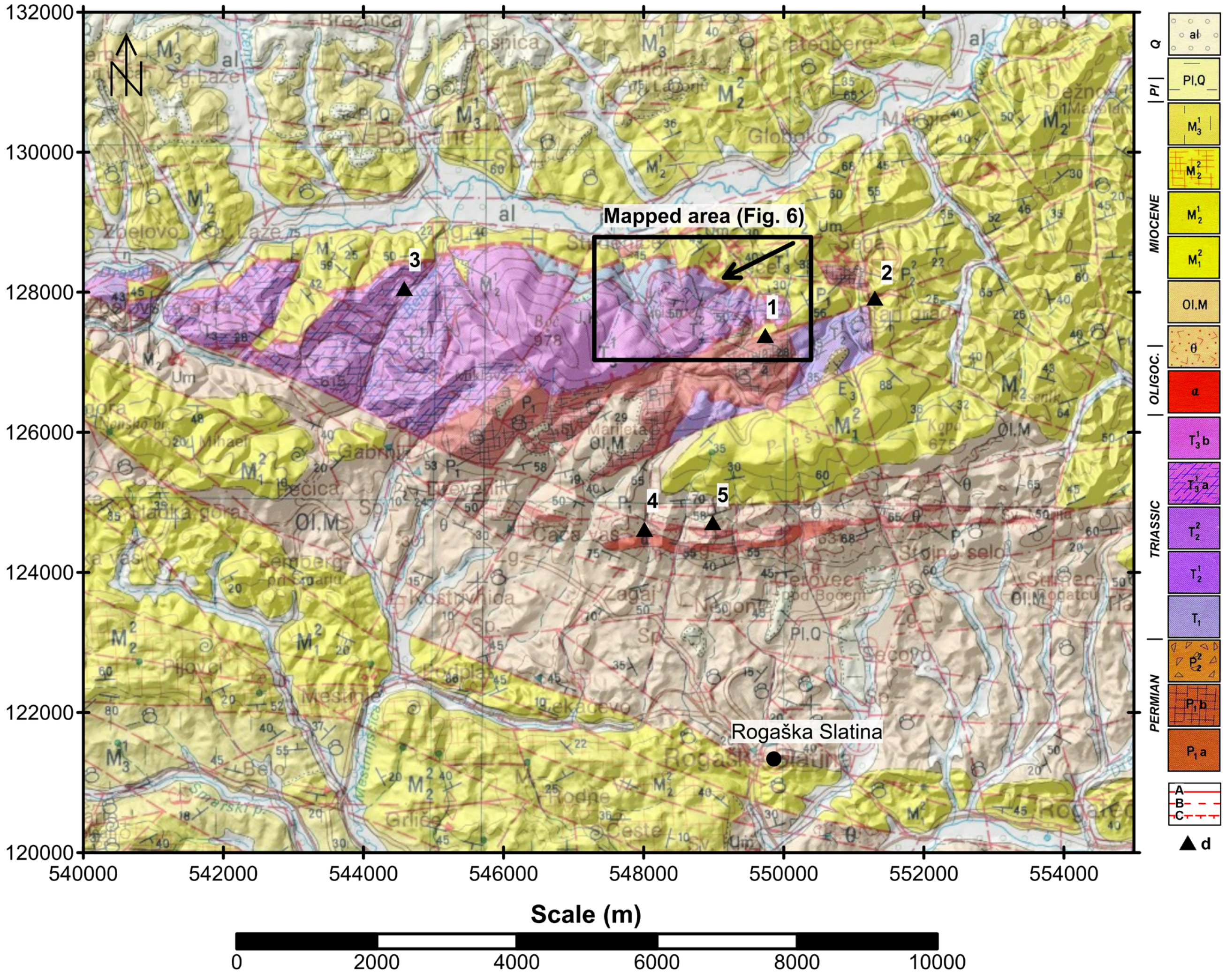

Fig. 2. Basic geological map 1 : 100.000, sheet Rogatec (Aničić & Juriša, 1984). Black arrow indicates tectonic contact between the Mesozoic South Alpine rocks and Neogene and Quaternary deposits within the SW Pannonian Basin. Legend: al - fluvial sediments; PlQ – gravel and sand; M$_3^1$ – marlstone, sandstone; M$_2^2$ – Lithotamnium limestone; M$_2^1$ – marlstone, coal; M$_1^2$ – Quartz sandstone and clay; OLM – sandstone, sandy marl, sandy clay; α – andesite; T$_3^1$ b – massive limestone; T$_3^1$ a – massive dolomite; T$_2^2$ – shale, platy limestone with chert, tuff; T$_2^1$ – massive dolomite; T$_1$ – dolomite, marly limestone; P$_2^2$ – carbonate breccia; P$_1$ b – massive limestone; P$_1$ a – shale, Quartz sandstone and conglomerate; A - fault, B – fault-covered; C – thrust; d – location of fault-slip data measurements.

Tectonic evolution of the area and structural setting

The territory of Slovenia is situated on the NE corner of the Tertiary collisional zone between the European Plate and the Adriatic Microplate. The study area is situated in the NE Slovenia where Pannonian (Central Paratethyan) sediments can be found. Pannonian Basin system was formed by back-arc extension between Late Lower Miocene and Middle Miocene (Horváth & Royden, 1981; Horváth & Cloetingh, 1996; Fodor et al., 1999). In the Carpathians-Pannonian area European plate is divided on two microplates: ALCAPA block in the north and Tisza-Dacia unit in the south (e.g. Csontos et al., 2002; Schmid et al., 2008). Units are separated by Mid-Hungarian fault zone (Fig. 1 b).

In Lower to Middle Miocene north directed push of Adria microplate induced separation of ALCAPA block from Southern Alps and its Eastward extrusion (Fodor et al., 1999). The main movement was dextral slip along the Periadriatic fault and Mid-Hungarian fault zone (e.g. Palotai & Csontos, 2010). In this period the ALCAPA unit was affected by 50°CCW rotation. At the same time Tisza-Dacia unit rotated 60° to 80°CW. An opposite sense of neighbouring microplates rotation is believed to be a reason for variation in orientation of compressional axis in different parts of Alps-Pannonian-Carpathians region through Late Oligocene and Lower Miocene: N or NW trending in Eastern Alps, WNW-ESE trending in western Carpathians and Pannonian Basin and NE-SW trending in Tisza-Dacia unit (Fodor et al., 1999).

During Late Lower Miocene and Middle Miocene back-arc extension in the Carpathian embayment induced formation of Pannonian Basin System. The Middle Miocene rifting in Carpathians can be divided into two stages. The older phase was characterised by SW-NE directed extension along the NW-SE striking normal faults, while the younger phase was characterised by E-W to NW-SE directed extension accommodated along the NNE-SSW striking normal faults (Fodor et al., 1999). Rifting was accompanied by normal faulting (e.g. Horváth & Cloetingh, 1996; Márton et al., 2002). The thermal subsidence continued deepening of formed grabens and half grabens as a result of thermal cooling (Sachsenhofer et al., 2001).

At the beginning of Upper Miocene central parts of the Pannonian Basin are characterised by SW-NE directed compression (Fodor et al., 1999; Csontos et al., 2002).

Pliocene was characterised by change of regional stress dynamics. The end of subduction in Carpathians finally disabled lateral extrusion of Eastern Alps towards east (e.g. Royden et al., 1983). Former extensional regime changed to N-S or NW-SE directed compression and induced tectonic inversion and structural reactivation of the former Basin structures (Fodor et al., 1999). This tectonic inversional phase is well documented by folds and reverse faults with an ENE-WSW strike in wider Donat zone area, where blocks of Permo-Mesozoic rocks and Oligocene vulcanites form strike-slip duplex structures (Márton et al., 2002; Fodor et al., 1998).

The area in the NE Slovenia, which is covered by the Neogene and Quaternary Pannonian Basin sediments, is called the Mura Basin. The Mura Basin continues into Croatia in the south, and to the east it continuous into Hungarian Zala Basin. Mura and Zala Basins are commonly mentioned as one structural unit, the Mura-Zala Basin. The western borders of the Mura-Zala Basin are Pohorje and Kozjak Mts. (Mioč, 1977). In the north it is limited by a belt of metamorphic rocks, covered by Neogene sediments (Southern Burgenland). To the east Mura-Zala Basin continues towards Balaton Lake in Hungary (Kertai, 1957; Kőrössy, 1988; Szentgyörgyi & Juhász, 1988) and in the south it is limited by Donat tectonic zone (Mioč & Žniradčič, 1996). The Mura Basin is characterized by WSW-ENE striking subdepressions and highs, from north to south: Radgona depression, Murska Sobota high, Ljutomer depression and Boč anticline, which towards east continuous into Ormož-Selnica anticline and Hungarian Lovaszi-Budafa anticlines (Hasenhüttl et al., 1999).

The major faults in the Eastern Slovenia are (Fig. 1b): Periadriatic fault, Lavantal fault, Donat fault and Sava fault. The most important is Periadriatic fault since it generally separates the Eastern Alps units from the South Alpine basement rocks (Sachsenhofer et al., 2001). Going from the Giudicarie area along the southern margin of Karavanke Mts. this WNW-ESE striking fault is accomodate at least 100 km of dextral motion. Eastwardly, the strike-slip motion is partly shared to the southern sub-parallel shear zones, i.e., the Šoštanj fault (Vrabec & Fodor, 2006). In the eastern part, the Periadriatic fault becomes more segmented. The main trace and its southern shear zones are cut by the NW-SE striking Lavanttal fault, whereas eastwardly from the Lavanttal fault, the Periadriatic fault continuous in two sub-parallel WSW-ENE striking fault traces – the Ljutomer fault (in Hungary it continuous into Balaton line) and the Donat fault zone (Fig. 1b).

The Boč Mt. is located within the WSW-ENE striking dextral strike-slip Donat fault zone (Fig. 1b and Fig. 2). The zone is built of several partly anastomose faults that are interconnected with Periadriatic fault in the west and to the Balaton and Mid-Hungarian fault zone in the east. The Donat fault zone was regionally important especially in Lower Miocene due to the continental escape of the Eastern Alps (Jelen et al., 1992; Csontos et al., 1992).

Methods

The mapping area was chosen along the northern foothill of the Boč Mt., where the Miocene/Permian-Mesozoic contact, the core of this study, is exposed well. Due to very steep relief in this part of the Boč Mt. that is usually covered by dense vegetation, in this study, investigated outcrops were located along E-W directed forest road that cuts the study area and several steep river channels and associated valleys.

The majority of observed contacts between stratigraphic units were found to be of tectonic origin, predominantly indicated by steep fault surfaces. Fault planes were visible partly, in individual outcrops. Therefore the traces of main faults in the analysed area were constructed on the basis of measured orientation of fault planes on individual outcrops. The contact between more competent Permo-Triassic carbonates and less competent Middle Miocene sandstones and marlstones was usually well visible. Where the territory between individual outcrops was covered by organic soil horizons, the contact between two lithological units was detected on the basis of soil colour or on the basis of the prevailing pieces of rocks, found in the soil. The age of determined strata was based on the information from the Basic geological map 1 : 100.000 (Aničić & Juriša, 1985). Simultaneously with structural mapping 74 fault-slip data on fault-planes in Upper Triassic, Oligocene-Miocene and Miocene rocks were observed and measured for paleostress analysis. Each observed fault plane was characterized in accordance to fault plane orientation, orientation of preserved striation and displacement along the fault plane. The sense of slip along fault planes was determined by kinematic microcriteria that were found on individual fault planes. The most common and the best preserved kinematic microcriteria were fibrose calcite crystals and associated steps (Fig. 3) that are by many authors (e.g. Petit, 1987; Doblas, 1988) believed to be reliable kinematic indicator. In the same time, Sperner & Zweigel (2010) suggested that calcite steps might not be completely reliable slip indicator. To ensure correctly determined sense of slip, in this study, beside fibrose calcite minerals and associated steps slickolites, moon-shaped fractures and others were used. This study included kinematic indicators measurements within 5 locations with preserved fault striation from a wider Boč Mt. area. Since the territory is highly deformed, covered by soil and vegetation and the structures on fault planes were often dissolved under atmospheric conditions (especially Miocene clastites have very low rock resistance), the number of fault-slip data measurements locations is relatively small.

Paleostress analysis of measured fault - slip data was done by Tectonics FP inversional method (Ortner et al., 2002). With an assumption that slip along the fault plane is parallel to the shear stress (Wallace, 1951; Bott, 1959), orientation of the principal stress axes σ_1 (maximum stress), σ_2 (intermediate stress) and σ_3 (minimum stress) in the inverse process is given by the eigenvalues of the reduced stress tensor (Angelier, 1994). Since the study area is highly deformed and the bedding orientation changes rapidly, paleostress inversion has been done separately for each outcrop. If less than three fault-slip measurements were available, the calculation of paleostress axis was not possible. In such cases kinematic axes of maximum extension (T-axis), intermediate kinematic axis (B-axis) and maximum contraction (P-axis) were presented in the results.

Results and discussion

The oldest mapped rocks are Lower Permian quartz sandstone, quartz conglomerate, shale, light grey limestone with fusulinides and red and dark grey organogenic limestone. In some places Lower Permian deposits continue into breccia with well rounded white, grey and red limestone clasts in carbonate matrix. Within the study area Lower Triassic is represented by massive, rarely bedded light to medium grey limestone. Anisian strata are also characteristic by massive grey limestone, whereas in Ladinian massive

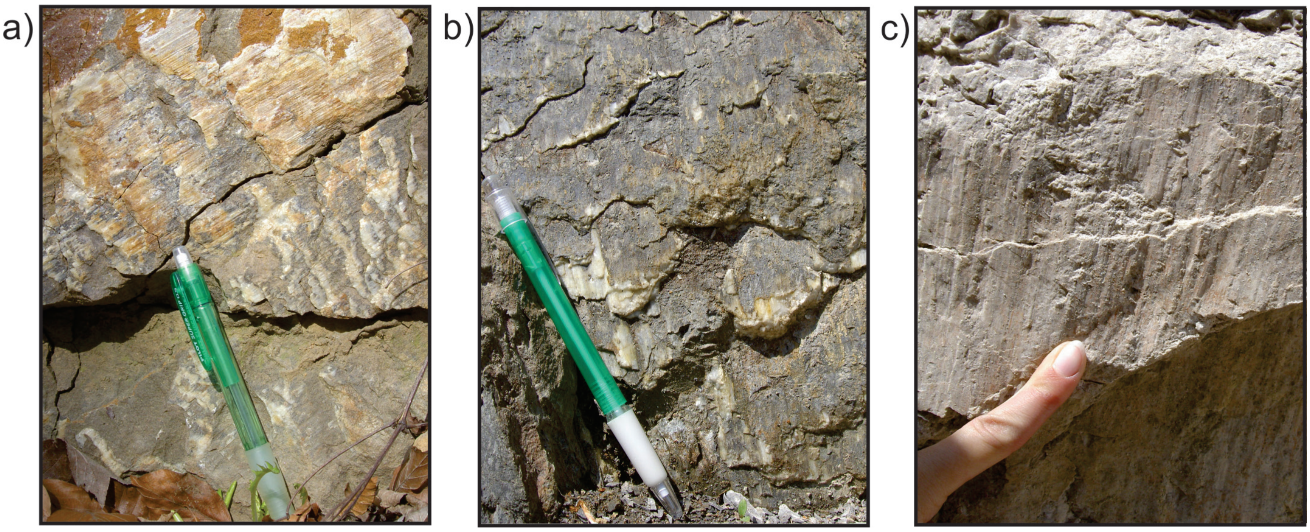

Fig. 3. Examples of fault striation, assocciated with fibrose calcite steps, that indicate: a) strike-slip fault (location 2 on Fig. 2); b) normal fault (location 4 on Fig. 2); c) reverse fault (location 3 on Fig. 2).

and bedded grey limestone with chert can be found. These massive limestones occasionally laterally interchange with massive silicified breccia, composed of angular predominantly quartz clasts in a quartz matrix (partly it is carbonate). In the hangingwall, Upper Triassic (Cordevol) strata are characteristic by light grey massive limestone that often change to white massive grained dolomite, especially in fault zones. The youngest unit in the mapped area are Middle Miocene marlstone, bituminose sandstone, breccia, dark grey limestone and brown coal. Middle Miocene stratigraphic unit belong to Central Paratethyan sedimentary sequence and are dominantly Badenian in age (Jelen & Rifelj, 2002; Mikuž et al., 2012; Bartol et al., 2014). The mapped lithological units are schematically presented on stratigraphic column on Figure 4.

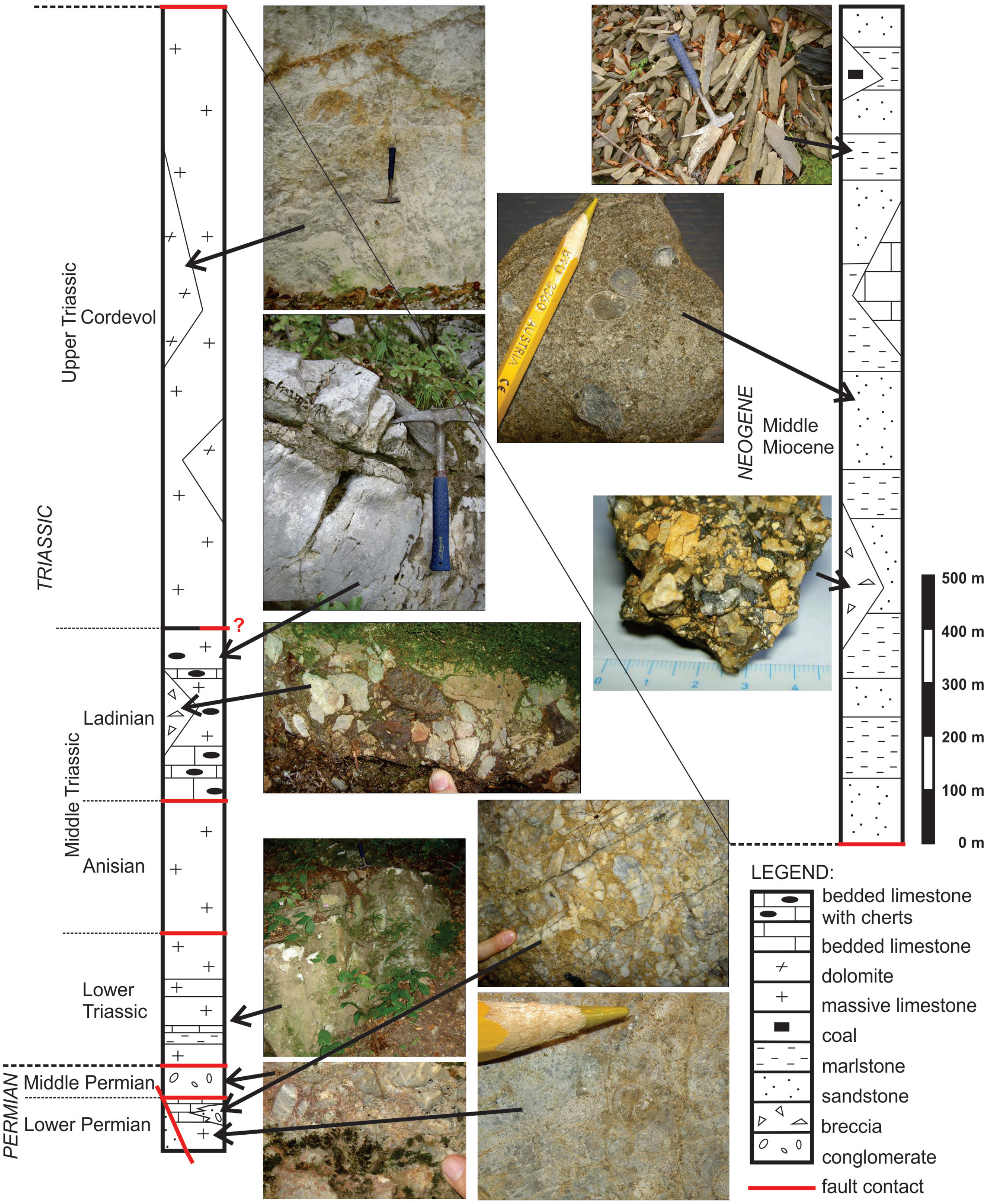

Fig. 4. Mapped lithological units. Thicknesses of each lithological unit is adopted after Aničić & Juriša (1984).

Mapped contacts between the individual stratigraphic units are in general tectonic, only transition from Ladinian to Cordevol in some places might be stratigraphic (Fig. 4). The dominantly observed structures in the study area are SW-NE striking faults, dipping 75° to subvertically, mostly towards SE (Fig. 5). Characterized by few to ten meters wide belt of highly deformed rock, mapped faults are subparallel to the Donat fault zone (Fig. 1b). In the same time, within the mapped area, two principal NE-SW striking faults were identified. The first one is situated in the SE part, near Tolsti vrh (TVF in Fig. Fig. 6), whereas the second one is situated in the NW part of the study area, near village Studenice (SF in Fig. 6). The Studenice fault is accompanied by a few subparallel NE-SW striking fault segments. In the central part of the researched area, between TVF and SF striking fault zones, several subvertical NNE-SSW striking faults were mapped (Fig. 6). This faulted area was characterized by significantly narrower belt of deformed rocks than the belt of deformed rock along NE-SW striking faults. Field mapping show that SSW-NNE striking faults do not crosscut NE-SW striking faults. Therefore it could be suggested that NE striking faults are the principal faults within the study area, whereas NNE striking faults are a lower order faults, formed between the main structures. The third documented fault group are E-W to ESE-WNW striking steep faults with dextral and normal slips, evident from fault slip microcriteria observed on those fault planes in Lower Miocene rocks. The fault planes of this

Fig. 5. An example of subvertical SW-NE striking fault plane (Tolsti vrh fault).

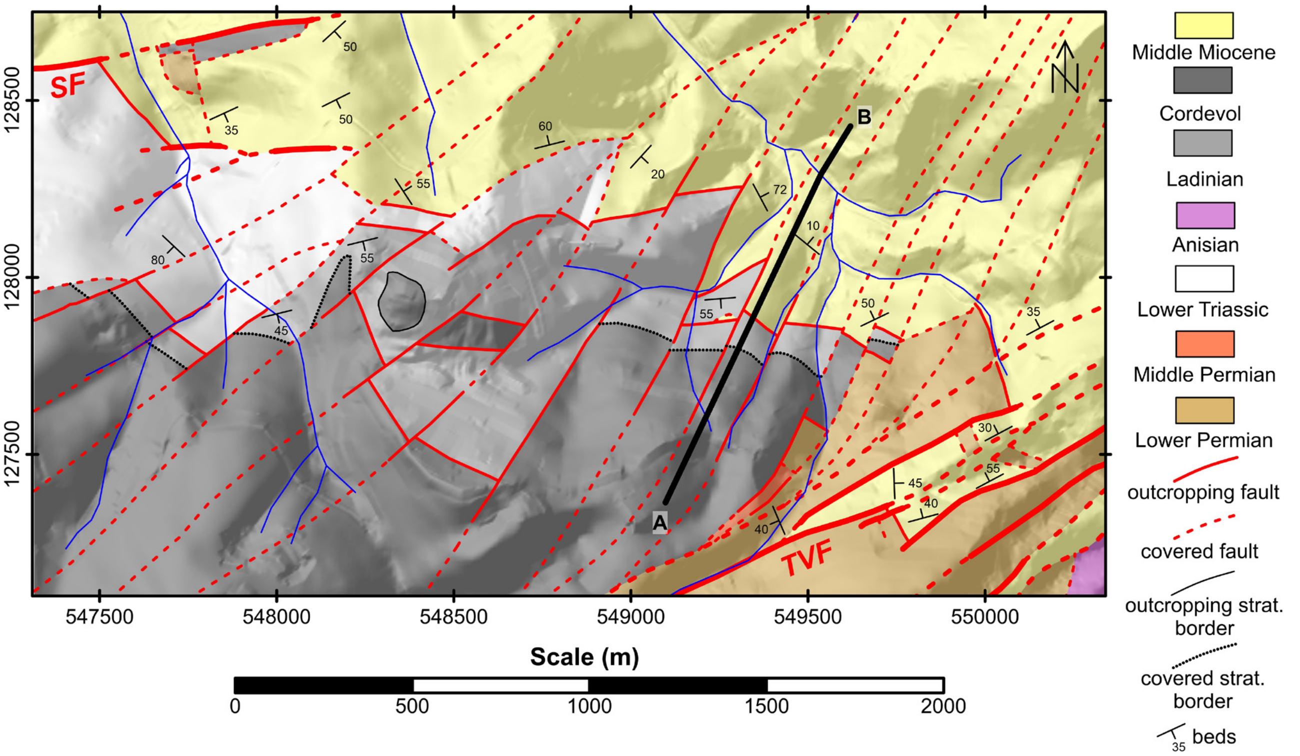

Fig. 6. Structural map of the Northeastern Boč region. The major fault zones – Studenice fault (SF) and Tolsti vrh fault (TVF) are highlighted by thicker lines.

orientation were mapped in the Eastern part of the area. The estimated deep structures are shown on an interpretative cross-section AB (Fig. 7a), where the presented geometry is based on measured bedding (Fig. 6) and observed fault plane geometry (Fig 7b).

Results of paleostress analysis

The mapped territory is highly deformed and structurally represents the most complex part of the Boč Mt. Therefore fault planes with well-preserved striation and reliable kinematic criteria in

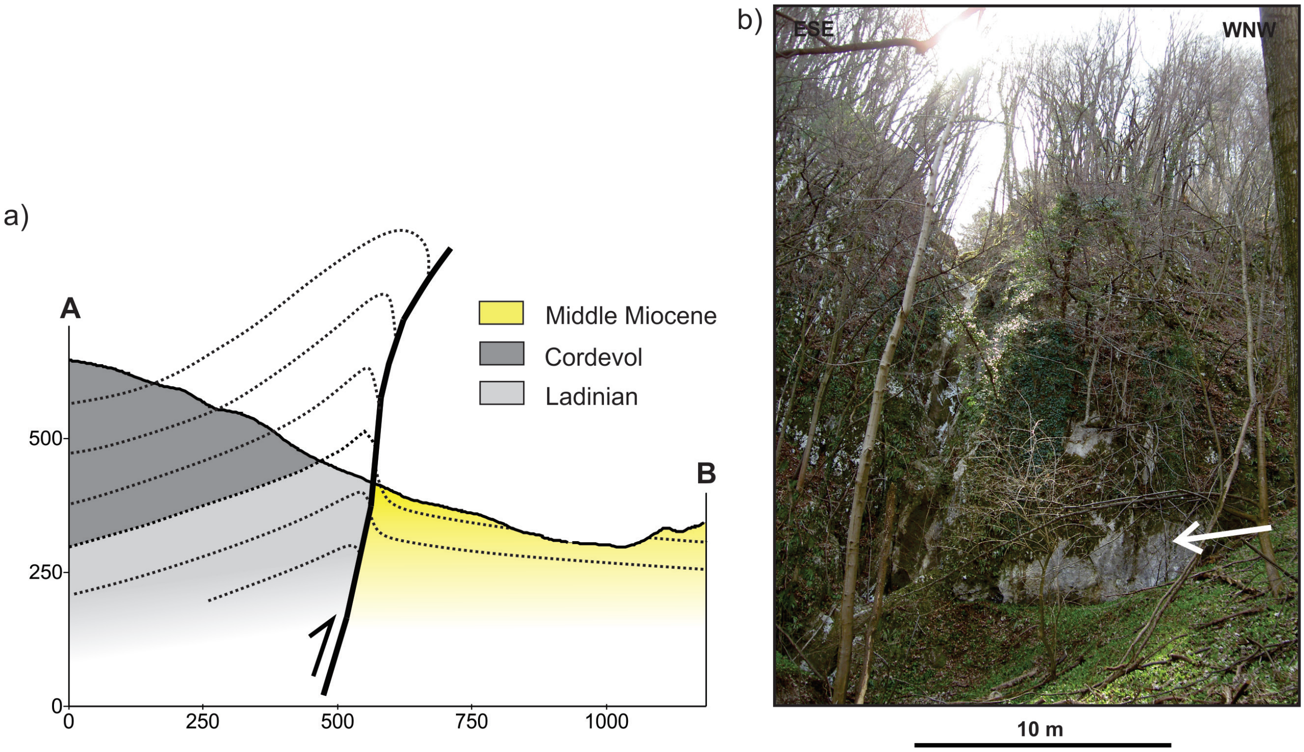

Fig. 7. a) Interpretative cross-section AB, oriented perpendicular to the contact between Miocene and Triassic rocks. b) Photograph of subvertical contact between Miocene and Triassic rocks from the cross-section (a).

Table 1. Results of fault-slip data analaysis.

Location	Age	Number of measurements	*sigma 1*	*sigma 2*	*sigma 3*	*P-axis*	*B-axis*	*T-axis*	*Phase*
1	*Lower Permian*	2				121/1	199/77	29/11	Phase 4
2	*Middle Miocene*	7	257/48	128/30	21/27	307/65	121/34	211/0	Phase 1
		2				338/24	110/56	237/22	Phase 4
3	*Cordevol*	5	6/2	102/70	275/20	319/9	82/74	227/14	Phase 4
		9	175/55	42/26	301/22	211/12	6/77	119/5	Phase 4
		5	138/1	45/67	228/23	176/6	37/77	267/10	Phase 4
		7	180/30	80/17	325/55	238/75	48/14	325/9	Phase 2
		9	186/43	18/47	282/6	215/50	17/30	296/9	Phase 2
4	*Oligocene-Miocene*	4	35/41	138/14	243/45	311/49	108/42	205/15	Phase 1
		1				22/8	109/36	283/54	?
		2				277/19	214/29	150/8	Phase 3
5	*Oligocene-Miocene*	4	91/2	200/85	1/5	231/8	99/80	323/6	Phase 3
		3				332/45	35/35	149/44	?
		10	303/39	100/49	204/12	255/17	44/68	159/4	Phase 3
		4	159/77	296/10	27/9	92/86	284/7	195/3	Phase 1

the mapped area were very rare, only one location was suitable to collect some fault-slip data (location 1 on Fig. 2). For this reason fault-slip data for paleostress analysis were measured also on four locations in a wider Boč area (locations 2-5 on Fig. 2). Since the territory presented on Fig. 2 is relatively small, we can presume that regional paleostress and kinematic pattern does not change on such small distances. Therefore general tectonic phases, characteristic for the mapped area should be evident also on the locations of measured fault-slip data in the surrounding of the Boč Mt. One location is within Lower Permian limestone, one in Upper Triassic dolomite, two locations are within Oligocene-Miocene sandstone and one in Lower Miocene siltstone. The number of measurements that were included in the individual kinematic compatible fault group, results of fault-slip data analysis and indication of individual paleostress phase, are presented in Table 1.

The results show four different paleostress tensors in the study area. These stress tensors can be explained by four individual paleostress phases though crosscutting relations of different fault striations were not observed, as well as no cross-cutting relationships between different fault planes. Therefore, ages of documented paleostress phases are assumed after previous structural studies in the border zone between Alps, Dinarides and Pannonian Basin (Peresson & Decker, 1997; Fodor et al., 1998; Fodor et al., 1999; Tomljenović & Csontos, 2001; Ilić & Neubauer, 2005; Ustaszewski et al., 2010; Bartel et al., 2015; Mladenović et al., 2015; Žibret & Vrabec, 2016).

The first phase (Phase 1, Figs. 8, 12) is characterized by SW-NE directed minimum paleostress axis σ_3 and NW-SE directed maximum paleostress axis σ_1 (at least partly) in strike-slip stress regime. This stress state is typically represented by normal to oblique-normal slips on moderately S to SW dipping, W to WNW striking fault planes. This phase that is characterized by NE-SW oriented tension (partly in strike-slip stress regime) can be correlated with Early and Middle Miocene tension, documented in the SW margin of the Pannonian Basin (e.g. Tomljenović & Cson-

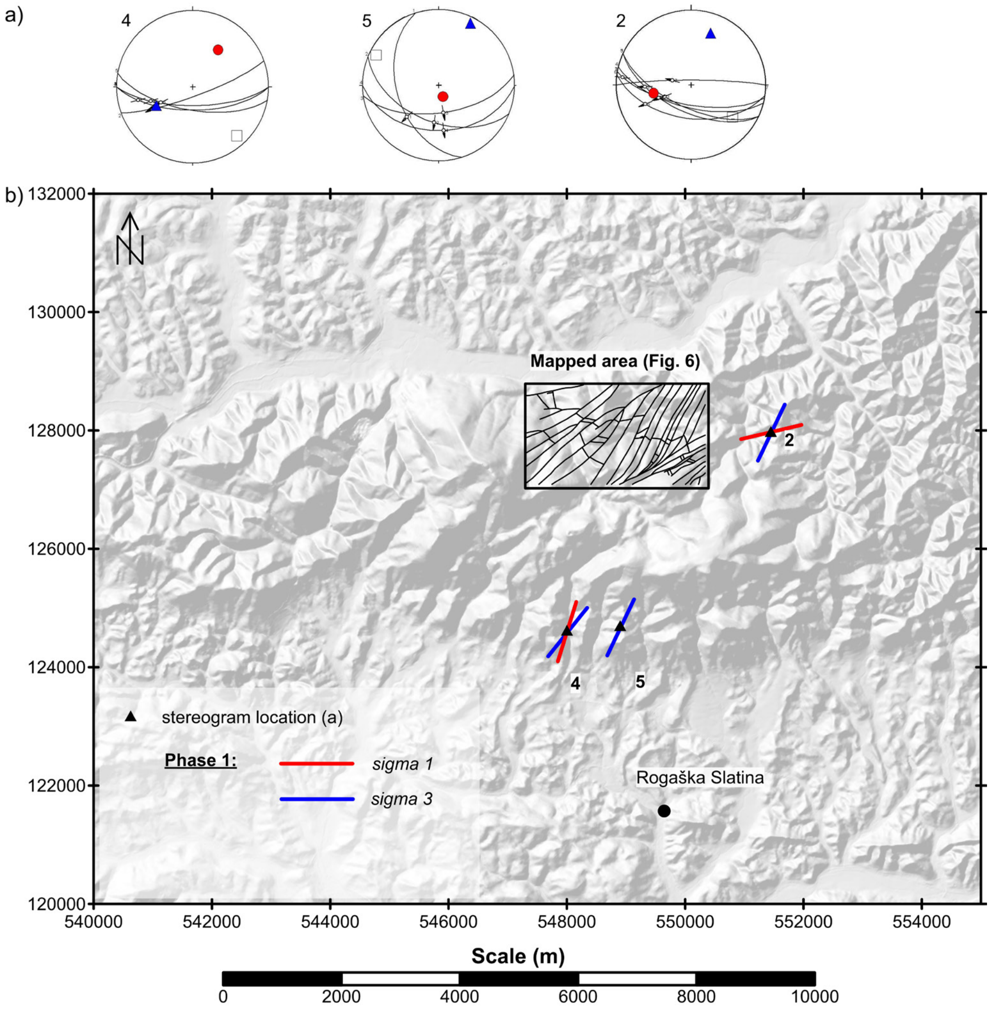

Fig. 8. a) Examples of fault-slip data and main stress/strain orientation for Phase 1 (Schmidt net, lower hemisphere). Arrows on fault plane show relative movement of the hanging-wall block. Red circle represents σ_1, blue triangle σ_3 and white rectangle σ_2. b) Local stress field of Phase 1 in the Boč Mt. region (in present-day reference frame, not accounting for any vertical-axis rotations).

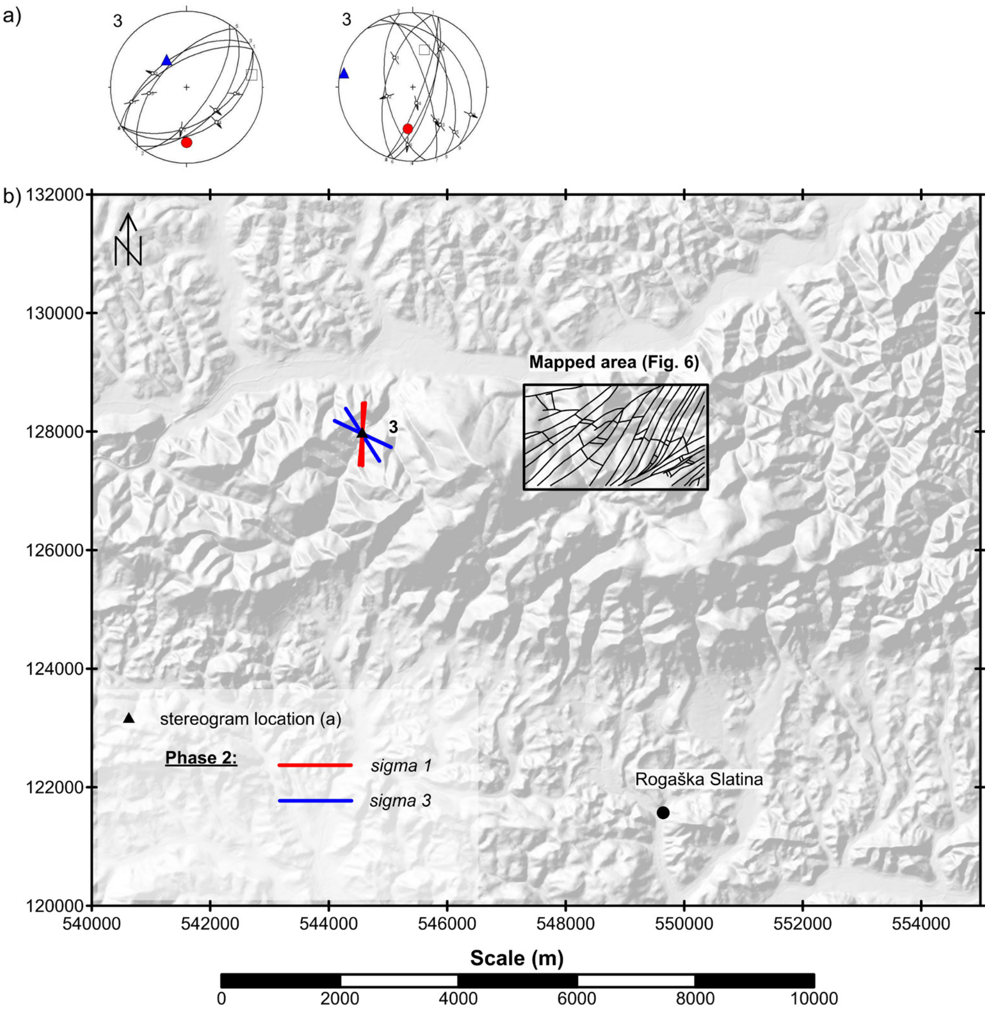

Fig. 9. a) Examples of fault-slip data and main stress/strain orientation for Phase 2 (Schmidt net, lower hemisphere). Arrows on fault plane show relative movement of the hanging-wall block. Red circle represents σ_1, blue triangle σ_3 and white rectangle σ_2. b) Local stress field of Phase 2 in the Boč Mt. region (in present-day reference frame, not accounting for any vertical-axis rotations).

tos, 2001), in the Internal Dinarides (e.g. Ilić & Neubauer, 2005), in the Internal Dinarides-Pannonian Basin transitional area (Ustaszewski et al., 2010), in the NW External Dinarides of Slovenia (Žibret & Vrabec, 2016) and in the central, eastern and northern parts of the Panonnian Basin system (Fodor et al., 1999). Mentioned studies geodynamically relate to Early and Middle Miocene NE-SW oriented tension to the Lower and Middle Miocene back arc extension with corresponding normal faulting in the Pannonian Basin system.

The second documented phase (Phase 2, Figs. 9, 12) is characterised by a NW-SE to WNW-ESE directed minimum paleostress axis σ_3, with generally N-S directed maximum paleostress axis σ_1 in a strike-slip stress regime. This stress state is typically represented by normal to oblique-normal slip motions on moderately NW and SE dipping fault planes and by sinistral motions on steep NNE striking fault planes. This dominant NW-SE to WNW-ESE oriented tension (partly in strike-slip stress regime) can be correlated with Middle and Late Miocene tension, transtension, previously described in the SW margin of the Pannonian Basin (e.g. Tomljenović & Csontos, 2001), in the Internal Dinarides (e.g. Ilić & Neubauer, 2005) and in the Internal Dinarides-Pannonian Basin transitional area (Mladenović et al., 2015). Middle to Late Miocene NW-SE to WNW-ESE oriented tension corresponds to the break-up of the ALCAPA block into East-Alpine and Pannonian-Carpathian part (Fodor et al., 1998; Fodor et al. 1999; Tomljenović & Csontos, 2001).

The third documented phase (Phase 3, Figs. 10, 12) is characterised by a W-E directed maximum paleostress axis σ_1 and N-S directed minimum paleostress axis σ_3 in a strike-slip stress regime. This stress state is typically represented by sinistral slip motions on steep to subvertical N striking fault planes and by dextral slip motions on steep to subvertical NNE- to NE- striking fault planes. This third phase characterized by E-W oriented compression, with N-S oriented tension in strike-slip stress regime can be correlated by

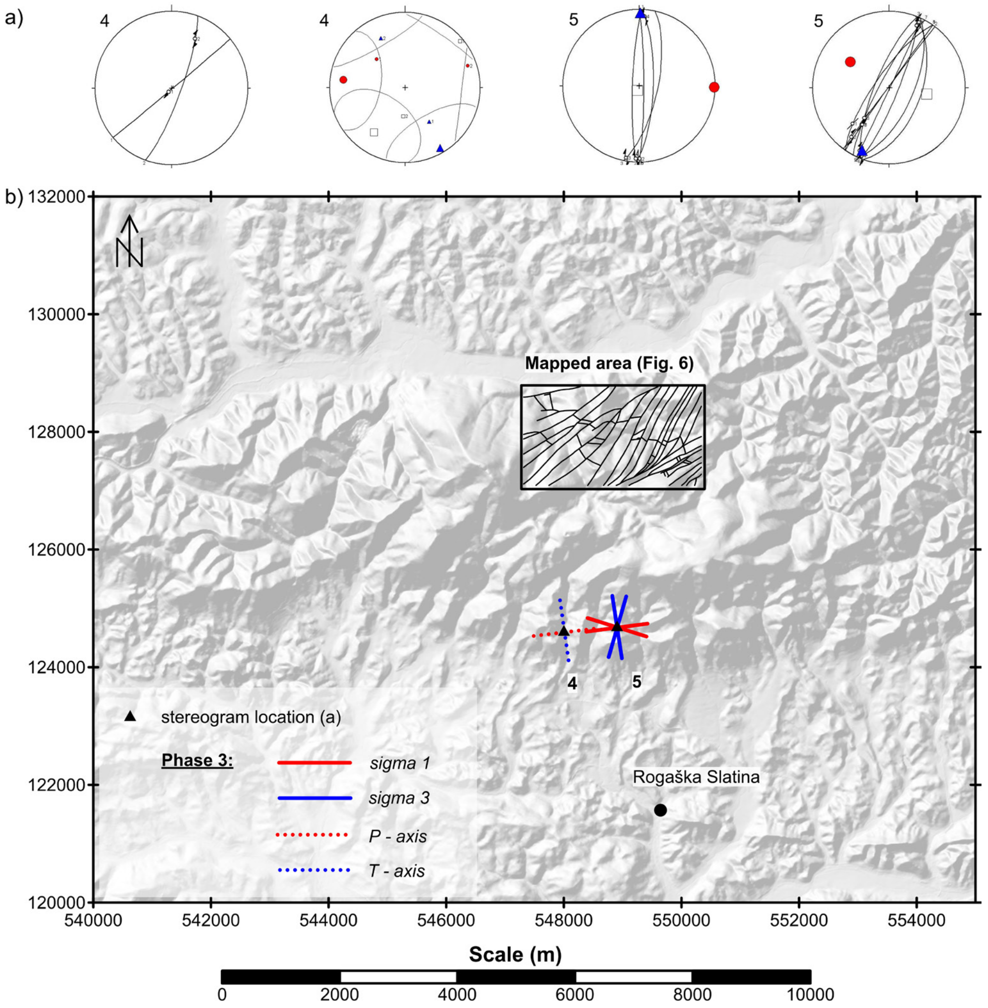

Fig. 10. a) Examples of fault-slip data and main stress/strain orientation for Phase 3 (Schmidt net, lower hemisphere). Arrows on fault plane show relative movement of the hanging-wall block. Red circle represents σ_1 (or P-axis where < 3 data), blue triangle σ_3 (or T-axis where < 3 data) and white rectangle σ_2 (or B-axis where < 3 data). b) Local stress field of Phase 3 in the Boč Mt. region (in present-day reference frame, not accounting for any vertical-axis rotations).

Late Miocene compression, documented in Vienna Basin (Peresson & Decker, 1997), in different parts of the Pannonian Basin system (e.g. Fodor et al., 1999) and in the NW External Dinarides of Slovenia (Žibret & Vrabec, 2016). According to the aforementioned studies Late Miocene compression geodynamically relates to the cessation of the subduction in the Eastern Carpathians.

The fourth identified phase (Phase 4, Figs. 11, 12) is characterised by a NNW-SSE to N-S directed maximum paleostress axis σ_1 and WWS-EEN to W-E directed minimum paleostress axis σ_3 in a strike-slip stress regime. This stress state is typically represented by dextral slip motions on steep to subvertical NW-SE to W-E striking fault planes and oblique-reverse slip motions on steep to subvertical NE-SW striking fault planes. Phase 4 with NNW-SSE to N-S oriented compression and WWS-EEN to W-E oriented tension in strike-slip stress regime coincides with the recent stress tensors of the wider South Alpine-Dinarides border area (e.g. Herak et al., 2009; Caporali et al., 2013) and can be correlated to Pliocene and Quaternary inversion/transpresion phase, documented in the NW External Dinarides (Ustaszewski et al., 2010; Žibret & Vrabec, 2016), in the SW margin of the Pannonian Basin and in Central Dinarides (e.g. Tomljenović & Csontos, 2001), in the Internal Dinarides (e.g. Ilić & Neubauer, 2005), in the Internal Dinarides-Pannonian Basin transitional area (Mladenović et al., 2015), in the northern and western parts of the Pannonian Basin (Fodor et al., 1999), in the SW part of the Panonnian Basin (Csontos et al., 2002) and in the Drau Range and Friuli South Alpine wedge (Bartel et al., 2015).

Conclusions

According to the detailed structural mapping in the NE Boč region the contact between Mesozoic carbonates and Middle Miocene Central Paratethyan formations is characterized by steep to subvertical W-E or NW-SE striking faults, segmented inside a Donat-Lavanttal

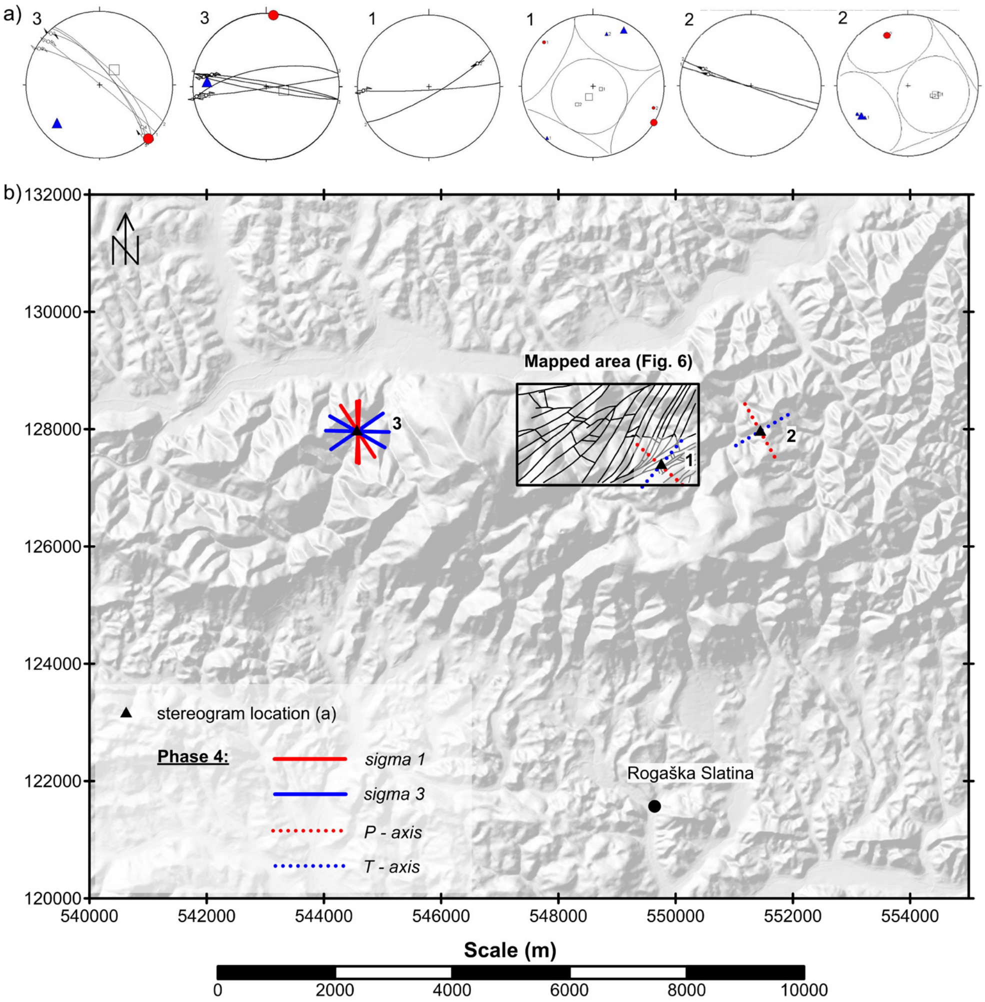

Fig. 11. a) Examples of fault-slip data and main stress/strain orientation for Phase 4 (Schmidt net, lower hemisphere). Arrows on fault plane show relative movement of the hanging-wall block. Red circle represents σ_1 (or P-axis where < 3 data), blue triangle σ_3 (or T-axis where < 3 data) and white rectangle σ_2 (or B-axis where < 3 data). b) Local stress field of Phase 4 in the Boč Mt. region (in present-day reference frame, not accounting for any vertical-axis rotations).

dextral transpressional zone. The regional acceptance of such contact was checked by paleostress analysis. Fault-slip data were measured in a wider Boč area and allowed to separate four paleostress tensors. Phase 1 tensor group is characterised by SW-NE directed minimum paleostress axis σ_3 (at least partly) in strike-slip stress regime, manifested by normal to oblique-normal slips on moderately dipping to steep W-E to WNW-ESE striking fault planes. It is well correlated with Lower and Middle Miocene tension, and may be attributed to the back arc extension in the Pannonian Basin system. Phase 2 tensor group is characterised by NW-SE to WNW-ESE directed minimum paleostress axis σ_3 and generally N-S directed maximum paleostress axis σ_1 in a strike-slip stress regime, manifested by normal to oblique-normal slips on moderately dipping SW-NE striking fault planes and by sinistral slips on steep NNE-SSW striking fault planes. Identified phase could correlate with Middle to Late Miocene tension, attributed to the break-up of the Alcapa block into East-Alpine and Pannonian-Carpathian part. Phase 3 tensor group is characterized by W-E directed maximum paleostress axis σ_1 and N-S directed minimum paleostress axis σ_3 in a strike-slip stress regime, manifested by sinistral slips on steep to subvertical N-S striking fault planes and by dextral slips on steep to subvertical NNE-SSW to NE-SW striking fault planes. This phase could coincide with Late Miocene compression, attributed to cessation of the subduction in the Eastern Carpathians. Phase 4 tensor group is characterised by a NNW-SSE to N-S directed maximum paleostress axis σ_1 and WWS-EEN to W-E directed minimum paleostress axis σ_3 in a strike-slip stress regime, manifested by dextral slips on steep to subvertical NW-SE to W-E striking fault planes and oblique-reverse slips on steep to subvertical NE-SW striking fault planes. This final phase could represent recent stress state and most probably represent Pliocene and Quaternary inversive/transpressive phase. The documented stress tensors are compatible with structural data from the Alps-Dinarides-Carpathians region which confirms the result of this study (the subvertical contact in the NE part of the Boč Mt.).

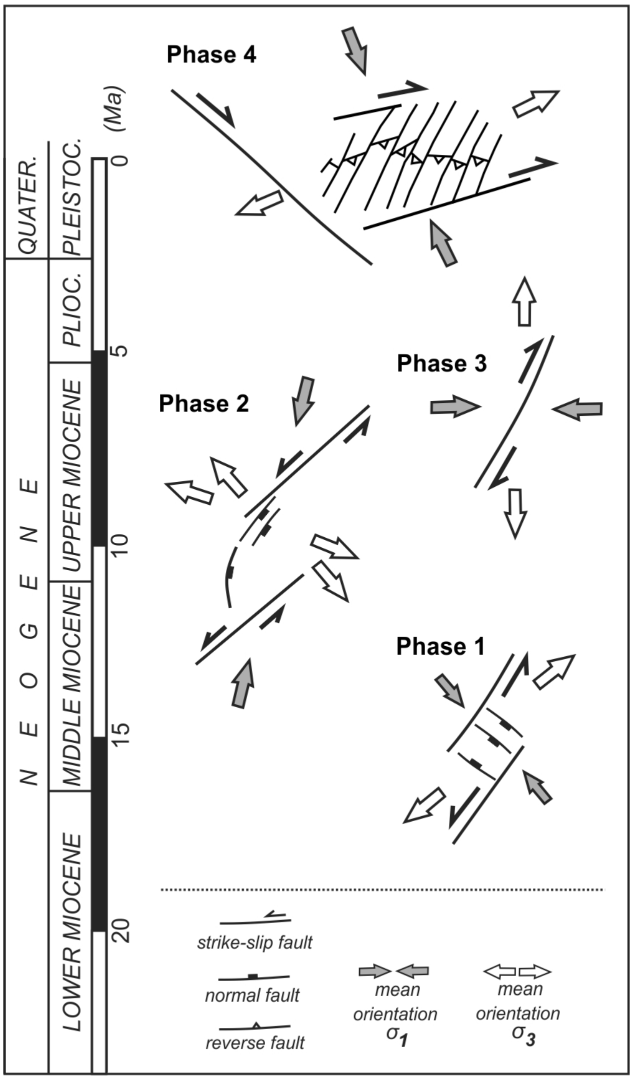

Fig. 12. Schematic structural patterns for the Boč region.

Acknowledgments

This research was conducted within the scope of Diploma Thesis titled "Structural analysis of the northeastern Boč region" by Lea Žibret, supervised by Prof. dr. Marko Vrabec. The results were used for the ARRS applied research project L1-0073 "Assessing the optimal balance between environmental protection and economic use of mineral and spring groundwater resources – a case study of the Rogaška Slatina fractured aquifer system" (head dr. Branka Trček). I would like to thank to dr. Bogomir Celarc and dr. Matevž Novak from the Geological Survey of Slovenia for introducing me the territory, for help at recognising stratigraphic units and for showing me some good locations for collecting fault-slip data. I would also like to thank to anonymous reviewers for many constructive comments that improved the manuscript.

References

Angelier, J. 1994: Fault slip analysis and paleostress reconstruction. In: Hancock, P.L. (ed.): Continental deformation. Pergamon Press. Oxford, 53-99.

Aničić, B. & Juriša, M. 1984: Basic Geological Map SFRJ 1 : 100.000 – Sheet Rogatec. Beograd, Zvezni geološki zavod.

Aničić, B. & Juriša, M. 1985: Basic Geological Map SFRJ 1 : 100.000. Explanations for sheet Rogatec L 33-68. Zvezni geološki zavod, Beograd: 76 p.

Bartel, E.M., Neubauer, F., Genser, J. & Heberer, B. 2014: States of paleostress north and south of the Periadriatic fault: Comparison of the Drau Range and Friuli Southalpine wedge. Tectonophysics, 637: 305-327, doi:10.1016/j.tecto.2014.10.019.

Bartol, M., Mikuž, V. & Horvat, A. 2014: Palaeontological evidence of communication between the Central Paratethys and the Mediterranean in the late Badenian/early Serravalian. Palaeogeogr. Palaeocl., 394: 144-157, doi:10.1016/j.palaeo.2013.12.009.

Bott, M.H.P. 1959: The mechanisms of oblique slip faulting. Geol. Mag., 96: 109-117.

Caporali, A., Neubauer, F., Ostini, L., Stangl, G. & Zuliani, D. 2013: Modeling surface GPS velocities in the Southern and Eastern Alps by finite dislocations at crustal depths. Tectonophysics, 590: 136-150, doi:10.1016/j.tecto.2013.01.016.

Csontos, L., Nagymarosy, A., Horváth, F. & Kováč, M. 1992: Tertiary evolution of the intra – Carpathian area: a model. Tectonophysics, 199: 73–91.

Csontos, L, Márton, E., Wórum, G. & Benkovics, L. 2002: Geodynamics of SW-Pannonian inselbergs (Mecsek and Villány Mts, SW Hungary): Inferences from a complex structural analysis. EGU Stepham Mueller Special Publication Series, 3: 227-245.

Doblas, M. 1998: Slickenside kinematic indicators. Tectonophysics, 295: 187-197.

Fodor, L., Jelen, M., Márton, E., Skaberne, D., Čar, J. & Vrabec, M. 1998: Miocene-Pliocene tectonic evolution of the Periadriatic line in Slovenia – implications for Alpine-Carpathian extrusion models. Tectonics, 17: 690–709.

Fodor, L., Csontos, L., Bada, G., Gyorfi, I. & Benkovics, L. 1999: Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesus of paleostress data. In: Durand, B., Jolivet, L., Horváth,

F. & Seranne, M. (eds.): The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. Geological Society London, Special Publications, 156: 295-334.

Hasenhüttl, C., Kraljic, B., Sachsenhofer, R.F., Jelen, B. & Rieger, R. 1999: Source rocks and hydrocarbon generation in Slovenia. Mar. Petrol. Geol., 18: 115-132.

Herak, D., Herak, M. & Tomljenović, B. 2009: Seismicity and earthquake focal mechanisms in North-Western Croatia. Tectonophysics, 465: 121-220, doi:10.1016/j.tecto.2008.12.005.

Horváth, F. & Royden, L. 1981: Mechanism for the Formation of the Intra-Carpathian Basins: a Review. Earth Evolution Science, 3: 307-316.

Horváth, F. & Cloething, S. 1996: Stress-induced late stage subsidence snomalies in the Pannonian Basin. Tectonophysics, 266: 287-300.

Ilić, A. & Neubauer, F. 2005: Tertiary to recent oblique convergence and wrenching of the Central Dinarides: Constraints from palaeostress study. Tectonophysics, 410/1-4: 465-484, doi:10.1016/j.tecto.2005.02.019.

Jelen, B., Aničić, B., Brezigar, A., Buser, S., Cimerman, F., Drobne, K., Monostori, M., Kedves, M., Pavlovec, R., Pavšič, J. & Skaberne, D. 1992: Model of positional relationships for Upper Paleogene and Miocene strata in Slovenia. In: Montanari, A., Cocccioni, R., Odin, G. S. (eds.): Interdisciplinary Geological Conference on the Miocene Epoch with Emphases on the Umbria-Marche Sequence. Abstracts and Field Trips. International Union of Geological Sciences, Subcommission on Geochronology, Ancona, 71–72.

Jelen, B. & Rifelj, H. 2002: Stratigraphic structure of B1 Tertiary tectonostratigraphic unit in eastern Slovenia. Geologija, 45/1: 115-138, doi:10.5474/geologija.2002.010.

Kertai, G.Y. 1957: The structures of Basins and oil reservoirs in Hungary, based on oil exploration wells (in Hungarian). Földtani Közlöny, 87: 383-394.

Kőrössy, L. 1988: Hydrocarbon geology of the Zala Basin in Hungary. Általános Földtani Szemle, 23: 3-162.

Márton, E., Fodor, L., Jelen, B., Márton, P., Rifelj, H. & Kevrić, R. 2002: Miocene to Quaternary deformation in NE Slovenia: complex paleomagnetic and structural study. J. Geodyn., 34: 627–651.

Mikuž, V., Bartol, M. & Ulaga, Š. 2012: The brachiopod Lingula from the Middle Miocene – Badenian beds of Slovenia. Geologija, 55/2: 271–274, doi:10.5474/geologija.2012.017.

Mioč, P. 1977: Geologic structure of the Drava Valley between Dravograd and Selnica. Geologija, 20: 193-230.

Mioč, P. & Žniradčič, M. 1996: Geological characteristics of the oil fields in the Slovenian part of the Pannonian Basin. Geol. Croat., 49: 271-275.

Mancktelow, N.S., Stöckli, D.F., Grollimund, B., Müller, W., Fügenschuh, B., Viola, G., Seward, D. & Villa, I.M. 2001: The DAV and Periadriatic fault systems in the Eastern Alps south of the Tauern window. Int. J. Earth Sciences (Geol. Rundsch.), 90: 593-622, doi:10.1007/s005310000190.

Mladenović, A., Trivić, B. & Cvetković, V. 2015: How tectonics controlled post-collisional magmatism within the Dinarides: Inferences based on study of tectono-magmatic events in the Kopaonik Mts. (Southern Serbia). Tectonophysics, 646: 36-49, doi:10.1016/j.tecto.2015.02.001.

Novak, M., Celarc, B., Žibret, L., Leis, A. & Trček, B. 2010: Geologic structure of the Rogaška Slatina aquifer system and its geochemical characteristics. In: Košir, A., Horvat, A., Zupan Hajna, N. & Otoničar, B. (eds.): Povzetki in ekskurzije = Abstracts and field trips, 3. Slovenski geološki kongres, Bovec, 16.-18. september 2010. Postojna: Znanstvenoraziskovalni center SAZU, Inštitut za raziskovanje krasa; Ljubljana: Paleontološki inštitut Ivana Rakovca, 36 p.

Ortner, H., Reiter, F. & Acs, P. 2002: Easy handling of tectonic data: The programs TectonicVB for Mac and TectonicsFP for Windows. Comput. Geosci., 28/10: 1193-1200.

Palotai, M. & Csontos, L. 2010: Strike-slip reactivation of a Paleogene to Miocene fold and thrust belt along the central part of the Mid-Hungarian Shear Zone. Geol. Carpath., 61/6: 483-493, doi:10.2478/v10096-010-0030-3.

Peresson, H. & Decker, K. 1997: Far-field effects of Late Miocene subduction in the Eastern Carpathians: E-W compression and inversion of structures in the Alpine-Carpathian-Pannonian region. Tectonics, 16/1: 38-56.

Petit, J.P. 1987: Criteria for the sense of movement on fault surfaces in brittle rocks. J. Struct. Geol., 9: 597-608.

Placer, L. 1998: Contribution to the macrotectonic subdivision of the border region between Southern Alps and External Dinarides. Geologija, 41: 223-255, doi:10.5474/geologija.1998.013.

Royden, L., Horváth, F. & Rumpler, J. 1983: Evolution of the Pannonian Basin System: 1. Tectonics. Tectonics, 2/1: 63-90, doi:10.1029/TC002i001p00063.

Sachsenhofer, R. 2001: Syn- and post-collisional heat flow in the Cenozoic Eastern Alps. Int. J. Earth Sci., 90: 579-592, doi:10.1007/s005310000179.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K. 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss J. Geosci., 101: 139–183, doi:10.1007/s00015-008-1247-3.

Sperner, B. & Zweigel, P. 2010: A plea for more caution in fault-slip analysis. Tectonophysics, 482/1-4: 29-41, doi:10.1016/j.tecto.2009.07.019.

Szentgyörgyi, K. & Juhász, G.Y. 1988: Sedimentological characteristics of the Neogene sequences in SW Transdanubia, Hungary. Acta Geologica Hungarica, 31: 209–225.

Tomljenović, B. & Csontos, L. 2001: Neogene-Quaternary structures in the border zone between Alps, Dinarides and Pannonian Basin (Hrvatsko zagorje and Karlovac Basins, Croatia). Int. J. Earth Sci., 90/3: 560–578, doi:10.1007/s005310000176.

Ustaszewski, K., Kounov, A., Schmid, S.M., Schaltegger, U., Krenn, E., Frank, W. & Fügeschuh, B. 2010: Evolution of the Adria-Europe plate boundary in the northern Dinarides: From continent-continent collision to back-arc extension. Tectonics, 29: 1–34, doi:10.1029/2010TC002668.

Vrabec, M. & Fodor, L. 2006: Late cenozoik tectonics of Slovenia: Structural styles at the north-eastern corner of the Adriatic microplate. In: Pinter, N., Gyula, G., Weber, J., Stein, S. & Medak, D. (eds.): The Adria Microplate: GPS Geodesy, Tectonics and Hazards. Nato Science Series: IV: Earth and Environmental Sciences, 61: 151–168.

Wallace, R.E. 1951: Geometry of shearing stress and relation to faulting. J. Geol., 59: 118-130.

Žibret, L. 2009: Structural analysis of the northeastern Boč region. Diploma Thesis, Faculty of Natural Sciences and Engineering, University of Ljubljana: 70 p.

Žibret, L. & Vrabec, M. 2016: Paleostress and kinematic evolution of the orogeny-paralllel NW-SE striking faults in the NW External Dinarides of Slovenia unraveled by mesoscale fault-slip data analysis. Geol. Croat., 69/3: 295–305, doi: 10.4154/gc.2016.30.