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Palaeostress and kinematic evolution of the orogen-parallel NW-SE striking faults in the NW External Dinarides of Slovenia unraveled by mesoscale fault-slip data analysis

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Abstract

The late Eocene to Recent dynamics of the NW External Dinarides in Slovenia are described. The study is focused on the orogen-parallel NW-SE striking family of faults, which represent the main source of seismic hazard in the NW External Dinarides today. Approximately 1700 fault-slip datasets were collected at 70 locations and used for palaeostress analysis. Structural relationships observed in the field, allowed the construction of a relative chronology between the documented fault and shear joint sets, facilitating the reconstruction of their kinematic evolution and the chronology of palaeostress phases. Four post-Palaeocene stress tensor groups are documented corresponding to four distinct tectonic phases. The first phase is marked by NE-SW directed compression attributed to Late Eocene top-to-SW thrusting of External Dinarides. The second phase is characterized by NE-SW oriented tension, documented by normal slips recorded on NW-SE striking faults. This tension is interpreted as an expression of the Early to Middle Miocene back-arc extension in the Pannonian basin system that also affected the studied part of the External Dinarides. The third phase is manifested by approximately E-W oriented compression with approximately N-S oriented tension in a strike-slip stress regime, causing sinistral reactivation of NW-SE trending faults. Geodynamically, this phase can be correlated with the Late Miocene short pulse of E-W directed compression, documented in parts of the Pannonian basin system. The youngest phase is characterized by approximately N-S oriented compression and approximately E-W oriented tension in a strike-slip stress regime, which caused dextral reactivation of NW-SE striking faults. This phase correlates with the recent inversive/transpressive phase, well-established from seismological data.

1. INTRODUCTION AND GEOLOGICAL SETTING

The research area is located in the NW External Dinarides of Slovenia. This part of the Dinarides formed during the Cenozoic convergence of the Adria and Eurasia plates (USTASZEWSKI et al., 2010; HANDY et al., 2015), which resulted in the formation of different tectonic units in the Alps-Dinarides-Carpathian orogenic system (e.g. SCHMID et al., 2008). In the N and NW part the study area borders the Southern Alps, while in the E part, the Dinaric and South-Alpine units are overlaid by Paratethyan sediments of the Pannonian basin system (PLACER, 2008). Two main thrust phases are characteristic for this area. The first phase was the latest Cretaceous to Eocene top-to-SW Dinaric thrusting on NW-SE striking fault planes. Based on the biostratigraphic age of flysch sediments in Istria, the Dinaric thrusting in this area lasted until the Late Eocene (BABIĆ et al., 2007). The second phase is Oligocene to Early Miocene top-to-S South-Alpine thrusting on E-W striking fault planes (e.g. PLACER, 1982; DOGLIONI & BOSELLINI, 1987; CASTELLARIN et al., 1992; PLACER & ČAR, 1997; PLACER, 1999; SCHMID et al., 2004, 2008; VAN GELDER et al., 2015). After the Middle-Late Eocene, the northward directed motion of the Adria microplate caused the formation of a few kilometres wide imbricate belt, with steep reverse fault planes in front of the External Dinarides along the Eastern Adriatic coast (PLACER et al., 2001, 2010; TARI 2002; VRABEC & FODOR, 2006). According to map-view reconstructions, the northward motion of the Adria microplate in the Neogene resulted in approximately 190 km total N-S shortening (USTASZEWSKI et al., 2008). In the kinematic reconstruction of PLACER (1981, 1998) the total SW-NE directed shortening across the Slovenian External Dinarides is around 50 km.

In the NW External Dinarides the major structures which accommodate recent crustal stresses are steep to subvertical NW-SE striking faults with a significant linear topographic expression, evident on a regional scale. They cut and displace Dinaric and South-Alpine thrust-related structures and are therefore commonly interpreted as reflecting the final stage of the tectonic evolution of the Dinarides (PICHA, 2002; VRABEC & FODOR, 2006). Their neotectonic importance is supported by earthquake focal mechanisms, which predominantly illustrate a strike-slip stress regime with a NNW-SSE directed σ_1 axis (POLJAK et al., 2000; KASTELIC et al., 2008; HERAK et al., 2009; KASTELIC et al., 2013). Recent NNW-SSE oriented contraction is also evident from regional GPS data analysis (WEBER et al., 2006; WEBER et al., 2010), analysis of geomorphic markers (JAMŠEK RUPNIK et al., 2014; MOULIN et al., 2014; ŽIBRET & ŽIBRET, 2014), and geophysical investigations (GOSAR, 1998; BAVEC et al., 2012; ZAJC et al., 2015). Spatial analysis of earthquake events demonstrates complex interactions in the fault zones, likely controlled by their complex geometry originating in their polyphase tectonic evolution (e.g. KASTELIC et al., 2008). To date, only a few studies have investigated late-orogenic structural and geodynamic evolution of the Dinarides, mostly in the Central Internal Dinarides of Croatia, Bosnia and Herzegovina, and Albania

(PAMIĆ et al., 1998; TOMLJENOVIĆ & CSONTOS, 2001; PICHA, 2002; TARI, 2002; ILIĆ & NEUBAUER, 2005, TOMLJENOVIĆ et al., 2008; USTASZEWSKI et al., 2010), while there is no integrated study concerning the Neogene tectonic evolution of the NW External Dinarides of Slovenia. The aim of this study is to reconstruct the palaeostress evolution in the NW External Dinarides and to examine the kinematic history of the NW-SE striking orogen parallel faults.

In the central part of the Dinarides, the oldest Cenozoic tectonic phase is characterized by generally NE-SW to E-W oriented compression, related to Palaeogene thrusting of the Dinarides towards the W-SW onto an undeformed Adria microplate (ILIĆ & NEUBAUER, 2005). There, the Oligocene to Early Miocene transition was characterized by post collisional volcanism, probably partly controlled by E-W oriented tension, since the magmatic processes during the aforementioned period were much more complex (MLADENOVIĆ et al., 2015). The Early and Middle Miocene is marked by NE-SW oriented tension, perpendicular to the strike of the Dinaric orogen. According to interpretations by TOMLJENOVIĆ & CSONTOS (2001), ILIĆ & NEUBAUER (2005) and USTASZEWSKI et al. (2010) the Early and Middle Miocene orogen-perpendicular tensional phase was related to syn-rift extension in the Pannonian basin system. In the central part of the Dinarides of Eastern Bosnia the Middle Miocene tensional phase becomes orogen-parallel (ILIĆ & NEUBAUER, 2005). Between the Late Miocene and Pliocene, subduction in the Carpathians terminated (HORVÁTH & CLOETINGH, 1996), causing a regional change in the stress regime. In the Dinarides this episode is reflected by generally N-S oriented compression in the strike-slip tectonic regime (ILIĆ & NEUBAUER, 2005, MLADENOVIĆ et al., 2015). The ongoing North directed push of the Adria microplate and termination of subduction in the Carpathian arc, which facilitated free movements of continental blocks towards the east during the Late Oligocene – Miocene, induced a counter-clockwise rotation of the Adria microplate during the Pliocene and Quaternary (MÁRTON et al., 2002). Today this is evident in decreased rates of slip along active faults from the SE to the NW External Dinarides (WEBER et al., 2010; KASTELIC & CARAFA, 2012).

2. DATA COLLECTION AND PROCESSING

Approximately 1700 fault-slip measurements acquired at 70 localities in the NW External Dinarides were analysed. Fault-slip data was collected at 51 localities in Mesozoic sediments derived from the Dinaric carbonate platform and in Miocene sediments of the Central Paratethyan area of Slovenia. Measurements were supplemented by data from GREGORIČ (2005) collected at 19 localities in Palaeogene sediments of Dinaric foreland basins (Fig. 1). Analysis included orientation of fault-plane and fault-slip lineation with the sense of slip determined using different types of kinematic indicators (e.g. PETIT, 1987; DOBLAS, 1998; SPERNER & ZWEIGEL, 2010).

Stress tensors were calculated by inversion of measured fault-slip data. These methods are based on the assumption that the direction of movement and the shear stress along the fault are parallel (WALLACE, 1951; BOTT, 1959). The mean stress tensor was determined, knowing the orientations and senses of slip on numerous faults, assuming that each observed fault-slip (indicated by a slickenside lineation) has the direction and sense of shear stress that corresponds to a single common stress tensor (ANGELIER, 1994). A fault-slip dataset may involve errors caused by dispersion in local stress patterns as well as fault seg-

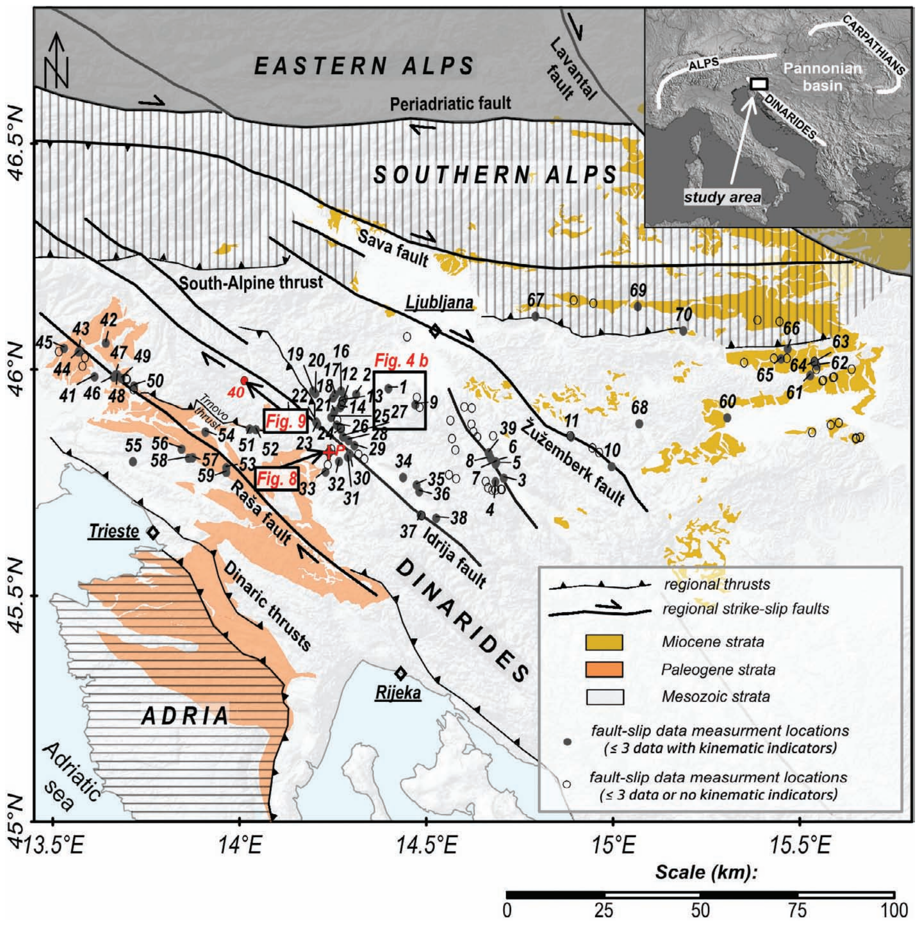


Figure 1. Fault-slip data measurement locations in the NW External Dinarides of Slovenia. Traces of major thrusts and strike-slip faults are compiled from VRABEC & FODOR (2006), KASTELIC et al. (2008), TOMLJENOVIĆ et al. (2008) and BUSETTI et al. (2010). Stratigraphic units are simplified after BUDKOVIČ et al. (2003).

ment interplay and for other reasons. Therefore, the aim is to look for the best fit between measured fault-slip data and a theoretical common stress tensor. The misfit between these is described by the angle between the actual slip and the theoretical shear stress on a fault plane (ANGELIER, 1994), the so called „misfit criteria”.

Stress tensors are generally described by six independent variables in matrix form (equation (1); ANGELIER, 1994):

$$\begin{matrix} a & d & e \\ d & b & f \\ e & f & c \end{matrix} \qquad (1)$$

in the co-ordinate system defined by the principal stress axes (equation (2); ANGELIER, 1994):

$$\begin{matrix} \sigma 1 & 0 & 0 \\ 0 & \sigma 2 & 0 \\ 0 & 0 & \sigma 3 \end{matrix} \qquad (2)$$

Three components of the stress tensor (eigenvalues) describe the orientation of the principal stress axes σ_1, σ_2, σ_3, where: σ_1 (maximum stress), σ_2 (intermediate stress) and σ_3 (minimum stress), and where $\sigma_1 \geq \sigma_2 \geq \sigma_3$. A fourth value is the ratio between the eigenvalues of a stress tensor (Bishop´s (1966) stress parameter) which describes the relative magnitude of the eigenvalues: $\phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. The last two variables describe the frictional and brittle characteristics of a rock mass (ANGELIER, 1994). However, it is not possible to estimate frictional and brittle characteristics directly from fault-slip data. Therefore only reduced stress tensors with four variables (eigenvalues and ϕ) can be determined.

For palaeostress analysis the Gauss method (ŽALOHAR & VRABEC, 2007) and the Multiple-slip method (ŽALOHAR & VRABEC, 2008) were used. In the Gauss method, the distribution of the misfit angle between the measured direction of slip and shear stress is approximated with the Gaussian distribution and an optimal stress tensor is determined by maximizing the Gaussian function (ŽALOHAR & VRABEC, 2007). The Multiple-slip method combines kinematic and dynamic approaches (ŽALOHAR & VRABEC, 2008). A fault plane is activated only when the applied shear stress exceeds the frictional shear strength. In both methods mechanical compatibility of solutions for individual stress tensors is controlled by the three-dimensional Mohr diagram.

Since most of the study region comprises highly deformed rocks and the orientation of the sedimentary beds changes very rapidly (in some cases every few metres), palaeostress inversion has been undertaken separately for each measurement location (outcrop). Where the orientation of sedimentary beds changes within the individual outcrop, the location was divided into an appropriate number of sub-locations with constant bed orientation, and each sub-location was then analysed separately. Because the measured fault-slip data were highly heterogeneous, each dataset (each locality/sub-locality) has been manually separated into homogeneous data subsets using a maximum misfit criteria of 30°.

In strike-slip fault zones internal block rotations are common (e.g. NOZAEM et al., 2013), and regional block rotations were also inferred in the study area (VRABEC & FODOR, 2006). Therefore some allowance was made in the analyses for variations in the orientation of principal stress axes, and stress fields close in axis orientation were assumed to have originated in the same general regional stress fields. A detailed description of the data separation procedure and of calculated palaeostress parameters for individual fault subsets is documented in the first author`s PhD thesis (ŽIBRET, 2015).

Regional relevance of the determined stress fields is supported by their consistent occurrence throughout the study area. A first-order timing constraint for palaeostress phases is given by the stratigraphic ages of rocks in which the respective fault-slip data occur. However, this only gives a very rough time bracket since the majority of investigated rocks are Mesozoic in age. A relative chronology of documented palaeostress phases was derived from the following field criteria:

- overprinting relationships between different families of fault striations on the same fault plane,
- cross-cutting relationships between outcrop-scale and regional-scale faults, and
- ductile/brittle character of deformation, assuming ductile phases preceded brittle deformations.

3. REGIONAL PALAEOSTRESS PHASES

3.1. Documented palaeostress tensors

NE-SW compression (Phase 1)

The first phase (Phase 1, Fig. 2) is characterized by a NE-SW directed maximum palaeostress axis σ_1, and approximately vertical σ_3 axis. This phase is manifested on reverse NW-SE striking faults and thrusts, which dip from 30° to 75° towards the SW and NE. It was reconstructed by fault-slip data recorded at only about 15 % of the measured sites and thus it seems that they are not well preserved, probably because of overprinting by younger movements. Nevertheless, in some places mesoscopic-scale duplex structures indicating NE-SW directed compression have been observed.

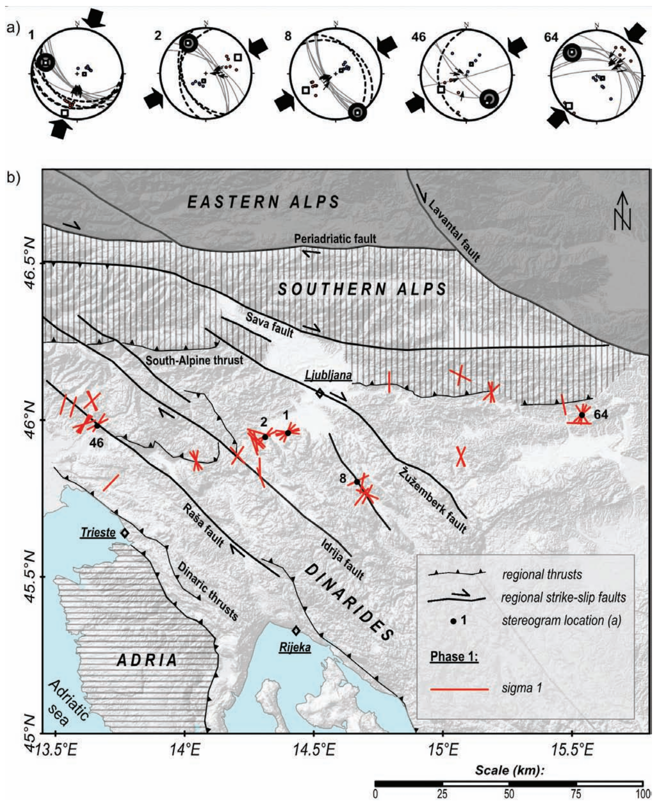


Figure 2. a) Examples of fault-slip data and derived stress tensors for Phase 1. b) Regional stress field of Phase 1 (in present-day reference frame, not accounting for any vertical-axis rotations).

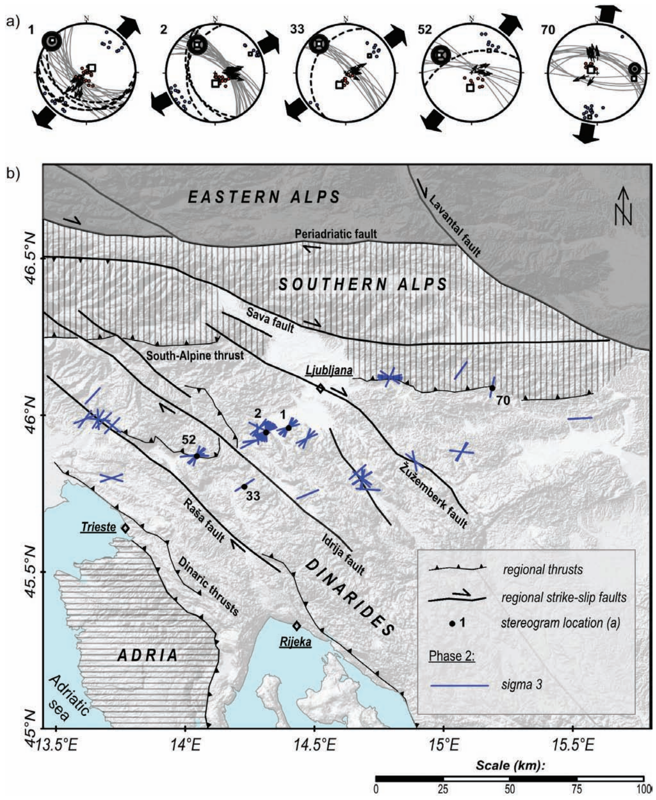


Figure 3. a) Examples of fault-slip data and derived stress tensors for Phase 2. b) Regional stress field of Phase 2 (in present-day reference frame, not accounting for any vertical-axis rotations).

NE-SW tension (Phase 2)

The second phase (Phase 2, Fig. 3) is marked by a NE-SW oriented minimum palaeostress axis σ_3 and an approximately vertical σ_1 axis. Fault-slip data that document this phase are very ubiquitous. At almost 40 % of the measured locations, normal to oblique-normal slips on steep to moderately dipping fault planes (dipping 60° to 85° towards NE or SW) have been recorded indicating a NE-SW directed tensional phase.

Structures originating from this palaeostress phase are noticeably present in both mesoscopic and map scales of observation. NW-SE striking faults with a normal sense of slip, dipping around 60° towards the NE or SW, often exhibiting conjugate geometry typical for neo-formed normal faults, were observed in many outcrops. At the map scale, normal offsets on NW-SE striking faults have also been recorded in several places. One example is presented in Figure 4., where consistent dipping of beds towards the faults suggests that normal faulting was accompanied by domino-style rotations of their hanging wall blocks.

E-W compression in a strike-slip regime (Phase 3)

The third phase (Phase 3, Fig. 5) is characterized by a palaeostress tensor with approximately E-W trending σ_1 and N-S oriented σ_3 axes in the strike-slip stress regime. This phase is typically represented by sinistral reactivations of NW-SE striking fault planes. It was recognized at approximately 20% of sites and is apparently a rather weak phase, since (except for collected fault-slip data) neither outcrop-scale nor map-scale structures were discovered that could be reliably related to this phase.

N-S compression in strike-slip regime (Phase 4)

The fourth phase (Phase 4, Fig. 6) is characterised by an approximately N-S oriented maximum palaeostress axis σ_1 with approximately E-W trending σ_3 axis in the strike-slip stress regime. Besides, it is presumed to be contemporaneous with NNW-SSE oriented maximum palaeostress axis σ_1 in compressional stress regime. Locally, the trend of σ_1 is NNE-SSW (Fig. 6b) and close to regional strike-slip faults, which could be explained as local vertical-axis block rotations. This stress-strain relationship is very common throughout the study area and was documented at more than 70% of the analysed locations. The main manifestation of this phase is a dextral reactivation of NW-SE-trending fault planes.

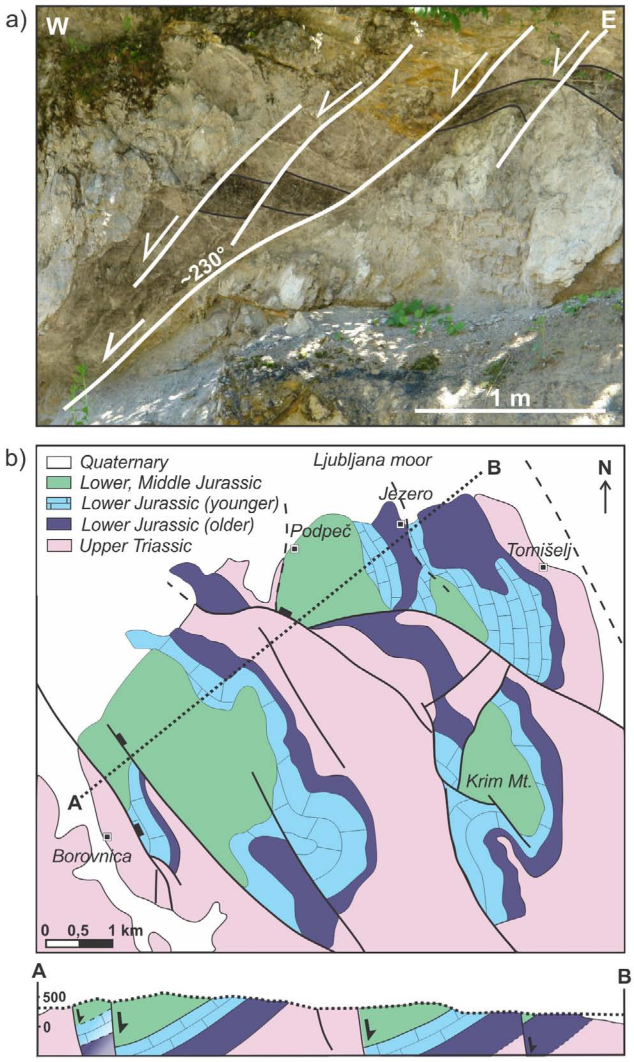


Figure 4. Examples of normal faulting in NE-SW tension (Phase 2). a) Outcrop-scale normal faults in Triassic dolomite at location 6 (x = 72804, y = 475508). b) Map-scale normal faults south of Ljubljana (for location see in Fig. 1), indicating domino-style rotations of hanging wall blocks (adapted from BUSER et al., 1963).

3.2. Relative chronology of documented palaeostress phases

The first-order constraint on the time-span of documented palaeostress phases is given by the biostratigraphic age of sedimentary rocks in which the data were acquired. Most of the studied rocks in the NW External Dinarides in Slovenia (Fig. 1) originated from the Mesozoic-Palaeogene Adriatic carbonate platform (TURNŠEK et al., 1982; ČRNE & GORIČAN, 2008; JEŽ et al., 2011), overlain in the W and SW part by a roughly NW-SE-trending belt of Palaeocene to Eocene Dinaric foreland flysch basin sediments (DEBELJAK et al., 2002; OTONIČAR, 2007; DROBNE et al., 2011; PAVLOVEC, 2012). Besides, in the NE part of the study area, the youngest analysed sediments belong to Central

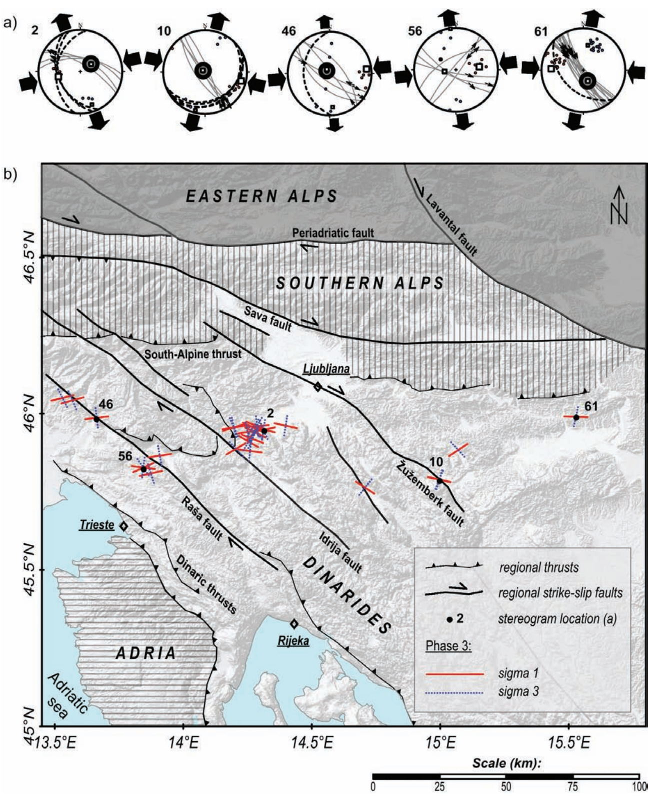


Figure 5. a) Examples of fault-slip data and derived stress tensors for Phase 3. b) Regional stress field of Phase 3 (in present-day reference frame, not accounting for any vertical-axis rotations).

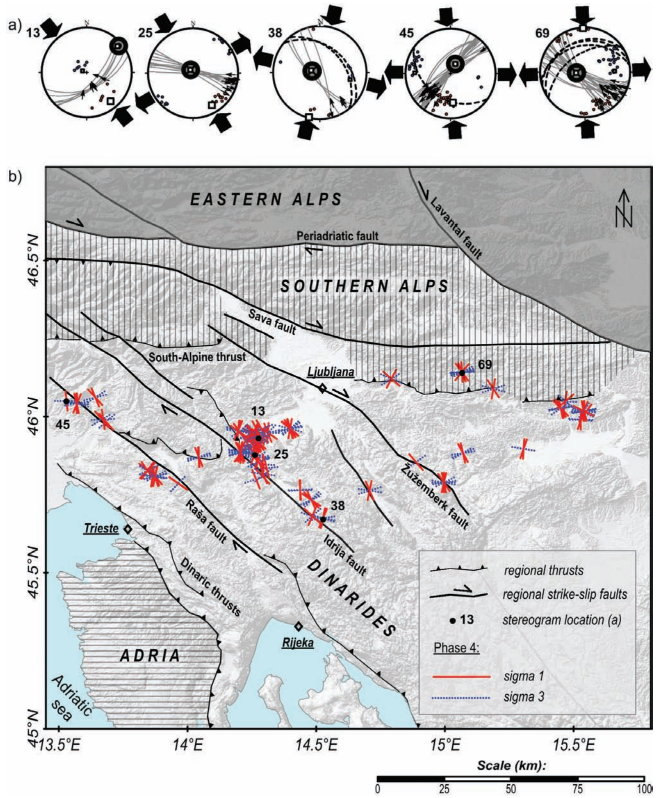


Figure 6. a) Examples of fault-slip data and derived stress tensors for Phase 4. b) Regional stress field of Phase 4 (in present-day reference frame, not accounting for any vertical-axis rotations).

Paratethyan formations dating from the Palaeocene to Late Middle Miocene (FODOR et al., 1998; JELEN & RIFELJ, 2002; FODOR et al., 2002; MIKUŽ et al., 2012; BARTOL et al., 2014).

As previously described in Section 2, the relative chronology of palaeostress phases (Phase 1 – Phase 4) is based on direct field observations of fault-slip data, their cross cutting relationships and the deformation style. Each of the three criteria is described below with representative examples.

3.3. The overprinting relationship of different generations of fault striations on the same fault plane

At Location 1 (Fig. 1) multiple generations of fault striations were documented on a single steep SW-dipping fault plane. On this plane slickenlines attributed to Phase 3 crosscut the dip-slip normal ones attributed to Phase 2 (Fig. 7 a). This structural relationship suggests that NE-SW oriented tension (Phase 2) is older than E-W oriented compression in the strike-slip palaeo-

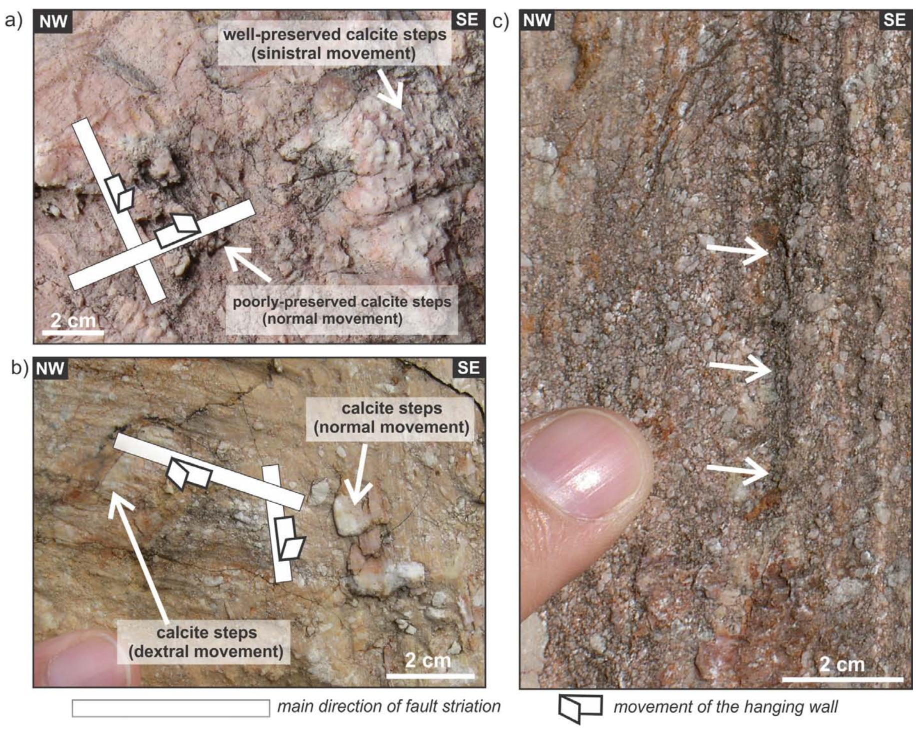


Figure 7. Examples of slickenlines overprinting criteria described in the text documented at Location 1 as indicated in Fig. 1 (location 1; x = 90946, y = 453387).

stress regime (Phase 3). Besides, on the same fault plane, slickenlines that indicate dextral slip overprint the dip-slip normal ones (Fig. 7 b), which again clearly indicates that NE-SW oriented tension (Phase 2) predates strike-slip reactivation of this fault, this time however, in a NNW-SSE oriented compression in the strike-slip palaeostress regime attributed to Phase 4. Whereas the overprinting criteria of striae on fault planes are occasionally strongly influenced by the viewpoint of the observer and are therefore rarely unambiguous (SPERNER & ZWEIGEL, 2010), the calcite accretionary steps that have grown inside sub-vertical grooves on this fault plane clearly indicate that the dextral sense of slip attributed to Phase 4 postdates the normal-slip episode of Phase 2 (Fig. 7 c).

3.4. Cross-cutting relationships between a regional thrust plane and normal faults

In central Slovenia the outcropping plane of the regional-scale Hrušica thrust (outcrop location P on Fig. 1 – in the central part of the Idrija fault zone south from the main fault trace, marked by red cross; also shown on Fig. 8) belonging to the Dinaric thrust system (PLACER, 1981) was examined. Here, the principal thrust plane, dipping 10° towards the NNE to NE (Fig. 8 a, c), is offset by small-scale NE-dipping normal faults, which exhibit dip-slip striae and calcite steps indicating normal slip (Fig 8 b, d). Again, this relationship suggests that the NE-SW tension (Phase 2) postdates Dinaric thrusting (Phase 1).

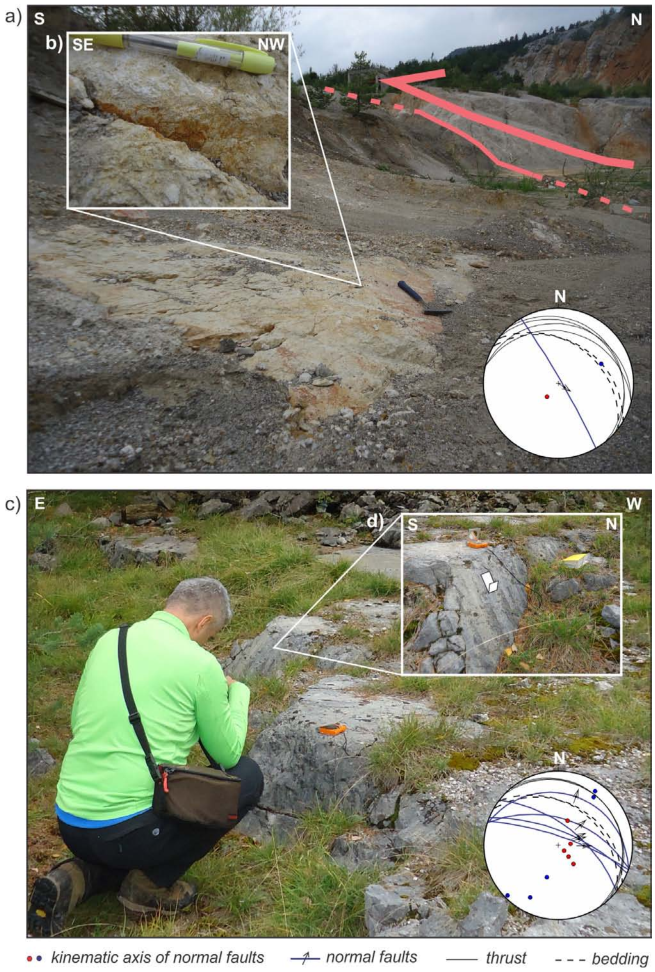


Figure 8. Mesoscopic scale cross-cutting relationships where the thrust plane of the regional-scale Hrušica thrust is offset by small-scale normal faults (for outcrop location see Fig. 1; x = 76192, y = 441388). See in text for details.

The Ductile/brittle character of deformation

The Bevk tectonic window mapped at location of x = 95048, y = 422800 exposes highly-deformed Eocene flysch deposits below the Trnovo thrust (outcrop location 40 on Fig. 1, also shown on Fig. 9). This is the highest major thrust of the Dinaric thrust system of Slovenia (PLACER, 1981; MLAKAR & ČAR, 2010). An approximately NE-SW-striking fault, which delimits the window to the east, rotated this structure so that here the Trnovo thrust plane dips slightly to the S(SW) instead of to the NE, which is typical elsewhere in the surrounding area. Eocene mudstones are strongly foliated (Fig. 9 a), with foliation intensity increasing towards the thrust contact. Micro folds and shear-bands in the foliation indicate top-to-the-S(SE) thrusting (Fig. 9 b). This foliation was cut under (semi)brittle conditions by WSW-ENE-striking shear zone with a clear sinistral sense of displacement, which produced decimetre-scale drag folds in the foliation and veins (Fig. 9 c). The shear zone was formed in NE-SW-oriented compression presumably during or immediately following the Dinaric thrusting, which we attributed to the palaeostress Phase 1. Moreover, this shear zone is cut by perpendicular dip-slip-normal faults with cm-scale displacements, which originated in NE-SW-directed tension attributed to Phase 2 (Fig. 9 d). Finally, brittle kinematic indicators on WSW-ENE-striking fault planes suggest late N(NNE)-S(SSW) directed compression with perpendicular tension in the strike-slip regime attributed to Phase 4. Based on the described examples and criteria used for the relative chronology of the documented fault-slip datasets, we distinguished five groups of faults attributed to four palaeostress phases shown in Figure 10. The results of palaeostress calculations based on fault-slip data obtained in rocks of different ages are summarized in Figure 11.

4. GEODYNAMIC INTERPRETATION

The palaeostress Phase 1, which is characterized by NE-SW directed compression, is documented by slickenside lineation and indicators for the sense of slip that are scarcely and poorly preserved and documented in the study area. Moreover, the overprinting and cross-cutting relationships of faults attributed to this phase with younger faults indicate that Phase 1 is the oldest documented phase in the study area. As this phase was documented in Eocene flysch deposits, it is certainly of Eocene or post Eocene age. The same stress calculation was obtained from fault-slip data collected in Neogene rocks (Fig. 11), but only at four distinct locations with a wide span of calculated compression orientation. Since no mesoscale structures that could be related to NE-SW oriented compression were observed in Neogene rocks, these results are considered to be unreliable. Therefore, we constrained the age of palaeostress Phase 1 as Eocene or post-Eocene to pre-Neogene. In a regional tectonic framework it fits well with the Middle-Late Eocene thrusting of the External Dinarides towards the SW onto the undeformed Adria microplate (e.g. ILIĆ & NEUBAUER, 2005; SCHMID et al., 2008; PLACER et al., 2010; VAN GELDER et al., 2015; Fig. 12).

Phase 2 is characterized by NE-SW oriented tension in the extensional tectonic regime (Fig. 12). Based on the relative chronology of slicken-side lineation and kinematic indicators, Phase 2 is older than Phases 3 and 4. With the assumption that Phase 1 is the oldest palaeostress phase of post-Eocene to pre-Neogene age, the activity of Phase 2 can be presumed to have occurred during the Neogene. Based on the presumed time of activity and calculated NE-SW directed tension perpendicular to the strike of the Dinaric orogen, Phase 2 correlates well with the Early and

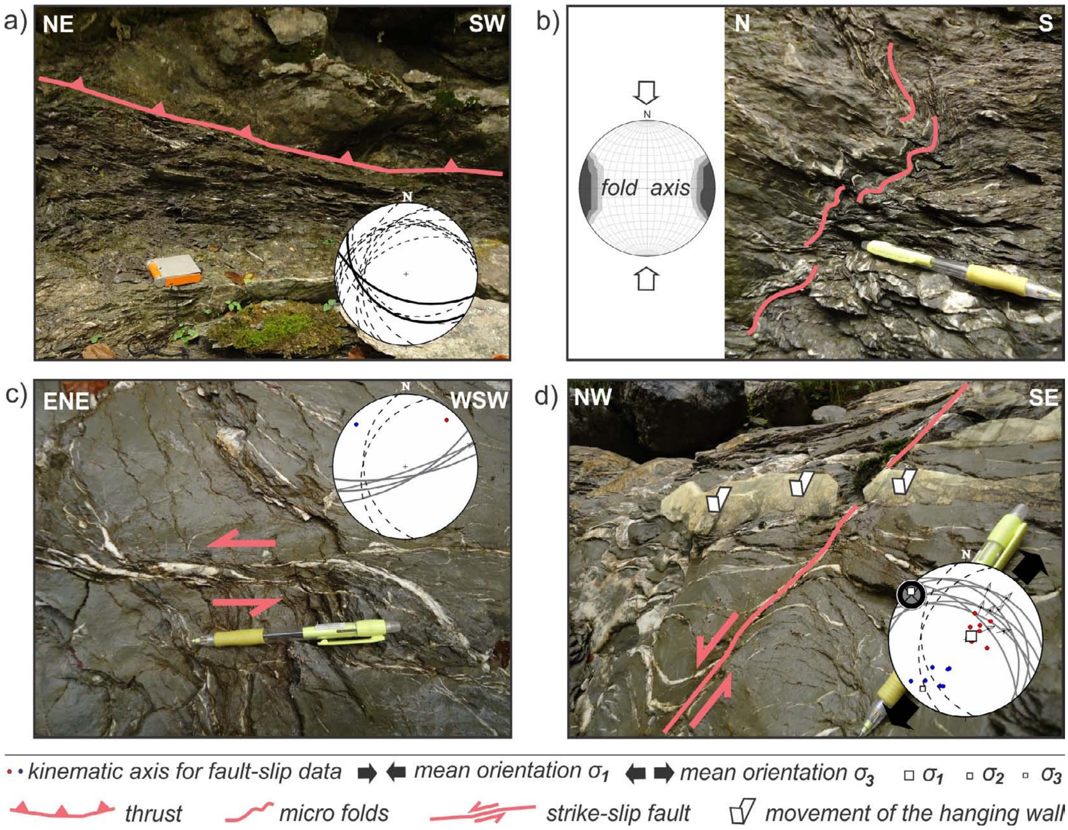
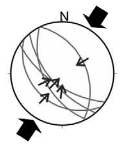
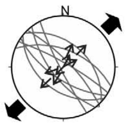
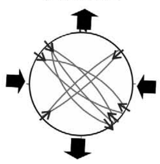
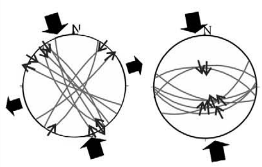


Figure 9. Ductile/brittle style of deformation (for location see Fig. 1). a) Foliated Eocene mudstone (dotted line on stereogram) below the thrust plane (continuous line on stereogram). b) Micro folds (indicated in red) in foliation. c) Drag folds in foliation and veins (dotted line on stereogram) along sinistral WSW-ENE-striking shear zone (continuous line on stereogram). d) The same shear zone cut by perpendicular dip-slip-normal faults (continuous line on stereogram).

Paleostress phase	Fault-slip indicators	Outcrop-scale features	Map-scale features
Phase 1 	Dip-slip striations on gently inclined predominately SW-dipping fault planes, but mostly withoutdirect kinematic indicators.	Thrust planes associated with strongly foliated mudstones and cataclastically deformend carbonates. (Semi)ductile tear faults. Duplex structures.	Regional-scale NW-SE-striking thrusts.
Phase 2 	Dip-slip to oblique-slip normal slickenlines, mainly occurring on NW-SE-striking fault planes.	Meter-scale normal offsets on NW-SE-striking fault planes and m-scale conjugate normal faults.	Normal displacements and block rotation along NW-SE-striking faults.
Phase 3 	Predominately horizontal to slightly oblique slickenlines showing sinistral motion on NW-SE-trending fault planes and (less often) dextral slip on NE-SW-trending fault planes.	Not observed.	Not observed.
Phase 4 	Predominately horizontal to slightly oblique slickenlines showing dextral motion on NW-SE-trending fault planes and (less often) sinistral slip on NE-SW-trending fault planes. Dip-slip to oblique reverse striations on gently inclined approximately E-W-striking fault planes.	Centimeter-scale to m-scale dextral offsets along NW-SE-striking faults.	Dextral offsets along NW-SE-striking faults.

mean orientation σ_1 mean orientation σ_3 fault plane movement of the hanging-wall

Figure 10. Relative chronology of documented palaeostress phases and description of related fault-slip datasets.

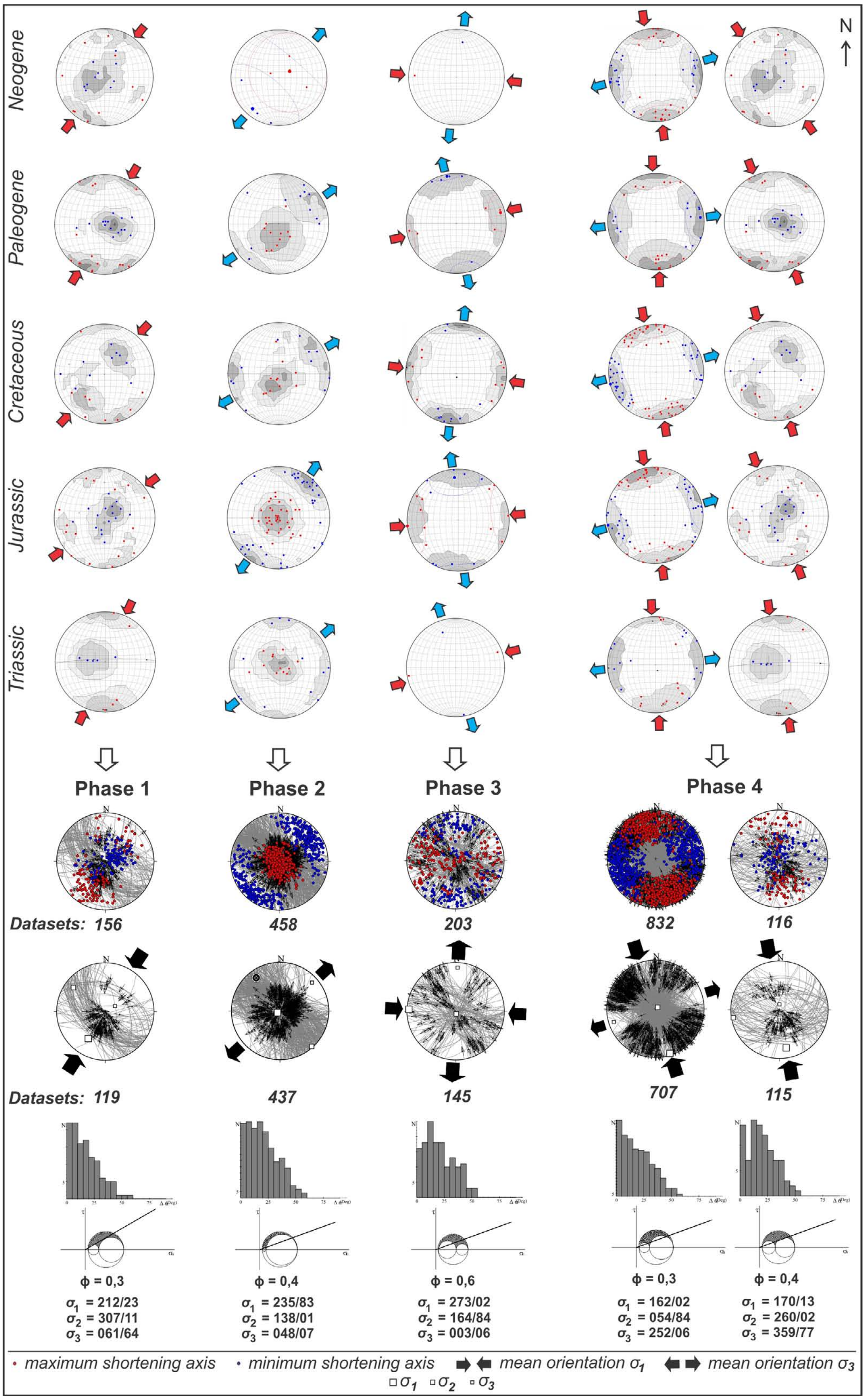


Figure 11. Comparison of determined palaeostress phases by age of rocks in which the fault-slip data was obtained. Each palaeostress tensor is represented by σ_1 orientation (red axis on stereograms) and σ_3 orientation (blue axis on stereograms). In the lower part of the Figure, mean palaeostress axis orientation and corresponding Mohr circle is shown for each phase.

Middle Miocene NE-SW oriented tension previously documented 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 (USTASZEWSKI et al., 2010). All the aforementioned studies assume that the Lower and Middle Miocene orogen perpendicular extensional phase is geodynamically related to the back arc extension in the Pannonian basin system.

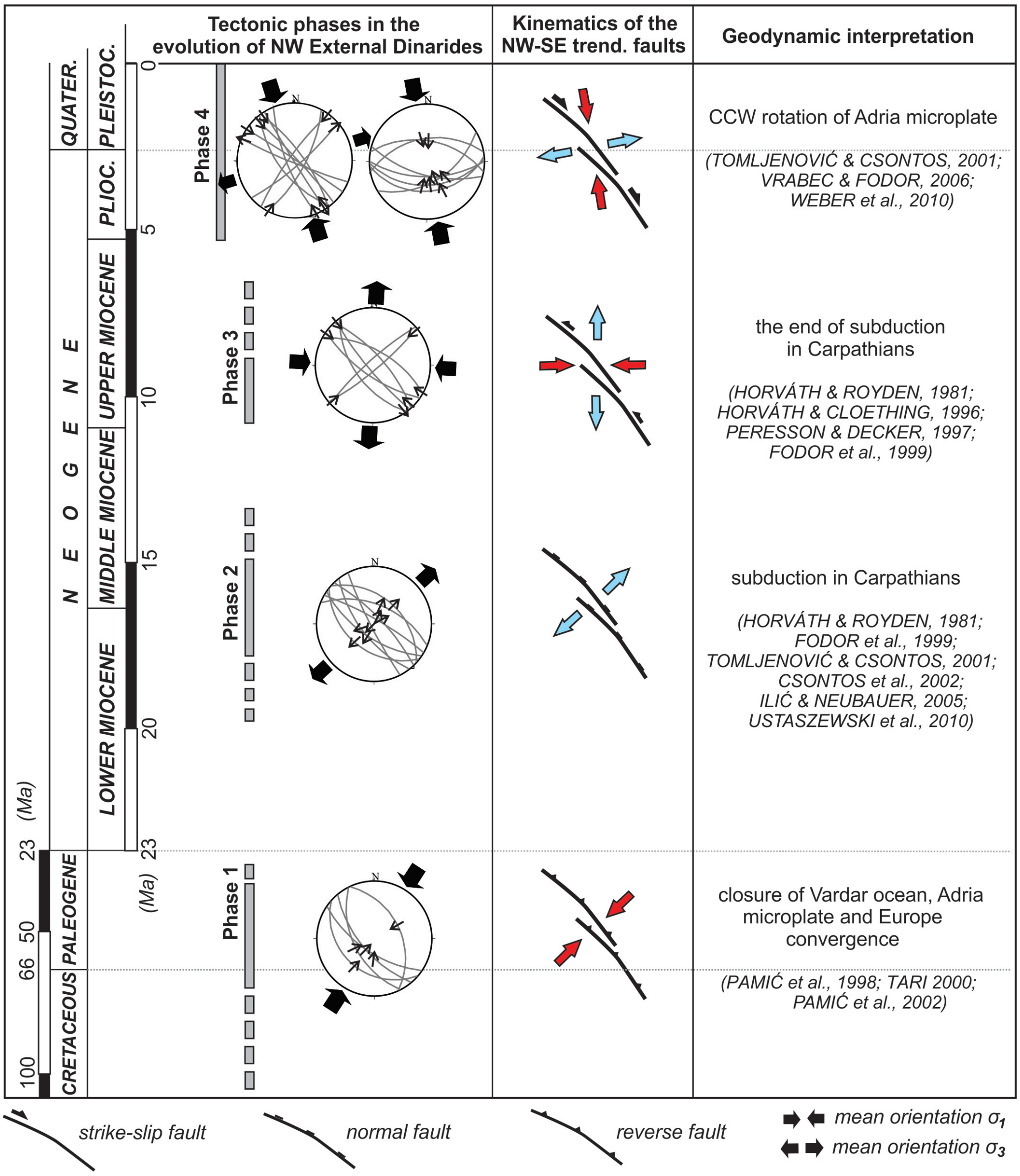


Figure 12. Geodynamic interpretation of the documented tectonic phases in the NW External Dinarides of Slovenia.

Phase 3 is marked by approximately E-W oriented compression with approximately N-S oriented tension in a strike-slip stress regime (Fig. 12). The relative chronology of slicken-side lineation and kinematic indicators show that Phase 3 is younger than Phase 2 and precedes Phase 4 which was presumably active since the Pliocene (see below). Therefore, the remaining time bracket for Phase 3 activity is the Late Miocene. In the Dinaric-Alpine-Carpathian-Pannonian region, the Late Miocene E-W oriented compression, which inverted previously sinistral NE-SW striking faults (formed during lateral extrusion in Early and Middle Miocene) into Late Miocene reverse faults was first described in the Vienna basin by PERESSON & DECKER (1997). Later, corresponding faults were detected in different parts of the Pannonian basin system (e.g. FODOR et al., 1999). According to PERESSON & DECKER (1997) this Late Miocene change of palaeostress reflects the cessation of subduction in the Eastern Carpathians which in turn disabled further eastward extrusion in the Eastern Alps. Therefore, the final pulse of subduction in the Eastern Carpathians may have established an E-W directed compressive regional stress field, that could have been transmitted through the crust of the Pannonian basin into the Eastern Alps (PERESSON & DECKER, 1997), and possibly even further south-westwards into the NW External Dinarides, thus causing inversion of the steep NW-SE striking normal faults in the NW External Dinarides into faults with a sinistral sense of slip (Fig. 12).

Palaeostress tensors attributed to Phase 4 that is characterized by approximately N-S oriented compression and approximately E-W oriented tension in a strike-slip stress regime is the most ubiquitous phase in the study area, coinciding with the recent stress tensors of the wider South Alpine-Dinarides transitional area (e.g. CAPORALI et al., 2013). Thus, it is probably representative of the well known inversive/transpressive regional phase in the NW External Dinarides and the SW margin of the Pannonian basin (e.g. TOMLJENOVIĆ & CSONTOS, 2001; USTASZEWSKI et al., 2010; Fig. 12). In this area, NW-SE striking steep to subvertical dextral faults are known as active during the Pliocene and Quaternary time (e.g. KASTELIC et al., 2008; HERAK et al., 2009; MOULIN et al., 2014), and their origin is explained by CCW rotation of the Adria microplate (TOMLJENOVIĆ & CSONTOS, 2001; MÁRTON et al., 2002; VRABEC & FODOR, 2006; WEBER et al., 2010).

5. CONCLUSIONS

According to the results of palaeostress analysis it was possible to separate (at least) four different stress tensor groups that have affected the NW External Dinarides in Slovenia from the Late Eocene to the Recent.

During the Neogene, the majority of the stress was accumulated and released along generally NW-SE striking faults (and to those fault related structures). The current study demonstrates that these faults have a complex polyphase kinematic history.

The oldest palaeostress tensor group (Phase 1) is characterized by NE-SW directed compression, manifested by reverse slips along generally NW-SE striking faults. Regionally this phase can be correlated with the main Eocene top-to-the-SW thrusting phase of the External Dinarides. The second palaeostress tensor group (Phase 2) is marked by NE-SW directed tension. This phase normally inverted older reverse and thrust faults connected to Dinaric thrusting (Phase 1). Normal inversion of NW-SE striking earlier reverse faults is obviously an important tectonic phase, evident not only in outcrop but also in map-scale structures. Regionally this phase coincides with back arc, syn-rift extension in the Pannonian basin system. The time bracket for this phase is Lower to Middle Miocene. The third palaeostress tensor group (Phase 3) is characterised by approximately E-W oriented compression with approximately N-S oriented tension in the strike-slip stress regime. Generally, E-W directed compression probably induced sinistral inversion of earlier NW-SE striking normal faults. Regionally this phase can be correlated with the Late Miocene short pulse of E-W directed compression, documented in the Vienna basin and also in different parts of the Pannonian basin system. The youngest palaeostress tensor group (Phase 4) is characterized by approximately N-S oriented compression and perpendicular approximately E-W oriented tension in the strike-slip stress regime, but also by generally N-S oriented compression in a pure compressional stress regime. This phase is partly accommodated by generally E-W striking reverse faults that overprinted older structures and partly by dextral inversion of previously formed faults with Dinaric strike. Regionally, this phase correlates well with the recent inversive/transpressive tectonic phase in the wider South Alpine – NW Dinarides area.

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