Kinematics of Foreland-Vergent Crustal Accretion: Inferences From the Dinarides Evolution

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Kinematics of Foreland-Vergent Crustal Accretion: Inferences From the Dinarides Evolution

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Key Points:
- The migration of contractional deformation in the Dinarides can be associated with lower plate crustal accretion during slab rollback
- Along the Dinarides orogenic strike there is a lateral variability of contractional deformation
- The entire Dinarides orogen was affected by Miocene extension and subsequent inversion

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Abstract One of the most common observation in Mediterranean areas is the migration of contractional deformation and associated slabs through time toward external orogenic areas, associated with lower plate crustal accretion. The Dinarides orogen of Central Europe is an optimal place to study such a sequence of contractional deformation. Compared with other areas, contraction in the Dinarides was less overprinted by subsequent extension, while a remnant of the subducted slab is observed in a far external orogenic position. Understanding the deformational evolution of the Dinarides is hampered by the reduced availability of kinematic studies. Therefore, we have performed a surface kinematic study in the external parts of the Dinarides. By correlating with available geophysical and evolutionary constraints, we constructed two large-scale, kinematically controlled regional transects. The results demonstrate a long-lived evolution of shortening that affected the Dinarides lower orogenic plate. While the Late Jurassic-earliest Cretaceous deformation was associated with an earlier obduction moment, the latest Cretaceous onset of continental collision has gradually focused deformation at inherited rheological weakness zones. We show that shortening was interrupted by a period of Miocene extension that affected all orogenic areas and created the Dinarides Lake System. The extension was followed by renewed shortening, which started during the latest Miocene and remains presently active, whose kinematics in the central and SE part of the Dinarides is revealed for the first time by our study. These results indicate a lower plate crustal accretion mechanism that was spatially and temporally connected with gradual slab retreat in the Dinarides.

1. Introduction

The geometry and evolution of mountain chains are primarily controlled by the mechanics of accreting sediments and crustal basement units during subduction and continental collision, coupled with magmatism and larger-scale mantle dynamic processes (Burov & Yamato, 2008; Doglioni et al., 2007; Faccenna et al., 2014; Gerya & Yuen, 2003). This interplay results in a large geometric variability, from double-vergent wedges to highly curved orogens associated with the formation of large-scale extensional backarcs or wide orogenic plateaus affected by regional magmatism (Beaumont et al., 2000; Heuret & Lallemand, 2005; Molnar et al., 1993; Sengör et al., 2008; Willett et al., 1993). Among this variety of mountain chains, observation studies have shown that deformation during collision may accrete lower continental plate material by a gradual migration of deformation and associated exhumation toward orogenic forelands (e.g., Forte et al., 2014; Matenco et al., 2010). Modeling studies have inferred that this sequence of deformation and exhumation is rheologically controlled. For instance, a rheological weak lower plate decouples from the upper crust, creating prolonged periods of continental subduction and orogens that display one dominant structural vergence (Vogt, Matenco, et al., 2017; Vogt, Willingshofer, et al., 2017; Willingshofer et al., 2013). Many such single-sided orogens are associated with periods of rapid slab retreat, where back-arc extension often overprints the predating nappe stacking during their gradual migration of deformation toward the foreland, as observed in many Mediterranean orogens or SE-Asia convergence zones (Brun & Faccenna, 2008; Faccenna et al., 2013; Jolivet & Brun, 2010; Pubellier & Morley, 2014). This extensional overprint makes it difficult to understand the mechanics of continental collision in these foreland accretion orogens, as well as its relationships with back-arc extension, slab retreat, and exhumation.

One interesting exception of such single-sided orogens are the Dinarides system of Central Europe (Figure 1a), which are less affected by the frequent large-scale extensional overprint observed in orogenic

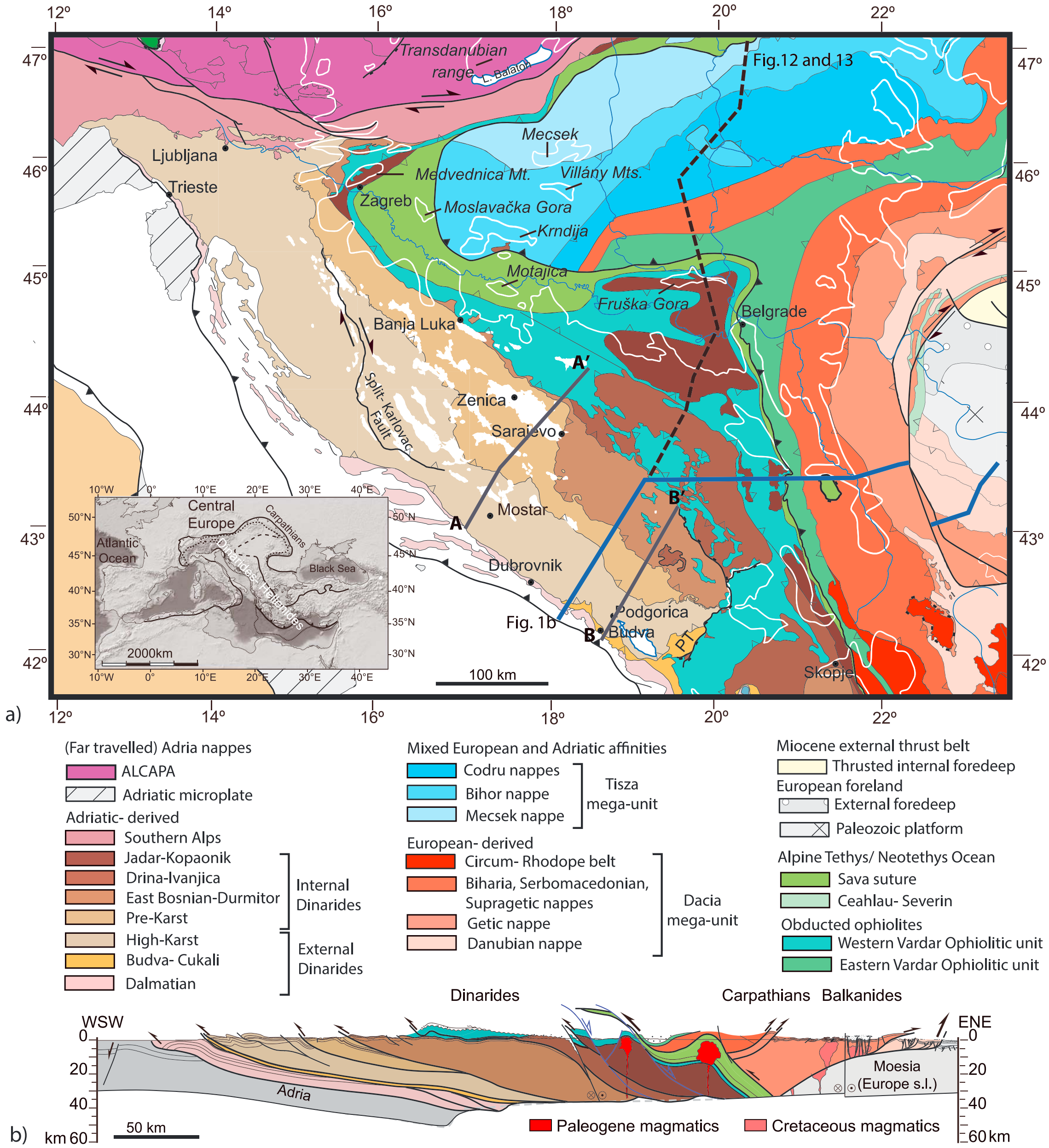

Figure 1. (a) Tectonic map of the Dinarides and their junction with the Alps and the Albanides in the SE Europe (location in the lower left inset, modified from Schmid et al. 2008). White line is the outline of the Miocene Pannonian Basin, and the white zones are the location of the Miocene Dinarides Lake System (DLS), (after Harzhauser & Mandic, 2008; De Leeuw et al., 2012). Thick blue line is the location of the cross section in Figure 1b. Gray lines are the locations of the crustal-scale cross sections of Figure 11. The black dashed line is the location of the reconstruction displayed in Figures 12 and 13. PT = Peshkopia tectonic half-window;
(b) Regional crustal cross section illustrating the main tectonic units and deformation along a Dinarides-Carpathians transect (modified from Matenco & Radivojević 2012). The location of the cross section is displayed by the thick blue line in Figure 1a.

areas such as the Aegean or the Apennines system (Jolivet & Faccenna, 2000; Jolivet et al., 2013). The Dinarides orogen mainly formed during the Jurassic-Eocene convergence between Europe- and Adriatic-derived units, associated with gradual subduction and continental collision (e.g., Schmid et al., 2008). The NE vergent nappe system observed in European-derived units (Figure 1b) formed due to the Cretaceous closure of one other ocean, Ceahlau-Severin, which was located more to the north and formed the orogenic structure of the Carpathians and Balkan Mountains (e.g., Iancu et al., 2005; Schmid et al., 2008). A number of recent studies have demonstrated an interplay between contraction and a period of Late

Oligocene-Miocene extension that affected the internal part of the Dinarides and their contact with the Carpathian units (Andrić et al., 2017; Erak et al., 2017; Matenco & Radivojević, 2012; Stojadinović et al., 2017; Ustaszewski et al., 2010). Shortening resumed during the latest Miocene and is still active at present in the external part of the Dinarides. This is interpreted to be an effect of the Adriatic plate indentation, associated with the subduction of a slab remnant observed in the external-most part of the orogen (e.g., Bennett et al., 2008 and references therein). The internal part of the Dinarides and their contact with the European-derived upper plate along the Sava Zone have recently benefitted from a number of detailed kinematic analyses (Erak et al., 2017; Ilić et al., 2005; Ilić & Neubauer, 2005; Mladenović et al., 2015; Schefer, 2010; Schefer et al., 2011; Stojadinović et al., 2013, 2017; Toljić et al., 2013; Ustaszewski et al., 2010; van Gelder et al., 2015).

In contrast, there are no regional kinematic studies available in the central and southeastern part of the Dinarides, a critical area for understanding the evolution of the collision system and the associated subducted slab (e.g., Bennett et al., 2008; Šumanovac et al., 2017). Therefore, in order to understand the regional Dinarides deformation and evolution, we have performed a kinematic study that was focused in this critical area (Figures 1 and 2, Dalmatian, Budva, High Karst, Pre-Karst units, and their contact with the overlying East Bosnian-Durmitor unit along the Bosnian Flysch zone). Given the known shortening variability along the strike of the orogen, we have constructed two regional orogenic cross sections in Bosnia and Herzegovina-Croatia and Serbia-Montenegro, respectively (Figure 2). In order to understand the superposition and localization of deformation, these cross sections are constrained by higher resolution field kinematic studies in areas that retained larger amounts of shortening or extensional deformation (Figure 2). The overall kinematic data are combined with previous studies (e.g., Balazs et al., 2017; Šumanovac et al., 2017) to create larger orogenic transects, which were interpreted in the overall crustal and lithospheric context of the Dinarides. We specifically note that our kinematic observations were not aimed at characterizing the entire deformation of the studied Dinarides, which is otherwise not possible in one study for such a large area. Outside the Miocene basins, which provided critical timing constraints for our kinematic data, we focused our observations in understanding the kinematics of highly deformed areas. These areas are known to have localized deformation and created large-offset structures, which are important to derive the succession of orogenic deformation. Following the regional characterization of deformation, we focused our study in understanding the relationship between orogenic buildup and the evolution of the retreating slab in the Dinarides.

2. Regional Dinarides Background

The Dinarides are part of the Mediterranean orogenic system that formed during Mesozoic-Cenozoic times in response to the closure of a northern branch of the Neotethys Ocean located between Europe- and Adria-derived continental units (Kreemer et al., 2003; Stampfli & Borel, 2002). The Middle Triassic opening of this ocean was associated with rift-related intermediate and basic magmatism and was followed by the formation of a wide Adriatic passive continental margin (Figure 3, Dimitrijević, 1997; Pamić, 1984). The distal part of this margin has recorded a gradual Middle Triassic-Late Jurassic deepening in depositional environment, changing from shallow water carbonates to deep water radiolarites and pelagic sediments (Djerić et al., 2007; Djerić & Gerzina, 2008; Goričan et al., 1999; Schefer et al., 2010; Toljić et al., 2013; van Gelder et al., 2015). In contrast, the proximal part of this passive continental margin (i.e., the external part of the Dinarides) recorded a ~2.2-km-thick, shallow water carbonate sedimentation during Middle Triassic-Eocene, part of the larger Adriatic carbonate platform system (Figure 3, Dimitrijević, 1997; Vlahovic et al., 2005). The exception is the formation of a Middle Triassic extensional (graben) structure in the external part of the Dinarides. This graben was gradually filled with Mesozoic deep-water carbonate and more pelagic sediments and was subsequently inverted, being presently exposed in the Budva thrusted unit of Southern Montenegro (Figures 2 and 3, Cadjenović et al., 2008; Crne et al., 2011; Goričan, 1994).

Starting with Middle Jurassic times, oceanic subduction took place in the Dinarides, which was followed by the obduction over the Dinarides passive continental margin of an up to ~180 km wide sheet of ophiolites and the formation of a genetically related ophiolitic mélange during Late Jurassic-earliest Cretaceous times (the Western Vardar Ophiolitic unit, Figures 1–3; Chiari et al., 2011; Robertson et al., 2009; Schmid et al., 2008; Ustaszewski et al., 2009). This was followed by the late Early Cretaceous formation of an unconformity

Figure 2. Geological map of the Dinarides compiled and simplified from the sheets of the 1:100.000 geological map of former Yugoslavia (Osnovna Geološka Karta SFRJ), with the locations of the four focus areas (black rectangles) and the two main crustal-scale transects investigated in this study. Note that outside the main tectonic contacts (slightly modified when compared with Figure 1a), lower amounts of deformation is displayed only in focus areas and along the crustal transects. K_1 = Early Cretaceous, J_3 = Late Jurassic, T_3 = Late Triassic, $T_2^{\,2}$ = late Middle Triassic, $T_2^{\,1}$ = early Middle Triassic, T_2 = Middle Triassic, and T_1 = Early Triassic.

well observed in the internal parts of the Dinarides (Figure 3b), which is likely associated with localized thrusting and metamorphism, possibly as an effect of a continuation of the obduction-related shortening (Dimitrijević, 1997; Ilić et al., 2005; Ilić & Neubauer, 2005; Schmid et al., 2008). Oceanic subduction subsequently continued, while the onset of continental collision between the Adria- and European-derived continental units took place during the latest Cretaceous, which resulted in the formation of the Sava zone as the suture of the Neotethys Ocean (Schmid et al., 2008). This suture separates the Adriatic-derived Dinarides from the European-derived Serbomacedonian and Tisza units in the orogenic upper plate (Pamić, 2002; Ustaszewski et al., 2010, 2009). The onset of collision was associated with the thick deposition of syn-contractional Campanian-Maastrichtian turbidites in a deep-water environment, which localized deformation during nappe stacking (Figure 3, Dimitrijević & Dimitrijević, 1987; Toljić et al., 2018). The collision continued during Paleogene times and was associated with an overall migration of the NE-SW oriented shortening

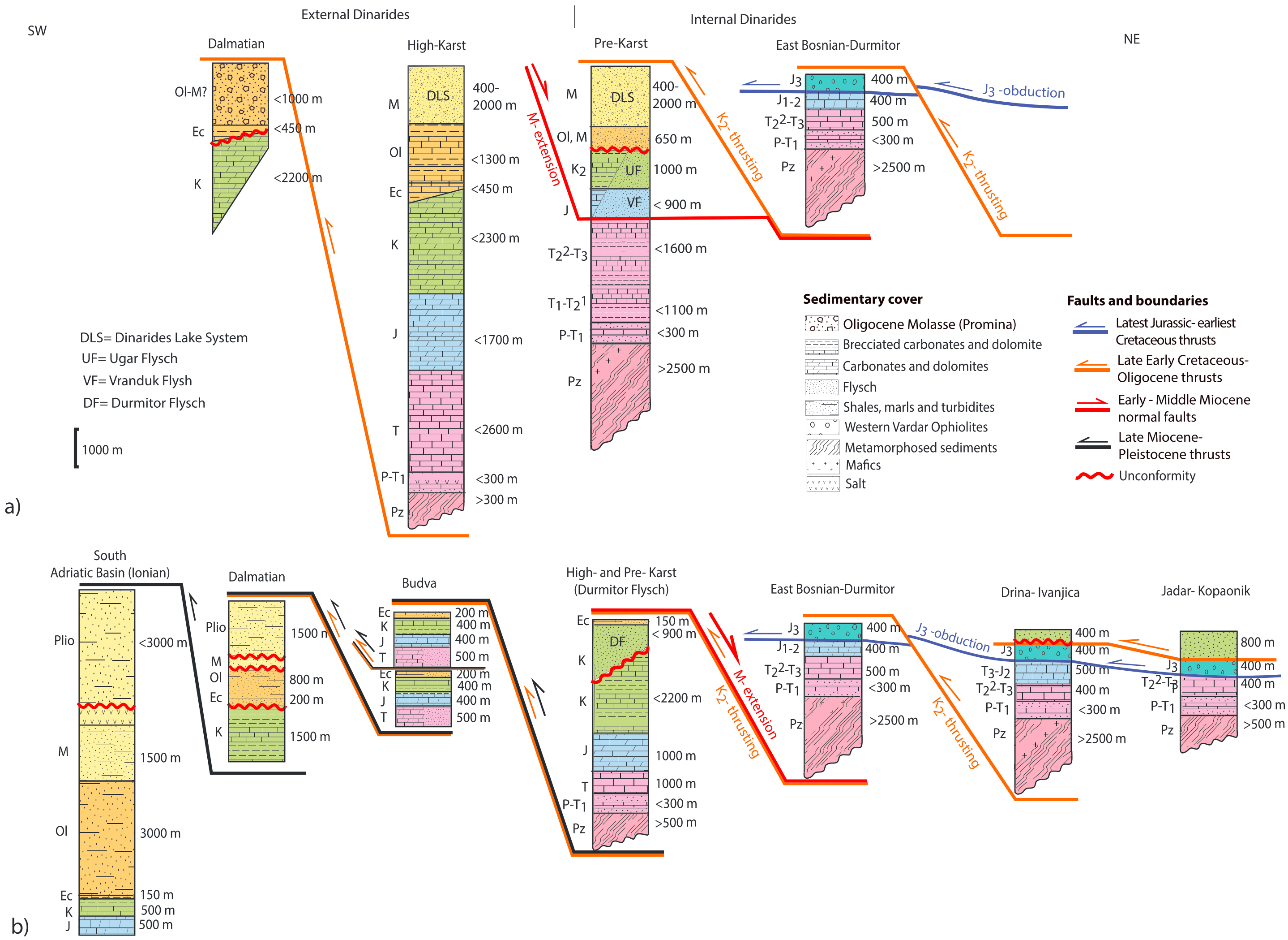

Figure 3. Correlation of lithostratigraphic columns across various tectonic units along the two studied transects: (a) Bosnia and Herzegovina-Southern Croatia transect; (b) Serbia-Montenegro transect. Abbreviations (from Pz to Plio) are standard stratigraphic periods of the Paleozoic, Mesozoic, and Cenozoic eras. Subscript numbers are stratigraphic epoch during periods. Superscript numbers are chronostratigraphic stages during epochs. The Variscan basement is generally overlain by Permian-Lower Triassic continental deposits with thin evaporitic intercalations. The 2- to 3-km thick generally shallow water upper Lower Triassic-Paleocene carbonates were deposited in the external parts of the Dinarides nappes. Note the gradual deepening of depositional environment toward more internal units, where deep-water carbonates, clastics, and pelagic sediments were deposited along the former passive continental margin. Ages: Plio = Pliocene-Pleistocene, M = Miocene, Ec = Eocene, Ol = Oligocene, K-Pg = Cretaceous-Paleocene, K_2 = Upper Cretaceous, K = Cretaceous, J = Jurassic, J_3 = Upper Jurassic, J_2 = Middle Jurassic, J_1 = Lower Jurassic, T_3 = Upper Triassic, T_2^2 = upper Middle Triassic, T_2^1 = lower Middle Triassic, T_1^2 = upper Lower Triassic, T_1^1 = lower Lower Triassic, T_1 = Lower Triassic, P-T_1 = Permo-Triassic, P = Permian, and Pz = metamorphosed Paleozoic.

toward more external areas of the Dinarides (Figures 1–3, Aubouin et al., 1970; Dimitrijević, 2001; Ustaszewski et al., 2010). The peak Eocene shortening in the External Dinarides created southwestward thrusting and was associated with the deposition of Eocene turbidites and a Late Eocene-Early Oligocene coarse conglomeratic regressive molasse sequence (the Promina Beds) deposited near thrust contacts (Figure 3, Mrinjek, 1993; Zupanič & Babić, 2011). Shortening during this period was also recorded in more internal units and near the Sava zone (Stojadinović et al., 2017; Ustaszewski et al., 2010). Among all syn-contractional turbidites observed in the Dinarides, the thickest deposition is observed in the Bosnian Flysch zone (Figure 2). This zone is located in the footwall of more internal units carrying obducted ophiolites in an upper structural position in the Dinarides or in the footwall of the Southern Alps thrusting (Figure 1, Dimitrijević, 1997; Goričan et al., 2012; Hrvatović & Pamić, 2005; Tari, 2002). The deposition of these turbidites started during the Kimmeridgian (the Vranduk Flysch, Figure 3) and continued during Cretaceous times, with thickest deposition being recorded during the latest Cretaceous (Maastrichtian, the Ugar-Durmitor Flysch, Figure 3). The Bosnian Flysch deposition was interrupted by local unconformities (Dimitrijević, 1997; Hrvatović, 2006; Hrvatović & Pamić, 2005; Mikes et al., 2008; Schmid et al., 2008), which may suggest several pulses of thrusting of the overlying East Bosnian-Durmitor unit.

The Late Oligocene-Miocene extension has affected the internal part of the Dinarides and their contact with the Carpathians. Generally, this extension was thought to be at least partly related to the formation of the Pannonian Basin backarc that started at ~20 Ma during the rollback of the Carpathian and Dinarides slabs (Figure 2, Horváth et al., 2015; Matenco & Radivojević, 2012). This extension has created large-scale detachments and other listric normal faults along the entire length of the Sava zone and other Dinarides nappe contacts, previously documented to have reached as far to the foreland as the Sarajevo-Zenica Basin (Figure 2, Andrić et al., 2017; Erak et al., 2017; Stojadinovic et al., 2013; Toljić et al., 2013; Ustaszewski et al., 2010; van Gelder et al., 2015). Outside the Pannonian Basin, the extension was partly coeval with the creation of the Dinarides Lake System, a group of Miocene intramontane basins that recorded lacustrine endemic fauna and endorheic sedimentation (Figures 2 and 3, Harzhauser & Mandic, 2008; Mandic et al., 2012). Among all basins, the largest observed is the Oligocene-Miocene Sarajevo-Zenica Basin (Figure 2). This basin started its evolution with Oligocene-Early Miocene continental to shallow-water lacustrine foreland flexural deposition over the Bosnian Flysch in the footwall of the East Bosnian-Durmitor thrusting (Figure 3a) and was affected by a large-scale asymmetric extension leading to the deposition of ~ 2 km of Middle-Upper Miocene continental alluvial to deltaic sediments (Figure 3a, Andrić et al., 2017; Hrvatović, 2006).

The extension was followed by an overall inversion that started somewhere in the latest Miocene and is presently active. This deformation took place in response to a general indentation and counterclockwise rotation of the Adriatic microplate, which has been documented from present-day crustal stress patterns, GPS velocities, and paleomagnetic studies (e.g., D'Agostino et al., 2008; Grenerczy et al., 2005; Handy et al., 2010; Heidbach et al., 2016; Márton et al., 2003; Pinter et al., 2005; Ustaszewski et al., 2014; Weber et al., 2010). These studies indicate that the present Adria kinematics is related to ~northward indentation in the NW Dinarides near the contact with the Southern Alps, while this indentation is oriented toward the NE in the central and SE part of this orogen, which agrees with the overall counterclockwise rotation of Adria (see also Vrabec et al., 2006). However, no significant rotation took place in the thrusted Dinarides units during post-Eocene times (de Leeuw et al., 2012), which would point to a decoupling between the kinematics of Adria and the one of the Dinarides during the presently active continental subduction. The geometry of this subduction is observed by the high-velocity mantle anomaly located beneath the External Dinarides of Montenegro (e.g., Bennett et al., 2008). To the NW, the presence of such a subducted slab is debated, although recent studies have envisaged a large-scale high-velocity anomaly along the entire external part of the Dinarides (Šumanovac et al., 2017; Šumanovac & Dudjak, 2016; Ustaszewski et al., 2008) that may continue beneath the eastern Alps (Kissling et al., 2006; Lippitsch et al., 2003).

3. Methodology

In order to understand the deformation in the external part of the Dinarides, we have first performed an outcrop kinematic study. Most of the structures measured are brittle, such as faults with kinematic senses of shear, folds, joints or larger cataclastic shear zones. Shear-sense criteria used are slickensides, Riedel shears, tension gashes, drag folds, and, in rheological weak or poorly consolidated sediments and fault gouges, brittle shear bands. Structures were subsequently plotted on stereograms, with joints, faults and shear zones as planes, and kinematic senses of shear, folds, and associated hinges as points. Timing indicators were derived from superposition criteria, such as cross-cutting faults or reactivated fault planes, tilted fault planes, refolded geometries, and from stratigraphic constraints. Deformation of Miocene sediments have provided critical timing constraints used to derive the relationship between the pre-Miocene shortening from the subsequent Miocene extension and latest Miocene-Recent inversion. These constraints have been used to derive a relative chronology of deformation events, which was further interpreted in a regional context.

In a first stage, the measured kinematic structures were grouped at local scale by calculating paleostress directions for the same deformation event (Figures 4, 6, 8, and 9, see also the supporting information). Structures were plotted in the Win-Tensor software (Delvaux & Sperner, 2003), by using a combination of PBT- (p, b and t kinematic axis, see Turner, 1953) and direct inversion methods (Angelier, 1984),

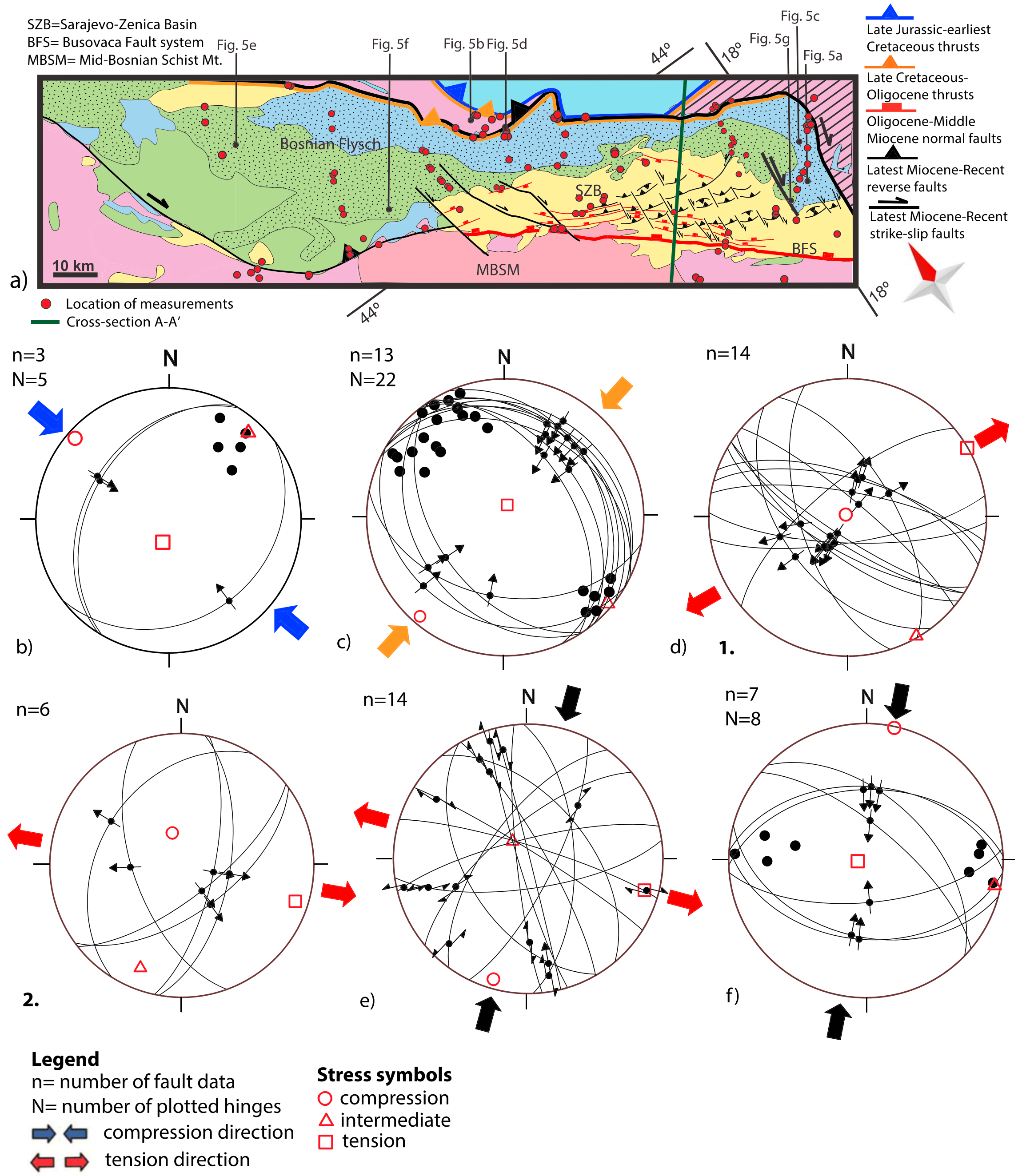

Figure 4. Kinematic data grouped per deformational event in the first focus area, the Bosnian Flysch zone and the Sarajevo-Zenica Basin. These data correspond to the NE part of cross-section A-A′ (Figure 11a). The data are plotted in Schmidt stereoplots, lower hemisphere projection. Lines with arrow symbols are projections of fault planes with kinematic sense of shear. Thick black dots are projections of fold hinges. Colors of the maximum and minimum stress directions, symbolized by arrows next to stereoplots, indicate the deformation event corresponding to the same color of map structures. (a) Geological and structural map of the Bosnian Flysch zone and the Sarajevo-Zenica Basin, where faults are color coded according to deformation events (compiled and simplified from sheets of the 1:100.000 geological map of former Yugoslavia, Osnovna Geološka Karta SFRJ). The same legend for the stratigraphic age applies as in Figure 2. The location of the map is given in Figure 2 (rectangle 1); (b) stereoplot showing the faults and folds associated with the Late Jurassic-Earliest Cretaceous contractional event; (c) stereoplot showing the faults and folds associated with the latest Cretaceous-Oligocene contractional event; (d) stereoplots showing faults associated with the Miocene extensional event: 1, normal faults characterizing a stress field with a NE-SW direction of tension; 2, normal faults characterizing a stress field with a WNW-ESE direction of tension; (e) stereoplot showing strike-slip faults associated with the inversion starting during latest Miocene times; (f) stereoplot showing reverse faults and folds associated with the inversion starting during latest Miocene times.

accounting for confidence criteria (Sperner & Zweigel, 2010). The analysis has demonstrated that only paleostress is not suitable for defining regional tectonic phases. This is due to large amounts of strain partitioning observed near and at large distance from large-offset structures during the same deformation event (e.g., coeval strike-slip faulting and thrusting) or because of large amounts of vertical axis rotation that took place during deformation or subsequent tectonic events. Such limitations of the paleostress methodology are otherwise widely known (see also Lacombe, 2012). Therefore, we have followed one other methodology (e.g., Andrić et al., 2017; van Gelder et al., 2015), where the observed deformation was described by defining directions of regional tectonic transport along main observed structures in map and cross-sections scale (i.e., by performing a strain analysis). The differentiation between stress calculations (compression-tension) and strain observations (contraction-extension) is subsequently used in the description of deformation events.

The kinematic analysis was distributed along two transects, one in central-eastern Bosnia and Herzegovina-Southern Croatia, and one other in Southern Serbia-Montenegro (Figure 2). The overall deformation in the Dinarides is generally focused at or near the main tectonic contacts that localized the strain in weakness zones and allowed the formation of large-offset thrusts or normal faults. These larger amounts of deformation are observed in particular in the Bosnian Flysch zone and the Budva unit of Montenegro, which were the main focus areas of our study (areas 1, 3, and 4 in Figure 2). Furthermore, the balance between shortening and intervening extension was studied in one other focus area, where the latter displays larger offsets, that is, the Herzegovina lower Neretva River Valley (area 2 in Figure 2). Our results and previous studies were integrated in these two onshore crustal profiles, the Southern Serbia-Montenegro profile being prolonged offshore until the frontal thrusting over the Adriatic unit by using previously published cross sections derived from reflection seismic interpretations (Bega, 2015). Given the lack of other reflection seismic data, our depth projections were combined with other available information of crustal thickness or potential fields, such as gravity maps (Marović et al., 2002; Šumanovac, 2010). Therefore, the deep part of the crustal profiles is fairly speculative and has to be viewed qualitatively. Kinematic and superposition criteria were used to extrapolate deformation to depth and to define the relative timing of deformation, which has subsequently been used to conceptually restore the crustal profiles. In order to discuss the results in the larger-scale context of the subduction zone evolution, the crustal profiles were extrapolated at lithospheric scale by using available mantle constraints derived from teleseismic tomography (Artemieva et al., 2006; Balazs et al., 2017; Bennett et al., 2008; Piromallo & Morelli, 2003; Šumanovac et al., 2017).

4. Kinematic Analysis in Focus Areas

4.1. The Bosnian Flysch Zone Near the Sarajevo-Zenica Basin

The Bosnian Flysch zone is mostly exposed north of the Sarajevo-Zenica Basin (Figure 4a). This zone is characterized by intense deformation as a result of multiple phases of folding, thrusting, strike-slip faulting, and normal faulting, associated with strata generally being tilted to steep subvertical positions.

The first deformation event observed in this area is characterized by the formation of thrusts, and isoclinal and décollement folds (Figures 4b, 5a, and 5b). These structures are strongly overprinted by all subsequent deformation events. The few fold hinges and thrusts we were able to document are NE-SW oriented and indicate an overall NW-SE oriented contraction direction (Figure 4b). One can derive an associated NW-SE oriented compressional stress field, but the number of measurements is too low to be regionally significant. Décollement and isoclinal drag folding can be associated with layer-parallel shearing and low-angle thrusting (Figure 5b). No large-offset structures that may be significant at regional scale could be associated with this deformation event.

The folds from the first deformation event are refolded by a second generation of asymmetric folds with NW-SE oriented hinges indicating a NE-SW oriented contraction direction (Figures 4c and 5c), often associated with hinge collapse structures between more competent layers (Figure 5d). These folds are centimeters to tens of meters scale in outcrops and form the main bulk of structures observed in the field. The folds are genetically associated with NW-SE oriented thrusts (Figure 4c), with larger offset SW vergent thrusts and smaller offset NE vergent thrusts. The overall stress field was characterized by a NE-SW oriented compression direction. The relationship between thrusts and asymmetric folds is visible in footwalls, where folds often form asymmetric drag folds or the overturned flank is truncated by thrust faults in a break-thrust folding mechanism (sensu Fischer et al., 1992). Fault-bend fold structures were observed in more competent

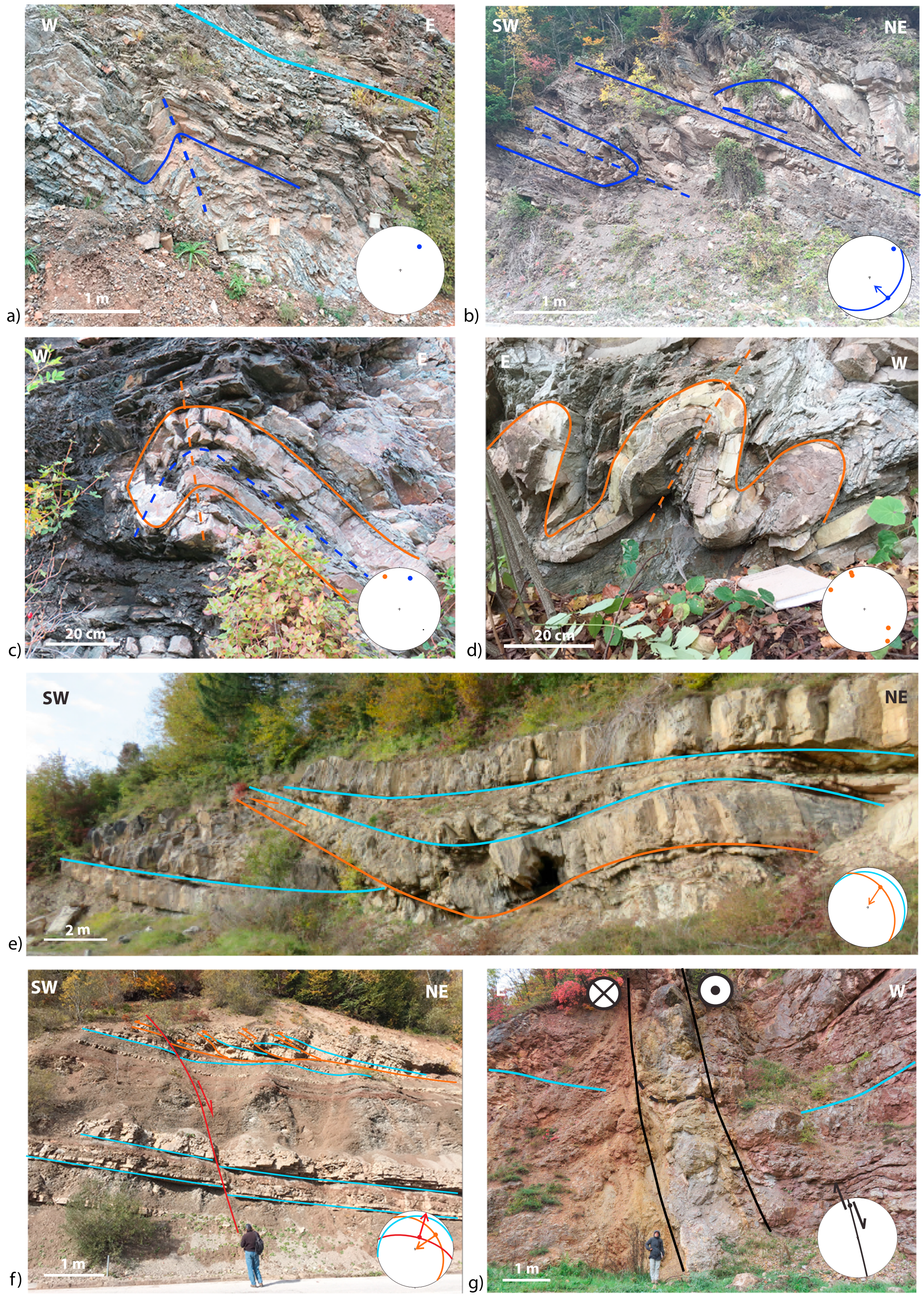

Figure 5. Interpreted field photos illustrating structures and their kinematics in the Bosnian Flysch zone and the Sarajevo-Zenica Basin. Location of the field photos are displayed in Figure 4a. Colors of the lines and symbols indicate the age of the deformation event corresponding to the same color of map structures. Dark blue, Late Jurassic-Earliest Cretaceous; orange, latest Cretaceous-Oligocene; red, Early-Middle Miocene; black, Latest Miocene-Recent; and light blue, bedding plane. (a) An asymmetric fold with a NE-oriented hinge; (b) a NW verging low-angle thrust associated with décollement and isoclinal drag folds with NE oriented hinges; (c) an isoclinal fold with a NE oriented hinge is refolded by a younger asymmetric fold with a NW oriented hinge; (d) asymmetric folding associated with NW-SE oriented hinges and hinge collapse structures; (e) a fault-bend fold structure with a SW vergence, associated with syn-kinematic deposition; (f) a high-angle NNE verging normal fault truncates an imbricated SW vergent thrust fan; (g) a large-offset NNW-SSE oriented dextral strike-slip shear zone.

strata, locally associated with syn-kinematic deposition in uppermost Cretaceous strata (Figure 5e). This is an important timing indicator, which demonstrates a latest Cretaceous age of deformation.

The NW-SE oriented thrusts and asymmetric folds are truncated by younger normal faults (Figure 4d). A typical situation is when normal faulting truncates imbricated thrust fans, formed by layer-parallel shear in fine sediments (Figure 5f). The normal faults are generally high angle to listric and show little to no tilting by subsequent deformation. The orientations of these normal faults are quite widespread (Figure 4d) but are in general agreement with the identification of two directions of tension in the reconstructed stress fields, NE-SW (Figure 4d-1) and WNW-ESE (Figure 4d-2). Similar directions of extension were previously documented in the much larger data set measured in the sediments of the adjacent Sarajevo-Zenica Basin, controlled by the large-scale Busovača fault system associated with syn-kinematic Lower-Middle Miocene sedimentation (Andrić et al., 2017; Hrvatović, 2006).

The last deformation event observed in the Bosnian Flysch is characterized by frequent large-offset NW-SE to NNW-SSE oriented dextral, and more rare and lower offset NE-SW to ENE-WSW oriented sinistral strike-slip faults (Figure 4e). These faults define a stress field with NNE-SSW oriented compression and WNW-ESE oriented tension. In the field, strike-slip faults are associated with E-W to (W)NW-(E)SE oriented high-angle reverse faults combined with drag and upright folds, which define a stress field with a NNE-SSW oriented compression direction (Figure 4f). Among all, a spectacular large-offset NNW-SSE oriented strike-slip shear zone is observed at the eastern termination of the Sarajevo-Zenica Basin (Figure 5g), which likely accommodated 10–20 km of dextral offset, indicated by the change in strike of the East Bosnian-Durmitor unit and Bosnian Flysch strata (Figure 4a). Furthermore, reactivation of the NW-SE oriented East Bosnian-Durmitor thrusting contact resulted in the formation of south-vergent high-angle reverse faults. These faults placed, or locally repeated, the Triassic strata of the East Bosnian-Durmitor units over the Jurassic strata of the Vranduk Bosnian Flysch (Figure 4a). Both the strike-slip and reverse faults can be grouped to a deformation event characterized by NNE-SSW oriented contraction (Figures 4e and 4f).

4.2. The Lower Neretva Valley Area

The lower Neretva Valley area (Figure 6a) shows multiple phases of thrusting, strike-slip, and normal faulting. The oldest structures in this area were observed in the SW, where most of the deformation is made up of NW-SE oriented, dominantly larger offset SW vergent thrusts and fewer smaller offset NE vergent backthrusts (Figure 6b). The SW vergent thrusts are often quite prominent in the topography, where they usually thrust Cretaceous limestones in their hanging wall over more distal Eocene mudstones to immature carbonate turbidites in their footwall (Figure 7a). These thrusts generally have offsets of less than 2 km.

On the flanks of the Konjic Basin, the NW-SE oriented thrusts are cross-cut by normal faults that are associated with syn-kinematic Miocene sedimentation inside the same basin. Similar with the Sarajevo-Zenica Basin and its flanks, the extension has two directions in the Konjic Basin and neighboring area. Larger offset normal faults are NW-SE oriented and define a stress field with a NE-SW oriented tension direction (Figure 6c-1), while smaller offset normal faults are NNE-SSW to NE-SW oriented and define a stress field with a (W)NW-(E)SE oriented tension direction (Figure 6c-2).

In the Miocene Konjic Basin and elsewhere to the south and southwest, the normal faults and predating NW-SE oriented thrusts are truncated by two types of structures. A large number of strike-slip faults were observed in the field, where larger offset (W)NW-(E)SE to NNW-SSE oriented dextral transpressive faults are associated with smaller offset NNE-SSW to NE-SW oriented sinistral strike-slip faults. These faults define a stress field with a roughly N-S oriented compression and a E-W oriented tension direction (Figure 6d). In the Konjic Basin, these dextral faults cross-cut the earlier formed normal faults (Figure 7b). These normal faults are also truncated by ~E-W oriented reverse faults and similarly oriented large-offset shear zones with both north and south vergence, which define a stress field with a NNE-SSW oriented compression direction (Figure 6e). Furthermore, the (N)NW-(S)SE dextral transpressive and ~E-W oriented reverse faults connect with each other along their strike, which is also fairly obvious in map view in the NE (Figure 6a). The largest structure can be observed along the Neretva River Valley, where combined strike-slip and reverse faults with offsets of more than 10 km have been observed in the field (Figures 7c and 7d). Both the strike-slip and reverse faults can be grouped to a deformation event characterized by N-S to NNE-SSW oriented contraction.

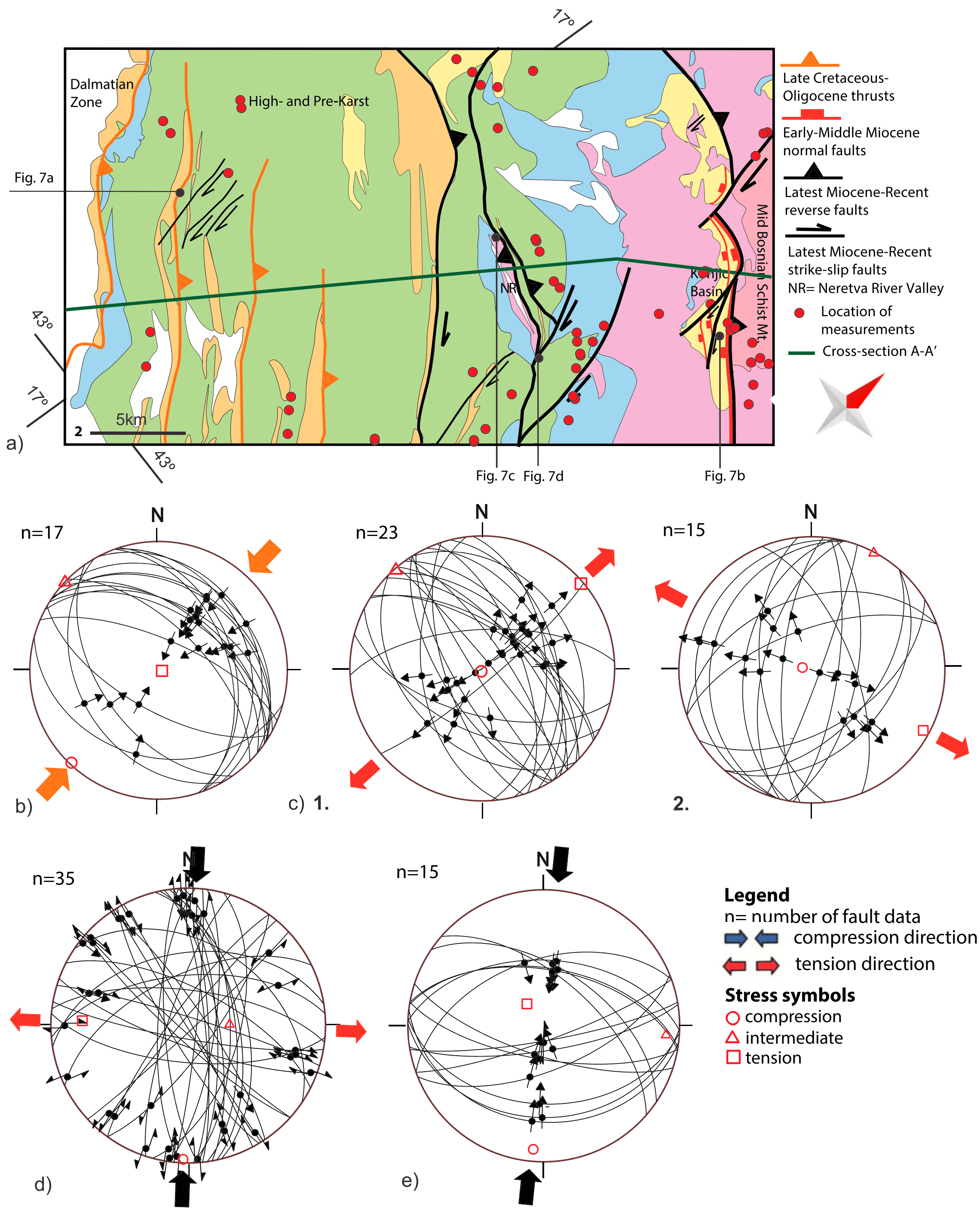

Figure 6. Kinematic data grouped per deformational event in the second focus area, central Bosnia and Herzegovina and southern Croatia. These data correspond to the SW part of cross-section A-A′ (Figure 11a). Further figure conventions as in Figure 4. (a) Geological and structural map of central Bosnia and Herzegovina and southern Croatia (compiled and simplified from sheets of the 1:100.000 geological map of former Yugoslavia, Osnovna Geološka Karta SFRJ). The same legend for the stratigraphic age applies as in Figure 2. The location of the map is given in Figure 2 (rectangle 2); (b) stereoplot showing the faults associated with the latest Cretaceous-Oligocene contractional event; (c) stereoplots showing faults associated with the Miocene extensional event: 1, normal faults characterizing a stress field with a NE-SW direction of tension; 2, normal faults characterizing a stress field with a NW-SE direction of tension; (d) stereoplot showing strike-slip faults, associated with the inversion starting during latest Miocene times; (e) stereoplot showing reverse faults, associated with the inversion starting during latest Miocene times.

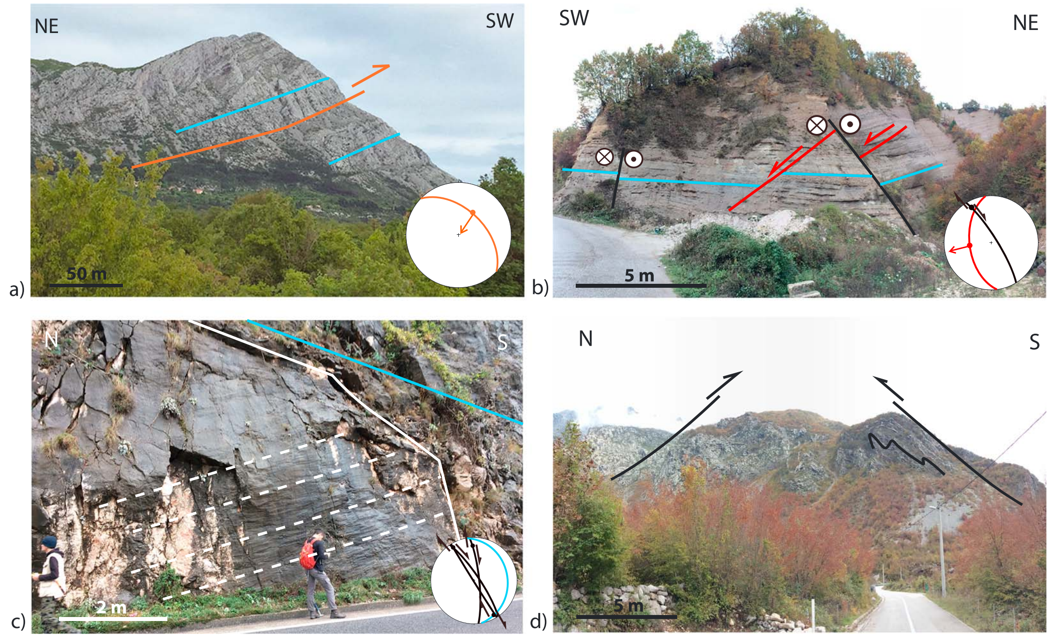

Figure 7. Interpreted field photos illustrating structures and their kinematics in the second focus area, central Bosnia and Herzegovina and southern Croatia. Location of the field photos are displayed in Figure 6a. Further figure conventions as in Figure 5. (a) A low-angle NW-SE oriented SW vergent thrust; (b) a NW-SE oriented dextral strike-slip fault cross-cuts a Miocene WSW verging normal fault; (c) large-offset NW-SE and NNW-SSE oriented dextral strike-slip faults; (d) high-angle ~E-W oriented N and S verging reverse faults associated with tight asymmetric folding.

4.3. The Durmitor Flysch of Montenegro

Only few observations have been done in the Bosnian Flysch zone exposed in Montenegro, that is, the Durmitor Flysch in the footwall of the East Bosnian-Durmitor thrusting (Figure 8a). These observations are in general agreement with the larger data set available in previous studies (Dohmen, 2012), which are plotted for comparison in Figure 8c.

Previous studies and our observations document a first deformation event characterized by NW-SE oriented thrusts with both a SW and NE vergence, associated with folds with NW-SE oriented hinges (Figure 8b). These structures define a stress field with a NE-SW oriented compression direction. Outcrop kinematics and the relationship with major structures show that this deformation event was responsible for the initial thrusting of the East Bosnian-Durmitor unit (Figure 8a).

The thrusts formed during the first deformational event (Figure 8b) were subsequently truncated by numerous normal faults that show, yet again, two directions of extension. Roughly NW-SE oriented normal faults document a stress field with a NE-SW oriented extension direction (Figure 8c-1), while ~NE-SW oriented normal faults document a stress field with a NW-SE oriented extension direction (Figure 8c-2). The largest offset is observed along the NW-SE oriented normal faults, which can be kinematically connected with the reactivation of the East Bosnian-Durmitor thrust as a listric normal fault and the formation of extensional klippens of the overlying Drina-Ivanjica unit in its hanging wall (Figures 1a and 8a).

A number of strike-slip faults have been observed in the field, dextral strike-slip faults are predominantly NNW-SSE to N-S oriented, associated with NE-SW to ENE-WSW oriented sinistral strike-slip faults (Figure 8d). These strike-slip faults formed during a deformation characterized by a stress field with a NNE-SSW to NE-SW oriented compression direction associated with a WNW-ESE to NW-SE oriented tension direction.

4.4. The Southern High Karst, Budva and Northern Dalmatian Units of Coastal Montenegro

A large amount of kinematic data was obtained in coastal Montenegro, in the highly deformed area of the southern High Karst, Budva, and northern Dalmatian units (Figure 9a). This area shows multiple phases of folding, normal faulting, thrusting, strike-slip faulting, and high-angle reverse faulting (Figures 9b–9g).

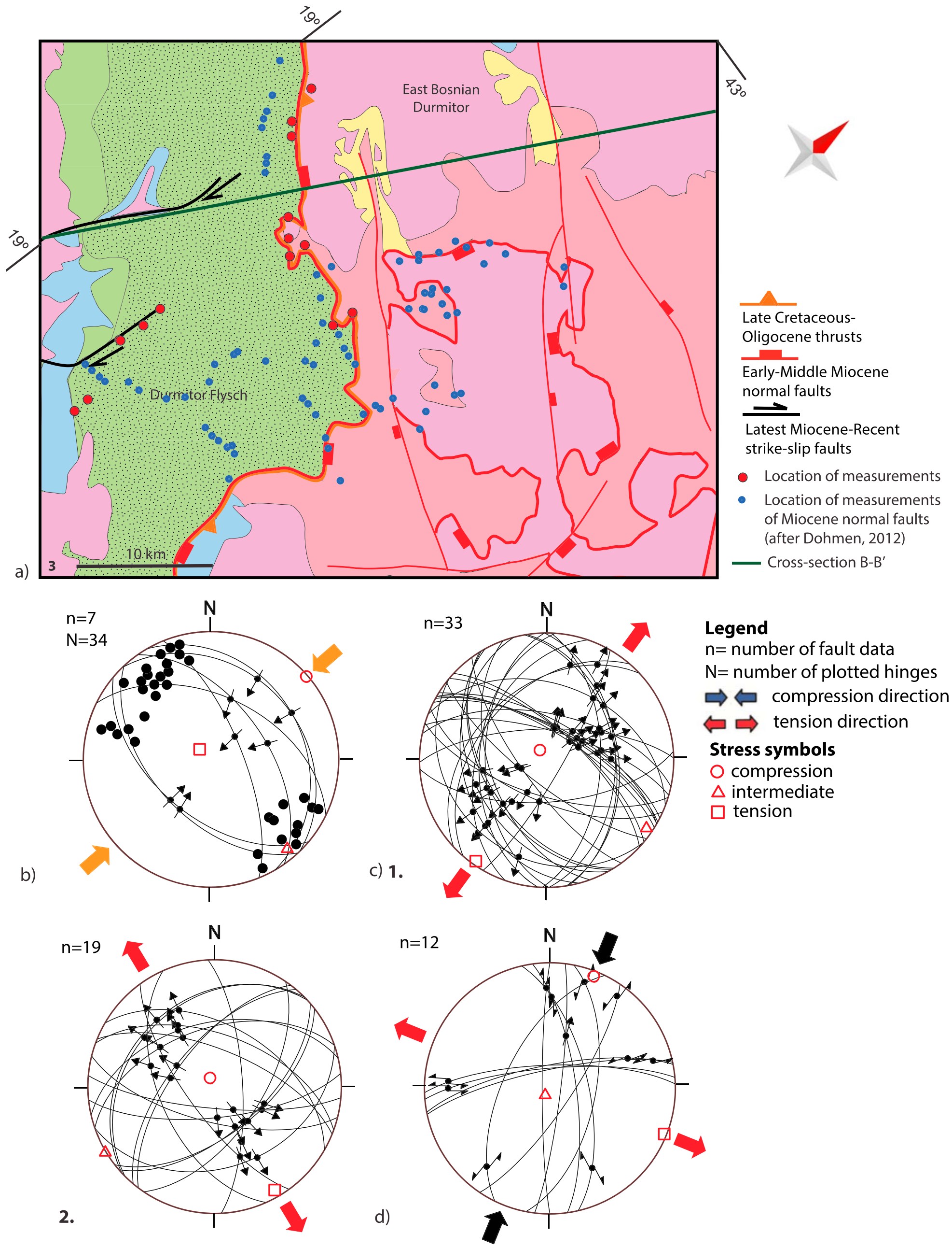

Figure 8. Kinematic data grouped per deformational event in the third focus area, the Durmitor Flysch zone of Montenegro. These data correspond to the NE part of cross-section B-B′ (Figure 11b). Further figure conventions as in Figure 4. (a) Geological and structural map of the Durmitor Flysch zone of Montenegro (compiled and simplified from sheets of the 1:100.000 geological map of former Yugoslavia, Osnovna Geološka Karta SFRJ). The same legend for the stratigraphic age applies as in Figure 2. The location of the map is given in Figure 2 (rectangle 3); (b) stereoplot showing the faults and folds associated with the latest Cretaceous-Oligocene contractional event; (c) stereoplots showing faults associated with the Miocene extensional event (part of the fault data is taken from Dohmen, 2012): 1, normal faults characterizing a stress field with a NE-SW direction of tension; 2, normal faults characterizing a stress field with a NW-SE direction of tension; (d) stereoplot showing strike-slip faults, associated with the inversion starting during latest Miocene times.

The first phase of deformation observed in the field is characterized by NW-SE oriented normal faults dipping both to the NE and SW, which define a stress field with a NE-SW oriented tension direction (Figure 9b). Most of these faults cross-cut Lower Triassic-Anisian sediments and are syn-kinematic with the onset of Uppermost Anisian-Ladinian deep water carbonatic, calci-turbiditic, radiolaritic, and volcanoclastic deposits (Figure 10a).

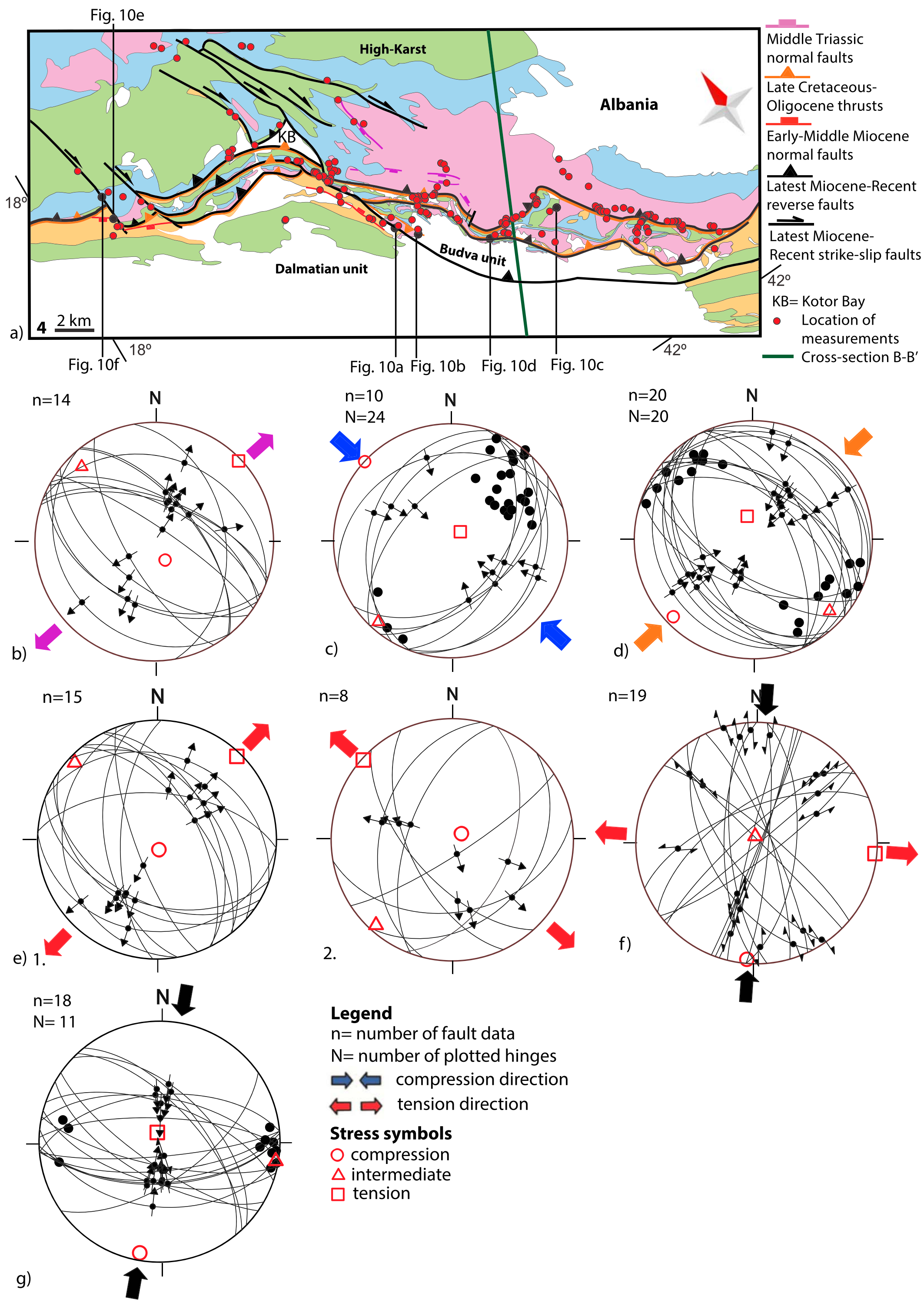

Figure 9. Kinematic data grouped per deformational event in the fourth focus area, coastal Montenegro. These data correspond to the SW part of cross-section B-B′ (Figure 11b). Further figure conventions as in Figure 4. (a) Geological and structural map of coastal Montenegro (compiled and simplified from sheets of the 1:100.000 geological map of former Yugoslavia, Osnovna Geološka Karta SFRJ). The same legend for the stratigraphic age applies as in Figure 2. The location of the map is given in Figure 2 (rectangle 4); (b) stereoplot showing the faults associated with the Middle Triassic rifting event; (c) stereoplot showing the faults and folds associated with the Late Jurassic-Earliest Cretaceous contractional event; (d) stereoplot showing the faults and folds associated with the latest Cretaceous-Oligocene contractional event; (e) stereoplots showing the faults associated with the Miocene extensional event: 1, normal faults characterizing a stress field with a NE-SW direction of tension; 2, normal faults characterizing a stress field with a NW-SE direction of tension; (f) Stereoplot showing strike-slip faults, associated with the inversion starting during latest Miocene times; (g) stereoplot showing reverse faults, associated with the inversion starting during latest Miocene times.

Figure 10. Interpreted field photos illustrating structures and their kinematics in the fourth focus area, coastal Montenegro. Location of the field photos are displayed in Figure 9a. Further figure conventions as in Figure 5. (a) NW-SE oriented normal faults with NE and SW vergences within Triassic strata; (b) a tight asymmetric fold with a NE oriented hinge; (c) asymmetric folding with a SE oriented hinge; (d) a NW-SE oriented SW vergent thrust; (e) a NE-SW oriented normal fault with a SE vergence; (f) a large-offset NW-SE oriented dextral strike-slip fault.

In places, normal faults served as conduits for the emplacement of volcanic and subvolcanic basaltic to andesitic bodies, which induced local contact metamorphism in neighboring Lower-Middle Triassic sediments, while the overlying Upper Triassic sediments are not metamorphosed. No larger, map-scale structures can be assigned to this deformation event, most likely due to significant overprinting by subsequent deformation events.

A second phase of deformation has been characterized by the formation of isoclinal and tight asymmetric folds with NE-SW oriented hinges commonly associated in outcrops with NE-SW oriented thrusts with both northwestward and southeastward vergences that affect strata as young as the Jurassic (Figures 9c and 10b). These structures define a stress field with a NW-SE oriented compression direction (Figure 9c). Although such deformation is quite obvious in particular in the deep-water sediments of the Budva unit, no large-scale structures could be associated with this deformation phase.

These structures are being deformed by a second contractional event observed in the field by numerous folds and large-offset thrusts (Figures 9a and 9d). Isoclinal to tight asymmetric folds with NW-SE oriented hinges are often observed at outcrop scale in the deep-water sediments of the Budva unit and the Eocene turbidites of the Budva and Dalmatian units (Figure 10c). These asymmetric folds become more open and larger (hundreds of meters to kilometers) in the massive Mesozoic shallow water limestones of the High Karst and Dalmatian units. The folds are associated with numerous NW-SE oriented thrusts with both southwestward and northeastward vergences (Figure 9d). Compared to the NE vergent thrusts, the southwestward vergent thrusts have larger, kilometer-size offsets and created thick fault gouges and brittle shear zones. Such shear zones typically emplace more massive limestone layers over a sheared mudstone-siltstone matrix containing rotated blocks of limestones (Figure 10d). The folds and thrusts demonstrate an event characterized by a stress field with a NE-SW oriented compression direction. Lateral changes in thicknesses suggest that the Eocene turbidites of the Budva unit were partly syn-kinematic deposited with this deformation. The deformation is particularly intense in these turbidites, which also have syn-kinematic patterns when they are overlying the upper part of the Dalmatian unit that is situated beneath the Budva thrust (Figure 9a). East of the Kotor Bay, thrusting can be correlated inside the Budva unit and along its thrusting plane over the Dalmatian unit (Figure 9a). In the area of the Kotor Bay, intense internal folding and thrusting of the Budva unit was affected by a subsequent event characterized by the reactivation of both the Budva and High Karst thrusts and strike-slip displacements.

The large-offset thrusts and tight folds are truncated by normal faults, which were observed to cross-cut sediments as young as the Eocene (Figures 9a and 10e). Similar with elsewhere, normal faults can be subdivided into two extensional events, larger offset normal faults are NW-SE oriented and define a stress field with a NE-SW oriented tension direction (Figure 9e-1), while smaller offset mostly NE-SW oriented normal faults define one other stress field with a NW-SE oriented tension direction (Figure 9e-2). The offsets of such normal faults are generally centimeters to meters scale (Figure 10e). These normal faults do not appear to be associated with larger offset map-scale structures.

All previous structures are truncated or tilted by a last deformation event that is characterized by two different types of structures. In the Kotor Bay area, large-offset NW-SE to NNW-SSE oriented dextral strike-slip faults are associated with lower offset NNE-SSW to NE-SW oriented sinistral strike-slip faults and define a stress field with a NNE-SSW oriented compression and a WNW-ESE oriented tension direction (Figure 9f). Large strike-slip faults are commonly truncating entire outcrops (Figure 10f) and are distributed throughout the area. The offsets of strike-slip faults decreases significantly at outcrop and map-scale east of the Kotor area (Figure 9a), where the second type of deformation is more dominant (Figure 9g). This second type is characterized by a large number of ~E-W to (W)NW-(E)SE oriented thrusts or high-angle reverse faults that are both north and south vergent. These faults define a stress field with a NNE-SSW oriented compression direction (Figure 9g). Outcrop-scale faults observed in all areas can be connected in map view along large-scale dextral strike-slip faults, which reach up to 5 km offset (Figures 9a and 10f). These faults are associated with significant rotations by forming large drag folds with E-W oriented hinges, such as in the area of the Kotor Bay (Figure 9g).

5. Interpreting the Kinematic Data in the Focus Areas Constraining the Crustal-Scale Transects

The analysis of kinematic data obtained in the four focus areas demonstrates that the Dinarides orogen was affected by a long-lasting polyphase tectonic evolution. This evolution shows that the largest amounts of thrusting have migrated gradually with time toward the foreland and were interrupted by periods of regional extension.

5.1. From Middle Triassic Rifting to Late Jurassic-Earliest Cretaceous Obduction

The first moment of deformation recorded by our data is the Middle Triassic (latest Anisian-Ladinian) rifting and the formation of the Budva graben, which is presently located in an external position in the Dinarides orogen (Figures 1 and 2). This interpretation agrees with previous studies that suggested a continental graben geometry, filled gradually by deep-water sediments (Goričan, 1994; Schmid et al., 2008). Our observations demonstrate that extension of the Budva graben was NE-SW oriented (Figure 9b) and was associated with intermediate and mafic magmatism and a syn-kinematic deposition that shows rapid deepening of the basin, illustrated by the sedimentation of pelagic radiolarites interbedded with calci-turbidites, which are likely transported across the slope formed by normal faults. Deep-water deposition continued until Upper Cretaceous times, although a gradual progradation and shallowing of facies is observed at the margins of the presently exposed Budva thrusted unit (Goričan, 1994). This deposition was also affected by regional geochemical changes induced by the onset of magmatism in the larger area of the Tethys, such as those that prevailed near the Triassic-Jurassic boundary (Crne et al., 2011). Our interpretation of a Middle Triassic NE-SW oriented extension in the Budva graben is also compatible with the rifting, drifting, and the gradual deepening of the Middle Triassic-Early Jurassic carbonate facies interpreted at farther distances in the internal part of the Dinarides (Figure 3, e.g., Dimitrijević, 1997; van Gelder et al., 2015). No indications of oceanic crust are found in the Budva unit, which has a rather limited extent along the Dinarides strike, being restricted to the SE Montenegro area (Figure 1). Therefore, Budva was likely a symmetric continental graben that pinched out to the NW and formed during the same Middle Triassic moment of continental rifting that opened the much larger Neotethys area situated northward, as previously interpreted (Schmid et al., 2008). Whether or not Budva becomes an ocean in its lateral prolongation in the Cukali-Pindos units of the Albanides and Hellenides is still unclear (e.g., Menant et al., 2016).

The exact onset of Neotethys oceanic subduction is unclear in the study area, but available ages of ophiolites and metamorphic soles at the base of the ophiolitic sequences in the Dinarides and Hellenides indicate that it took place during Middle Jurassic times (e.g., Ustaszewski et al., 2009 and references therein). Our data from the Kimmeridgian-Valanginian Vranduk Flysch (e.g., Djeric et al., 2007) show a contractional event associated with a low number of top NW thrusts and associated folds (Figures 4b, 5a, and 5b). Such folds with NE-SW oriented hinges have been mapped also in the Budva graben of Montenegro (Figures 9c and 10b). The NW-SE orientation of this contraction direction is rather unique in more internal Dinarides units, interpreted to be the result of the Late Jurassic-Earliest Cretaceous obduction event. The low number of kinematic data is otherwise similar with the internal part of the Dinarides, where a low number of similarly oriented folds and shears have been observed in the underlying ophiolitic mélange (Chiari et al., 2011; Schmid et al., 2008). We have not observed any syn-kinematic deposition in the Vranduk Flysch, and therefore, the deposition of these sediments may be assigned to any process that creates deep water turbidities, such as along the slope of a continental passive margin. However, the switch from carbonatic to siliciclastic turbidites overlying the Pre-Karst unit is almost coeval with the moment of obduction of the Western Vardar Ophiolites over more internal Adriatic units and the related formation of an active source area for these turbidites (Mikes et al., 2008). Therefore, this first NW-SE oriented contractional event can possibly be correlated with the NW verging Kimmeridgian-Valanginian obduction of the Western Vardar ophiolites. The influence of this tectonic event on the formation of the NE-SW oriented fold hinges and thrusts observed in the Budva units is rather unclear in our study, most likely due to severe overprint by subsequent deformation events. It is possible that a far-field contractional effect, induced by the obduction of the neighboring Albanian ophiolites (Figure 1, Bortolotti et al., 2012), has affected also the deep-water sedimentation of the Budva graben, but such a correlation is beyond the data available in our study.

5.2. Top SW Late Cretaceous-Oligocene Thrusting

The Bosnian Flysch zone was affected by large-scale thrusting and folding that started during Late Cretaceous times (Figures 4c and 8b). This is documented by syn-depositional thrusts and folds observed in the dominantly Campanian-Maastrichtian sediments of the Ugar and Durmitor flysches (e.g., Figures 5c–5e). However, the depositional onset of these turbidites may have started earlier, during the Upper Cretaceous, owing to differences in biostratigraphic interpretations (Dimitrijević, 1997; Rampnoux, 1970). The termination of thrusting in this area is constrained by observations of syn-kinematic sedimentation along the northern margin of the Sarajevo-Zenica Basin (Figure 4a), which demonstrate Eocene thrusting that continued during early Oligocene times (Andrić et al., 2017). Our field observations and the distribution of the syn-kinematic sediments show that the bulk of shortening taken by the Bosnian Flysch zone and its southern margin is Campanian-Maastrichtian in age, while the subsequent Eocene-Oligocene contraction is relatively minor by comparison (Figure 11a).

In contrast, the Eocene-Oligocene thrusting is the main deformation that affected the external part of the Dinarides and was localized with larger thrusting and folding effects in the Budva unit of Montenegro (Figures 9d and 11b). Large-offset thrusts separate this unit in two main thrust sheets affected by intense internal deformation, which were subsequently truncated by the strike-slip faults and thrusting of the High Karst unit (Figure 9a). Outside the Budva unit, this deformation is observed by lower offset thrusts and widely spaced (hundreds of meters to kilometers) open folds (Figure 11b). The onset of this deformation is constrained by the syn-kinematic deposition of Eocene turbidites in the footwall of numerous thrusts. Outside

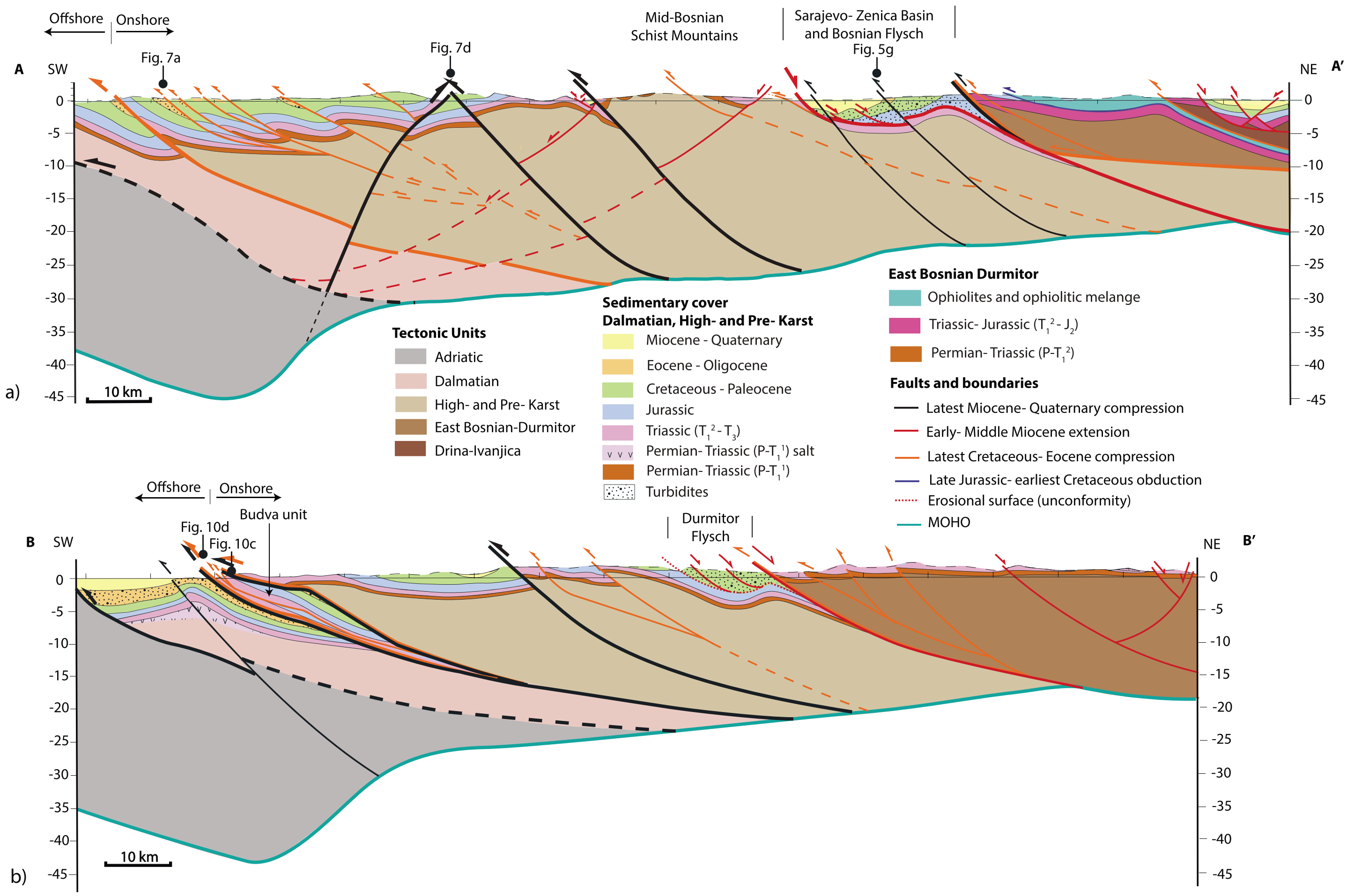

Figure 11. Two regional orogenic cross sections built from measured surface kinematics. The color of the faults represents the timing of the most significant deformations. The Moho depth has been taken from Šumanovac et al. (2017). The location of the cross sections is displayed in Figures 1a and 2. (a) Cross-section A–A′ extends from the East Bosnian-Durmitor unit in central-eastern Bosnia and Herzegovina toward the Dalmatian zone in southern Croatia. The part of the cross-section NE of the Bosnian Flysch and East Bosnian-Durmitor contact is modified after Ustaszewski et al. (2010); (b) cross section B–B′ extends from the East Bosnian-Durmitor unit in southern Serbia toward the Dalmatian zone in Montenegro.

the Sarajevo-Zenica Basin, there are no clear indications of prolongation of this tectonic event in the studied area during early Oligocene times, but such an age is compatible with the deposition of the Middle Eocene-Early Oligocene Promina Beds in the NW Dinarides of Croatia (Mrinjek, 1993). Outcrop observations at the thrust contact of the East Bosnian-Durmitor unit overthrusting the Bosnian Flysch zone indicate an inclination between 45° and 60° of the thrust fault plane (Figure 11). This present geometry of this fault reflects rather its large-scale reactivation during the subsequent Miocene extension, while depth projections suggests an initial Late Cretaceous-Eocene cumulated offset in the order of 10 km.

5.3. Bidirectional Miocene Extension

Thrusting was followed by a period of Miocene extension. In all studied areas of the Dinarides, large offset normal faults define a NE-SW oriented extension, while smaller offset normal faults define a NW-SE oriented extension (Figures 4d, 6c, 8c, and 9e). These are likely two successive episodes of Miocene extension, although clear superposition criteria are missing in our data set. The largest effects of this deformation are observed by the formation of a low-angle normal fault system that follows the NE direction of burial of the Bosnian Flysch beneath the thrusting of the overlying East Bosnian-Durmitor unit (Figure 11a). In other words, the thrusting of the East Bosnian-Durmitor unit was reactivated by large-offset normal faults dipping northeastward in the Bosnian Flysch. The formation of this asymmetric fault system was likely influenced by the rheological weakness of the NE dipping Bosnian Flysch turbidites, which are squeezed between the southern Paleozoic basement and overlying carbonate platform of the Pre-Karst unit, and the northern Paleozoic basement, carbonate platform and overlying ophiolites of the East Bosnian-Durmitor unit (Figures 4a and 11a). In the area of the Sarajevo-Zenica Basin, the main offset of the normal fault system is located at the base of the Bosnian Flysch and created ~ 8 km of Miocene exhumation in the footwall of the Busovača Fault, which is also partially responsible for the exhumation of the mid-Bosnian Schist Mountains (Figures 11a, see also Andrić et al., 2017). The faults geometry suggests an isostatic rebound in the footwall of an extensional detachment. The same geometry is also inferred by observations in Montenegro, with the difference that the main Miocene extensional detachment reactivates the inherited Late Cretaceous East Bosnian-Durmitor thrust, which overlies the Durmitor Flysch (Figure 11b).

Southwestward of the Bosnian Flysch, the demonstration of Miocene extensional deformation that affected the external part of the Dinarides is novel and implies that the formation of the entire Dinarides Lake System during the Early Miocene was associated with extension, as observed for instance in the Konjic Basin (Figure 6a). The Miocene normal faults in the external parts of the Dinarides cumulate hundreds of meters of offsets and formed similarly thick lacustrine basins (see also De Leeuw et al., 2010, 2011, 2012; Harzhauser & Mandic, 2008; Mandic et al., 2011, 2012). Similar extensional structures have been observed in the NE Dinarides, interpreted to be active during Neogene times (e.g., Žibret & Vrabec, 2016). These offsets are lower when compared with the kilometer-scale offsets observed in the Bosnian Flysch and numerous other large-offset low-angle normal faults and detachments accompanying the formation of several kilometers thick Miocene basins in more internal parts of the Dinarides. When combined, all these observations demonstrate that the Miocene period of extension affected all areas of the Dinarides until the Sava zone (Figure 2).

5.4. Latest Miocene-Recent N-S to NNE-SSW Oriented Contraction

The Miocene extension was followed by the latest Miocene (~ 8 Ma) onset of strike-slip faulting (NW-SE to NNW-SSE oriented dextral strike slip and NE-SW oriented sinistral strike slip), thrusting (top-S and top-N), and high-angle reverse faulting and folding with E-W oriented hinges. Field observations clearly demonstrate that these structures connect each other and the two paleostress fields measured (strike slip and compression), reflect in fact the same N-S to NNE-SSW contraction event, which partitions deformation to either strike slip, thrusting, or reverse faulting and folding. This observed deformation is roughly compatible with the mechanism of northward to northeastward Adriatic indentation in the Dinarides (Handy et al., 2010; Pinter et al., 2005).

In more details, the inherited rheological structure and localization of deformation plays an important role on the type of structures formed. The inherited rheological weakness and the geometry of the Bosnian Flysch turbidites and deep-water sediments of the Budva unit localize deformation by the formation of major low-angle thrusts, reactivating such inherited structures or low-angle normal faults (Figure 11). This mechanism is in agreement with the Bosnian Flysch localization of southward thrusting that deformed the sediments of the Sarajevo-Zenica Basin starting with latest Miocene times (Andrić et al., 2017). We have not found clear field evidence for such a localization in the along-strike prolongation of the Bosnian Flysch in Montenegro. Instead, most of the localization of this deformation in the Serbia-Montenegro profile takes place in the Budva unit, observed by the large High Karst thrusting and truncation of its previous Eocene thrust sheets (Figure 11b). This is also compatible with the coeval emplacement of the Dalmatian unit over the Adriatic margin, observed in offshore seismic interpretations (Figure 11b, see also Bega, 2015).

The total amounts of thrusting in the External Dinarides units can be estimated based on minimum cumulative offsets. For the Montenegro profile (Figure 11b), the geometry of the Peshkopia tectonic half-window, where the sediments of Budva-Cukali unit are outcropping in neighboring Albania (Figure 1), suggests a minimum 30 km cumulated Eocene and post-8 Ma thrusting offset of the High Karst from the Budva unit. The depth projection shows that a cumulated offset for the same period is in the order of ~20 km for the thrusting of the Budva unit over the Dalmatian unit (Figure 11b). This means that the total High Karst to Dalmatian cumulated offset is in the order of ~50 km. This estimate contrasts with the depth projection of the Eocene High Karst over Dalmatian thrusting in the Bosnia and Herzegovina-Croatia profile, which is in the order of 10 km and where the post-8 Ma deformation is minor (Figure 11a). All these observations and depth extrapolations show that the bulk of the post-8 Ma thrusting was transferred along the strike from the

Bosnian Flysch in the Bosnia and Herzegovina-Croatia profile to the High Karst, Budva, and Dalmatian units in the Serbia-Montenegro profile (Figures 2 and 11). Parts of these differential amounts of shortening may have been accommodated by the counterclockwise rotation of the Adriatic lower plate, while most Dinarides thrusted units do not record this rotation (De Leeuw et al., 2012).

The large-scale thrusting in the more internal Bosnian Flysch in the Bosnia and Herzegovina-Croatia profile and the more external Budva unit in the Serbia-Montenegro profile is likely connected along the orogenic strike by the numerous larger offset dextral strike-slip and high-angle reverse faults observed in the field, which may allow an effective deformation transfer between the two areas. The total amount of shortening recorded during this deformation event, which started during the latest Miocene and is still presently active, can be evaluated by the differential shortening and strike-slip transfer between the Bosnia and Herzegovina-Croatia and Serbia-Montenegro profiles, which is in the order of minimum 45 km.

6. Mechanics of Orogenic Deformation

Given the scarcity of depth information, such as wells or seismic lines, in the onshore external part of the Dinarides, the depth prolongation of major structures in our crustal profiles (Figure 11) is rather estimative and based mostly on surface-to-depth projections. Understanding the balance between thin- versus thick-skinned deformation relies on the availability of décollement horizons located stratigraphically above the Paleozoic. These Paleozoic rocks crop out in all internal parts of the Dinarides units in the hanging wall of the major thrusts or nappe contacts, which shows that deformation is thick skinned relative to this basement. Thin-skinned deformation is proved or inferred in the High Karst unit located in the NE Dinarides of Croatia, which is facilitated by the presence of thicker Permo-Triassic salt or other evaporite layers that serves as the main décollement level for a number of thrust systems (Korbar, 2009; Kulušić & Borojević Šoštarić, 2014). However, such evaporite layers decrease in thickness and finally disappear along the strike of the onshore Dinarides to the SE, being replaced in the studied area by dominantly Permo-Triassic continental sediments, rarely intercalated with scarce or thin layers of mostly gypsum deposits (Figure 3). A good place to find such potential décollement horizons is the mid-Bosnian Schist Mountains (Figures 2 and 11a), where the Paleozoic basement and its overlying Mesozoic sedimentary cover were exhumed during the Paleogene contraction and the Miocene extension in the footwall of the Busovača Fault (Figures 11a, Hrvatović, 2006). We note that the Paleozoic basement contains late Early Cretaceous metamorphic ages (Pamić et al., 2004), and therefore, at least the upper part of the ductile lower orogenic crust is exposed in the Bosnian Schist Mountains. Our extensive field observations have failed to find a pre-Miocene décollement horizon potentially located at or near the contact between the metamorphosed Paleozoic basement and its Permo-Mesozoic cover or inside this cover (Kulušić & Borojević Šoštarić, 2014), as we have only observed unconformable or continuous sedimentation. These types of contacts show that the orogenic deformation is thick skinned, rooted below the exposed Paleozoic metamorphosed basement that crops out or was drilled also in more external onshore Dinarides units in our studied area (Pamić et al., 2002; Velić et al., 2015). The surface to depth projection and the wavelength of deformation in the studied area indicate that almost all thrusts or high-angle reverse faults must be rooted in the lower crust. Therefore, similar with previous Dinarides interpretations (Figure 1b, see also Schmid et al., 2008), we have chosen to root such faults at the base of the crust, which agrees with the mechanics of such orogenic systems accounting for a rheological weakness zone at the crust-mantle transition (Erdös et al., 2015; Jammes & Huismans, 2012; Lacombe & Bellahsen, 2016; Ziegler et al., 1995).

6.1. Gradual Transfer of Deformation Toward the Orogenic Foreland

From Late Jurassic times all units in the studied external part of the Dinarides recorded the main orogenic phases of deformation. The top NW Late Jurassic-earliest Cretaceous obduction (e.g., Dimitrijevic, 1997; Schmid et al., 2008) has resulted in the onset of deposition and deformation of the Bosnian Flysch in the frontal part of the obduction system and similar deformation affected also the Budva deep-water deposits, the latter possibly in connection with the emplacement of the Albanian ophiolites. The detailed effects of this deformation are difficult to be assessed in the studied area, being almost completely overprinted by subsequent deformation events. Subduction continued in Cretaceous time until the latest Cretaceous peak moment of continental collision between the Dinarides and Tisza-Dacia continental units. The accretionary wedge sediments presently observed farther northeastward in the Sava zone show significant Early Cretaceous-Cenomanian contractional deformation followed by the Turonian-Santonian formation of an

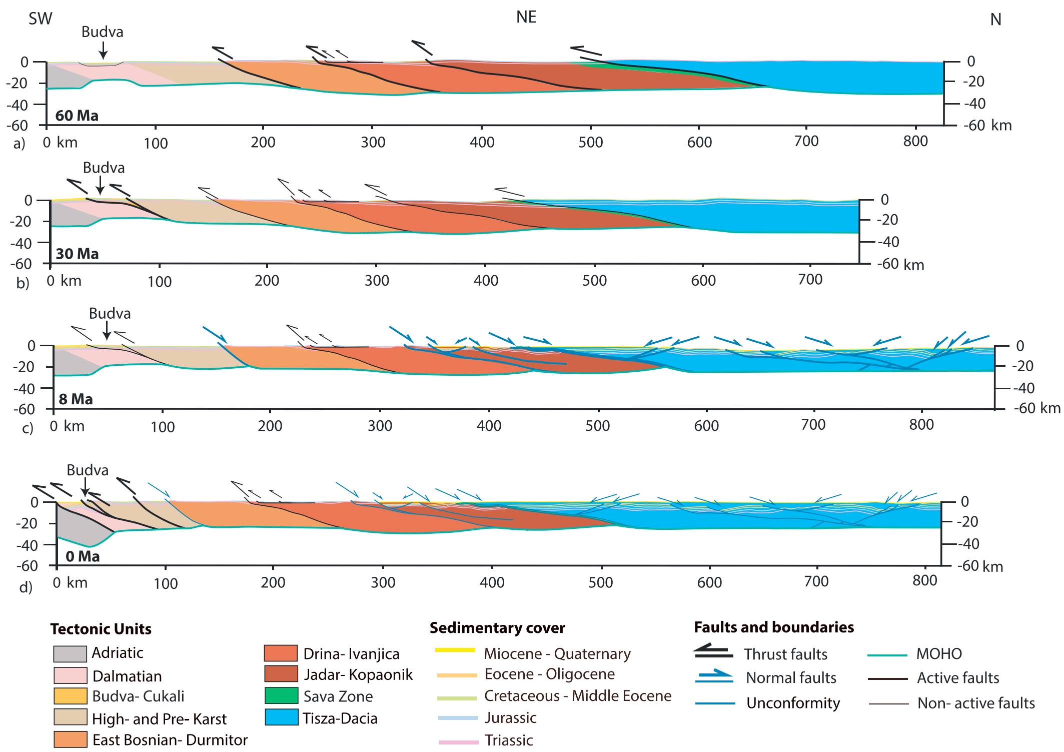

Figure 12. Kinematic reconstruction of a cross section that combines the crustal-scale cross section displayed in Figure 11b in the external part of the Dinarides with its prolongation in the internal part of the Dinarides, Sava Zone, and Tisza unit (modified after Balazs et al. 2017). The trace of the combined cross section is displayed in Figure 1 (gray line B-B′ - black dotted line). (a) The latest Cretaceous moment of continental collision resulted in the gradual migration of contractional deformation toward the orogenic foreland, associated with southwestward nappe stacking in the internal part of the Dinarides; (b) continued contraction until early Oligocene times affected mainly the external parts of the Dinarides, characterized by the southwestward nappe stacking of the High Karst and Budva units; (c) Miocene extension induced normal faulting and reactivation of former thrusts in the entire Dinarides, Sava Zone, and Tisza unit; (d) the N-S to NNE-SSW oriented contraction that started during latest Miocene times induced high-angle reverse faulting and reactivated former structures and nappe contacts in the Dinarides. The cross sections speculatively suggest that the unusual crustal root observed in the Adriatic unit is a combination between an originally thick Adriatic crust on the SW flank of the Budva graben and its post-middle Miocene thickening by the High Karst, Budva, and Dalmatian thrusting.

extensional fore-arc basin (Figure 1, Toljić et al., 2018). The effects of this ongoing Cretaceous subduction at farther distances from the Sava zone in the Dinarides are significantly reduced, mostly observed by a late Early Cretaceous moment of burial and the formation of a regional unconformity recorded in the internal part of the Dinarides (Ilić & Neubauer, 2005; Schefer, 2010). No clear effects of these deformation events can be defined in the studied area.

The large-scale deformation shows a gradual migration toward the orogenic foreland during the latest Cretaceous onset of continental collision (Figure 12a) and its continuation of contractional deformation until early Oligocene times (Figure 12b). This overall pattern was influenced by the preexistence of the Bosnian Flysch and the Budva unit, which contained rheological weak sediments and localized larger amounts of contractional deformation, although at different times. The main moment of latest Cretaceous continental collision was recorded especially at the contact between the Dinarides and European-derived units along the Sava zone and at the contact between the Jadar-Kopaonik and Drina-Ivanjica units (e.g., Schmid et al., 2008; Toljić et al., 2018; Ustaszewski et al., 2010). Significant deformation is documented by our study in the Bosnian Flysch zone, most likely an effect of localization along this inherited weakness zone. The continuation of contraction during Eocene-Early Oligocene concentrated in a second, more external rheological weak zone, the Budva unit of Montenegro (Figure 12b). However, given this unit gradual lateral reduction to disappearance along the strike of the orogen toward the NW, deformation becomes more regionally distributed in this direction along the entire High Karst to Dalmatian area, where a large number of thrusts with lower offsets are observed (comparing Figure 11a with Figure 11b). The total amount of Eocene-Early Oligocene offset is similar in both areas in the order of 30 km. In other words, the Eocene-Oligocene

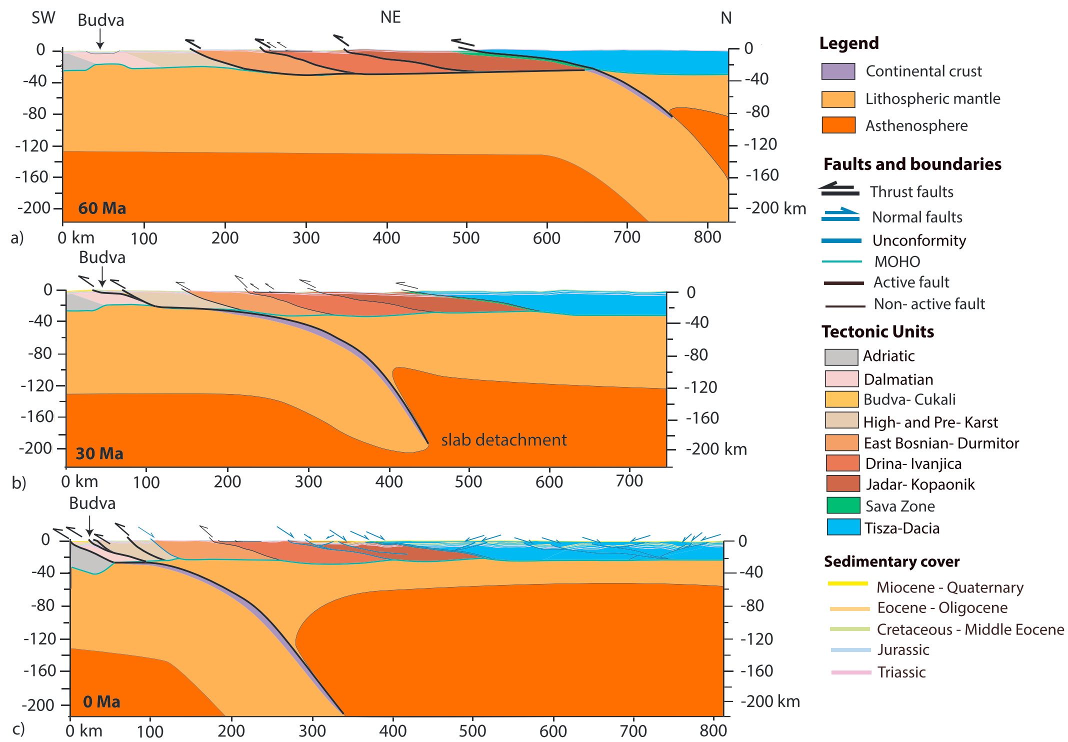

Figure 13. Schematic representation of the lithospheric evolution by using the reconstruction of the cross section displayed in Figure 12. (a) Immediately after the first stage of the latest Cretaceous collision (~60 Ma) we assumed that the location of the slab is in the prolongation of the Sava suture zone, which is in agreement with the position of the Late Cretaceous back-arc magmatism (see Gallhofer et al., 2015); (b) slab break-off took place during Oligocene times (~30 Ma), at a time when the slab was located more to the foreland, which is in agreement with the observed Eocene-Oligocene foreland migration of magmatism (see Andrić et al., 2018); (c) the crustal structure derived from the present study combined with the present-day lithospheric configuration indicates that the position of the detached slab is in the frontal part of the Dinarides orogen, which has been derived from teleseismic tomography (modified after Balazs et al., 2017).

shortening is similar along the strike of the orogen, but the deformation is largely localized in the Serbia-Montenegro transect due to the presence of the rheologically weaker sediments of the Budva unit. Elsewhere in more internal areas of the Dinarides, coeval deformation has significantly smaller effects in the order of hundreds of meters to possibly few kilometers. The Budva unit cannot reflect an oceanic suture zone connected to the present-day observed slab, because this unit does not retain any oceanic characteristics and pinches out along the orogenic strike toward the NW, in the SE Dinarides (Figure 11), while the high-velocity slab anomaly is continuous more to the NW. Therefore, the overall latest Cretaceous-Early Oligocene migration of peak deformation toward the orogenic foreland (Figure 12b) cannot have any other mechanism but a general migration of the subduction zone during collision (Figures 13a and 13b) on its way to the presently observed location in the frontal part of the orogen (Figure 13c). This mechanism is the only one compatible with the observed southwestward migration toward the orogenic foreland of the Cretaceous-Oligocene subduction-related magmatism that crosses the oceanic suture (Sava) zone (see discussion in Andrić et al., 2018; Cvetković et al., 2013). This mechanism is also compatible with the present thermal, crustal, and lithospheric configuration (Figure 13c) and with an overall migration of the onset of Dinarides extension, from Oligocene near the Sava zone (e.g., Erak et al., 2017; Stojadinović et al., 2017) to Miocene in their external parts.

The lithospheric configuration and evolution (Figure 13) as well as the overall pattern of foreland migration of deformation and slab retreat during continental collision is observed in many other orogens, such as the Carpathians, the Betics, or the Aegean system (e.g., Faccenna et al., 2014; Jolivet & Brun, 2010; Matenco et al., 2016; Vergés & Fernàndez, 2012). The migration implies a change in location of the subduction zone by accretion of continental material from the lower tectonic plate during collision. Such a gradual accretion of continental material and migration of the subduction zone in single-vergent orogens agrees with the prediction from numerical or analog modeling studies (Vogt, Matenco, et al., 2017; Vogt, Willingshofer, et al., 2017; Willingshofer et al., 2013). These studies have inferred that such orogenic wedges form when significant rheological decoupling exists between crustal and/or mantle lithospheric layers, or when the upper tectonic plate is rheologically stronger during collision. Such rheological inheritance may result in foreland migration of deformation and of the subduction zone that can be associated with significant amounts of continental subduction (Figure 13, Vogt, Willingshofer, et al., 2017; Vogt, Matenco, et al., 2017; Willingshofer et al., 2013). The main difference of the Dinarides in our studied sector is that the entire accretion of continental material during collision is inferred to be thick skinned, as opposed to for instance the Carpathians or the Apennines (e.g., Matenco et al., 2016; Picotti & Pazzaglia, 2008), where most of the accretion is thin skinned and only the last phases of deformation are thick skinned. Alternatively, one other explanation for the overall foreland migration observed in the Dinarides may be the indentation of the lower crust of the upper plate during collision, when only the overlying upper crust is being shortened (Andrić et al., 2018). In this hypothesis, decoupling between the upper and lower crust will create a midcrustal décollement level where all Late Cretaceous-Early Oligocene thrusts are rooted, which is less likely in our depth extrapolations (Figure 11).

Structural, kinematic, magmatism, and numerical modeling studies have inferred that slab detachment took place in the Dinarides during Oligocene times (Figure 13b; e.g., Andrić et al., 2018; Schefer et al., 2011). Our observation that the Miocene extension was observed in all areas of the Dinarides (Figure 12c) implies that this extension was related to a postorogenic process with respect to the Dinarides mechanics, which predated the onset of the Adriatic indentation during the latest Miocene (Figure 12d). Whether this postorogenic process is related to eduction (exhumation of the lower plate by reversing the motion of the subduction plane, e.g., Andersen et al., 1991; Andrić et al., 2018) during or after slab detachment or the typical gravitational collapse of an overthickened orogen is difficult to be quantified based only on crustal-scale information, as often discussed for instance in other Mediterranean orogens, such as the Betics-Rift system (e.g., Platt et al., 2013; Vergés & Fernàndez, 2012).

7. Conclusions

The field kinematic study and the construction of regional-scale transects in the central and SE part of the External Dinarides have demonstrated a long and polyphase tectonic evolution that started with the Middle Triassic rifting and continued with the Late Jurassic onset of orogenic deformations that are still presently active.

The Middle Triassic rifting is observed in the studied area by the formation of the Budva graben and widespread magmatism that has also created, north of our studied area, the Vardar branch of the Neotethys Ocean. The Middle Jurassic onset of oceanic subduction and intraoceanic obduction was followed by the Late Jurassic-Earliest Cretaceous emplacement of ophiolites and mélanges onto the Dinarides northern continental margin. The effects of this tectonic event were largely overprinted by reactivations during subsequent deformations, but few relict structures testifying the typical NW-SE direction of contraction were still observed in the Bosnian Flysch and the Budva unit of Montenegro.

This deformation was followed in the studied area by a long lasting latest Cretaceous-Early Oligocene continental collision. Although the effects of this tectonic event are observed in the entire studied area, our analysis of its maximum effects shows a gradual migration of the main deformation toward the orogenic foreland, interpreted to result from a migration of the subduction zone by continental accretion during collision.

Following the likely Oligocene moment of slab detachment, our study demonstrates that the Miocene extension previously observed in the internal Dinarides units has affected the entire orogen, including the external part of the Dinarides foreland. This extension may be related to either eduction during and after slab detachment or to the extensional gravitational potential collapse of an overthickened orogen after slab detachment.

The Miocene extension was followed by the latest Miocene onset of Adriatic indentation in the Dinarides, a process that is still active today and is not intrinsically related to the Dinarides orogenic evolution but likely related to the much larger Africa-Europe convergence.

The localization of latest Cretaceous-Early Oligocene shortening was significantly influenced by the existence of deep-water sediments, preconditioning rheological weakness zones in the Bosnian Flysch and the Budva unit of Montenegro. These units have localized large amount of thrusting during Late Cretaceous and Eocene, respectively. Although the total amount of latest Cretaceous-Early Oligocene deformation is similar in the two studied profiles, the lateral disappearance of the Budva unit to the NW and its rheological weakness along the strike of the orogen has distributed the localized deformation over a much larger area to the north in the High Karst and Dalmatian units. The specificity of the Dinarides collision is the thick-skinned accretion that was active during the entire collisional moment. Interesting is also that the continental subduction has continued after slab detachment and postorogenic extension, driven by the subsequent Adriatic indentation. The differential and rotational ~N-S to NE-SW direction of indentation, when compared with the overall NW-SE strike of the inherited orogen, has resulted in localization of oblique thrusting along the inherited rheological weak zones that were connected by a system of strike-slip and high-angle reverse faults elsewhere. This overall evolution shows that the evolution of the Dinarides was driven initially by the evolution of its genetically related slab. Once this slab was detached, the Dinarides evolution was conditioned by the more regional mechanism of Adriatic indentation, which has similar continental subduction effects, but with slightly different kinematics. Such a differentiation between two different geodynamic mechanisms, producing similar effects during mountain building, is very interesting also for other orogens situated elsewhere. Therefore, the Dinarides may represent a prime example of such a geodynamic juxtaposition.

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