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RESEARCH ARTICLE

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Towards resolving Cretaceous to Miocene kinematics of the Adria–Europe contact zone in reconstructions: Inferences from a structural study in a critical Dinarides area

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Abstract
One key element in the current debate analysing the Central Mediterranean evolution is the Cretaceous structure and kinematics of the present-day oroclinal bent contact between Adria- and Europe-derived continental units in the Dinarides, interpreted in different tectonic reconstructions as a subduction-related thrust system or a large-scale strike-slip fault zone. We provide a solution to the debate by a structural and kinematic study in a key area located in central Serbia along the Europe–Adria orogenic suture of the Sava Zone. The results demonstrate that large-scale, top-SW, in- to out-of-sequence thrusting is the dominant mechanism that deformed the observed accretionary wedge-trench sediments during the Late Cretaceous subduction of the Neotethys Ocean and the ensuing Adria–Europe collision. The subsequent Oligocene–Miocene extension of the Pannonian Basin was associated with opposite-sense rotations of different Sava Zone segments, which created the observed ~80° oroclinal bending.

1 | INTRODUCTION

The evolution of the Central Mediterranean has been the subject of many tectonic reconstruction studies (e.g. Barrier, Vrielynck, Brouillet, & Brunet, 2018; Csontos & Voros, 2004; Dercourt et al., 1986; Handy, Ustaszewski, & Kissling, 2015; Jolivet & Faccenna, 2000; Le Breton et al., 2021; Ricou, 1994; Stampfli & Kozur, 2006; Ustaszewski et al., 2008; van Hinsbergen et al., 2020). One of the key remaining issues in these reconstructions is the kinematics of the Adria–Europe convergence in the Dinarides, particularly during the Late Cretaceous–Palaeogene formation of their orogenic suture, known as the Sava Zone (Figure 1a, Pamić, 2002; Schmid et al., 2020). Reconstructions accounting for high-resolution kinematic data in the Alps (Handy et al., 2015; Le Breton et al., 2021) postulate large-scale Late Cretaceous–Palaeogene dextral transcurrent motions along the Dinarides contact between Adria- and Europe-derived Tisza and Dacia units (Figure 1b). In contrast, reconstructions accounting for detailed kinematics in all Central Mediterranean orogens (van Hinsbergen et al., 2020, based on Schmid et al., 2020) infer distributed thrusting during the same period, reaching maximum shortening during the latest Cretaceous (Figure 1c). The result is a significantly different Cretaceous palaeogeography and tectonic plates configuration in available quantitative reconstructions.

Studying the Cretaceous kinematics of the Adria–Europe contact is complex because the Sava Zone was subsequently reactivated almost along its entire Dinarides strike by extensional detachments during the Pannonian Basin formation (e.g. Fodor et al., 2021; Matenco & Radivojević, 2012). This resulted in extensive erosion of Cretaceous sediments from the suture zone or their burial beneath an Oligocene–Miocene overburden. Furthermore, the Sava Zone and large parts of the Dinarides–Hellenides orogenic system show a remarkable ~80° oroclinal change in the strike from ~E–W to ~N–S in present-day configuration (Figure 1a). This change in the strike is thought to be related to the roll back in the Carpathians and/or the Aegean area, inducing partial clockwise rotation of the inner Dinarides (Schmid et al., 2020), possibly connected with an inherited major Neotethys transform fault at the Dinarides–Hellenides transition (i.e. the Scutari-Peć lineament, Aubouin & Dercourt, 1975; Bernoulli & Laubscher, 1972; Dercourt, 1968; Handy et al., 2019).

Along the strike of the Sava Zone in the Dinarides, the Rudnik area in central Serbia is one of the few regions where Cretaceous sediments are largely exposed and are less affected by the subsequent extension of the Pannonian Basin (Figure 2a). This is the best-suited location to understand the Cretaceous–Palaeogene kinematics of the Adria–Europe convergence and resolve discrepancies in palaeogeographic reconstructions. To this aim, we conducted a field structural and kinematic study along ~100 km E–W oriented transect that cross-cuts the Cretaceous sediments of the Sava Zone (Figure 2b). We identified the main structural units and tectonic contacts and analysed their kinematics. We furthermore conducted a map-view restoration based on existing regional kinematic and palaeomagnetic data to understand the timing and effects of the observed ~80° Sava Zone oroclinal bending and reconstruct the suture geometry after the Late Cretaceous–Eocene orogenic build-up.

Statement of significance

This study aims to define the Cretaceous kinematics of the Adria–Europe contact zone and the relationship with its presently observed oroclinal bending in a key segment of the Dinarides orogen, which is important to resolve the current debate in Central Mediterranean tectonic reconstructions. We analyse the tectonic mechanism that controlled the deformations in a Cretaceous accretionary wedge-trench system during the subduction of the Neotethys and the collision between Adria- and Europe-derived continental units sutured along the Sava Zone. The results demonstrate that in- to out-of-sequence thrusting is the main mechanism of deformations during Late Cretaceous to Eocene times, prior to the Oligocene–Miocene formation of the Pannonian Basin. Furthermore, we analyse the mechanics and reconstruct the evolution of the observed ~80° oroclinal bending of the sutured Sava Zone, while concluding that the observed kinematics is at odds with Central Mediterranean reconstructions assuming large-scale Cretaceous transcurrent motions along the Dinarides margins.

2 | THE EVOLUTION OF THE ADRIA–EUROPE CONVERGENCE ZONE IN THE STUDIED SEGMENT OF THE DINARIDES

The convergence between Adria- and Europe-derived continental units took place during the Late Jurassic to Eocene closure of the northern segment of the Neotethys (or Vardar) Ocean (e.g. Dimitrijević, 1997). Following the latest Jurassic–earliest Cretaceous bi-vergent obduction of ophiolites over both continental margins and associated thrusting (the Western and Eastern Vardar Ophiolitic units of Schmid et al., 2008, Figure 2a, see also Porkoláb et al., 2019),

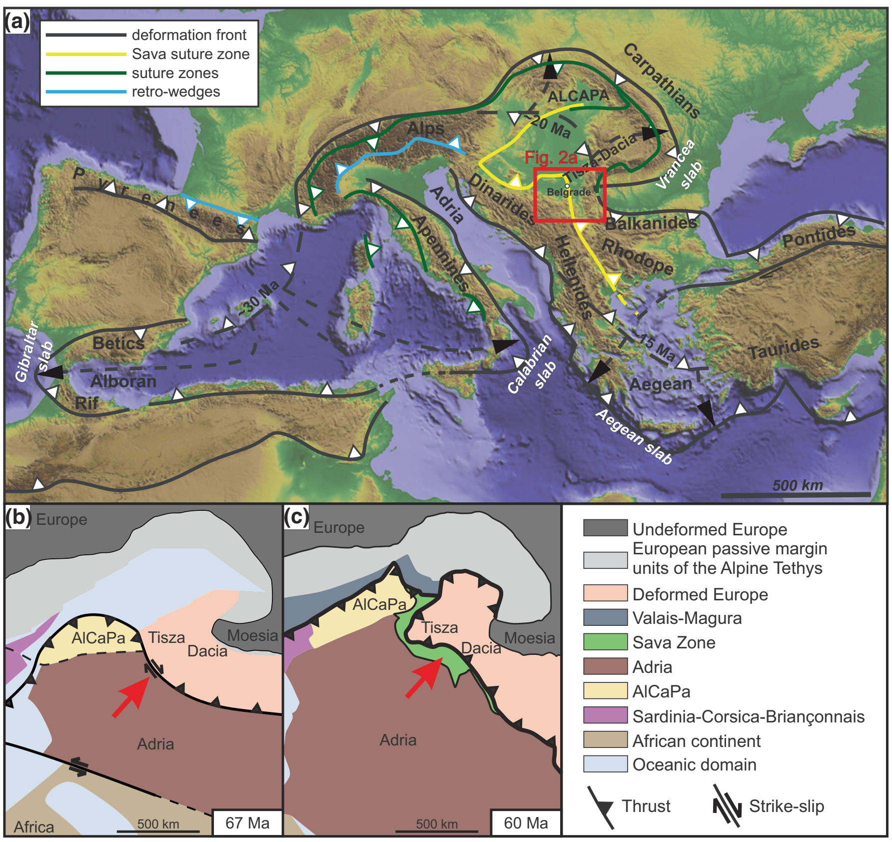


FIGURE 1 (a) Topographic map of Mediterranean Mesozoic–Cenozoic orogens, displaying suture zones, orogenic fronts, and retro-wedges (modified after Krstekanić et al., 2020). The red rectangle indicates the location of Figure 2a; (b) palaeogeographic and geodynamic reconstruction of the Europe–Adria interaction during the Late Cretaceous–Palaeogene times simplified from Le Breton et al. (2021). Strike-slip deformation along the Sava zone is indicated by the red arrow; (c) palaeogeographic and geodynamic reconstruction of the Europe–Adria interaction during the Late Cretaceous–Palaeogene times simplified from van Hinsbergen et al. (2020). Shortening along the Sava zone is indicated by the red arrow. [Colour figure can be viewed at wileyonlinelibrary.com]

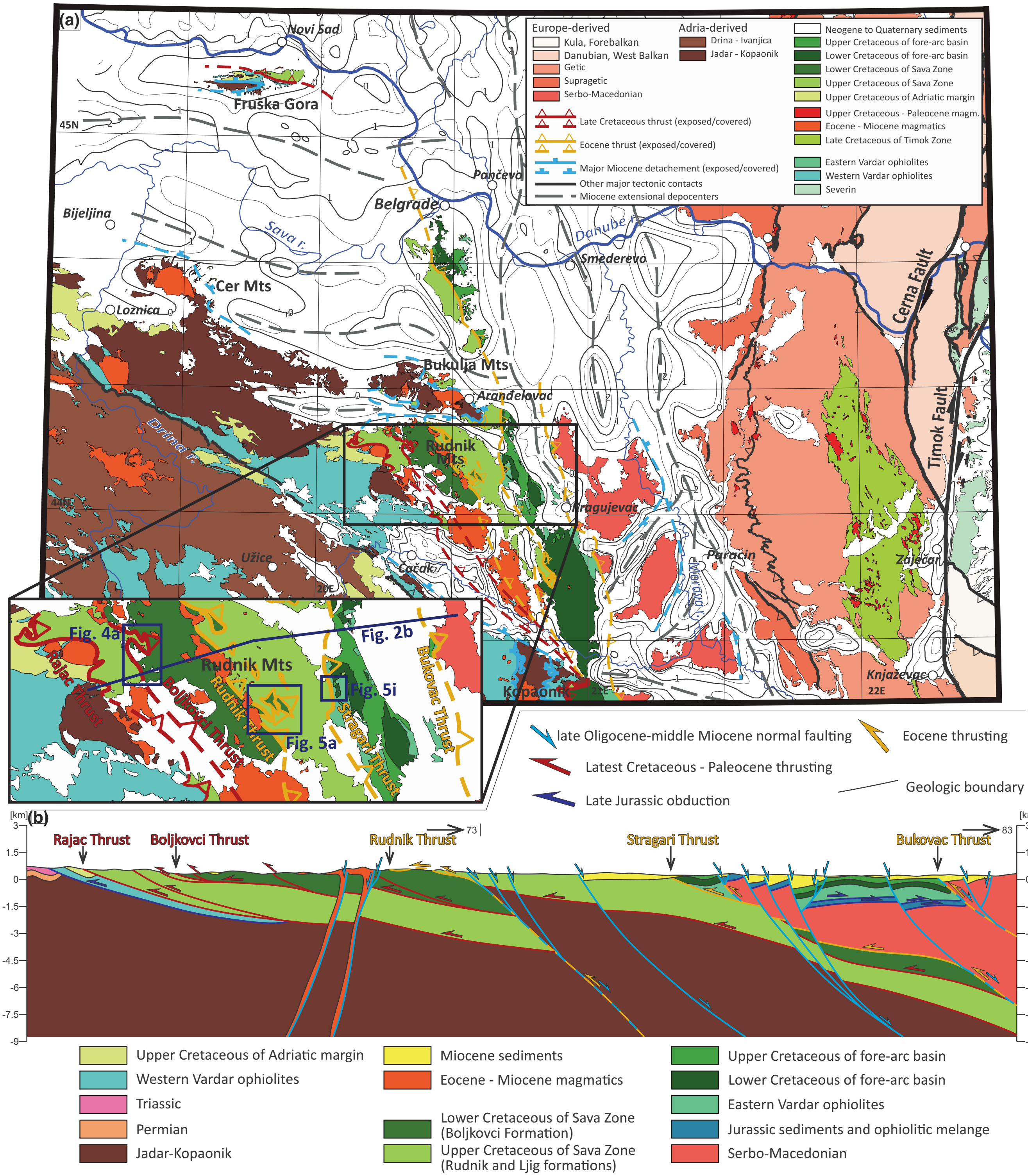


FIGURE 2 (a) Geological map of the connection between the Dinarides, South Carpathians and Pannonian Basin, with the zoom-in view of the study area delimited by the black rectangle (modified after Matenco & Radivojević, 2012). Blue rectangles in the zoom-in indicate the location of local geological maps in Figures 4 and 5, and the thick blue line indicates the location of the cross-section in (b). The location of major detachments and large-offset normal faults is displayed in the figure. Other normal faults with smaller offsets are ignored for the clarity of lateral prolongation along major Cretaceous–Eocene thrusts, including their reactivations; (b) cross-section across the Dinarides–Carpathians connection. Surface to depth projection in the cross-section is based on the field data from this study and the basic geological map of former Yugoslavia. The strike azimuth of the cross-section is indicated in the upper right corner of the section. No vertical exaggeration has been applied. [Colour figure can be viewed at wileyonlinelibrary.com]

the Early Cretaceous subduction of the remaining Neotethys oceanic lithosphere beneath the European margin led to the deposition of trench sediments subsequently incorporated into an accretionary wedge. The ongoing Late Cretaceous subduction accelerated the subsidence of the downgoing Adriatic margin, accompanied by continued accretion of trench sediments. The latest Cretaceous onset of collision initiated the Europe–Adria suturing along the Sava Zone (Ustaszewski et al., 2010). Shortening continued during Eocene with larger effects towards the external Dinarides and was followed by an Oligocene–Miocene bi-directional extension that formed the Pannonian Basin and affected also larger areas in the Dinarides and Carpathians (e.g. Matenco & Radivojević, 2012). A roughly E–W oriented extension started during the Oligocene along the Morava River corridor (Figure 2a), while gradually expanding N-wards and changing to a N–S direction during the Miocene. The extension created a number of detachments or large-offset normal faults separating half-grabens with top-E and top-N sense of shear, reactivating the Sava Zone and its vicinity (Figure 2a, Ustaszewski et al., 2010; Balázs, Matenco, Magyar, Horváth, & Cloetingh, 2016; Erak et al., 2017; Stojadinovic et al., 2017). The extension produced significant crustal thinning, with the thickness decreasing from 33 km in the south to 22 km northwards in the main Pannonian Basin depocentres (e.g. Horváth et al., 2015). Since the early Miocene, the extension was also associated with significant rotations recorded in different segments of the reactivated Sava Zone (Lesić, Marton, & Cvetkov, 2007; Lesić, Marton, Gajić, Jovanović, & Cvetkov, 2019; Márton, Pavelić, Tomljenović, Pamić, & Márton, 1999; Márton, Toljić, & Cvetkov, 2022).

2.1 | Cretaceous sedimentation in the Sava zone

The Cretaceous sedimentation in the proximity of the Sava Zone varies laterally and can be described in terms of sediments deposited on and still overlying the Adriatic margin, displaced accretionary wedge sediments of the Sava Zone, and sediments deposited in a fore-arc basin over the European margin (Figure 3). Three fore-arc depositional cycles were identified during the Early to

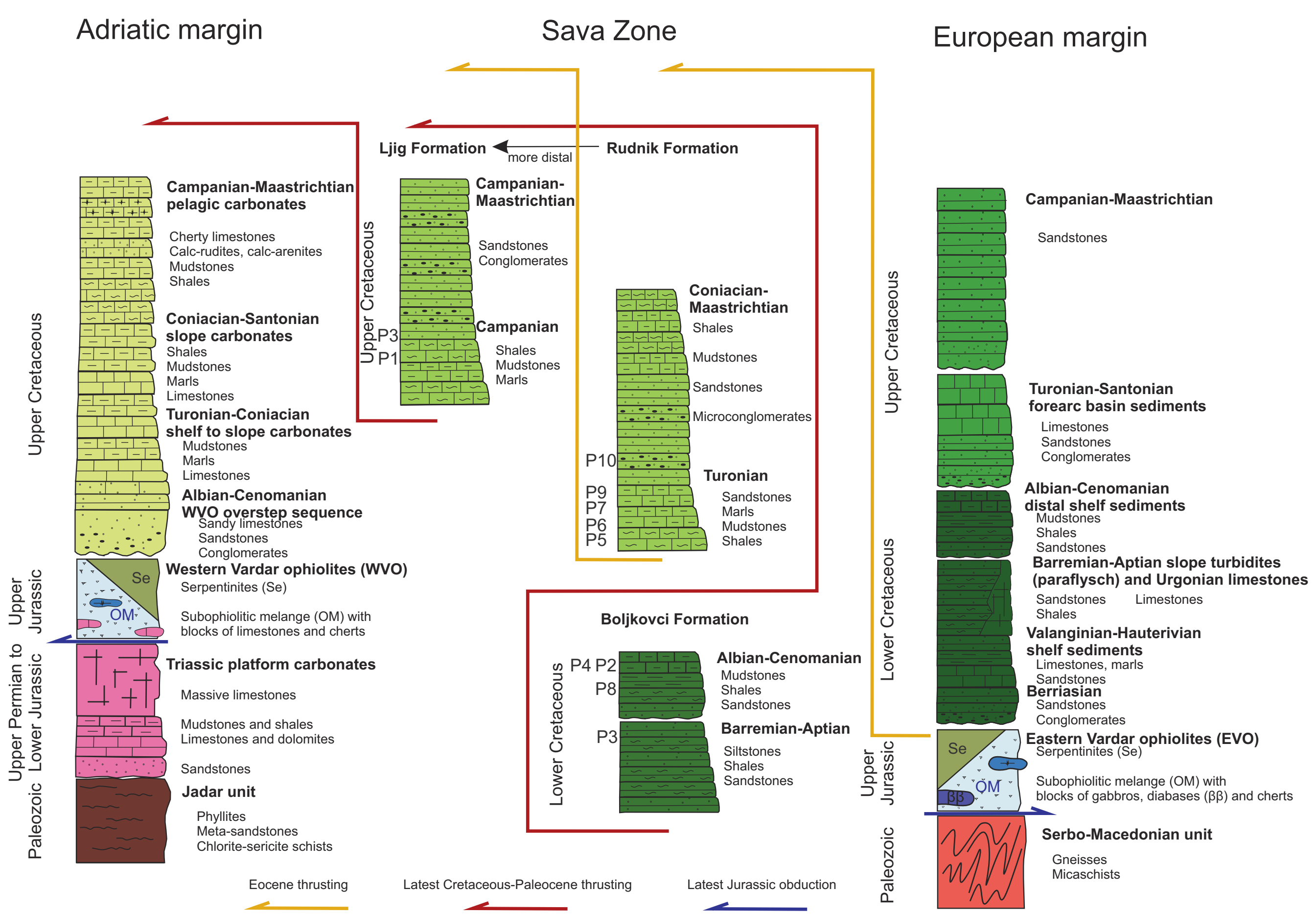


FIGURE 3 Correlation between Cretaceous deposition along the Adriatic margin, in the Sava zone, and along the European margin (modified after Brković, Radovanović, & Pavlović, 1979; Filipović et al., 1976; Gajić, 2014; Nirta et al., 2020; Obradović, 1987; Toljić et al., 2018). Blue arrows mark the latest Jurassic obduction-related thrusting. Red arrows mark the latest Cretaceous–Palaeocene thrusting during the onset of the Adria–Europe collision. Yellow arrows mark Eocene out-of-sequence thrusting during the final stages of collision. P1–P10 indicate the approximate position of observation points in geological columns. Spatial locations of observation points are indicated in Figures 4 and 5. [Colour figure can be viewed at wileyonlinelibrary.com]

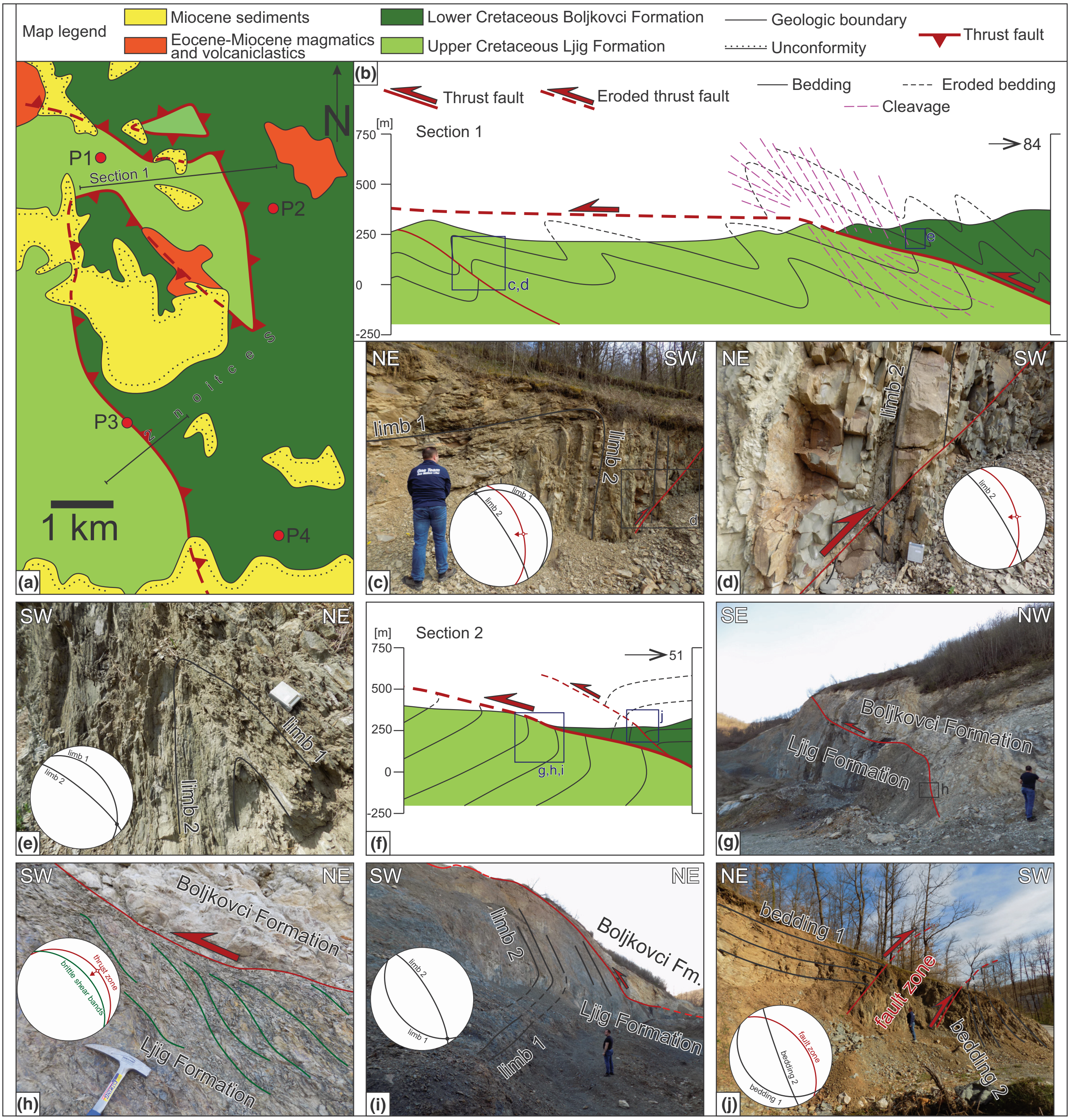
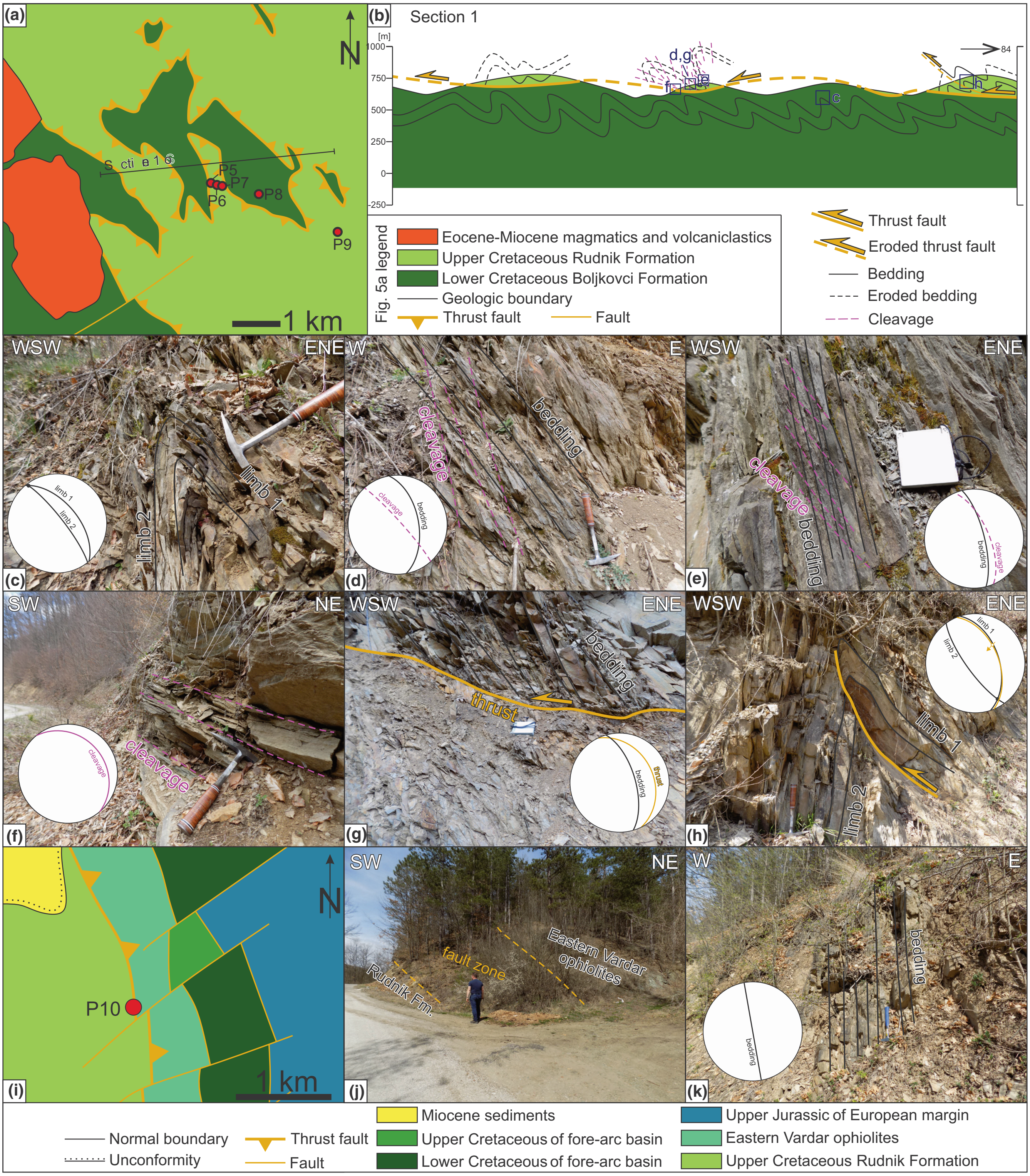


FIGURE 4 (a) Local geological map of the segment of the Boljkovci thrust where the Lower Cretaceous sediments of the Boljkovci formation structurally overlie Upper Cretaceous turbidites of the Ljig formation. Straight lines indicate locations of cross-sections in (b and f); (b) structural cross-section of folded and faulted Sava trench turbidites across the ramp-flat geometry of Boljkovci thrust. Blue rectangles and letters c-e indicate the approximate position of outcrop-scale structures in (c–e), respectively; (c) southwest-vergent overturned fold in the Campanian turbidites of the Ljig formation. The overturned fold limb is truncated by top-W reverse fault. Observation point P1; (d) top-W reverse fault truncating overturned limb of the fold in (c). Observation point P1; (e) tight southwest-vergent overturned fold in the Albian–Cenomanian mudstones and shales of the Boljkovci formation. Observation point P2; (f) structural cross-section of the immediate vicinity of the Boljkovci thrust. Blue rectangles and letters (g–j) indicate the approximate position of outcrop-scale structures in (g–j), respectively; (g) Boljkovci thrust separating the Lower Cretaceous sediments of the Boljkovci formation in the hangingwall and the Upper Cretaceous trench turbidites of the Ljig formation in the footwall at the observation point P3. The black rectangle indicates the position of (h); (h) detail of the shear zone at the contact of the Boljkovci and Ljig formations at the observation point P3. Brittle shear bands in the several meters thick shear zone indicate top-SW thrusting; (i) SW-vergent overturned to recumbent syncline in the Upper Cretaceous turbidites in the immediate footwall of the Boljkovci thrust. Observation point P3; (j) NW-SE oriented reverse fault zone truncating and tilting Lower Cretaceous sediments in the hangingwall of the Boljkovci thrust at the observation point P4. [Colour figure can be viewed at wileyonlinelibrary.com]



Late Cretaceous (Figure 3), reflecting three stages of deformation, contractional, extensional and ultimately contractional again during the collision (Toljić, Matenco, Stojadinović, Willinshofer, & Ljubović-Obradović, 2018). The Cretaceous sedimentation in the inner Dinarides was associated with an overall Late Cretaceous transgressive cycle, demonstrating progressive deepening of the distal Adriatic margin (Figure 3).

The sedimentation in the Sava Zone is characterized by Cretaceous turbidites and pelagic sediments incorporated in an accretionary wedge system (Figure 3). The observed sedimentation started with Barremian–Aptian distal clastic turbidites, followed by Albian–Cenomanian laminated clastics and carbonates (i.e. the Boljkovci Formation, Figure 3). These sediments were gradually accreted to the upper plate into an accretionary wedge. Turbiditic

FIGURE 5 (a) Local geological map of the segment of the Rudnik thrust where the Upper Cretaceous trench turbidites of the Rudnik formation structurally overlie the Lower Cretaceous sediments of the Boljkovci formation. The Lower Cretaceous sediments outcrop west of the Rudnik thrust and in several erosional windows. The straight line indicates the location of the cross-section in (b). (b) Structural cross-section of folded and faulted sediments of the Rudnik and Boljkovci formations separated by the Rudnik thrust. Blue rectangles and letters (c–h) indicate the approximate position of outcrop-scale structures in (c–h), respectively; (c) tight to isoclinal overturned SW-vergent fold in the Albian–Cenomanian sediments of the Boljkovci formation at observation point P8; (d) Normal bedding with high-angle cleavage in the Upper Cretaceous turbidites of the Rudnik formation. Observation point P6; (e) overturned bedding indicated by lower angle cleavage in the Upper Cretaceous trench turbidites. Observation point P7; (f) Rudnik thrust-parallel low-angle axial plane cleavage in the immediate hangingwall at observation point P5; (g) low-angle reverse fault truncating mid- to high-angle bedding of the Upper Cretaceous trench turbidites in the immediate hangingwall of the Rudnik thrust. Observation point P6; (h) top-SW reverse fault with associated fault-propagation fold in the Upper Cretaceous trench turbidites at observation point P9; (i) local geological map of the segment of the Stragari thrust where the Upper Cretaceous Sava trench turbidites of the Rudnik formation are thrust by the eastern Vardar ophiolites and their overlying Cretaceous fore-arc sediments; (j) the ~ENE-dipping Stragari thrust fault zone juxtaposing the eastern Vardar ophiolites and the Sava trench turbidites of the Rudnik formation at observation point P10; (k) vertical bedding in the Upper Cretaceous Sava trench turbidites in the immediate footwall of the Stragari thrust. Observation point P10. [Colour figure can be viewed at wileyonlinelibrary.com]

sedimentation continued during the Late Cretaceous, with Turonian distal mudstones overlain by the distal Coniacian–Maastrichtian clastic–carbonatic turbidites of the Upper Cretaceous Rudnik Formation. Transgressive enlargement of the sedimentation zone during the Campanian–Maastrichtian led to the deposition of siliciclastic turbidites of the Ljig Formation (Figure 3).

3 | METHODOLOGICAL APPROACH

The studied ~100 kilometres E–W oriented transect in the Rudnik area (Figures 2a,b) shows intensively deformed Cretaceous sediments, visible in outcrops by thrust faults or shear zones and folds, while several regional-scale faults were previously recognized in the available geological maps (Basic geological map of Yugoslavia scale 1:100,000, sheets Gornji Milanovac and Kragujevac). The field mapping was focused on analysing the deformation along these large-offset faults or their immediate vicinity. We used folding patterns and geometries, their relationship and superposition with observed faults and shear zones and their kinematics, to derive the tectonic transport and sequence of deformation. The measured structures show a clear pattern that allowed the interpretation of (post-) Cretaceous structural evolution and correlation with regional kinematic and palaeomagnetic studies.

3.1 | Geometry and kinematics of regional structures in the Sava zone

The Upper Cretaceous Ljig Formation is thrust by the Lower Cretaceous Boljkovci Formation along the Boljkovci Thrust (Figures 2a,b, and 4a). This thrust has a low-angle, flat-ramp geometry and significantly deforms sediments in both the footwall and hangingwall (Figure 4b) by asymmetric SW-vergent overturned tight to isoclinal folding (Figures 4c–e) indicating top-SW tectonic transport. The Boljkovci Thrust outcrops directly at observation point P3 (Figure 4a) where a several meters thick low-angle reverse shear zone separates the Lower Cretaceous and Upper Cretaceous trench sediments (Figures 4f,g). In detail, this shear zone displays brittle shear bands (Figure 4h) indicating top-SW thrusting along the Boljkovci Thrust. The thrusting tilted and folded the Upper Cretaceous turbidites into an overturned decametre-size SW-vergent syncline (Figures 4f,i). Locally, coeval lower-offset second-order thrusts formed either by shearing along the axial plane cleavage, observed in the footwall (Figures 4b–d), or by ramping up from the Boljkovci Thrust in the hangingwall, which tilted the Lower Cretaceous sediments (Figures 4f,j).

Eastwards, the Upper Cretaceous Rudnik Formation structurally overlies the Lower Cretaceous Boljkovci Formation along the Rudnik Thrust (Figures 2a,b, and 5a). The hangingwall made up by the Upper Cretaceous turbidites is relatively thin in the frontal parts of the nappe, while the sub-horizontal frontal contact exposes the footwall in several erosional tectonic windows (Figures 2a and 5a,b). These footwall sediments are folded in ~SW-vergent overturned decametre-size folds (Figure 5b) and smaller, decimetre-scale tight to isoclinal SW-vergent folds (Figure 5c). The hangingwall sediments display similar high-angle bedding that is folded in decametre-scale ~SW-vergent folds documented by the relationship between bedding and axial plane cleavage (Figures 5d,e). This folding indicates top-SW tectonic transport along the Rudnik Thrust. In contrast with the high-angle intensely folded bedding of both hanging and footwall, the contact between the two is observed to be a low-angle to sub-horizontal thrust (Figure 5b) documented by thrust-parallel cleavage (Figure 5f) and faults with 5–10 cm thick fault gouge (Figure 5g). In the hangingwall, SW-vergent fault-propagation folds were observed (Figure 5h), related to top-SW second-order thrusting by ramping up from the Rudnik Thrust (Figure 5b).

Further eastwards, the fore-arc sediments and their underlying Eastern Vardar ophiolites are thrust on top of the Sava Zone turbidites along the Stragari Thrust (Figures 2a,b, and 5i). This thrust is associated with ~10 m thick fault gouge zone (Figures 5j), while the bedding in the Upper Cretaceous Sava turbidites of the Rudnik Formation is tilted to vertical positions in its footwall (Figure 5k).

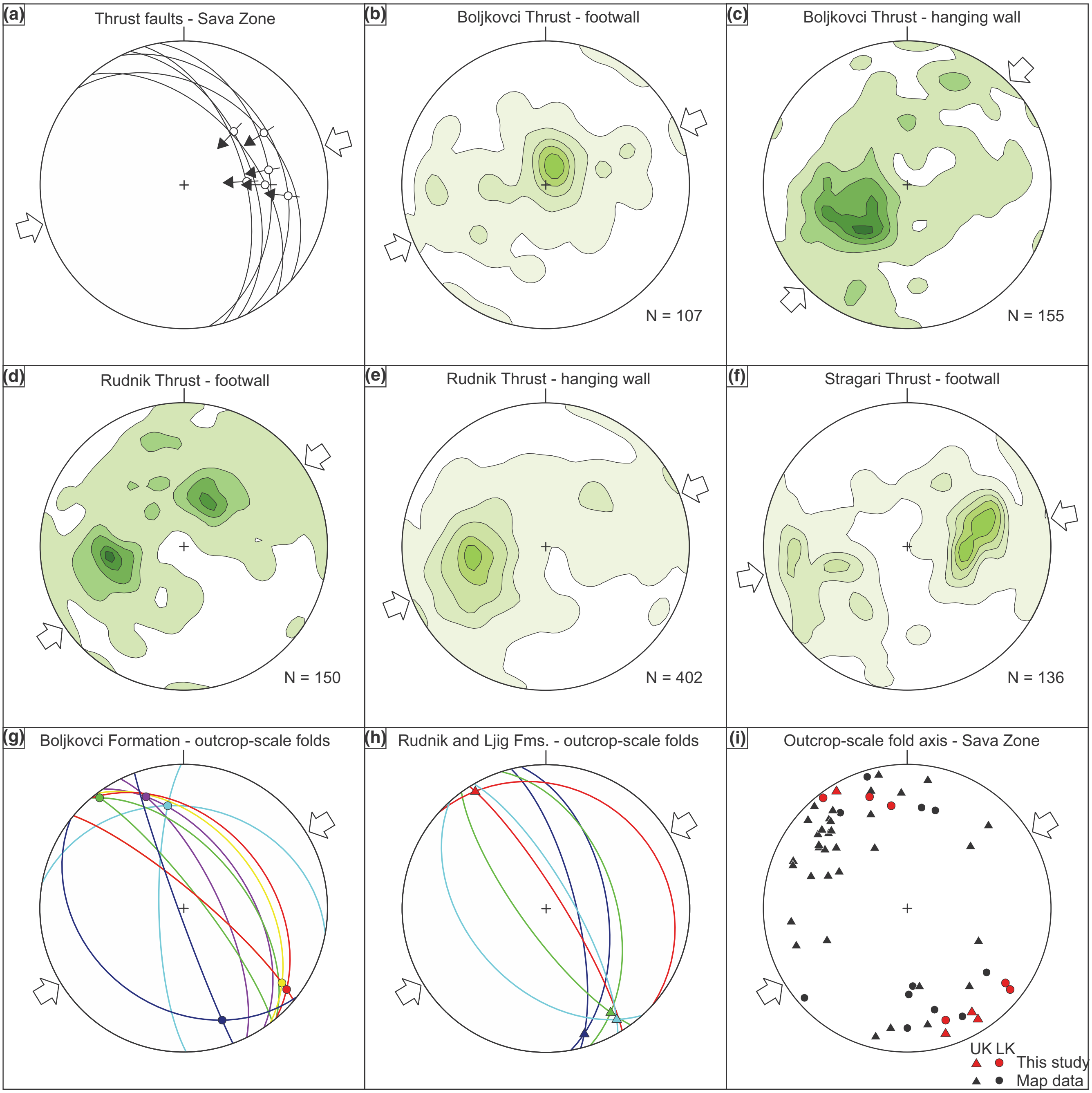


FIGURE 6 Stereoplots of cumulated structural data from this study and geological maps for the studied area. (a) Stereonet projections of all reverse faults and their kinematics observed in outcrops. (b–f) Density contours of poles to bedding in Cretaceous sediments in immediate footwalls and hangingwalls of Boljkovci, Rudnik and Stragari thrusts for the areas in Figures 4a and 5a,i. The colour of the maximum area corresponds to the colours of the Lower Cretaceous and Upper Cretaceous sediments in maps in Figures 1–4. (b) The maximum bedding dip direction/dip is 198/11. Dissipation of data towards NE and SW indicates local folding and tilting in the footwall of the Boljkovci thrust due to NE–SW contraction. (c) The maximum bedding dip direction/dip is 41/37 which indicated dominant SW-vergent tilting. Dissipation and several sub-maximums that show SW dip direction indicate, together with dominant NE dip, asymmetric SW-vergent folding in the hangingwall of the Boljkovci thrust. (d) The maximum bedding dip direction/dip is 81/42 and the sub-maximum is 209/28. This indicates folding due to the NE–SW contraction in the footwall of the Rudnik thrust. (e) The maximum bedding dip direction/dip is 81/42 and the sub-maximum is 225/41. The dominant ENE dip direction and local SW dip-direction indicate asymmetric folding in the hangingwall of the Rudnik thrust due to NE–SW contraction. (f) The stretched maximum bedding dip direction/dip has peaks in 254/46 and 274/34 and the sub-maximums are 76/42 and 86/69. This indicates strong tilting in the footwall of the Stragari thrust and local folding, all due to ENE–WSW contraction. (g, h) Stereonet projections of outcrop-scale observed folds in the Lower Cretaceous Boljkovci formation and the Upper Cretaceous Rudnik and Ljig formations, respectively. Fold limbs related to the same observed fold, as well as the fold axis are in the same colour. All fold vergence indicate top-SW tectonic transport and NE–SW shortening. (i) Cumulated stereonet projections of outcrop-scale fold axes observed during this study (red) and from the geological maps (black) in both Lower Cretaceous (LK, circles) and Upper Cretaceous sediments (UK, triangles). Fold axes dominantly demonstrate NE–SW shortening. [Colour figure can be viewed at wileyonlinelibrary.com]

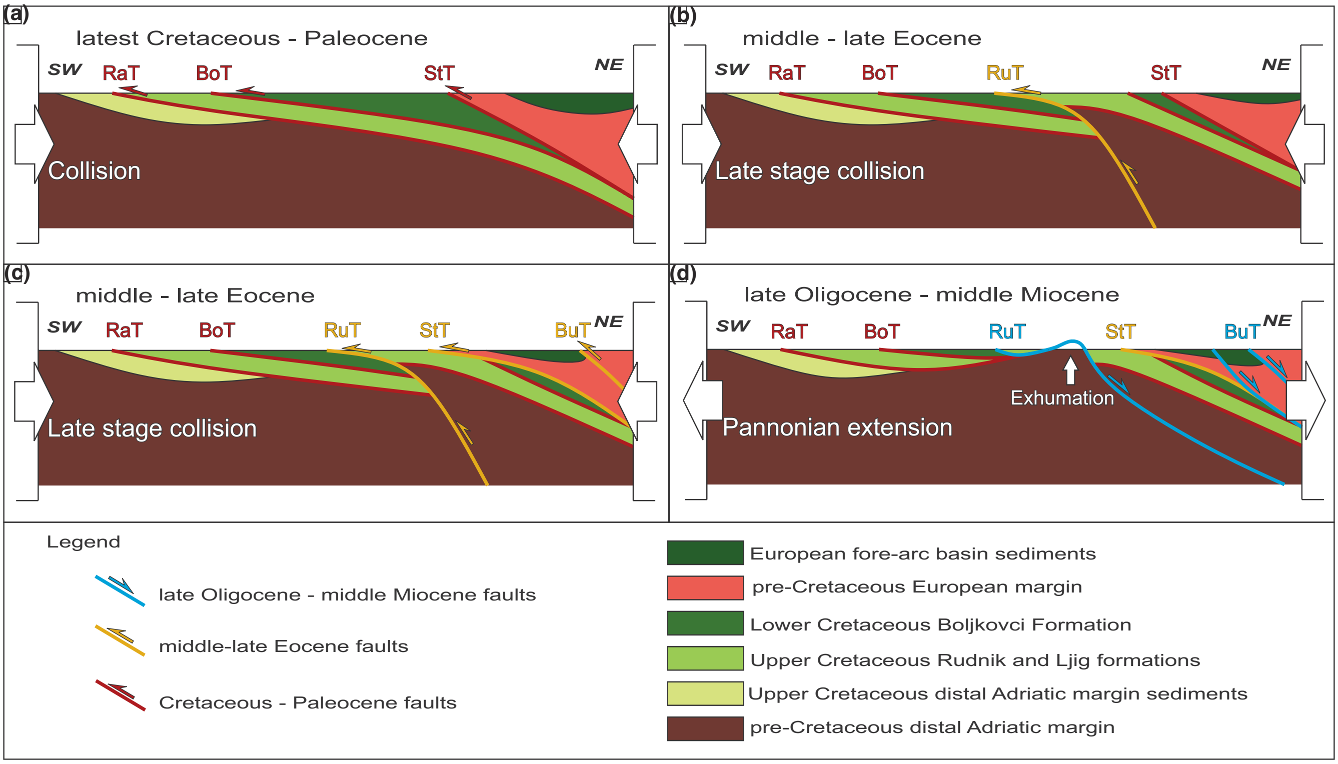


FIGURE 7 Conceptual cross-section sketch of the evolution of the Adria–Europe convergence zone in Central Serbia during Late Cretaceous–Miocene times. RaT—Rajac thrust, BoT—Boljkovci thrust, StT—Stragari thrust, RuT—Rudnik thrust, BuT—Bukovac thrust. (a) Latest Cretaceous to Palaeocene continental collision and SW-ward thrusting of the European fore-arc basin and its basement and Lower Cretaceous Sava sediments of the Boljkovci formation over the Upper Cretaceous Sava trench turbidites of the Rudnik and Ljig formations and distal Adriatic margin deposits; (b) middle to late Eocene out-of-sequence thrusting and exhumation of the Upper Cretaceous Sava trench turbidites of the Rudnik formation underneath the overlying Lower Cretaceous deposits of the Boljkovci formation along the thick-skinned Rudnik thrust; (c) ongoing out-of-sequence reactivation of the Stragari thrust and overthrusting of the European units over the Upper Cretaceous Sava trench turbidites of the Rudnik formation, followed by further out-of-sequence thrusting of the European basement on top of the fore-arc basin along the Bukovac thrust. (d) Oligocene–Miocene extensional reactivation of segments of the inherited thrusts and exhumation of the Adria lower plate outside of the studied area. [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Kinematic evolution of the Sava zone in Central Serbia

The structural pattern of the Sava Zone shows consistent NE–SW shortening that uniformly affected both Lower Cretaceous and Upper Cretaceous trench turbidites (Figure 6). All structural features, including top-W to SW low-dipping reverse faults (Figure 6a), folding and tilting of sediments in footwalls and hangingwalls of major thrusts (Figures 6b–f), and SW-vergent outcrop-scale tight to isoclinal and recumbent folds (Figures 6g,h) with NW–SE oriented fold axes (Figure 6i), demonstrate top-SW tectonic transport across the entire suture zone. All these observations indicate that large-scale top-SW thrusting is the main kinematic mechanism of the Late Cretaceous–Eocene Adria–Europe suturing.

During this Adria–Europe collision, the Cretaceous sedimentary cover of the Adriatic margin was thrust by the Upper Cretaceous trench turbidites of the Ljig Formation along the basal Sava Zone thrust (i.e. the Rajac thrust, Figure 7a). Coevally, the Lower Cretaceous sediments of the Boljkovci Formation were thrust over the Upper Cretaceous turbidites of the Ljig and Rudnik formations along the Boljkovci thrust (Figures 2b and 7a). During the middle to late Eocene final stages of collision, thick-skinned out-of-sequence thrusting along the Rudnik Thrust (Figures 2b and 7b) exhumed the Upper Cretaceous turbidites of the Rudnik Formation underneath the overlying Lower Cretaceous Boljkovci Formation. The coeval apatite fission-track cooling ages obtained from the Upper Cretaceous turbidites in the hangingwall of the Rudnik thrust confirm the Eocene exhumation (Stojadinovic et al., 2017). Further out-of-sequence thrusting emplaced European fore-arc on top of the Upper Cretaceous Rudnik Formation and European metamorphic basement on top of the fore-arc sediments (Stragari and Bukovac thrusts, respectively, Figures 2b and 7c; see also Toljić et al., 2018). The subsequent Oligocene–Miocene extension reactivated or truncated segments of the inherited thrusts and exhumed the Adria plate margin outside the studied area along a series of extensional detachments (Figure 7d).

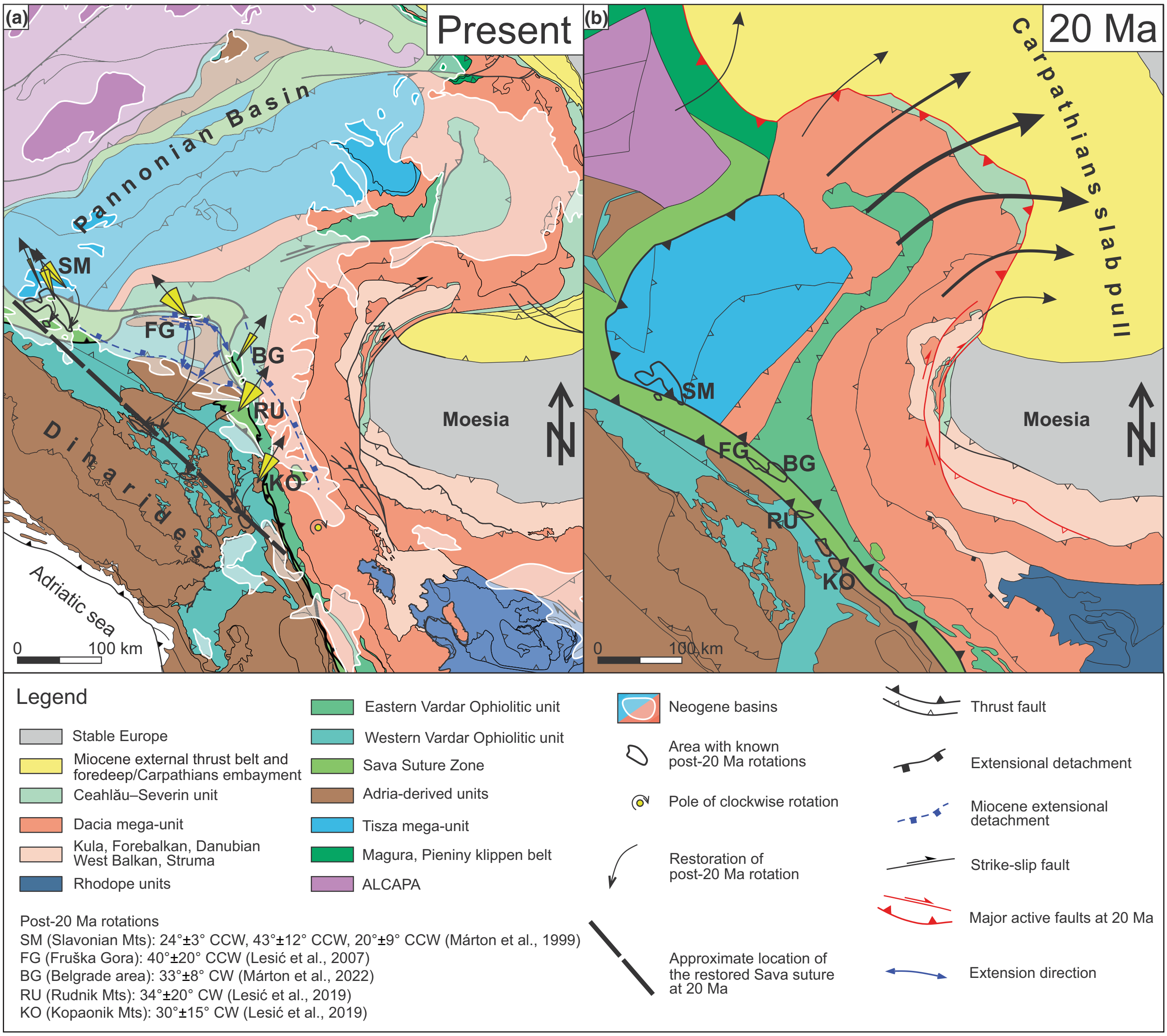


FIGURE 8 Quantitative reconstruction of the Sava zone oroclinal bending starting from the present-day geometry of the Sava zone (Schmid et al., 2020), controlled by available kinematic and palaeomagnetic rotation data. We have modified the restoration at 20 ma previously performed by van Hinsbergen et al. (2020) with the higher resolution dataset available in our and previous studies to account for the northward translation of the Dinarides during the post-20 ma extension. (a) Present-day back-arc convex geometry of the Sava zone; (b) restoration at 20 ma. The oroclinal bending of the Sava zone was controlled by the Carpathians slab retreat since the early Miocene, which pulls on the upper plate and creates the back-arc extension of the Pannonian Basin and the opposite-sense rotations of different segments of the Sava zone. The Slavonian Mountains rotated counter-clockwise between 20° and 40°, while the Fruška Gora rotated ~40° counter-clockwise. In contrast, the Belgrade area, Rudnik Mts, and Kopaonik Mts rotated clockwise for about 30° during the same period. The pole of the clockwise rotation of the N-S segment of the suture was taken after Erak et al. (2017), while the pole of the counter-clockwise rotation of the E–W segment must have been located west of the Slavonian Mts as both Slavonian Mts and Fruška Gora experienced similar rotations. By restoring the effects of post-20 ma rotations, we reconstruct the Sava zone geometry to an NW–SE-oriented straight suture. [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Reconstructing the geometry of the Sava zone

The present-day change in the Sava Zone strike taking place between the Fruška Gora and Belgrade area can be correlated with opposite-sense post-20 Ma rotations (counter-clockwise in the E–W segment in Fruška Gora and westwards and clockwise southwards, Figure 8a, Lesić et al., 2007, 2019; Márton et al., 1999, 2022), and with different Late Cretaceous tectonic transport directions in the E–W and N–S oriented segments of the Sava Zone (top-S and top-SW, respectively, Toljić et al., 2013, 2018 and this study). These associations indicate that the Sava Zone oroclinal bending occurred during the post-20 Ma period. When these opposite-sense rotations are restored with the higher resolution details of our study, the Sava Zone geometry in the early stages of the Pannonian Basin extension is relatively straight (Figure 8b). This is somewhat different when compared with more regional reconstructions, such as the one of van Hinsbergen et al. (2020) that still retained around 25° of oroclinal bending at 20 Ma.

We interpret the post-20 Ma Sava Zone oroclinal bending to be driven by the retreating Carpathian slab. The bi-directional extension in the southeastern Pannonian Basin is the effect of the two retreating slabs, the Carpathian and Dinaridic (Matenco & Radivojević, 2012). While the Dinaridic slab-retreat driven extension started already during the Oligocene (see Andrić et al., 2018), the extension controlled by the Carpathian slab-retreat started after 20 Ma, when the main Pannonian Basin depocentres formed. At a more regional scale south of our studied area, the Dinarides–Hellenides geometry was likely influenced by the clockwise rotation during the back-arc extension associated with the rollback of the Aegean slab as previously inferred. However, our interpretation shows that this rotation was not responsible for the Sava Zone oroclinal bending in the NE Dinarides.

4 | CONCLUSIONS

Our study demonstrates that large-scale top-SW thrusting represents the main mechanism of deformations during the latest Cretaceous–Eocene Adria–Europe collision along the Sava Zone. Therefore, regional Central Mediterranean tectonic reconstructions must assume a frontal nappe-stacking by dominant thrusting type of collision in the Dinarides. The subsequent Oligocene–Miocene Pannonian Basin formation was associated with extensional reactivation of the Sava Zone along its NW–SE Dinarides strike. The extension was controlled by the retreating Carpathians slab, where the slab pull triggered the opposite rotations of different Sava Zone segments, resulting in the presently observed ~80° oroclinal bending.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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