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Tectonic evolution of the Vršac Mts. (NE Serbia): Inferences from field kinematic and microstructural investigations

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Abstract: The Vršac Mts. in NE Serbia represent the key area to investigate structural relations between the Northern Serbo-Macedonian Subunit and Supragetic Unit of the Dacia Mega-Unit. The geodynamic events during the Variscan orogeny in the Late Paleozoic colligated the two units and led to their metamorphic differentiation. The Late Cretaceous extension exhumed the medium-grade Serbo-Macedonian metamorphic rocks and structurally juxtaposed them against the low-grade metamorphosed basement of the Supragetic Unit along an E-dipping shear zone, which outcrops in the crystalline basement of the Vršac Mts. The subsequent Oligocene–Miocene extension, which led to the formation of the Pannonian Basin, overprinted the effects of earlier tectonic phases to a large extent. Hence, large segments of the Northern Serbo-Macedonian Subunit and the Supragetic Unit, including their contact, were buried beneath the Neogene deposits of the southern part of Pannonian Basin. The tectonic uplift of the Vršac Mts. occurred in middle to late Miocene times along the SW-dipping normal faults that controlled deposition in the adjacent Zagajica Depression. The Miocene extension, triggered by the retreat of Carpathian slab, exhumed the crystalline basement of the mountains, and exposed the Late Cretaceous Serbo-Macedonian/Supragetic extensional contact.

Keywords: Northern Serbo-Macedonian Subunit, Supragetic Unit, kinematic analysis, multi-stage extensional deformations.

Introduction

The Vršac Mts., situated in the Banat province of north-eastern Serbia, represent a small inselberg of low- to medium-grade metamorphic rocks surrounded by the Pliocene to Quaternary deposits of the Pannonian Basin (Fig. 1; Vuković et al. 1970). The metamorphic core of the mountains belongs to the Serbo-Macedonian and Supragetic Unit of the Dacia tectonic Mega-Unit (Kräutner & Krstić 2002, 2003) and thus represents a key area where the contact between these two units can be studied at the surface in their northern segments. However, the geometry and kinematics of this contact are still not fully understood. The aim of this study is to investigate structural features of metamorphic units exposed in the Vršac Mts. and constrain their tectonic evolution during the Alpine orogeny. For this purpose, we conducted coupled micro- to map-scale structural analyses, which were supported by petrological observations. The obtained results enabled new inferences concerning kinematics of the Serbo-Macedonian/Supragetic contact in its northern segments. Furthermore, we correlated our findings with the results of previous studies in the area and elsewhere in the Serbo-Macedonian Unit (Matenco & Radivojević 2012; Antić et al. 2016a, b; Erak et al. 2017; Stojadinovic et al. 2017) in order to constrain the timing and amount of the Vršac Mts. recent tectonic uplift and define the tectonic processes responsible for it.

Tectonic framework

The Serbo-Macedonian Unit represents a belt of medium grade metamorphic rocks located along the European continental margin between the Pannonian Basin in the north and the Hellenic-Rhodope orogens in the south (Fig. 1, Dimitrijević 1997; Antić et al. 2016a, b). Tectonically, it comprises the innermost segments of the Dacia Mega-Unit of the European affinity (Schmid et al. 2008; Matenco & Radivojević 2012). To the west, it is juxtaposed against the Adria-derived units of the Dinarides across the Adria–Europe zone of collision (Pamić 2002; Schmid et al. 2008; Ustaszewski et al. 2010). Located to the east (in present-day coordinates) of the Serbo-Macedonian Unit, the Supragetic Unit represents the uppermost nappe of the Dacia Mega-Unit nappe system, predominantly comprised of low-grade greenschist facies metamorphic rocks (Fig. 1b, Kräutner & Krstić 2002; Iancu et al. 2005a; Schmid et al. 2008).

According to the existing studies, both the Serbo-Macedonian and Supragetic Unit originate from late Neoproterozoic–Silurian volcano-sedimentary complexes (Fig. 2, von Raumer et al. 2003; Iancu et al. 2005b). The two units were subsequently colligated during the late Paleozoic Variscan orogeny (e.g., Karamata & Krstić 1996; Antić et al. 2016a). The Variscan collisional tectonics led to burial of the two units in different crustal positions, which resulted in discrepancy of

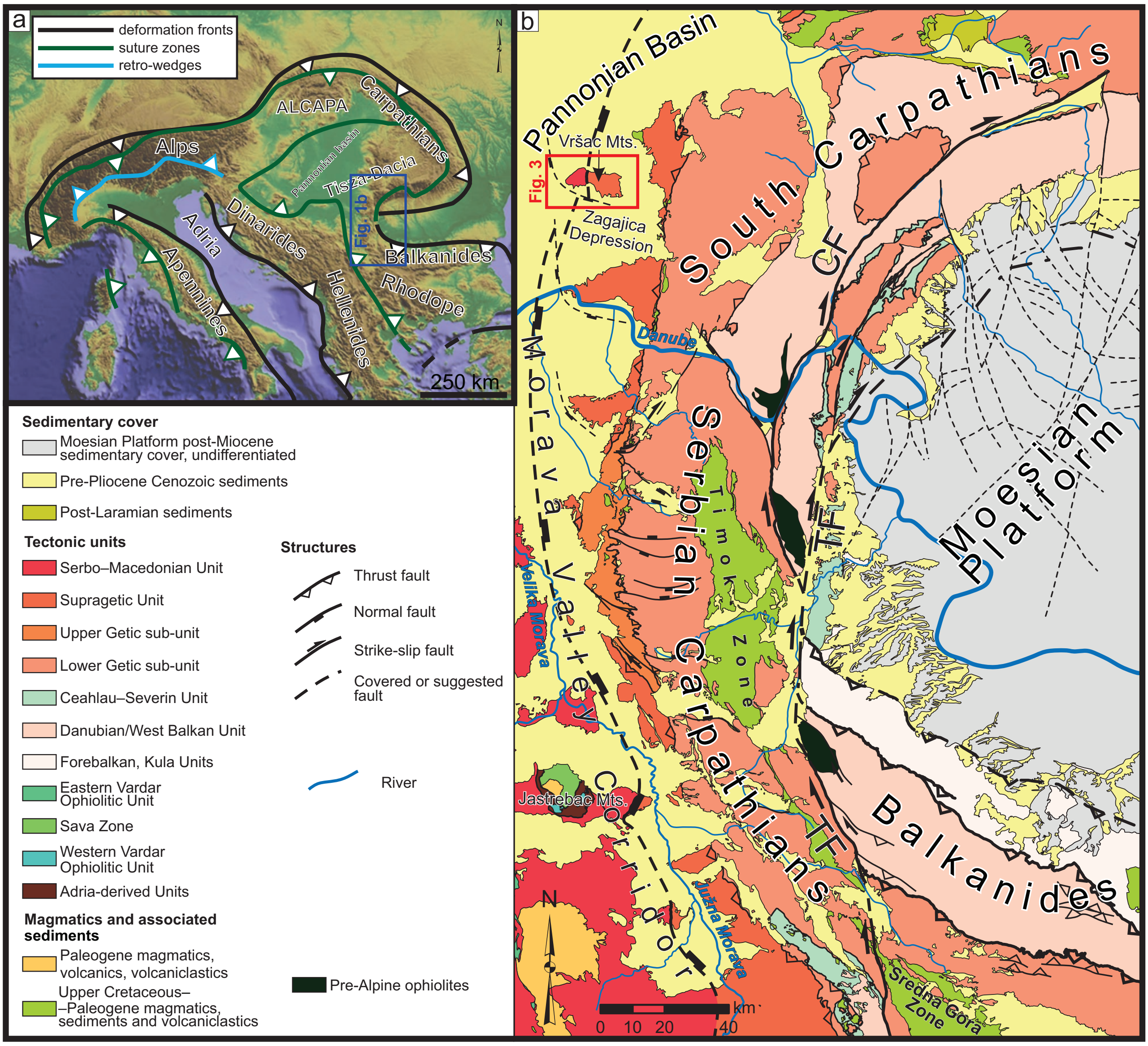

Fig. 1. a — Simplified topographic map of south-east Europe overlain by the Alpine-age first-order structural elements (modified from Krstekanić et al. 2020). **b** — Tectonic and structural map of the Serbian Carpathians and adjacent areas (modified after Basic geological map of former Yugoslavia, scale 1:100,000; Maţenco 2017; Krstekanić et al. 2020; Schmid et al. 2020). CF=Cerna Fault; TF=Timok Fault. The red rectangle indicates the location of Fig. 3.

the metamorphism they underwent (Fig. 2). The subsequent Alpine tectonic events within the Dacia Mega-Unit (including the Serbo-Macedonian and Supragetic Unit) were closely associated with the evolution of the two surrounding oceans. To the west and south-west (in present day coordinates), the northern branch of the Neotethys Ocean (or the Vardar Ocean, Sandulescu 1984; Dimitrijević 1997; Schmid et al. 2008) separated the Dacia Mega-Unit from Adria-derived continental units (i.e., the Dinarides), while to the east, Dacia was decoupled from Europe by the narrow Ceahlău–Severin branch of the Alpine Atlantic Ocean (Schmid et al. 2008). Following the latest Jurassic obduction of the Eastern Vardar ophiolites over the European margin (Schmid et al. 2008), the ongoing Early Cretaceous convergence between the Europe-derived Dacia Mega-Unit and Adria-derived units of the inner-most Dinarides led to the E-ward subduction of the remaining Neotethys oceanic lithosphere beneath the European upper plate (i.e., the Sava subduction system, Schmid et al. 2020). Coevally, following the Early Cretaceous W-ward subduction and late Early Cretaceous closure of the Ceahlău–Severin Ocean and Carpathians continental collision, the Supragetic Unit was thrusted over the Getic Unit, forming the largest of the E-vergent Dacia Mega-Unit nappes (e.g., Krstekanić et al. 2017, 2020). The retreat and steepening of the subducting Neotethys oceanic lithosphere during the Late Cretaceous triggered the syn-subductional extension in the European upper plate (Toljić et al. 2018, 2020). This extension resulted in subsidence in the fore-arc and back-arc regions of the Sava subduction system, and associated calc-alkaline magmatism of the Apuseni–Banat–Timok–Sredna Gora (ABTS) belt (Gallhofer et. al. 2015). Recent thermochronological and kinematic investigations indicate that the Late Cretaceous extension also resulted in exhumation of medium-grade metamorphic rocks in the central parts of the Serbo-Macedonian Unit, in south-eastern Serbia (Antić et al. 2016b; Erak et al. 2017). These studies inferred Late Cretaceous extensional detachments, which exhumed the medium-grade crystalline basement of the Serbo-Macedonian Unit from below the low-grade metamorphic rocks of the Supragetic Unit. The following phase of the latest Cretaceous–Paleogene collision thrusted Europe-derived continental units W-ward over the Late Cretaceous to Paleogene Sava trench turbidites and Adria-derived units of the Dinarides (Pamić 2002; Ustaszewski et al. 2010).

The subsequent Oligocene–Miocene extension in the south-eastern Pannonian Basin resulted from the interplay between geodynamic processes associated with the evolution of the two slabs, Carpathian and Dinaridic (Matenco & Radivojević 2012; Andrić et al. 2018). Contrary to the central parts of the Serbo-Macedonian Unit in south-eastern Serbia, its northern segment between the Vršac Mts. in the north and the Jastrebac Mts. in the south (Fig. 1b) was strongly influenced by processes associated with the Pannonian Basin extension. This extension overprinted the effects of earlier deformational phases to a large extent. Hence, large segments of the northern Serbo-Macedonian and Supragetic Unit, including their contact, are currently buried beneath the Neogene deposits of the Morava Valley Corridor, as the southern prolongation of the Pannonian Basin (Fig. 1b). In addition, the southernmost parts of the Serbo-Macedonian Unit in Greece underwent extensional unroofing during Eocene to Miocene times in connection with the evolution of another, Hellenic slab (Kilias et al. 1997, 1999).

Therefore, based on the different post-Cretaceous tectonic evolution of its various segments, here we separate the Serbo-Macedonian Unit into three sub-units: Northern (affected by the Pannonian Basin extension), Central (unaffected by significant Cenozoic extension) and Southern (affected by the Aegean extension). The Northern Serbo-Macedonian Subunit can be traced from its northernmost outcrops in the Pannonian Basin (i.e., the Vršac Mts.) to the southern termination of the Morava Valley Corridor (Fig. 1b). The Central Serbo-Macedonian Subunit outcrops south of the Morava Valley Corridor, in south-eastern Serbia, Bulgaria and North Macedonia, while the Southern Serbo-Macedonian Subunit is located further south, in southern North Macedonia and Greece.

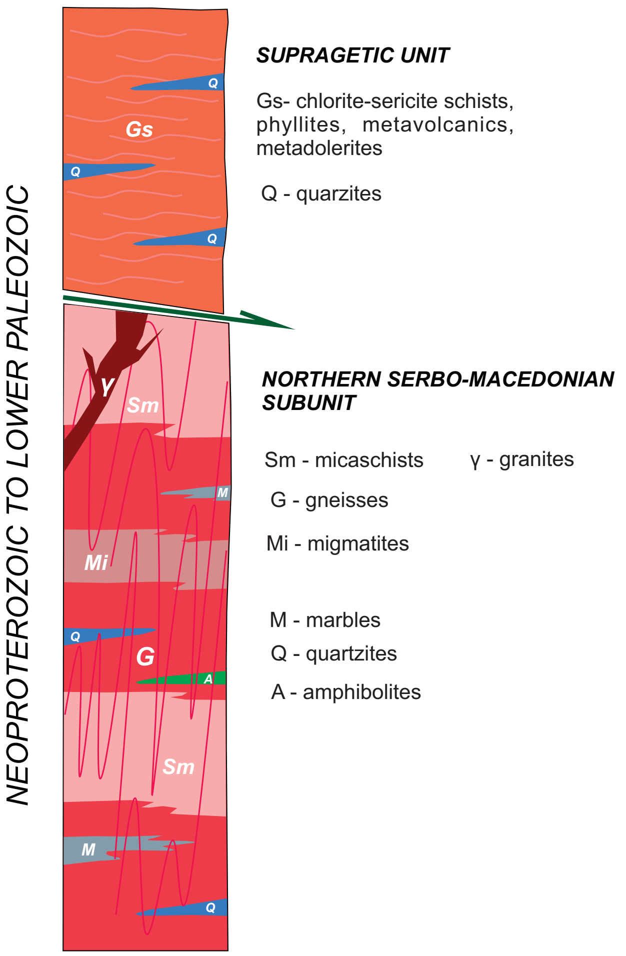

Fig. 2. Synthetic geological column of the Serbo-Macedonian and Supragetic metamorphics. The green arrow marks the tectonic contact with normal sense of shear between the two units.

Geological setting

The Vršac Mts. metamorphic core is comprised of medium-grade amphibolite facies metamorphic rocks of the Northern Serbo-Macedonian Subunit in contact with low-grade greenschist facies metamorphic rocks of the Supragetic Unit (Figs. 2 and 3, Kräutner & Krstić 2003; Matenco & Radivojević 2012). The western part of the mountains is predominantly made up by the Serbo-Macedonian biotite–muscovite gneisses and micaschists with intercalations of quartzites, amphibolites, and marbles, intruded in the north-west by a Paleozoic age granitic body (Fig. 3). Towards the east these show gradual transition through the zone of retromorphosed albite gneisses that are, again, juxtaposed to albite-muscovite schists, chlorite-sericite schists, quartzites, and metavolcanics of the Supragetic Unit metamorphic basement in the east (Vuković et al. 1970).

Along the flanks of the Vršac Mts., the metamorphic rocks are covered by Miocene to Quaternary sediments. Sedimentation in the south-eastern Pannonian Basin starts with lower Miocene continental alluvial to lacustrine sediments, deposited during the phase of rift initiation in the Zagajica Depression, a local sub-basin in the southern prolongation of the Vršac Mts. (Fig. 1b). This is passing upwards into the marine rift climax

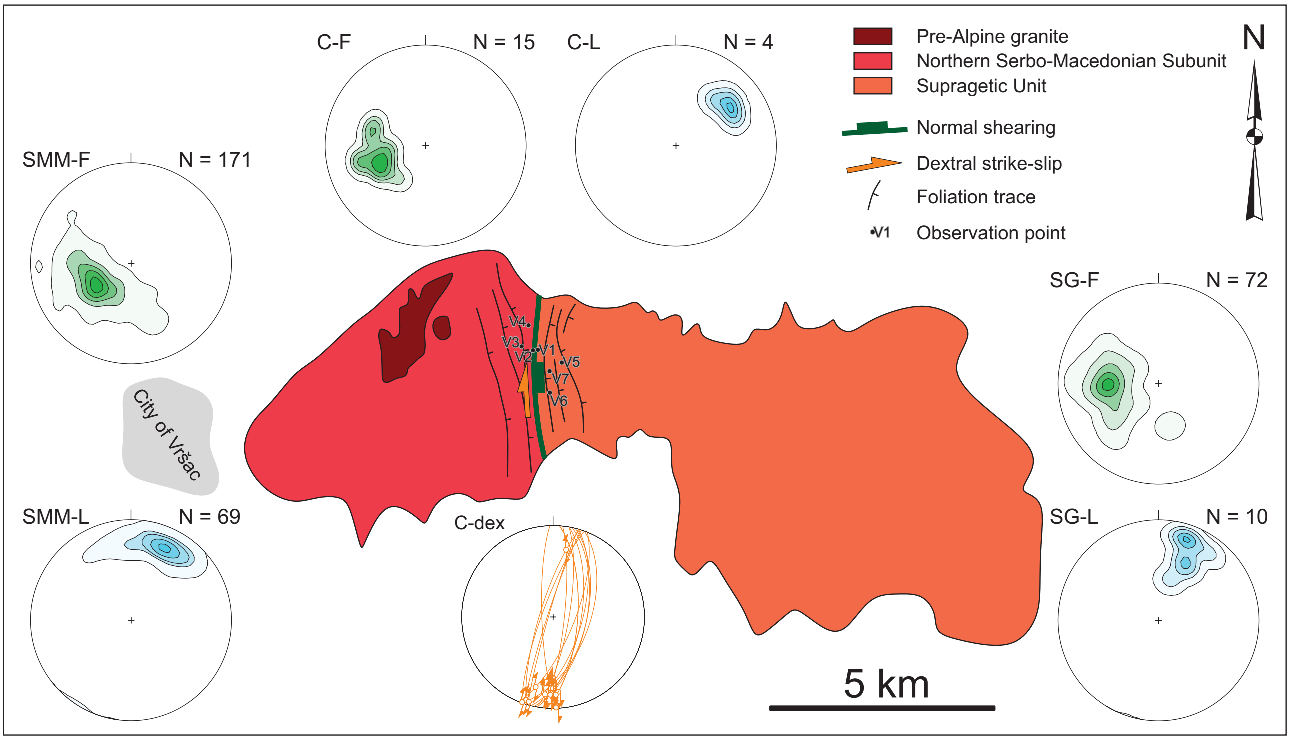

Fig. 3. Simplified structural map of the Vršac Mts. with stereonet density plots of foliation poles and stretching lineation and stereonet projections of dextral strike-slip faults. SMM-F=Serbo-Macedonian Massif foliation; SMM-L=Serbo-Macedonian Massif stretching lineation; C-F=Serbo-Macedonian\Supragetic contact foliation; C-L=Serbo-Macedonian\Supragetic contact stretching lineation; C-dex=Dextral brittle faults in Serbo-Macedonian\Supragetic contact zone; SG-F=Supragetic unit foliation; SG-L=Supragetic unit stretching lineation; N=number of structural measurements used in density plot calculation.

deposition that starts in Badenian and reaches its peak in Sarmatian–Pannonian times (Matenco & Radivojević 2012). The post-rift deposition is represented by Pliocene to Quaternary sediments, which are covering the flanks of the Vršac Mountains (Vuković et al. 1970).

Methodological approach

In order to constrain the geometry and kinematic evolution of the contact between the Northern Serbo-Macedonian Subunit and the Supragetic Unit, we conducted structural analyses across various scales. On the map scale we statistically analysed foliation orientation measurements obtained during the geological mapping of the Vršac Mts. (Vuković et al. 1965, 1970). Foliation dip direction/dip and stretching lineation trend/plunge taken in the Serbo-Macedonian and Supragetic Unit and at their contact (i.e., measurements taken in the tens of metres wide zone at the contact between the two tectonic units) were separately analysed. By combining map data and our field measurements, we obtained statistical mean orientations of foliation and stretching lineation in these three geologically different structures (Fig. 3). Such spatial separation of data was necessary in order to constrain the structural variability of these two tectonic units across their contact and the effect of the kinematics on the structural pattern. The outcrop-scale structural analysis included field observations of geometry, kinematics and superposition of brittle faults and ductile shear zones (Fig. 4), where the sense of shear was determined by various brittle or ductile kinematic indicators (e.g., Simpson & Schmid 1983; Doblas 1998). For micro-scale studies, four oriented samples were collected, one in the Supragetic Unit, two in the Northern Serbo-Macedonian Subunit and one at the contact between them (Fig. 5, Table 1). Each thin-section was cut parallel to the stretching lineation in the sample. We used optical microscopy to determine mineral assemblages, metamorphic grade, and micro-scale deformations in the Serbo-Macedonian, Supragetic and their contact. The microstructures were analysed to determine the deformation sequence and the tectonic transport on the thin-section scale.

Results

Map-scale structural analysis

In the Northern Serbo-Macedonian Subunit, a statistical analysis of poles to foliation shows foliation dip direction/dip maximum of S_{SMM} 058/32° with a significant variability in foliation orientation (SMM-F in Fig. 3) that changes from northward- and north-eastward-dipping in the west to more eastward-dipping closer to the contact with the Supragetic Unit. Stretching lineation in the Northern Serbo-Macedonian Subunit is more uniform (SMM-L in Fig. 3), with trend/plunge maximum of L_{SMM} 025/23° and a local dissipation towards the north. At the contact between the Serbo-Macedonian and Supragetic Unit, foliation dip-direction/dip has maximum in

Fig. 4. Interpreted field photos of structures (and their stereonet projections) observed in outcrops. Locations of photos are displayed in Fig. 3. **a** — Older (probably pre-Alpine) fold hinges (red line) locally preserved in pervasive east-dipping foliation (green line) in Supragetic unit. Observation point V5. **b** — C–C' structure within Supragetic low-grade green-schists indicating top-NE normal shearing. Observation point V5. **c** — Ductile top-NE normal shearing within medium-grade Serbo-Macedonian gneisses. Observation point V3. **d** — Brittle dextral fault in the Serbo-Macedonian gneisses. Observation point V4. **e** — Normal fault with Riedel shears observed in Supragetic unit. Observation point V7. **f** — Tilted conjugated normal joints in the Supragetic unit observed in point V1.

S_{CA} 070/40° and a sub-maximum in S_{CB} 105/45° (C-F in Fig. 3). Along the same contact, rarely preserved stretching lineation shows maximum of trend/plunge in L_C 055/43° (C-L in Fig. 3). Compared to the Northern Serbo-Macedonian Subunit, the Supragetic Unit shows more uniform eastward-dipping foliation with dip-direction/dip maximum of S_{SG} 090/41° accompanied by slight scattering around this value (SG-F in Fig. 3). Stretching lineation in the Supragetic Unit is very similar to those in the Serbo-Macedonian with trend/plunge maximum in L_{SGA} 020/17° and sub-maximum in L_{SGB} 025/37° indicating local perturbations (SG-L in Fig. 3).

Outcrop-scale deformations

The most dominant structure observed in outcrops in both the Supragetic and Serbo-Macedonian Units is pervasive, NE- to E-dipping foliation with moderate dip angles (Fig. 4). Sometimes older isoclinal fold-hinges are preserved incorporated in the pervasive foliation (Fig. 4a) indicating transposition of earlier foliation. This pervasive foliation accommodates the normal sense of shear in top-ENE shear zones, observed by C-C' structure in the Supragetic Unit (Fig. 4b). Similarly, top to ~ENE ductile shear zones with sigma and delta clasts of feldspars and quartz are observed in the Serbo-Macedonian in the vicinity of its Supragetic contact (e.g., Fig. 4c).

In contrast to the dominant ductile deformation of both tectonic units, locally foliation has been reactivated or truncated by brittle deformation. One set of brittle structures are high-angle to sub-vertical ~N–S oriented dextral faults (C-dex in Figs. 3, 4d), observed in the vicinity of the Serbo-Macedonian/Supragetic contact. The other set of brittle structures that truncate all other deformation are rare extensional structures that include normal faults (Fig. 4e) or tilted conjugated normal joints (Fig. 4f) that both indicate ~NE–SW extension.

Metamorphic grades and thin section-scale deformations

Two samples of the Serbo-Macedonian gneisses taken at the point V3 (Figs. 3, 5a, b; Table 1) show that the main rock-forming minerals are quartz, muscovite, biotite, orthoclase, microcline, plagioclase, epidote, and garnet, while zircon and apatite are accessory. Quartz and feldspars demonstrate undulose extinction, bulging recrystallization and subordinate sub-grain rotation recrystallization locally (Fig. 5a, b). Garnets were probably formed in a single pre-Alpine metamorphic phase as they do not show overgrowth rims or indications of subsequent multi-stage growth or recrystallization in medium or high grade conditions. Other indicators of medium grade conditions are twinning and perthitic growth of feldspars (Fig. 5a). In contrast with these, the well-developed sericitization in orthoclase (Fig. 5a) can indicate slight retrograde metamorphic changes. Muscovite and biotite form spaced foliation at micro-scale that is pervasive in outcrops, while muscovite shows intense folding and transposition of older foliation observed by rarely preserved isoclinal fold hinges (Fig. 5b). Based on the observed mineral assemblage and recrystallization features of the main rock-forming minerals, we estimate that the primary metamorphic event that affected the Northern Serbo-Macedonian Subunit was in the amphibolite facies at temperatures of 500–550 °C and pressure of 0.5–0.7 GPa, with a potential retrograde overprint, presumably in greenschist facies.

A similar mineral assemblage is observed in the sample taken at the Serbo-Macedonian/Supragetic contact (point V2, Fig. 5c–e; Table 1), but with a more dominant muscovite and biotite that form spaced to domainal spaced foliation. Sigmoidal muscovite and biotite indicate top to NE normal shearing (Fig. 5c–e). Garnet is retrogressively completely changed to chlorite (Fig. 5d). Undulose extinction, dominant bulging recrystallization, and local sub-grain rotation in quartz and feldspar grains, as well as the mineral assemblage with retrograde chlorite indicate that the shearing event occurred at temperatures of ~400–450 °C and 0.3–0.5 GPa, indicating retrograde greenschist metamorphic facies which followed primary amphibolite facies metamorphism responsible for garnet crystallization, similar to the samples of the Serbo-Macedonian gneisses.

The Supragetic metamorphic rocks include quartz, plagioclase, biotite, epidote, orthoclase, and accessory apatite (point V1, Fig. 5f; Table 1). Biotite forms pervasive domainal slaty to slaty cleavage, along which top to ENE normal sense of shear can be observed based on growth around feldspar porphyroclasts (Fig. 5f). Quartz and feldspars show undulose extinction and bulging recrystallization. We infer that the greenschist metamorphic conditions affected the Supragetic crystalline basement, with temperatures around 400 °C (potentially up to 450°C at most), while pressure is estimated at around 0.3 GPa.

Interpretation and discussion

The results of our kinematic and petrological investigations infer sharp transition between the medium-grade Serbo-Macedonian gneisses in the footwall and low-grade greenschists of the Supragetic Unit in the hanging-wall of the E-dipping shear zone at their contact (Fig. 3). According to our interpretation, this ductile extensional shear zone predates brittle strike-slip and extensional deformation and, in correlation with other studies elsewhere (e.g., Willingshofer et al. 1999, 2001; Gröger et al. 2013; Reiser et al. 2017), was activated during the Late Cretaceous extensional event that affected the Dacia Mega-Unit. The Late Cretaceous extensional detachment, which exhumed the Northern Serbo-Macedonian Subunit below the Supragetic Unit, probably reactivated inherited Paleozoic contact between the two units and had top-NNE direction of tectonic transport. This extension affected both units in a very wide zone which is demonstrated by a retrograde greenschist metamorphic overprint associated with pervasive stretching lineation that has uniform orientation on both sides and even at higher distances to the detachment and is irrespective to the pre-existing foliation

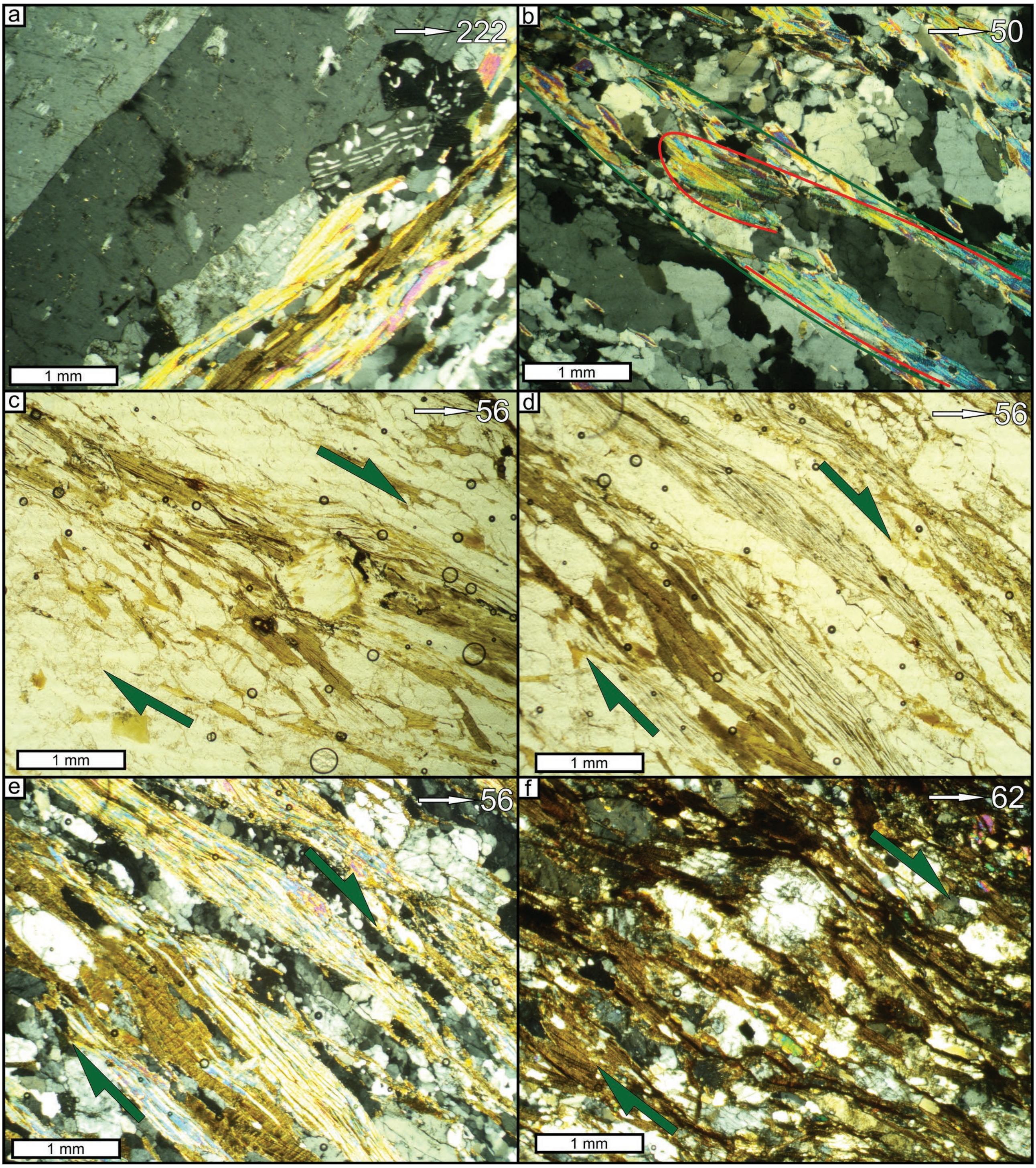

Fig. 5. Oriented thin sections taken across the Serbo-Macedonian\Supragetic contact zone. The number in top right corner indicates the strike azimuth of the thin section. Thin sections are parallel to the stretching lineation at the site of sampling. Locations of sampling sites are displayed in Fig. 3. **a** — Orthoclase twins and perthitic growth within foliation built of muscovite and biotite in Serbo-Macedonian Massif gneisses in cross-polarized lights. Sampling site V3. **b** — Muscovite forming isoclinal fold hinge (red line) incorporated in the younger foliation (green lines). Sampling site V3. Cross-polarized lights. **c–e** — Top-NE normal sense of shear in the contact zone of the Serbo-Macedonian Massif and Supragetic units. Sampling site V2. Parallel-polarized lights in c and cross-polarized lights in d and e. **f** — Top-NE normal sense of shear in the Supragetic unit in cross-polarized lights. Sampling site V1.

Table 1: Sampling and mineralogy information about the analysed thin sections.

Sample	Latitude	Longitude	Foliation dip-direction/dip	Stretching lineation trend/plunge	Mineral assamblage	Metamorphic conditions
V1	45°08’12.20”N	21°24’04.16”E	097/45°	063/36°	quartz, plagioclase, biotite, epidot, epidote, subordinate orthoclase, accessory alanite and apatite	greenschist facies (400° C, 0.3 GPa)
V2	45°08’11.90”N	21°23’58.89”E	063/40°	056/35°	muscovite, biotite, quartz, plagioclase, orthoclase, epidote, chlorite, garnet, accessory apatite	Primary: amphibolite facies (500 °C, 0.5-0.6 GPa); Retrograde: greenschist facies (400 °C, 0.3-0.5 GPa)
V3	45°08’14.61”N	21°23’53.06”E	040/35°	050/30°	quartz, muscovite, orthoclase, microcline, epidote, garnet, accessory zircon and apatite	Primary: amphibolite facies (500 °C, 0.5-0.7 GPa); Retrograde: greenschist facies?
V4	45°08’13.50”N	21°23’47.50”E	077/49°	042/40°	muscovite, biotite, quartz, microcline, plagioclase, orthoclase, garnet, sericite	Primary: amphibolite facies (550 °C, <0.7 GPa); Retrograde: greenschist facies?

with different orientations (Fig. 6a). South of the study area, similar structural relations were observed in the Jastrebac Mts., and also further to the south, in the Central Serbo-Macedonian Subunit of the south-eastern Serbia (Fig. 1b). There, results of coupled kinematic and thermochronological studies also inferred that the aforementioned separation was formed by the Late Cretaceous extensional detachments (Antić et al. 2016b; Erak et al. 2017). Hence, both in the Northern and Central Serbo-Macedonian subunits, the Late Cretaceous extension exhumed the Serbo-Macedonian metamorphic basement below the Supragetic Unit.

The Serbo–Macedonian/Supragetic extensional shear zone was reactivated in post-Cretaceous times as a brittle dextral strike-slip fault zone, probably with not very high offset as we are still able to observe the initial structures. Due to the dextral drag within the fault zone and in its close vicinity, obliquely oriented foliation together with stretching lineation was rotated clockwise for ~30° (Fig. 6b). However, such drag did not affect the pre-existing structures at higher distances from the Serbo-Macedonian/Supragetic contact or those foliations parallel to the fault zone. This created present-day differences in the orientation of Late Cretaceous ductile structures within the shear zone (including its immediate vicinity) compared to areas at higher distances from it (Fig. 6b). We infer that this dextral overprint is a part of a wider deformation related to the Oligocene–early middle Miocene Cerna and Timok faults of the South and Serbian Carpathians, located to the east and south-east of the study area (Fig. 1b). To the south of the study area, such low-offset strike-slip deformation was documented away from the Cerna and Timok faults, in the internal Serbian Carpathians, where it locally reactivates or otherwise truncates the Cretaceous Supragetic thrust (Krstekanić et al. 2020).

Coevally, the entire Northern Serbo-Macedonian Subunit between the Vršac Mts. in the north and the Jastrebac Mts. in the south was strongly influenced by processes associated with the Pannonian Basin extension. The Oligocene–Miocene extension (Matenco & Radivojević 2012; Balázs et al. 2016; Erak et al. 2017) overprinted the effects of the Late Cretaceous extension. Consequently, large segments of the Northern Serbo-Macedonian and Supragetic Unit, including their contact between the Vršac Mts. and the Jastrebac Mts., are still buried beneath the Neogene sediments along the Morava Valley Corridor (Fig. 1b). The final tectonic uplift of the Vršac Mts. occurred in middle to late Miocene times along the SW-dipping normal faults that control deposition in the Zagajica depression adjacent to the Vršac Mts. (Figs. 1b, 4e; Matenco & Radivojević 2012). Therefore, Miocene extension exhumed the core of the mountains and exposed the Late Cretaceous Serbo–Macedonian/Supragetic extensional contact. Low-temperature thermochronology dating in the main metamorphic units would provide precise constraints for the suggested deformational/exhumation phases. However, taking into consideration the degree of metamorphism of the Serbo-Macedonian metamorphic rocks and the maximum vertical offsets of 2–3 km along the Miocene normal faults recorded by syn-kinematic sedimentation observed in seismic cross-sections south of the Vršac Mts. (Matenco & Radivojević 2012), we suggest that their exhumation occurred during the two separate Late Cretaceous and Miocene extensional phases.

NE–SW oriented Miocene extensional exhumation recorded in the Vršac Mts. was triggered by the retreat of the Carpathian slab (Maţenco 2017). South of the Vršac Mts., in the Morava Valley Corridor (Fig. 1b) such exhumation was hampered by the presence of the rigid Moesian Platform indenter (see Krstekanić et al. 2020). In this southern prolongation of the Pannonian Basin, the E–W oriented extension was governed by the retreat of the Dinaridic slab (Matenco & Radivojević 2012; Andrić et al. 2018). However, the effects of this extension, as well as the associated exhumation significantly decrease E-wards and NE-wards going from the Adria margin towards the margin of Europe (Krstekanić et al. 2020). Therefore, the Serbo-Macedonian/Supragetic contact remained buried along the eastern margin of the Morava Valley Corridor up to the Jastrebac Mts. in the south (Fig. 1b, Erak et al. 2017). In the western-central part of the Morava Valley Corridor a cluster of gneiss domes made up by the medium-grade Serbo-Macedonian metamorphic rocks emerges from

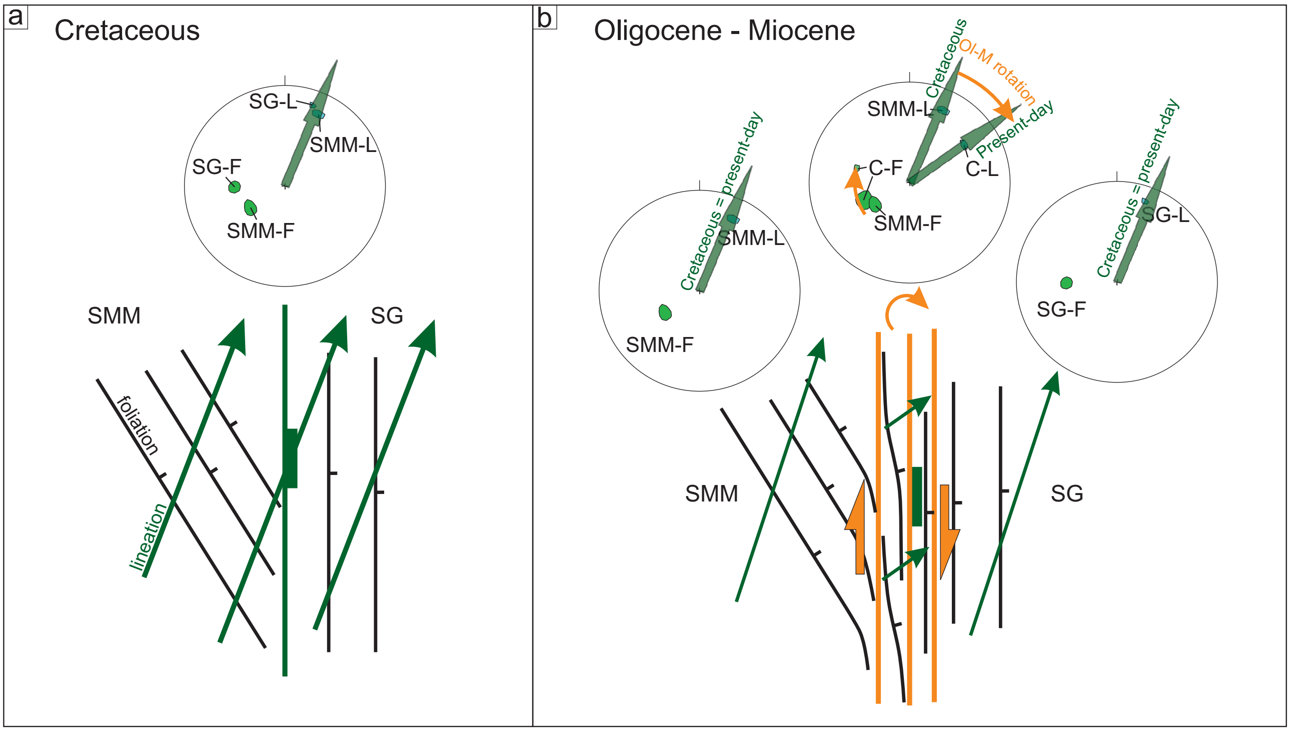

Fig. 6. Mechanism of the structural evolution of the Serbo-Macedonian\Supragetic contact. Stereonets contain the highest density contour from respective stereonets in Fig. 3 indicated by same plot codes. SMM=Serbo-Macedonian Massif; SG=Supragetic unit. **a** — Cretaceous top-NNE extensional exhumation of the Serbo-Macedonian Massif. Foliation in the Serbo-Macedonian are oblique to the extensional detachment, while foliation in the Supragetic (i.e., the hanging wall) are sub-parallel to the contact. Stretching lineation indicate tectonic transport and is pervasive and uniform in both hanging- and footwall affected by this shearing event. **b** — Oligocene–Miocene dextral reactivation of the Serbo-Macedonian\Supragetic extensional detachment. Clockwise rotation induced by dextral drag affected the foliation in the Serbo-Macedonian Massif that was originally oblique to the detachment and strike-slip corridor. This dragging and rotation reoriented the foliation and stretching lineation in the vicinity of the SMM\SG contact while they remained in their Cretaceous-times orientation outside of the strike-slip zone.

the surrounding Neogene sediments (Fig. 1b). Their recent tectonic uplift was induced by arching of corrugated detachment faults during the final stages of E–W oriented Dinaridic extension (Stojadinović et al. 2017; Sant et al. 2018).

Conclusions

Exhumation of the Vršac Mts. metamorphic core occurred during the two separate extensional phases, in the Late Cretaceous and middle to late Miocene. The Late Cretaceous extension took place along the present-day E-dipping shear zone that can be traced along the eastern margin of the Northern Serbo-Macedonian Subunit, from the Vršac Mts. in the north, across the Jastrebac Mts. and further towards the south in the Central Serbo-Macedonian Subunit in south-eastern Serbia. This extensional exhumation structurally juxtaposed the medium-grade Serbo-Macedonian metamorphic rocks against the low-grade metamorphic rocks of the Supragetic Unit. Contrary to the Central Serbo-Macedonian Subunit, the Northern Serbo-Macedonian Subunit between the Vršac Mts. in the north and the Jastrebac Mts. in the south was strongly influenced by processes associated with the Pannonian Basin extension. The Oligocene–Miocene extension overprinted the effect of earlier tectonic phases to a large extent. Hence, large segments of the Northern Serbo-Macedonian Subunit, including its contact with the Supragetic Unit, were buried beneath the Neogene sediments of the Morava Valley Corridor, as the southern prolongation of the Pannonian Basin. The recent tectonic uplift of the Vršac Mts. occurred in middle to late Miocene times. The NE–SW oriented extension, which was triggered by the retreat of the Carpathian slab, exhumed the core of the mountains, and exposed the Late Cretaceous extensional contact between the Serbo–Macedonian/Supragetic crystalline basements.

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