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New evidence for Alpine overprint of poly-deformed gneisses in the 'Median Dacides' of SE Europe: Restoring polyphase deformations and transposition cycles

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Abstract

Using outcrop and microscale structural constraints on metamorphosed fragments of Carpathian-Balkan exotic north Gondwanan continental crust amalgamated onto southeastern Eurasia (Moesia), we detect significant variability in outcrop scale deformation patterns. The structural style variability results from recurrent peripheral subduction processes producing a series of collisional orogens, Variscan suturing of 'Median Dacides' with Danubian/'Marginal Dacides' (western Moesian realm), and postdating Alpine overprinting. The 'Median Dacides' comprise the two gneiss amphibolite-facies basement units, Serbo-Macedonian and Getic/Kučaj, embedded into Southern Carpathians (Romania) and Carpathian-Balkans (Serbia, North Macedonia, Bulgaria), and Hellenides (northern Greece). Variscan inliers were involved in the peripheral Paleozoic Variscan and Mesozoic Alpine geodynamic events (including tentative Late Triassic Cimmerian involvement). To unravel polyphase deformation processes on the two nappe-stacked Carpathian-Balkan gneissic inliers, we have incorporated the data available in the reports on protoliths, metamorphic and exhumation events, coupled with new extensive structural field-based analysis.

The composite review and new field data results show that far-traveled composite Serbo-Macedonian and Getic/Kučaj exotic Peri-Gondwanan basements experienced different geodynamic conditions affecting the existing structural fabric. The deformation patterns expose polystage deformation history (D_{1-2}) fashioned by the youngest Alpine overprinting (D_{3-4}). The structural data and protolith analyses suggest a Lower Paleozoic Cadomian to Cenerian geodynamic linkage between the two gneissic basement units. Notably, the pre-Variscan anatexis, migmatitization, metamorphism (D_{1-1}), and the formation of Cenerian (axial planar) foliation (D_{1-2}) are precursors of the tight isocline Variscan folds (D_{2-1}). After Variscan amalgamation with Danubian/Moesian Euxinic microcraton, the Serbo-Macedonian occupied the outboard position, whereby the Getic/Kučaj was tectonically amalgamated with the Danubian basement. Progressive deformation of the Variscan structural fabric (meter-scale folds) produced complete transposition (D_{2-2}) with a few preserved meter-scale folds. The successor Alpine shortening (D_3) (re)activated the existing remnants of Variscan axial plane cleavages (or overlapped foliation-to-cleavage planes), further producing the well-developed schistosity and new folding pattern.

Keywords: Continental crust, Serbo-Macedonian gneiss, Getic/Kučaj gneiss, Cenerian deformation, Variscan deformation, Alpine deformation, transposition.

Introduction

In convergent margins, the configuration of subducting and overriding plates has often been used for constraints on collision-type geodynamics and associated driving forces (e.g., van Hinsbergen *et al.* 2005; Ellouz-Zimmermann *et al.* 2007; Murphy *et al.* 2012; Maffione and van Hinsbergen 2018; Neubauer *et al.* 2022; Bühler *et al.* 2023). Such configurations usually include significant spatiotemporal developments revolving around the timing of the observed hosting deformations. Most of the available studies deal with *P–T–d* paths of deformed rocks, offering a variety of geodynamic reconstructions that elucidate the tectonothermal history of exposed (polydeformed) metamorphic zones (e.g., Iancu *et al.* 1998; Henriques *et al.* 2017; Plissart *et al.* 2017; Martinez *et al.* 2020; Trapp *et al.* 2020; Tropper *et al.* 2023). In the polydeformed Carpathians-Balkan belt case, available reconstructions mainly deal with the Alpine tectonic configuration of the exposed cluster of metamorphosed Cadomian-derived Cenerian and Variscan basement inliers (Krätner and Krstić 2002, 2006; Iancu *et al.* 1998, 2005; Seghedi *et al.* 2005; Balintoni *et al.* 2010a,b,c; Plissart *et al.* 2012, 2018; Zagorchev *et al.* 2012; Neubauer and Bojar

2013; Bonev *et al.* 2015; Antić *et al.* 2017; Balkanska *et al.* 2021a; Fig. 1abc, 2, 3). The chronology of deformation events, progressive development, and their effect on previously deformed metamorphic assemblages is not fully understood (see Oriolo *et al.* 2022 for a general discussion). The complex superimposition nature of multiple collisional imprinting (Vangelov *et al.* 2013; Iancu and Seghedi 2017; Spahić *et al.* 2021) led study attention mainly on the late Alpine tectonically-induced exhumation events (e.g., Dallmeyer *et al.* 1996; Medaris *et al.* 2003; Neubauer and Bojar 2013; Neubauer 2015; Antić *et al.* 2017; Balkanska *et al.* 2021b, 2022; Bonev *et al.* 2023; Kounov *et al.* 2023). Up to now, attempts to separate the tectonic events that produced underthrusting and medium to high-grade metamorphism from the stages reflecting progressive exhumation and cooling only offer a limited distinction between Variscan and Alpine structural imprints.

Fig. 1. HERE

The investigated 'Median Dacides or Getic-Supragetic, i.e., "Median Dacide gneiss units," stand for a set of displaced lithospheric-scale slices of continental crust amalgamated on rigid Moesian microcraton (Săndulescu 1984; Iancu *et al.* 1998, 2005; Krätner and Krstić 2002, 2006; Spahić and Gaudenyi 2019; Figs. 2, 3). The Carpathian-Balkan fold-and-thrust-belt as a whole incorporates an essentially metamorphosed Variscan crust that is geodynamically reworked by the Alpine orogeny (Krätner and Krstić 2002, 2006; Iancu *et al.* 2005; Neubauer and Bojar 2013). Variscan and Alpine deformations have obscured the structures related to the active Neoproterozoic - Lower Paleozoic Gondwana-related subduction-driven convergence (Balintoni *et al.* 2011, 2014; Spahić *et al.* 2021). As a result of plate tectonic configuration, Lower Paleozoic, Variscan, and Alpine orogens were superimposed (e.g., Krstić *et al.* 1996; Milićević *et al.* 1996; Stampli and Borel 2002; Stampfli *et al.* 2013; Spahić *et al.* 2019b). The early Paleozoic drifting of 'Median Dacides' produced Variscan amalgamation with Danubian-/'Marginal Dacides'. The amalgamated 'Median Dacides' had a lower crustal position (descending plate) during this event (Iancu et al., 2005; Spahić and Gaudenyi, 2019a; Fig. 3). Protracted Variscan crustal thickening was succeeded by the Mesozoic – Paleogene Alpine cycle and opening of (peri)Tethyan oceans.

NeoTethyan descending-type subduction zone underplated the 'Median Dacides'/Danubian/Moesia during the terminal Alpine stages. Consequently, 'Median Dacides' changed the polarity during the Alpine cycle, occupying the upper crustal position over the descending Tethyan slab (Fig. 1c, 3). Within the late Alpine nappes, the original Lower Paleozoic to Variscan fabric is largely overprinted by the postdating Alpine tectonism (Dallmeyer *et al.* 1996; Neubauer and Bojar 2013; Plissart *et al.* 2012, 2018). Thus, a variety of poorly explored ductile and brittle deformations of different ages are imprinted into the 'Median Dacides': (i) internal gneissic Getic/Kučaj unit (Sebeş-Lotru terrane; Iancu *et al.* 1998, 2005; Balintoni *et al.* 2010a; Neubauer and Bojar 2013), (ii) intervening Supragetic greenschist facies unit disconnecting the two gneissic units, and (iii) external gneisses belonging the Serbo-Macedonian Unit (Antić *et al.* 2017; Spahić and Gaudenyi 2019; Figs. 1c, 2, 3).

Fig. 2. HERE

A focused study dealing with the structural features of broadly similar metamorphic rocks exposed in the Alpine nappe stack of eastern Serbia provides new insight into the deformation chronology and their progressive to polystage character. The recurring collisional processes occurred along the central portion of the southern margin of Alpine Eurasia, its Moesian microcraton (Fig. 1a). Initially, peripheral subduction at a north Gondwanan cratonic boundary produced Cadomian to Ordovician imprints to eventually be transported and embedded into the Variscan thickened continental crust (Fig. 1a, 2, 3). The thick Variscan crust is likely influenced by mild Cimmerian imprints (Spahić 2022a,b) dismembered during the early and late Alpine cycles (e.g., Săndulescu 1984; Iancu *et al.* 2005; Neubauer and Bojar 2013; Balintoni *et al.* 2014; Neubauer 2015; Antić *et al.* 2017; Spahić and Gaudenyi 2019; Fig. 1b). Despite a number of geodynamic reconstructions, comparison between different orogenic structural imprints in the investigated gneissic units lacking. To provide new constraints on the superimposed deformation phases, we look for structural markers: (i) rare Variscan folds, (ii) cleavage formation, (iii) incomplete and complete transposition cycles (Xypolias *et al.* 2013; Plissart *et al.* 2018), and (iv) brittle deformation overprinting fabric patterns of Alpine relevance (nappes). Thus, we focus on structural evidence of Cadomian (late Neoproterozoic) to Cenerian (mid-Ordovician) and their role in Variscan and Alpine ductile-brittle deformations. In particular, we investigate two gneiss units across three key areas (Fig. 3, red circle numbers #1, 2, and 3) by mapping largely obliterated original structural elements and their involvement in complex Variscan and Alpine folding patterns. Such a complex structural restoration provided evidence of several transposition cycles responsible for such an intense overprinting in the first place.

Regional Setting

The South Carpathians and Carpathian-Balkan Mountain region is a segment of the Alpine fold-and-thrust belt, which is in an abutting position, encircling the Moesian Euxinic micro-craton (Iancu *et al.* 2005; Krätner and Krstić 2002, 2006; Balintoni and Balica 2016; Spahić and Gaudenyi 2019; Balkanska *et al.* 2021; Figs. 2, 3). This Alpine Carpathian-Balkan connects several Balkan countries: Romania in the north, Serbia in its central part, and Bulgaria in its western domain, whereby North Macedonia and Greece contain its southern limb that stretches into the Aegean Sea (Spahić and Gaudenyi 2019; Schmid *et al.* 2020). (Fig. 1, 3; Table 1). The geotectonic setting of the Carpathian-Balkan belt is consistent with the Alpine peripheral collision, which produced several large nappes displacing the Variscan configuration: 'Marginal Dacides' (Danubian) and 'Median Dacides' (Getic/Supragetic plus external Serbo-Macedonian) (Săndulescu 1984; Iancu *et al.* 1998; Krätner and Krstić 2002, 2006; Spahić and Gaudenyi 2018; Fig. 3).

Fig. 3. HERE

Table 1. HERE

'Marginal Dacides' (Danubian)

The oldest Carpathian-Balkan gneissic basement unit is settled within the 'Marginal Dacides' represented by the two discrete units of the Danubian unit (Iancu et al., 2005; Spahić and Gaudenyi 2019; Figs. 2, 3). The Danubian gneiss unit consisted of an older Proterozoic Avalonian arc inheritance and was amalgamated onto the Moesia much prior to the Variscan event

(Balintoni *et al.*, 2010c; Balintoni and Balica 2016; Spahić and Gaudenyi 2019). Thus, remote Danubian gneiss is out of the scope of this study. In addition, Variscan-age deformations among Alpine Carpathian-Balkan basements were mainly constrained for the Danubian unit (Plissart *et al.* 2012, 2018).

The long-lasting Lower Paleozoic to Variscan-age subduction processes involving the 'Median Dacides' as lower plate moving beneath Danubian led to the development of a Devonian back-arc (Plissart *et al.* 2017; Neubauer *et al.* 2020; Figs. 2, 3). The Devonian oceanic crustal extrusion was followed by the ophiolite obduction on top of the already docked stabile Danubian basement (Plissart *et al.* 2017; Fig. 2). The lithospheric-scale contact is interpreted as a set of sinistral transpressive mylonitic zones (Plissart *et al.* 2012, 2018) with an NW–SE shortening axis similar to the Southern Variscides where Schlingen folds developed (Bühler *et al.* 2023). Simultaneously, the Variscan underthrusting produced a Lower Carboniferous turbidite system scattered over both 'Marginal'- and 'Median Dacides' (Boncheva *et al.* 2010; Spahić *et al.* 2019a). Finally, the 'early Variscan' collision was followed by the emplacement of 'late Variscan' granitoid complexes (Plissart *et al.* 2012; Jovanović *et al.* 2019; Fig. 2).

'Median Dacides'

Getic/Kučaj/Sredna Gora unit

The largest unit of 'Median Dacides' of the Carpathian-Balkan fold-and-thrust belt, the Getic/Kučaj unit covers the area to the west of Danubian and to the east of the Supragetic unit (Spahić and Gaudenyi 2019; Figs. 2, 3). The Getic/Kučaj basement unit consists of various metamorphic rocks like gneiss, including abundant amphibolite-type gneiss, mica-rich gneiss, and augen gneiss, as well as the rare occurrence of eclogites and granulites (Iancu *et al.* 1995, 1998; Kräutner and Krstić 2002, 2006). According to some authors, this unit is an exception, experiencing relatively mild Alpine deformations (Getic/Kučaj/ Sredna Gora; Mukasa *et al.*, 2003; Plissart *et al.*, 2018).

Supragetic/"Vlasina"/Morava unit

Intervening between westernmost Serbo-Macedonian and more internal Getic/Kučaj is the aforementioned Neoproterozoic to Lower Paleozoic (Ordovician) greenschists/greenstones Supragetic basement (Iancu *et al.* 1998; Kräutner and Krstić 2002; Antić *et al*., 2016; Spahić *et al.* 2019; Machev *et al.* 2021; Fig. 3). Magmatic activity in connection with Suprgetic basement /"Vlasina unit" lasted from late Neoproterozoic until early Cambrian, wherein the gabbro, diabase records age of ca. 550 - 560 Ma (Antić *et al*., 2016). The Ordovician age of the upper Supragetic section is proven by the extraordinary findings of inarticulate brachiopods in southern Serbia (Pavlović 1959, 1962; see Spahić *et al*., 2019, and references cited therein). The greenschist-facies assembly consists of chlorite, biotite, muscovite, sericite, epidote schists, phyllites, quartzites, and conglomerates but also includes arc-related tholeiitic basalts and their tuffs, intruded by gabbros and granites dated between 577 Ma and 521 Ma (Kounov *et al.* 2012; Antić *et al.* 2016; Žak *et al.* 2020, and references cited therein).

Serbo-Macedonian Unit

The Serbo-Macedonian Unit represents a discrete nappe stacked westernmost gneissic basement unit of the Carpathian-Balkan fold and thrust belt, very similar to the Getic/Kučaj and Rhodopean Massif gneiss (e.g., Krenn *et al.* 2010; see Spahić and Gaudenyi 2021, for a discussion). The Serbo-Macedonian Unit occupies the flanking position during the Variscan and Alpine orogenic stages, formerly the central segment representing the Neotethyan Vardar continental margin (Figs. 1a, 3; Spahić and Gaudenyi, 2022). Consequently, the western Serbo-Macedonian tectonically overlaps the subducted relics of the younger Neotethyan Vardar Zone (Marović *et al.* 2007a; Erak *et al.* 2017; Spahić and Gaudenyi, 2019b; Fig. 1c, 3). Such a position most likely was an essential factor that influenced the progressive development of a variety of Alpine compressional deformations (folds, oblique shear zones, metamorphism, transposition; Marović *et al.* 2007a).

*

With regards to the latest Neoalpine event (Neogene; Marović *et al.* 2007b), some geophysical studies show an essential difference in crustal thickness between more internal Danubian and Moesian crust compared to the external lithosphere thicknesses (Fig. 4a,b,c; Milivojević, 1993; Grinc 2013; Stanciu and Ioane 2021). The effect of Neogene extension is mainly observable beneath the Serbo-Macedonian, further affecting the current Cadomian, Variscan, and Alpine imprints (Fig. 4). The entire area of 'Median Dacides' is crosscut by a large number of extensional faults (Marović *et al.* 2007b).

Fig. 4. HERE

Approach and Methods

Research status

Variscan gneissic basement terranes of Carpathian-Balkan are scattered in Romania, Serbia, Bulgaria, and Greece, having rather partial correlation (e.g., Himmerkus *et al.* 2009; Balintoni *et al.* 2010, 2014; Kounov *et al.* 2012; Zagorchev *et al.* 2015; Antić *et al.* 2016; Abbo *et al.* 2020). Most reports deal with sediment provenance (parametamorphic rocks) and evidence of widespread anatexis and peraluminous magmatism (othoprotoliths). Despite a large field data repository (*e.g.*, Savezni Geološki Zavod 1970; Kalenić *et al.* 1978; Bogdanović *et al.* 1978; Iancu *et al.* 1998, 2005; Kräutner and Krstić 2002, 2006; Kounov *et al.* 2010, 2017; Antić *et al.* 2015, 2017; Plissart *et al.* 2018; Fig. 3), the superimposition imprints of (i) Variscan, (ii) (Eo)Cimmerian, and (iii) Alpine deformation have not been investigated in depth. The absence of comprehensive field structural studies within 'Median Dacide' gneiss units is likely due to several reasons:

- Prioritizing the latest Alpine nappe-stacked configuration, including the Eoalpine extensional basin formation stage (Marović *et al.* 2007a; Schmid *et al.* 2008; Robertson *et al.* 2008; Robertson 2012; Maffione and van Hinsbergen 2018);
- Difficulties connected with multiple superimposed orogenic-type Cadomian, Cenerian, Variscan, Cimmerian and Alpine-type tectonic imprints (e.g., Balogh *et al.* 1994; Kräutner

and Krstić 2002, 2006; Medaris *et al.* 2003; Balintoni *et al.* 2010a, 2011; Kovacs *et al.* 2014; Antić *et al.* 2015, 2017; Jovanović *et al.* 2019; Abbo *et al.* 2020; Spahić *et al.* 2021, 2023; Machev *et al.* 2022; Spahić 2022a,b; Table 1);

- Variscan to Alpine geodynamic interaction and its differentiation (deformation history) is studied mainly by using constraints on magmatic imprints (Jovanović *et al.* 2019; Neubauer *et al.* 2020; Trapp *et al.* 2020; Balkanska *et al.* 2021);
- Focus on different tectonic exhumation times, inclusive constraints on dominant retrogressive metamorphic imprints (e.g., Bonev *et al.* 2013; Kydonakis *et al.* 2014; Kounov *et al.* 2011, 2017; Antić *et al.* 2015, 2017).

Synthesis and Mapping

To define the early Paleozoic geodynamic setting, we collected data describing the pre-metamorphic protoliths and their ages across South Carpathians and Carpathian-Balkans (on both sides of the Danube River, southwestern Romania, and eastern Serbia; Figs. 2, 3). The Lower Paleozoic depositional and stratigraphic setting of the metamorphosed Serbo-Macedonian and Getic basement units was reconstructed starting from the available published data (mainly detrital zircons and biostratigraphic data, Kalenić *et al.* 1975; Fig. 5). Afterwards, these data were integrated with the field observations.

In the field, measured geometric characteristics of folds, analytic geometry, and stereographic projection were employed to estimate the orientation of the fold axis and axial surface (see Lisle and Layshon 2004). Fold axes and axial surfaces were constructed from measured fold limbs using the π pole method (construction of b axes of folds) or by directly measuring at outcrops (e.g., Ramsay and Huber 1987; Lisle and Layshon 2004). For the statistical analyses and computation of the fold axis from measured fold limbs as an intersection of planes and fold axial surfaces as a plane bisecting inter-limb angle between two planes (fold limbs), OpenStereo software has been used (Grohmann and Campanha, 2010). The different deformation stages and superposition relationships were separated by analysing geometrical orientation data, tectonic foliation, and b- or fold axes measurements. The distinction between fold structures related to different folding stages in the field was not the case. Outcrops expose destroyed fold hinges, with just a few locations exposing intersecting cleavages. Despite a limited number of areas with the orientation of fold axes intersecting at high angles (Antić et al., 2017), we used statistical analysis of foliation trends. Thus, it was possible to distinguish the Variscan NE-oriented fold axis from the Alpine NW-directed folding axis (see Đoković 1985 for details).

To study transposition cycles, we have mapped the foliation patterns and ductile deformations within the metamorphic systems (Bishop 1972; Antić *et al.* 2017; Plissart *et al.* 2018). We limit our analysis to the Variscan and late Alpine intervals because of the unresolved controversy over the relatively mild effect and questionable presence of Cimmerian folds (Tari *et al.* 1997; Tschumachenko *et al.* 2004; Spahić *et al.* 2022a,b). Postdating Eo-Alpine extensional overprint and localised localized shear zones (Marović *et al.* 2007a; Erak *et al.* 2016; Stojadinović *et al.* 2013, 2022) as well as delimiting Variscan mylonites towards Danubian footwall were omitted too (different level of deformations and severity of overprint; Plissart *et al.* 2018). The focal point was the development of multiple foliation patterns in 'Median Dacides'. This allowed us to distinguish progressive from polystage deformation and the chronology of the deformations (e.g., Oriolo *et al.* 2022). In addition to the discussion on the variety of protoliths, field observations show that the foliation is axial planar to the observed tight isoclinal Variscan folds, thus interpreted as the (initial) transposition foliation (e.g., Xypolias *et al.* 2013, and references cited therein). The younger crenulation cleavage in the outcrop is assumed to represent a secondary transposition cycle (Mortimer 1993; Grey 1995).

Fig. 5. HERE

Results: Deformation patterns

Pre-Variscan to Variscan deformations

From the Late Proterozoic to the early Paleozoic, the northern edge of Gondwana underwent a peripheral Andean type Avalonian–Cadomian non-collisional orogeny (e.g., Samson *et al.* 2005; Murphy *et al.* 2002, 2012; Balintoni *et al.* 2011; Henriques *et al.* 2017; Oriolo *et al.* 2021). With a few exceptions (e.g., Oczlon *et al.* 2007; Şen 2023), there is a general agreement that most of the Carpathian-Balkan-Rhodope-Hellenic pre-Alpine basement inliers are exotic terranes of peripheral Cadomian of (north)eastern Gondwanan inheritance (Dallmeyer *et al.* 1996; Iancu *et al.* 1998; Balintoni 14; Kounov *et al.* 2012; Zagorchev *et al.* 2012; Bonev *et al.* 2013; Balintoni and Balica 2013; Neubauer 2014; Zulauf *et al.* 2014; Peytcheva *et al.* 2015; Antić *et al.* 2016; Siegesmund *et al.* 2018; Stephan *et al.* 2018; Spahić *et al.* 2019a, 2021, 2023; Žak *et al.* 2022; Gerdjikov *et al.* 2023; Fig. 1a). The presence of the intervening mid-Ordovician Cenerian-Sardic and Permian-Triassic 'Late Variscan' or 'Early Cimmerian' imprints have just recently been discussed (Spahić *et al.* 2021, 2022a,b, 2023; Finger and Riegler 2023). Because the majority of these pre-Variscan imprints are obliterated by the following tectonic events, in addition to field data, we use available published data on protoliths, age of metamorphism, and emplacement of magmatic bodies. In that manner, we put new constraints and discuss the Early Paleozoic paleodepositional environment. The field study provided one of the most significant markers of intervening tectonic episodes – barely preserved Variscan folds.

Pre-Variscan to Variscan deformations in Getic/Kučaj basement unit

The Getic/Kučaj gneiss comprises several litho(stratigraphic) members dating back to Neoproterozoic – Lower Paleozoic depositional environments (Table 2). The gneiss included the oldest and deepest crustal augen gneiss and migmatites (D_{1-1}), abundant mica schists, and biotite-bearing gneiss. Ductile deformations within the gneiss itself are rare, exposing some meter-scale younger folds (Fig. 6a). In the field and thin sections, a notable scarcity of mantled porphyroblasts coating is observed by comparing the abundance in the Serbo-Macedonian gneiss (Fig. 6b, 7). Nevertheless, large portions of gneiss contain well-preserved quartz exudates, outlining the presence of relic lithology (sandstone protolith) (Fig. 6c; also Mukherjee *et al.* 2019). In addition, field mapping shows the presence of well-preserved serpentinite lenses embedded into the Getic/Kučaj gneiss (Fig. 6d). The evidence of original pre-Variscan mafic crust is in line with the proposed Ordovician framework (Spahić et al., 2023). The presence of (late) Ordovician mafic rocks aligns with the east Rhodopean Upper Ordovician amphibolite protoliths) embedded into the same age gneiss (455 Ma; Bonev *et al.* 2013; Fig. 1b for location). The almost identical situation is in central-southern Serbo-Macedonian/Ograzhdenian amphibolites (Zagorchev and Milovanović 2006; Spahić et al., 2021).

In addition to documenting the presence of mafic orthoprotoliths, the most dominant member across the Getic/Kučaj basement area is massive amphibolitic gneiss (Fig. 7a,b,c,d). Massive amphibolite gneisses rarely expose foliation, represented exclusively in quartz-bearing competent thin inliers (Fig. 8a,b,c,d). The (pre-Variscan) foliation fabric is preserved as thin, often folded quartz-bearing mini-ribbons (presumably original thin layers with sandstone protolith or S_0; Fig. 8a,b,c,d). The ribbons outline the observed tight folding geometry (subparallel limbs in Fig. 8b,e). In very few other amphibolite gneiss outcrops, rocks expose rare asymmetric drag folds. These δ-type aggregates are the same pre-Variscan Cenerian Ordovician age (Fig. 8e).

Fig. 6. HERE
Table 2. HERE
Fig. 7. HERE

On a few occasions, the meter-scale folds are preserved (Fig. 6a, 8a,b,c). These presumably Variscan folds (D_{2-1}) have NW-SE-orientated fold axis/b-axis 334/64 and b-axis 146/15. Such a spatial orientation shows the Alpine trends, with no evidence of refolding (b-axis directed towards NW, Đoković, 1985). We observed different foliation patterns at the flanks (Fig. 6a, compare S_0 and S_1). Please note that the tectonic shortening trends for Adria/Carpathian-Balkan are taken from Đoković (1985). Despite Alpine alignment, meter-scale folds fit into the Variscan framework because the Alpine folds are often more prominent in scale but are not visible in the field (can only be inferred via statistical foliation analysis; see later in the text). Thus, the distorted orientation of the meter-scale Variscan folds provides evidence of structural rotation caused by the Alpine interference (Figs. 6a, 8a). The associated centimetre-scale mini-folds are apparently grown along the axial plane cleavage (Fig. 8c,d). In this case, the cm-scale folds provide evidence of incomplete (Variscan) transposition because some fold structures are still preserved and visible. The Variscan tectonic reactivation apparently affected the older (Cenerian) foliation-to-cleavage generation (not fully developed $D_{2-2;}$).

Fig. 8. HERE

Pre-Variscan to Variscan deformations in Serbo-Macedonian basement

The dominant lithological member of Serbo-Macedonian is also gneiss, mostly mica-rich gneissic rocks (Kalenić *et al.* 1978; Kalenić 2004; Spahić 2006, 2022b; Zagorchev and Milovanović, 2006; Marović *et al.* 2007a; Zagorchev *et al*., 2012; Antić *et al.* 2016, 2017; Spahić and Gaudenyi, 2020; Fig. 7e,f,g,h, 9). The metamorphic assembly includes migmatite, minor content of amphibolite, and amphibolite gneiss. Together with gneiss, Serbo-Macedonian contains various marbles, calkschists, and schists rich with organic matter.

Fig. 9. HERE

In addition to the oldest "quasi-layered" migmatites whose structure corroborates the complete obliteration of the original Lower Paleozoic configuration, vast portions of the Serbo-Macedonian gneiss are by a well-foliated texture or S_1 (Fig. 9, 10, 11). The widespread foliation is a significant difference relative to Getic/Kučaj gneiss, likely controlled by differences between ortho- and para-protoliths. Different foliation patterns with dominant sedimentary protoliths (e.g., Milovanović *et al.* 1998; Kalenić 2004) exhibit evidence that pre-Variscan/Variscan events obliterated the preexisting early fabric, allowing no detailed insight into field stratigraphy and superposition (D_1, Fig. 9a, 11d). Nevertheless, we discovered a number of exceptionally exposed compressional-type deformations, particularly tight overturned folds (Fig. 9b,c,d, 11a,b,c). These folds represent a set of preserved compressional structures largely destroyed by foliation or "transposition foliation." Destruction of the original configuration caused spatial alignment between the Lower Paleozoic AP_1 to be parallel with the Variscan AP_2 (Fig. 9b,c,d, 10b, 11a,b,c). The mapped folds are tight, overturned (D_2, Fig. 11d), and transposed (transposition foliation; Fig. 9c,d). Such a development of "transposition layering" is the marker of the lower crustal levels characterised by strain softening (e.g., Grey 1995). Regardless of the size of the preserved folds, their axis shows very consistent Variscan spatial arrangement and is plunging towards the SW(NE) (perfect fit with Variscan style; Fig. 9f). Such an arrangement indicates an excellent preservation of the Variscan trend, with a minor Alpine rotation (unlike in the Getic/Kučaj basement). Variscan folds have an NW-vergence, fitting with the observed centimetre- and meter-scale folds (Fig. 9f).

Fig. 10. HERE

Fig. 11. HERE

Alpine deformations

In addition to the observed foliation, folding patterns, and the documented presence of transposition processes (Fig. 11d), the observed Alpine deformations include ductile δ-type aggregates and schistosity, supported by evidence of refolding of Serbo-Macedonian gneiss. Together, such a structural pattern, in particular schistosity, is a good indicator of (another) transposition cycle (Fig. 11d). The dominance of late Alpine shortening across the area is aligned with mild late Alpine compressional deformation and nappe stacking (Schmid *et al.* 2008; Plissart *et al.* 2018). Retrogressive low-grade metamorphic ductile shear zones show protracted Alpine activity lasting from Permian to Cretaceous (^{40}Ar/^{39}Ar white mica; Neubauer and Bojar 2013).

Getic/Kučaj unit. Statistical analysis of the measured foliation and fold data (b-axis; Fig. 12a,b) shows a typical overprinting fabric. The extracted foliation pattern in the area of Donji Milanovac yielded four different maxima, further exposing the two main shortening directions (dip-direction/dip in polar Schmid's net, lower hemisphere; Fig. 12a,b). The first shortening direction outlined by the statistical fold axis is consistent with the Alpine configuration (Fig. 12a, #1), whereas the second has a slight deviation from the Variscan trend (indicating mild rotational movements; Fig. 12a, #2). As a result, most of the area underwent significant (brittle) structural rearrangement of Alpine relevance (mainly nappe stacking), preserving the record of precursory Variscan shortening. This actually means that Variscan folds, if preserved, will exhibit both Variscan and dominantly Alpine styles, depending on the locations. The N-S striking brittle reverse faults or nappes and their East-vergence (Fig. 3) are perpendicular with the resulting E(SE)-W(NW) directed displacement (Fig. 11c). This is consistent also with the direction of tectonic transport that is perpendicular relative to fold axis (in this case N-S striking axis). Thus, the observed general E-W displacement direction aligns with the Alpine e-vergent nappe configuration of N-S-striking thrusts (Figs. 2, 3). The incomplete transposition is presumed because some Variscan folds are preserved, and mylonitic displacements were not observed. The absence of Variscan ductile **δ**-type aggregates is consistent with the upper crustal position or mainly brittle deformation. Such interpretation fits with the scarce cleavage measurements, which show the same tectonic rotation trend, slightly deviating from the initial strike (Fig. 12c). Deformation and weak zones were likely controlled by the basement rheological and protolith differences (mainly massive amphibolite gneiss; Fig. 6, 8).

Fig. 12. HERE

Serbo-Macedonian Unit. In the Serbo-Macedonian Unit, the foliation S_2 represents the axial-plane cleavage of visible folds, including statistical anticlines or anticlines that are destroyed in the field and are solely visible in diagrams (Fig. 10a, 12c, 13). The S_3 represents a newly developed schistosity overlapping with the same foliation planes (Fig. 11d). The foliation and schistosity are frequently accompanied by the δ-type aggregate quartzitic porphyroclasts with top-to-the-SSE(SE) tectonic transport (Fig. 10a). The observed folds have a largely preserved Variscan pattern, further characterized by the presence of subhorizontal cleavage (fracture-like planes pointed by yellow arrows at Fig. 10b). The cleavage indicates the presence of brittle deformations, showing the transposition process following the lineation striking in ca. E - W direction, L 106/32 (Fig.10 c,d). Indeed, the cleavage planes of older Variscan folds (Fig. 11a,b) are the main (subhorizontal) structures controlling the youngest transposition cycle (D_3; Fig. 11c,d).

Fig. 13. HERE

Discussion

Protolith types and their age: Constraints on early tectono-depositional setting

The investigated Carpathian-Balkan Cadomian-derived basement in Romania is subdivided into terranes or tectonic units: Cumpana, Sebeş-Lotru, and Fagaraş (Iancu *et al.* 1998; 2005; Fig. 3). Their analogues to the south in Serbia (Serbo-Macedonian Unit; Antić *et al.* 2016; Spahić and Gaudenyi 2020) and Bulgaria (Ograzhden Supercomplex; Zagorchev *et al.* 2012; Machev *et al.* 2022) can be subdivided into crystalline fragments with the ortho- and paragneisses. The Serbo-Macedonian Unit is further striking across North Macedonia and includes the analogous basement unit referred to as the "Eastern Veles Series" (Antić *et al.* 2016; Spahić and Gaudenyi 2019; Spahić *et al.* 2019). From there, the Serbo-Macedonian gneissic ribbon continues into the northern Inner Hellenides as the Vertiskos unit, consisting mainly of ortho-protoliths (Himmerkus *et al.* 2009; Meinhold *et al.* 2009, 2010; Spahić *et al.* 2020; Abbo *et al.* 2020; Figs. 1, 2; Table 2).

In Neoproterozoic – Lower Paleozoic paleogeographical terms, these peri-Gondwanan systems 'Median Dacides' (Serbo-Macedonian/Supragetic/Getic) were in an outer flank of the northeastern Gondwanan active margin (Fig. 15). A similarity in the age of the Serbo-Macedonian Unit and the northern gneissic analogue or Sebeş–Lotru composite terrane has also recently been raised (Antić *et al.* 2016). Southern analogous Rhodope massif is of similar inheritance, highlighted particularly by the occurrence of almost identical amphibolite packages documented within 'Median Dacides' (Bonev *et al.* 2023; Fig. 8). These gneissic crustal slices, including the Ograzhden supergroup in western Bulgaria (Zagorchev *et al.* 2012), have the identical yet combined Neoproterozoic and Lower Paleozoic protoliths (e.g., Săbău and Massonne 2003; Iancu *et al.* 2005, 2008; Seghedi *et al.* 2005; Balintoni *et al.* 2010a; Balintoni and Balica 2013; Balintoni *et al.* 2014; Fig. 5). A portion of protoliths of the Ograzhden gneisses and schists are similar clastic-type sedimentary rocks of pelitic and psammitic character like in Serbia (Kalenić 2004; Zagorchev *et al.* 2012; Spahić *et al.* 2021). Orthogneisses from the easternmost segment of the nappe stack, or Vlahina Mt., western Bulgaria, are classified as metagabbro-metadiorites having 541 Ma in age (Machev *et al.* 2022). The mapped augen gneisses frequently change towards migmatites, both widespread across Getic/Kučaj, Serbo-Macedonian Unit, and inclusive the Ograzhden unit (Fig. 14). Some portions of augen gneisses or augen-orthogneiss (Iancu *et al.* 1998) have either a Mid-Ordovician or even Variscan age (Zagorchev *et al.* 2012).

The protolith analyses of the intervening Supragetic greenschist-facies basement unit, including adjoining analog units, indicate the presence of clastic volcano-sedimentary sequences with Ordovician fossils and the presence of basaltic volcanism (Pavlović 1959, 1962, 1977; Dimitrijević 1997; Iancu *et al.* 2005; Figs. 3, 15). Protoliths of these metamorphic rocks are pelitic and, to a lesser extent, are in the form of psammitic sediments, occurring together with the arc-related tholeiitic basalts and their tuffs (e.g., Petrović 1969; Antić *et al.* 2016; Spahić *et al.* 2019a). The analogue crystalline basement of the Struma Unit consists of the variably deformed continent- and ocean-derived rocks of Ediacaran to early Cambrian protolith age derived from the Metasaharan craton (e.g., Kounov *et al.* 2012; Žak *et al.* 2020).

Fig 14. HERE

Pre-Variscan tectonomagmatic imprints: Cenerian event

Orthogneiss from the Cumpăna unit of Sebeş-Lotru terrane contains the zircons of the typical Cenerian crystallisation ages 466.0 to 458.9 Ma (Balintoni *et al.* 2010a; Figs. 2, 3). In addition, leucocratic dykes from southern Serbia are also the Ordovician in age (Antić *et al.* 2016). Orthogneiss in the same area has an age of 472 ± 4 Ma, including amphibolites ranging from 462 ± 6 Ma to 456 ± 2 Ma. These ages fit the Ordovician timeframe, thus interpreted as Cenerian tectonism (Zurbriggen 2015; Cocco and Funedda 2017; Cocco *et al.* 2023; Spahić *et al.* 2023). The oldest igneous emplacement resulting from Rb^{87}-Sr^{86} gave late Cadomian 540 Ma on K-feldspar granites of Juhor Mt., and Sr^{87}/Sr^{86} showed 470 Ma. The pre-Variscan age of augen gneiss cropping out in central Serbia is documented by the postdating 350 Ma-old granite-gneiss intruded the former (Rb^{87}-Sr^{86}; Deleon *et al.* 1972; Spahić *et al.* 2021). With regards to deeper crustal deformations, the recycling trend lasted from the late Neoproterozoic to the Ordovician, and a gradual increase in εHf(t) from the Ordovician onwards is recorded (Spahić *et al.* 2021; Abbo *et al.* 2022). Such magma involvement corroborates a peripheral north Gondwana

Neoproterozoic to the Ordovician position of Serbo-Macedonian. Indeed, gneissic rocks of the Serbo-Macedonian Unit in the Juhor area (central Serbia) are lowermost Cambrian in age (541 Ma on Sr^{87}-Sr^{86} on biotite and mica; Deleon *et al.* 1972; Fig. 5b). In addition, detrital zircons from the parametamorphic rocks collected from southern Serbia (near Sijarinska Banja) indicate that the maximum depositional age is near 565 Ma (Antić *et al.* 2016). The pre-gneiss magmatic and sedimentary assemblages are newly formed continental lithosphere (Kalenić, 2004; Spahić et al., 2021).

Metamorphism

The metamorphic events recorded within the investigated gneissic units record from early Paleozoic to Variscan times, including overwhelming evidence of Alpine overprints (Haydoutov 1989; Balogh *et al.* 1994; Haydoutov and Yanev 1997; Liégeois *et al.* 1996; Medaris *et al.* 2003; Zagorchev and Milovanović 2006; Balintoni *et al.* 2010a,b Bonev *et al.* 2013a,b; Macheva *et al.* 2016; Balintoni *et al.*, 2010a,b; Plissart *et al.* 2018; Spahić *et al.* 2023; Fig. 15). Several tectonometamorphic episodes affect the Serbo-Macedonian Unit as a whole: (i) the oldest metamorphic event occurred between Precambrian to latest Cambrian (Balogh *et al.* 1994; Zagorchev and Milovanović 2006), (ii) the youngest are of Mesozoic age (Balogh *et al.* 1994; Zidarov *et al.* 2002; Himmerkus *et al.* 2009), or (iii) even belonging to the Cenozoic events (Ricou *et al.* 1998; Abbo *et al.* 2020). Most post-Paleozoic evidence of amphibolite-type overprint comes from Rhodopean gneissic massif, whereby magmatic protoliths have a mean age of 455 Ma (Bonev *et al.* 2013a,b). Variscan age-different HP metamorphism is proven on Getic-Supragetic units (excluding Serbo-Macedonian Unit; Iancu *et al.* 1998; Medaris *et al.* 2003). The amphibolite- and eclogite facies are confirmed in Getic/Supragetic and may mark the early subduction stage leading to Variscan orogeny (Iancu *et al.* 1998; Săbău and Massonne 2003). However, external gneiss (Serbo-Macedonian Unit) experienced slightly older than Variscan or latest Cambrian-Ordovician metamorphic imprints (Balogh *et al.* 1994; Fig. 15). The Neoproterozoic - Ordovician stage includes widespread evidence of peraluminous mid-

Ordovician anatexis (Zagorchev and Milovanović 2006; Zagorchev *et al.* 2012; Spahić *et al.* 2021; Fig. 15).

Deformation asymmetry and transposition cycles

The structural data complement metamorphic imprints in Paleozoic terms, showing that the metamorphism fits the Cenerian framework. At the same time, Getic/Kučaj fits with the proposed back-arc opening of north Gondwana characterised by the massive presence of mafic rocks (now represented by amphibolite gneiss; Bonev et al., 2013; Spahić et al., 2023). However, there is a significant asymmetry in the post-Cenerian deformations between Serbo-Macedonian and Getic/Kučaj gneissic units (Fig. 1b). The main difference between the two investigated gneiss segments is the variable presence of imprinted ductile structures, particularly folds. Apart from the missing ductile folds and δ-type aggregates within amphibolite gneiss in the Getic/Kučaj unit, there is a difference in the postdating Alpine overprinting styles. Protolith-controlled foliations represent another critical difference. Foliation is rare in the Getic/Kučaj unit, whereas in the Serbo-Macedonian Unit, it is widespread across the entire segment in Serbia. With regards to the postdating Alpine overprinting styles, counterintuitively, the Serbo-Macedonian Unit as a segment of the Neotethyan Vardar margin (Figs 3, 5a) has well-preserved the Variscan folding (NE-directed fold axis instead of the expected NW-directed fold axis). At the same time, the observed folds within the remote Getic/Kučaj unit are almost entirely rotated towards the NW, outlining the Alpine-type compressional style (Fig. 12, 13). Such a deformation pattern is asymmetric, meaning basements near NeoTethys have better preserved Variscan imprints. It is to be noted that the observed deformation in the investigated eastern Serbian sector differs from other parts of the Carpathian-Balkan belt (e.g., Kreszek *et al.* 2013, 2023).

By definition, transposition disrupts the folded layer, so the orientation of the individual segments no longer fits in the gross orientation of the parent layer (Bishop 1972). As shown, new field and statistical data indicate several cycles of transposition. The earliest Cadomian to Ordovician Cenerian magmatic arc stage obliterated the preexisting early fabric. The earliest rocks were associated with juvenile continental crust and interchanging deposition (Kalenić, 2004). During Cenrian paroxysm, these early depositional systems were mainly embedded into gneisses and underwent migmatitization and anataxis; see, e.g., Balintoni *et al.* 2014; Zagorchev *et al.* 2015; Spahić *et al.* 2021, for details; Fig. 9a, 15a). Early north Gondwana's latest Cambrian-Ordovician metamorphism of Cenerian relevance (Balogh et al. 1994), including barely preserved ductile shear zones, obliterated the pre-existing fabrics (complete transposition; TrCicle#1; Fig. 6a, 15b). Data further show that the original fabric was succeeded by the formation of similar age or slightly younger foliation (AP1 II AP2, D_2, S_1; Fig. 9a). Microstructural imprints of these older events remain in the form of porphyroclastic mineral fabrics, suggesting that every lithological layer behaved as a separate rheological unit or mineral aggregate (Fig. 7, 15b).

The relics of complete transposition (TrCicle#1) are loose shear zones (Spahić *et al.*, 2021). The successor progressive (Variscan) deformation formed m- to cm- folds that are mainly transposed along the “transposition foliation” (by definition, newly formed isoclinal folds of a preexisting foliation; Xypolias et al., 2013). Consequently, the second transposition cycle (TrCicle#2) affected the pre-existing fabrics, foliations S_1 and S_2 (Fig. 6a, 9b). The Variscan folds are precursors to the second shearing stage, further displaced with their fold's axis/hinge lines perpendicular to the transport direction (slightly deviated from the Alpine fold axis). The transposition occurred accounting for the shearing of a preexisting steeply inclined foliation oriented nearly parallel to the stretching direction (Fig. 9c,e, S_2) or the foliation planes that are roughly parallel to the axial plane cleavage (Fig. 9b). The successor Alpine shortening is best reflected by the observed spaced axial plane cleavage (Fig. 10b). Brittle fracturing along axial plane cleavage (Fig. 10b, AP_3) indicates the presence of a new cycle of (inherited) deformations. A brittle domain suggests that deformation occurred under lower temperature levels. Such deformations progressed to the areas of lower pressure using tectonic exhumation (E-vergent nappes, supported by evidence of the top-to-the-ESE movements; Fig. 10b). Bounded by the nappes, coupled with brittle axial plane cleavage observed within gneissic basements, such a configuration suggests the presence of another but incomplete structural transposition (TrCicle#3). The upward-directed tectonic transfer by brittle reverse faults affected the rotation of the remnants of the pre-existing Variscan foliation fabric (Fig. 15c). The rotation could further be induced by the latest Eo-Alpine stage (Marović *et al.*, 2007b).

Fig. 15. HERE

Concluding remarks

This study shows the superimposed deformations depicted in the complex Carpathian-Balkan fold-and-thrust belt. The regional research shows, for the first time, a field observation that allowed a new interpretation of the polystage deformation history involving the oldest tectonically overprinted Cadomian to Cenerian gneiss systems embedded into the Carpathian-Balkan belt of the Alpine age. For the first time, the restored deformations are separated into the Cenerian, Variscan, and Alpine orogenic stages. Other conclusions are as follows:

- The Lower Paleozoic Carpathian-Balkan crustal amalgamation and its original geometry were obliterated by several post-dating primary deformation cycles spanning Lower Paleozoic metamorphism, Variscan, and Alpine overprinting episodes, D_1 – D_4;
- The first deformation event (D_1) is characterised by the Lower Paleozoic Cenerian metamorphism and anatexis, the formation of numerous shear zones, which completely obliterated the paleodepositional north Gondwanan configuration;
- The first generation of visible yet rare folds (D_2) is produced during the Variscan orogeny by compensating the bending of the S_1 foliation. It consists of linear forms (b-axis) oriented NE-SW, whereby the folds have NW-vergence. The Variscan folds were mainly transposed along the foliation planes, parallel to the axial plane cleavage;
- The second generation of folds (D_3) resulted from the contraction and bending of previously folded and transposed Variscan configuration. The new Alpine stage

produced folds with the new arrangement of linear forms (b-axis) oriented NW-SE;

- Newly depicted Alpine deformation asymmetry between the Serbo-Macedonian Unit and its imprints into the Getic/Kučaj gneiss. The asymmetry or different intensity and character of deformations between two gneiss units is expected because of the proximity of the Neotethyan Vardar European margin segment. The direct contact with Neotethys and colliding late Alpine Apulia/Adria/Dinarides had the westernmost Serbo-Macedonian Unit. However, despite the proximity to the late Alpine deformation front, Serbo-Macedonian still contains a number of preserved Variscan folds (several outcrop-scale folds). The more internal Getic/Kučaj gneiss unit (relative to Neotethys) records the rotation of rare Variscan folds. The folds are rotated towards the NW, being aligned with the Alpine compressional style;
- The study put additional constraints on the three discrete transposition cycles (visible only in the upper crustal domain; Serbo-Macedonian and Getic/Kučaj basement units), two complete- or Lower and Upper Paleozoic age, and one incomplete transposition cycle of Alpine age: (i) Cadomian to Ordovician cycle, which obliterated the early complex juvenile continental crust configuration, (ii) Variscan, and (iii) Alpine incomplete transposition. Transposition by the development of foliation along the axial plane of tight folds was introduced in the nearby southernmost Serbo-Macedonian Unit (Marović *et al.* 2007; Antić *et al.* 2017) and Hellenides in the area of Cyclades (Xypolias et al. 2013);
- Quantitative displacement was not possible to constrain, but the distance between the parallel main Alpine nappes can be used as an approximation (horizontal displacement of ca. 35-40 Km; Fig. 3);

- Despite the transposition cycles having been defined, the major shear zones and simple-shear-dominated deformation of the lower domain need further investigation (Spahić *et al.* 2021).

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Table captions

Table. 1. Reports describing the main tectonic events imprinted into the Carpathian-Balkan basements. Blue colours are basements of Cadomian inheritance, and orange is Avalonian.

Table 2. Main age constraints on metamorphism and exhumation of Carpathian-Balkan metamorphic (C-B) assembly. Please see Figure 8 for the main sampling regions.

Figure captions

Figure 1. a. The distribution of the peri-Gondwanan affinities in Europe, including the Balkans: Serbo-Macedonian Unit, Getic/Supragetic, Danubian, and Moesia (positioned westward of the Trans European Suture Zone). Affinities of the Alpine Europe and peri-Moesian basement assemblage after Garfunkel (2015), Spahić, and Gaudenyi (2018). Abbreviations: Af—Cadomian ourcrops in Afyon zone; Bit—Bitlis massif; BM—Bohemian massif; K—Kraracahisar; LH—Tregor-La Hague terrane; M—St. Malo and Mancellian terranes; MD—Moldanubian zone; Men—Menderes massif; MG—Mid-German Crystalline High; N-Ar—northern Armorican massif; Nr—Narcea antiform; OMZ—Ossa Morena zone; Pelagonian—Pelagonian zone; StB—Baie de St. Berieuc Terrane; S-Th—Saxo-Thuringian zone; Sn—Sandikli; T—Tauern Window; TB—Tepla-Barrandian zone, Py – Pyrenees. b. Sampling and field mapping locations across the Serbo-Macedonian gneissic unit, including Ograzhden, Vertiskos, and Sebeş-Lotru terranes in the Southern Carpathians. c. Lithostratigraphic units of Carpathian-Balkan belt in Romania and Serbia (see Fig. 1a for a position; inset from Neubauer and Bojar 2013, significantly modified), key: 1 - Avalonian basement with Devonian ophiolites; 2 - Carboniferous (Pennsylvanian); 3 - Permian (in Romania); 4 - Permian-Triassic up to Upper Triassic followed by the regional-scale unconformity; 5 - Lower Jurassic; 6 - Middle Jurassic; 7 - Upper Jurassic; 8 - "Neocomian" to Barremian; 9 - Aptian to Albian unconformity; 10 - 11 - Turonian - Maastrichtian; 12 - Severin nappe (in Romania), 12 - Getic thrust; 13 - Supragetic thrust; 14 - Serbo-Macedonian Unit: west-vergent over Vardar Zone (VZ, green) and east-vergent over Supragetic unit, D - Danubian; A - Ariana nappe; S - Severin nappe; G- Getic nappe; SG - Supragetic nappe; SMU - Serbo-Macedonian Unit.

Figure 2. Main tectonic units/nappes of eastern Serbia, without the Serbo-Macedonian Unit. (simplified according to Kräutner and Krstić 2002), Jovanović et al., 2019). Number#1 in the rectangle shows the area of fieldwork. A thick dashed white line designates the approximation of the tectonic contact between Getic/Supragetic and Danubian fragments (note that the line is approximated due to the Alpine displacement, so there is also the Getic or Sebeş-Lotru thrust sheet on top of the Danubian basement to the east of the line; see also Fig. 3). The position of the former tectonic contact between descending vs. overriding plates is outlined (in the Variscan reference frame).

Figure 3. The compiled geological sketch map of the lithotectonic units connecting the South Carpathians with the Carpatho-Balkanides, including the Serbo-Macedonian Unit (modified after Kräutner and Krstić 2002, 2006). The compiled map shows a highly complex geometry between basement units and their Paleozoic, Mesozoic, and Neogene sedimentary covers. Abbreviations: GE-Getic Unit; SMU-Serbo-Macedonian Unit; SG-Supragetic Unit; LD-Lower Danubian; UD-Upper Danubian; VZ-Vardar Zone. Numbers in the red circle indicate the areas covered with field mapping.

Figure 4. a. 1D inversion model of the lithospheric thickness in the Carpathian–Pannonian Basin region (see Grinc 2013 for further explanation). b and c. 3D inversion for Carpathian Pannonian Basin region with standard parameters: surface densities, the average crustal densities (inset from Grinc 2013, slightly modified).

Figure 5. Main sampling area for detrital zircon analyses, including the areas mapped in this study: 1. Getik/Kučaj area, 2. Central Serbo-Macedonian, 3. Jastrebac Mt. area, Serbo-Macedonian: b. Chart of detrital zircon datasets extracted from gneissic basements. Numbers designate data extracted from each particular basement inlier: (1) Antić et al. (2016); (2) Žak et al. (2020); (3) Kounov et al. (2012); (4) Himmerkus et al. (2006); (5) Himmerkus et al. (2009); (6) Peytcheva et al. (2009), (7) Haydoutov et al.(2010), (8) Balintoni et al. 2010, (9) Balintoni and Balica 2013; (10) Šoster et al. 2020, (11) Abbo et al. 2020, (12) Zagorchev et al. 2012, (13) Zagorchev et al. 2015 (14) Deleon et al. 1972.

Figure 6. Examples of deformations within Getic/Kučaj gneiss, area of Donji Milanovac. a. Rare meter-scale anticline, juxtaposed to the main foliation trends. b. Rare distorted quartz grains

resembling δ-type aggregates. c. The entire area is filled with quartz exudates. d. Relics or serpentinite lenses surrounded by marble.

Figure 7. Photomicrographs of the most common microstructures depicted within Getic/Kučaj and Serbo-Macedonian units. a. Augen gneiss with micro zonation, showing undulate extinction in an XZ structural section (parallel Nicols) b. Augen gneiss with orthoclase porphyroblasts (crossed nicols). Micrograph showing the shape-preferred orientation of orthoclase crystals and aggregates parallel to the macroscopic S1 foliation in an XZ structural section. Orthoclase crystals with sigmoidal morphology; c. Amphibolitic gneiss (parallel nicols). Note that there are two generation cleavage planes: (i) parallel to the foliation (trending from the upper left corner to the lower right one in hornblende), and (ii) roughly perpendicular to macroscopic foliation; d,e,f. Biotite gneiss (parallel and crossed nicols), please note that the "f" photo shows augen (biotite) gneiss. Macroscopic foliation on the micrograph parallels cleavage (from the lower left to upper right corner); g—mica-rich gneiss with staurolite (parallel nicols parallels). Note extraordinary cleavage planes within staurolite grain, roughly perpendicular to macroscopic foliation—sigmoidal, slightly elongated staurolite porphyroblasts with a chlorite strain fringe in textural equilibrium.

Figure 8. Tight folds are observed in the Getic/Kučaj basement, comprised mainly of amphibole gneiss across this area. a,b. Competent cm-scale quartz ribbons outline the precursory tectonic foliation. c. An example of axial plane cleavage and minor offset along cleavage planes. The exposed cm-scale is symmetrical, with parasitic folds in the hinge zone. d. Partially preserved fold hinge. e. Rare asymmetric drag folds, δ-type aggregates.

Figure 9. Extraordinary deformations across the Serbo-Macedonian Unit. a. Migmatites; b. Isocline tight folds and axial plane cleavage; c. Extraordinary preservation of tight isocline folds; d. An example of preserved fold exposing displacement of the cm-scale anticline; e. The same fold as in Fig. 11e with the position and fit of the foliation—an indicator of transposition foliation. f. Measured flanks of the same tight fold on Schmid's diagram perfectly fit Variscan trends (b-axis).

Figure 10. Examples of mixed deformations embedded into the Serbo-Macedonian Unit. a. Schistosity, crenulation cleavage, including δ-type aggregates showing top-to-the-SSE movements in muscovite-rich schists. Exceptional example representing an $S_1/S_2/S_3$ composite foliation developed by multiple transposition processes. On top of the fully transposed structures (foliation), the mapping data show a developed schistosity (S_3; a potential indicator of another yet younger transposition cycle). The shape of the δ-type aggregate shows a high simple shear component. b. cm-scale folds in amphibolite schists. Folds are exposing spaced fractures/cleavage (brittle). Folds are rotated towards the SSE. c. The rare intersection point of the two foliation trends. d. The late Alpine fault follows the foliation fabric. The kinematic indicators, including offset, are likely marking the (partial) transposition. In addition, the presence of brittle features makes this phenomenon rarely uncovered and mapped into the Alpine stage. Stretching lineation directed top-to-ESE (106/32).

Figure 11. a and b. Exceptionally well-preserved pre-Alpine folds containing the organic matter, graphitic schists cropping out within the Serbo-Macedonian Unit, Jastrebac Mt. (see also Spahić 2006; Marović et al. 2007); c. Field study in the wider Jastrebac Mt. area exposed another outcrop with exceptionally well-exposed evidence of transposition: displaced meter-scale Variscan fold. d. Schematic drawing of the deformation patterns – folding and transposition. Deformation stages start from the original but largely obliterated Lower Paleozoic configuration, including the Cenerian event ($_{D1}$). The mechanism of Variscan progressive deformations, folding, and subsequent transposition (D_2). The Alpine refolding mechanism reaches the incomplete transposition stage (D_4) (details are in the text). Stages D_2 (Variscan) and D_3 (Alpine) are consistent with the deformation stages elaborated in Antić et al. (2017).

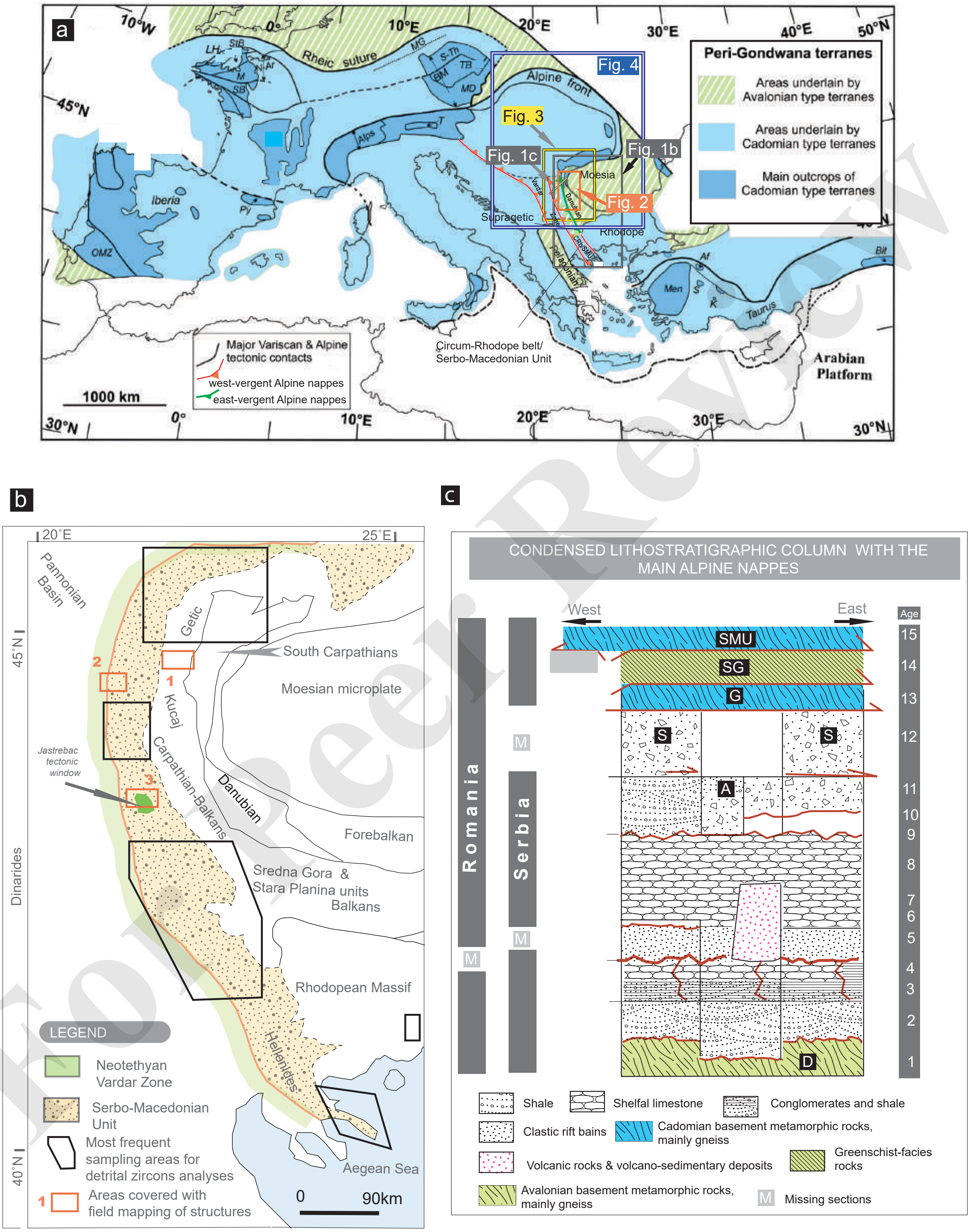
Figure 12. Statistical data, Schmid's diagrams, lower hemisphere, measured foliation, and b-axis within the Getic/Kučaj area. a. Statistical b-axis exposing four maxima or two main deformation stages producing folds with different spatial configurations. b. Measured b-axis in the exact location, exposing two maxima, NW to SE. Perfect with the Alpine deformation style. c.

Juxtaposed Alpine overprint (b-axis) onto the cleavage planes. The combined structural elements show the primary or dominant transposition directions, E(N)E - W(S)W.

Figure 13. Statistical data, Schmid's diagrams, lower hemisphere, measured foliation and b-axis within the Serbo-Macedonian area. a and b. The statistical b-axis exposes the two maxima or fold with the axial plane axis striking N-S. Such a spatial arrangement indicates rotated elements from the NE towards the NW. c The measurements also depict the Variscan axial plane relics and b-axis.

Figure 14. Two types of augen gneiss: a & b – Getic/Kučaj gneiss (Donji Milanovac area), c and d. Serbo-Macedonian Unit (vicinity of Jastrebac, i.e., Kruševac area).

Figure 15. a. Complete deformation history of the Serbo-Macedonian and Getic/Kučaj gneiss, including the intervening Supragetic (explanation in the text; data from Balintoni et al. 2010a, 2014; Neubauer and Bojar 2013; Petrović et al. 2015; Plissart et al. 2017, 2018; Antić et al. 2017; Spahić et al. 2019a,b, 2021, 2023;). b. Cadomian to Ordovician cycle, c. Variscan cycle, d. Alpine orogenesis.



a
Peri-Gondwana terranes
Areas underlain by Avalonian type terranes
Areas underlain by Cadomian type terranes
Main outcrops of Cadomian type terranes
Major Variscan & Alpine tectonic contacts
west-vergent Alpine nappes
east-vergent Alpine nappes
1000 km
Fig. 4
Fig. 3
Fig. 1c
Fig. 1b
Fig. 2
Alpine front
Rheic suture
Moesia
Supragetic
Rhodope
Circum-Rhodope belt/ Serbo-Macedonian Unit
Iberia
Alps
Taurus
Arabian Platform
10°W
0°
10°E
20°E
30°E
40°E
50°N
45°N
30°N
b
20˚E
25˚E
45˚N
40˚N
Pannonian Basin
Getic
South Carpathians
Moesian microplate
Kucaj
Carpathian-Balkans
Danubian
Forebalkan
Sredna Gora & Stara Planina units
Balkans
Rhodopean Massif
Hellenides
Dinarides
Jastrebac tectonic window
Aegean Sea
0
90km
1
2
3
LEGEND
Neotethyan Vardar Zone
Serbo-Macedonian Unit
Most frequent sampling areas for detrital zircons analyses
Areas covered with field mapping of structures
c
CONDENSED LITHOSTRATIGRAPHIC COLUMN WITH THE MAIN ALPINE NAPPES
West
East
Age
Romania
Serbia
M
SMU
SG
G
S
A
D
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Shale
Shelfal limestone
Conglomerates and shale
Clastic rift bains
Cadomian basement metamorphic rocks, mainly gneiss
Volcanic rocks & volcano-sedimentary deposits
Greenschist-facies rocks
Avalonian basement metamorphic rocks, mainly gneiss
Missing sections

Fig. 1

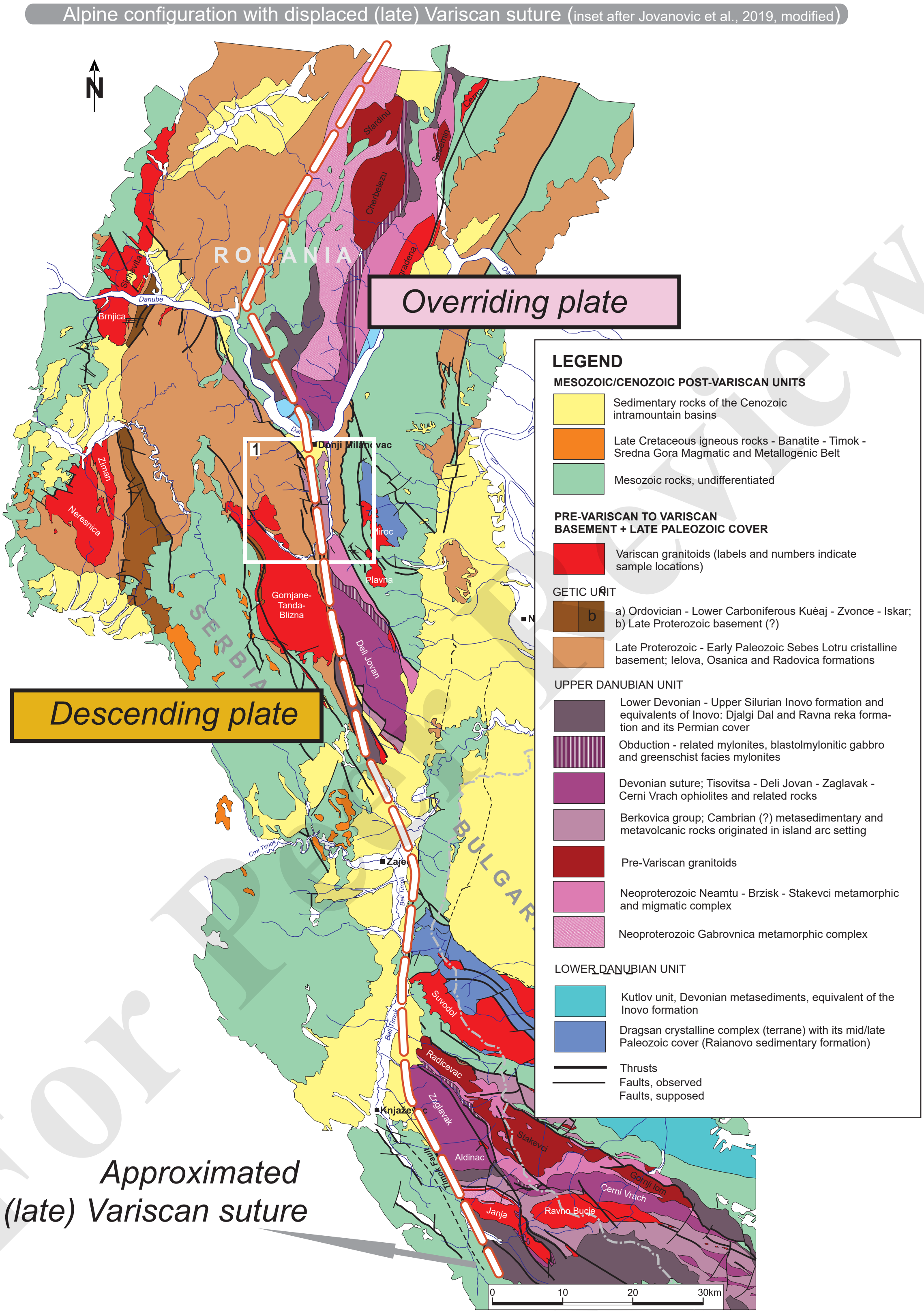

Alpine configuration with displaced (late) Variscan suture (inset after Jovanovic et al., 2019, modified)
N
Overriding plate
Descending plate
Approximated (late) Variscan suture
ROMANIA
SERBIA
BULGARIA
Danube
Brnjica
Ziman
Neresnica
Stardinu
Cherbelezu
Sfardinu
Ogradena
Donji Milanovac
1
Miroc
Plavna
Gornjane-Tanda-Blizna
Deli Jovan
Crni Timok
Zaječar
Beli Timok
Suvodol
Radicevac
Zaglavak
Knjaževac
Timok Fault
Aldinac
Stakevci
Janja
Ravno Bucje
Cerni Vrach
Gornji lom
0
10
20
30km
LEGEND
MESOZOIC/CENOZOIC POST-VARISCAN UNITS
Sedimentary rocks of the Cenozoic intramountain basins
Late Cretaceous igneous rocks - Banatite - Timok - Sredna Gora Magmatic and Metallogenic Belt
Mesozoic rocks, undifferentiated
PRE-VARISCAN TO VARISCAN BASEMENT + LATE PALEOZOIC COVER
Variscan granitoids (labels and numbers indicate sample locations)
GETIC UNIT
a
b
a) Ordovician - Lower Carboniferous Kuèaj - Zvonce - Iskar; b) Late Proterozoic basement (?)
Late Proterozoic - Early Paleozoic Sebes Lotru cristalline basement; Ielova, Osanica and Radovica formations
UPPER DANUBIAN UNIT
Lower Devonian - Upper Silurian Inovo formation and equivalents of Inovo: Djalgi Dal and Ravna reka formation and its Permian cover
Obduction - related mylonites, blastomylonitic gabbro and greenschist facies mylonites
Devonian suture; Tisovitsa - Deli Jovan - Zaglavak - Cerni Vrach ophiolites and related rocks
Berkovica group; Cambrian (?) metasedimentary and metavolcanic rocks originated in island arc setting
Pre-Variscan granitoids
Neoproterozoic Neamtu - Brzisk - Stakevci metamorphic and migmatic complex
Neoproterozoic Gabrovnica metamorphic complex
LOWER DANUBIAN UNIT
Kutlov unit, Devonian metasediments, equivalent of the Inovo formation
Dragsan crystalline complex (terrane) with its mid/late Paleozoic cover (Raianovo sedimentary formation)
Thrusts
Faults, observed
Faults, supposed

Fig. 2

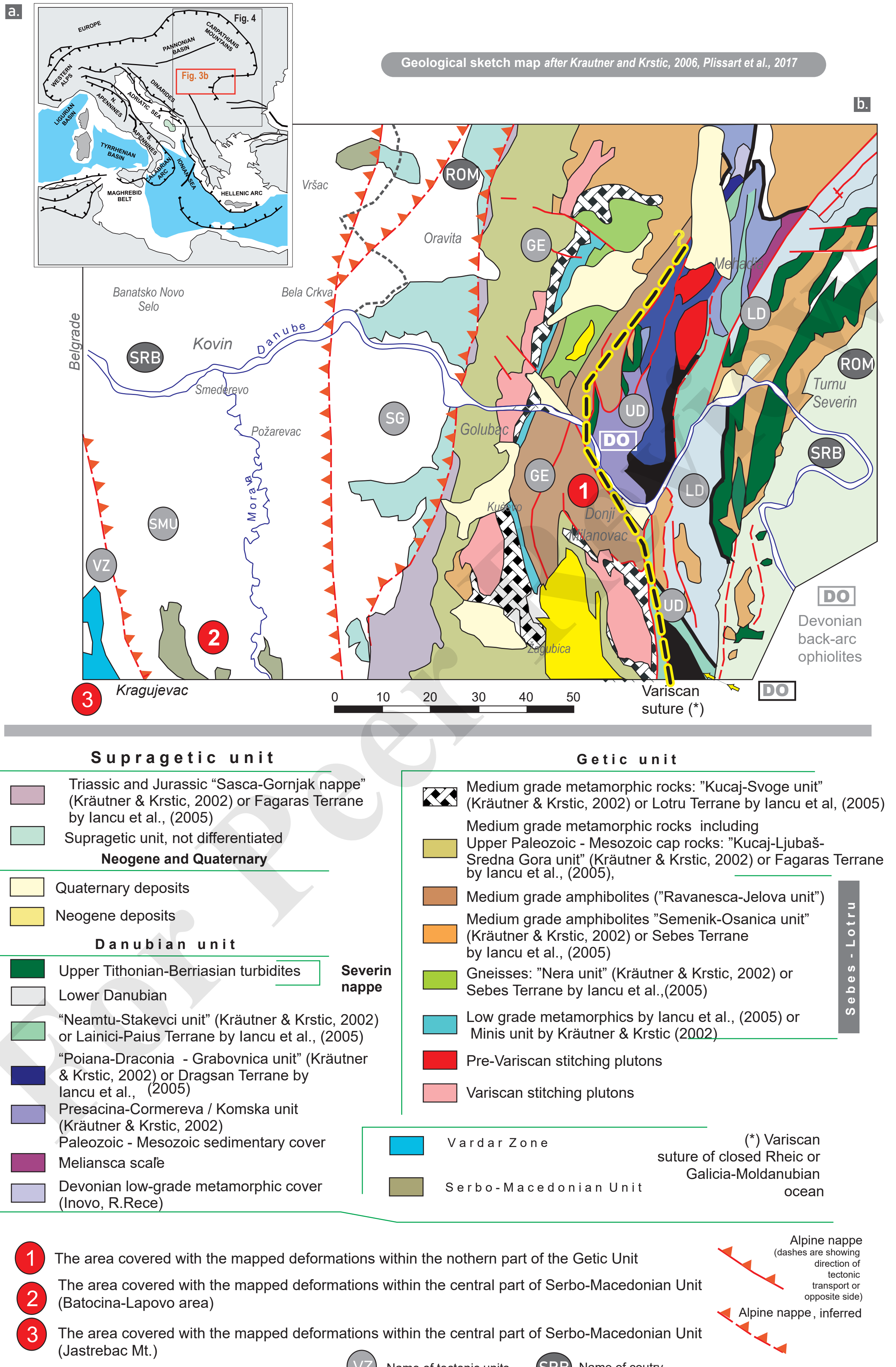
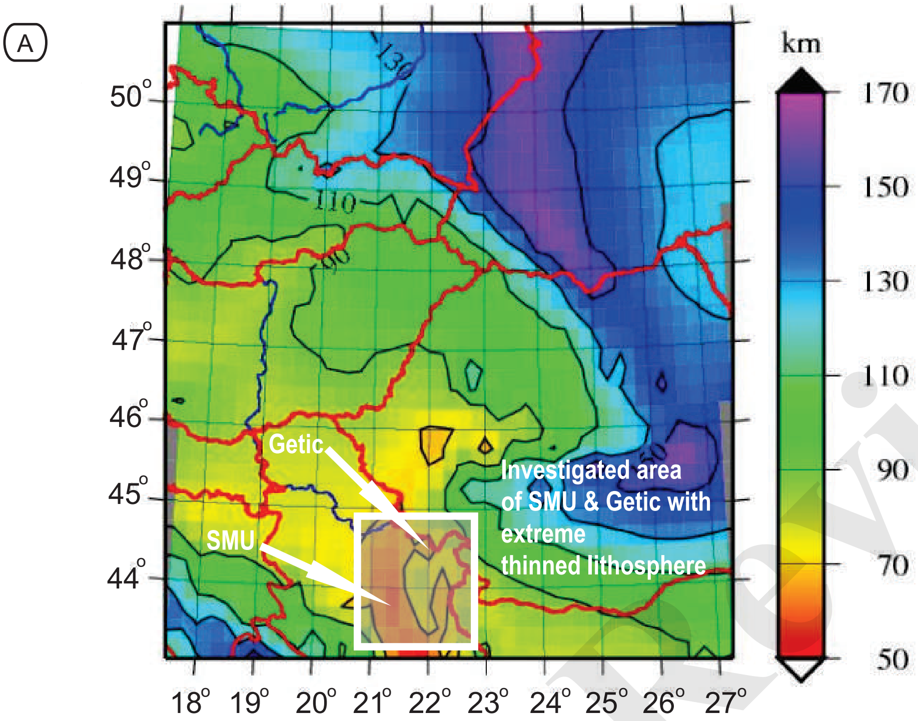

a.
Fig. 4
EUROPE
PANNONIAN BASIN
CARPATHIANS MOUNTAINS
Fig. 3b
WESTERN ALPS
DINARIDES
ADRIATIC SEA
N. APENNINES
LIGURIAN BASIN
TYRRHENIAN BASIN
S. APENNINES
CALABRIAN ARC
IONIAN SEA
HELLENIC ARC
MAGHREBID BELT
Geological sketch map after Krautner and Krstic, 2006, Plissart et al., 2017
b.
Vršac
ROM
Oravita
GE
Mehadia
Banatsko Novo Selo
Bela Crkva
LD
Belgrade
Kovin
Danube
SRB
ROM
Turnu Severin
Smederevo
SG
UD
Požarevac
Golubac
DO
SRB
GE
1
LD
Kučevo
Donji Milanovac
SMU
Morava
VZ
UD
DO
Devonian back-arc ophiolites
2
Žagubica
3
Kragujevac
0 10 20 30 40 50
Variscan suture (*)
DO
Supragetic unit
Triassic and Jurassic "Sasca-Gornjak nappe" (Kräutner & Krstic, 2002) or Fagaras Terrane by Iancu et al., (2005)
Supragetic unit, not differentiated
Neogene and Quaternary
Quaternary deposits
Neogene deposits
Danubian unit
Upper Tithonian-Berriasian turbidites
Severin nappe
Lower Danubian
"Neamtu-Stakevci unit" (Kräutner & Krstic, 2002) or Lainici-Paius Terrane by Iancu et al., (2005)
"Poiana-Draconia - Grabovnica unit" (Kräutner & Krstic, 2002) or Dragsan Terrane by Iancu et al., (2005)
Presacina-Cormereva / Komska unit (Kräutner & Krstic, 2002)
Paleozoic - Mesozoic sedimentary cover
Meliansca scale
Devonian low-grade metamorphic cover (Inovo, R.Rece)
Getic unit
Medium grade metamorphic rocks: "Kucaj-Svoge unit" (Kräutner & Krstic, 2002) or Lotru Terrane by Iancu et al, (2005)
Medium grade metamorphic rocks including Upper Paleozoic - Mesozoic cap rocks: "Kucaj-Ljubaš-Sredna Gora unit" (Kräutner & Krstic, 2002) or Fagaras Terrane by Iancu et al., (2005),
Medium grade amphibolites ("Ravanesca-Jelova unit")
Medium grade amphibolites "Semenik-Osanica unit" (Kräutner & Krstic, 2002) or Sebes Terrane by Iancu et al., (2005)
Gneisses: "Nera unit" (Kräutner & Krstic, 2002) or Sebes Terrane by Iancu et al.,(2005)
Low grade metamorphics by Iancu et al., (2005) or Minis unit by Kräutner & Krstic (2002)
Sebes - Lotru
Pre-Variscan stitching plutons
Variscan stitching plutons
Vardar Zone
Serbo-Macedonian Unit
(*) Variscan suture of closed Rheic or Galicia-Moldanubian ocean
1 The area covered with the mapped deformations within the nothern part of the Getic Unit
2 The area covered with the mapped deformations within the central part of Serbo-Macedonian Unit (Batocina-Lapovo area)
3 The area covered with the mapped deformations within the central part of Serbo-Macedonian Unit (Jastrebac Mt.)
Alpine nappe (dashes are showing direction of tectonic transport or opposite side)
Alpine nappe, inferred
VZ Name of tectonic units
SRB Name of coutry

Fig. 3

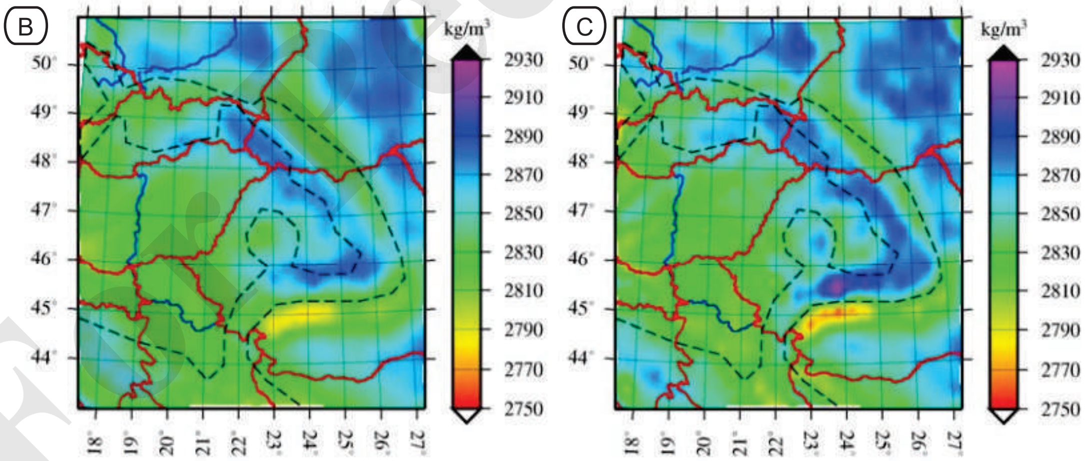
Crustal density: thinnest crust at Getic & Serbo-Macedonian Unit (modified after Grinch, 2013)



Investigated area of SMU & Getic with extreme thinned lithosphere

SMU - Serbo-Macedonian Unit; Getic - Getic basement unit

Average crustal density without smoothing (modified after Grinch, 2013)



Black dashed lines delineate mountain topography, Caprathian-Balkan rac, Apuseni Mt., and Dinarides

Fig. 4

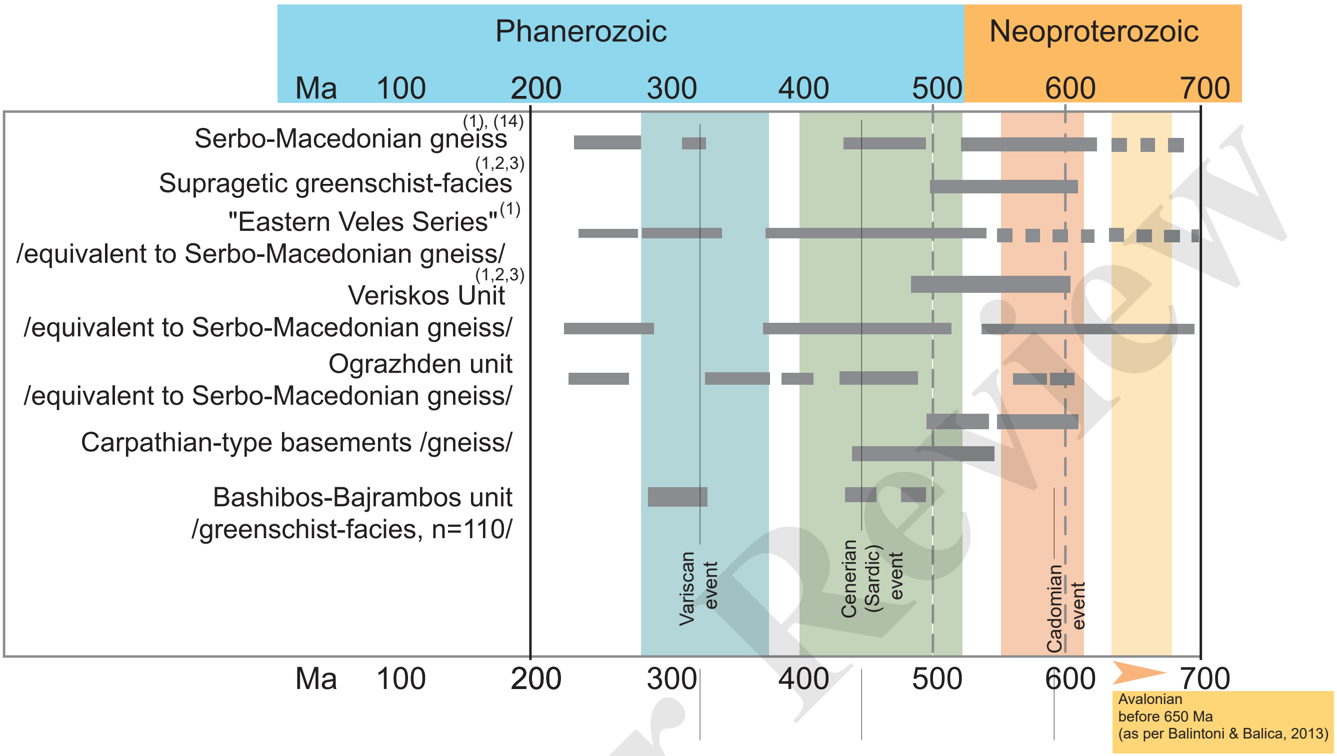

Phanerozoic
Neoproterozoic
Ma
100
200
300
400
500
600
700
(1), (14)
Serbo-Macedonian gneiss
(1,2,3)
Supragetic greenschist-facies
"Eastern Veles Series"(1)
/equivalent to Serbo-Macedonian gneiss/
(1,2,3)
Veriskos Unit
/equivalent to Serbo-Macedonian gneiss/
Ograzhden unit
/equivalent to Serbo-Macedonian gneiss/
Carpathian-type basements /gneiss/
Bashibos-Bajrambos unit
/greenschist-facies, n=110/
Variscan event
Cenerian (Sardic) event
Cadomian event
Avalonian
before 650 Ma
(as per Balintoni & Balica, 2013)

Fig. 5

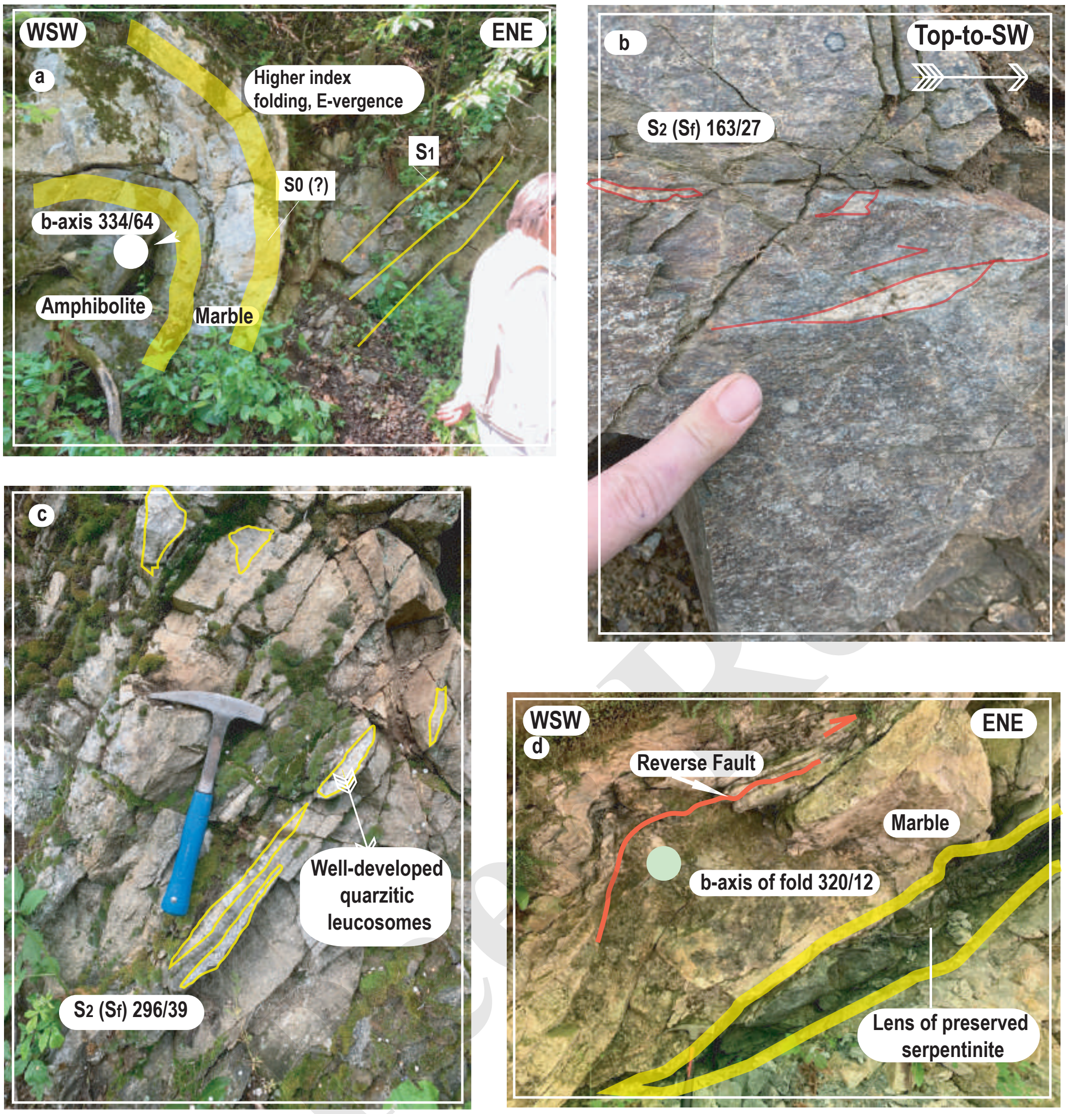
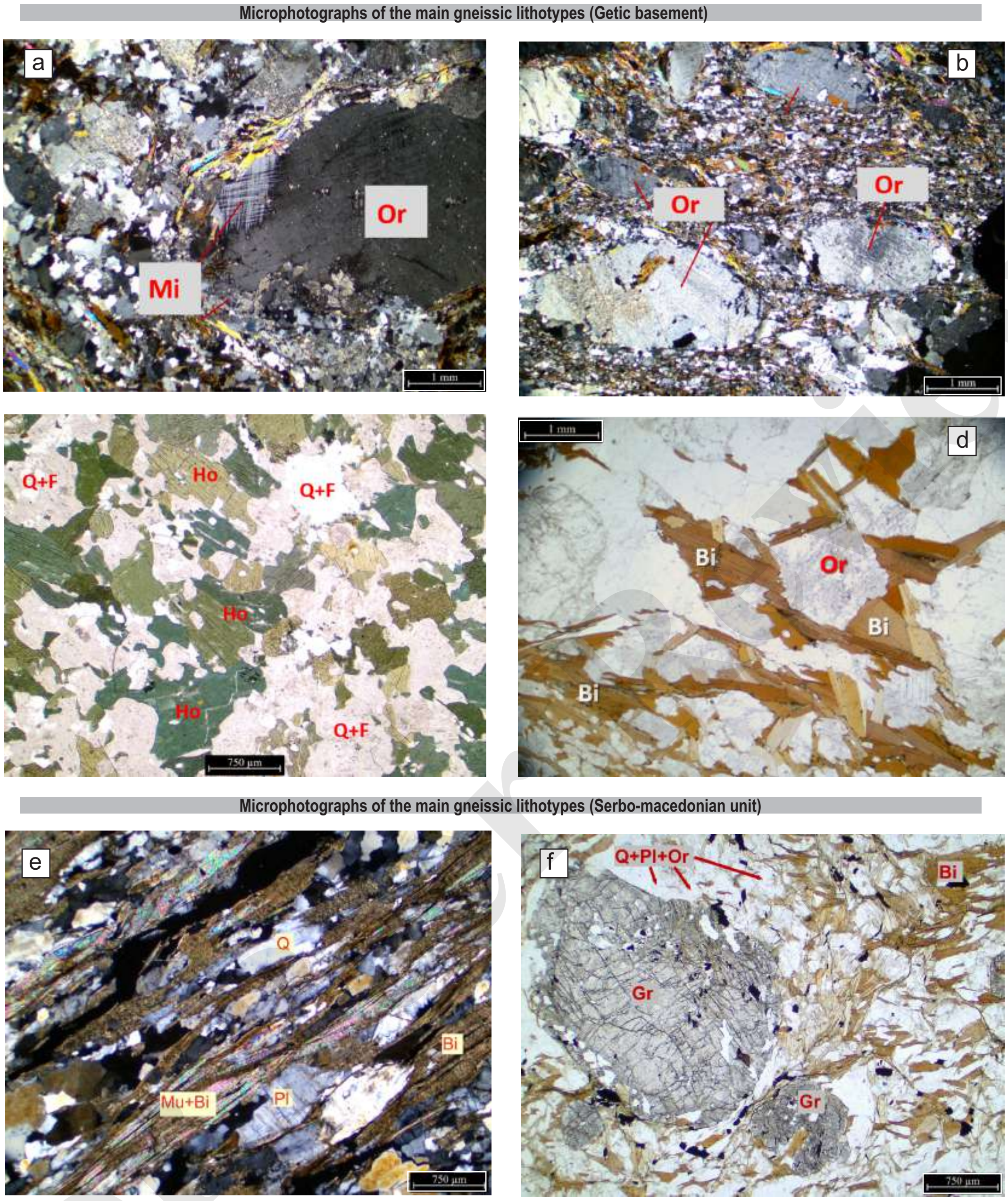
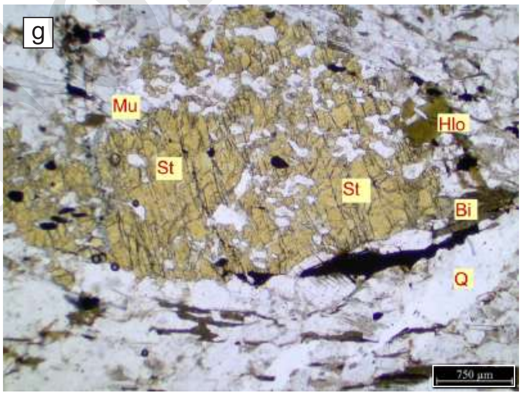

WSW
ENE
a
Higher index folding, E-vergence
S1
S0 (?)
b-axis 334/64
Amphibolite
Marble
b
Top-to-SW
S2 (Sf) 163/27
c
Well-developed quarzitic leucosomes
S2 (Sf) 296/39
WSW
d
ENE
Reverse Fault
Marble
b-axis of fold 320/12
Lens of preserved serpentinite

Fig. 6





Legend:

1. Q – Quartz, 2. Pl – plagioklase, 3. Bl – Biotite, 4. Mu – mica/muscovite, 5. Ho – hornblende, 6. Hlo – hlorite, 7. Gr – granate, 8. St – staurolite, 9. Mi - Microcline, 10. Or - Orthoclase.

Lithologies at microphotographs:

a & b. Augen gneiss;
c. Amphibolitic gneiss;
d, e, f. Biotite gneiss (f. Augen gneiss);
g. Mica-rich gneiss with staurolite

Fig. 7

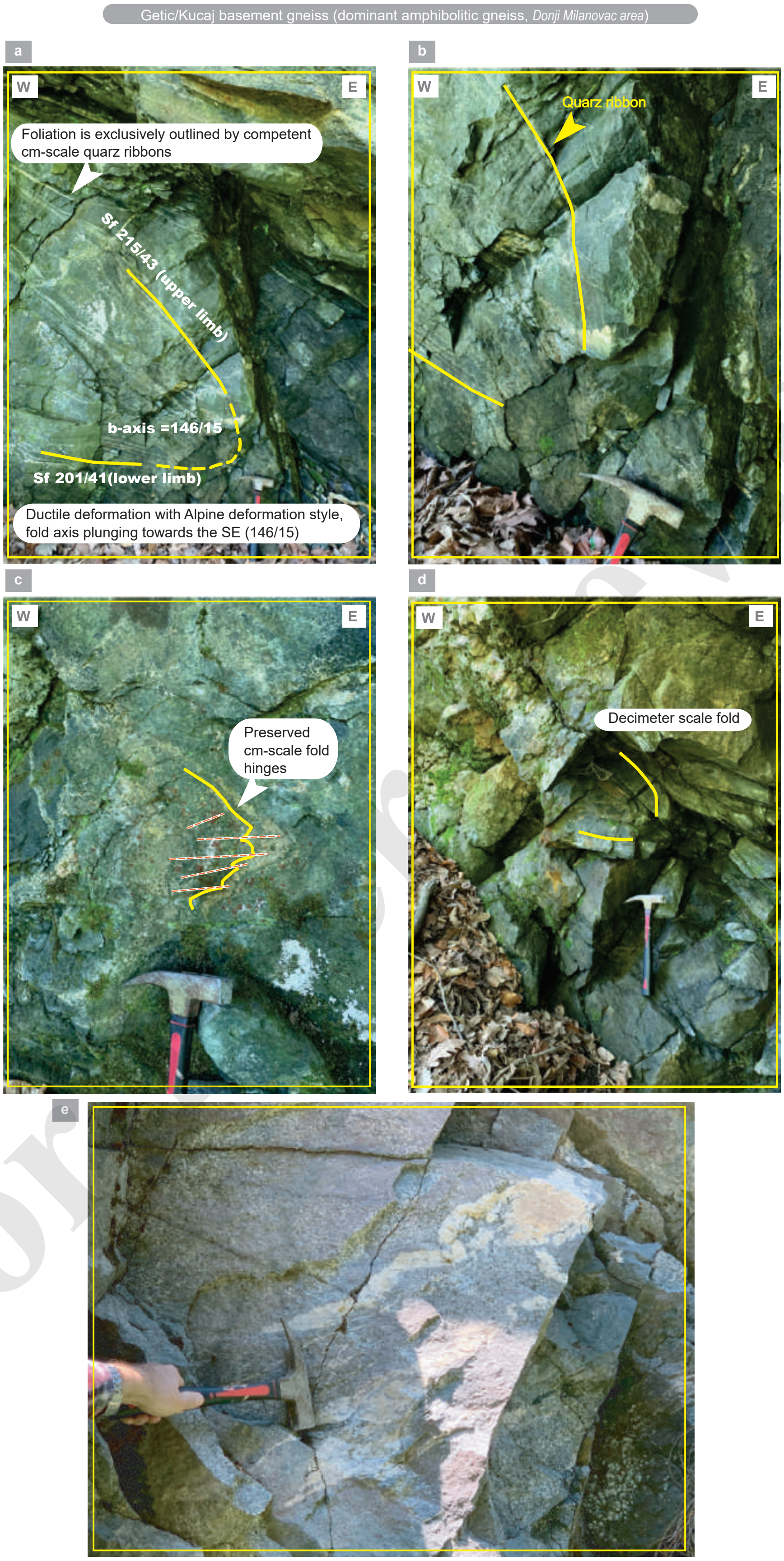

Getic/Kucaj basement gneiss (dominant amphibolitic gneiss, *Donji Milanovac area*)
a
W
E
Foliation is exclusively outlined by competent cm-scale quarz ribbons
Sf 215/43 (upper limb)
b-axis =146/15
Sf 201/41(lower limb)
Ductile deformation with Alpine deformation style, fold axis plunging towards the SE (146/15)
b
W
E
Quarz ribbon
c
W
E
Preserved cm-scale fold hinges
d
W
E
Decimeter scale fold
e

Fig. 8

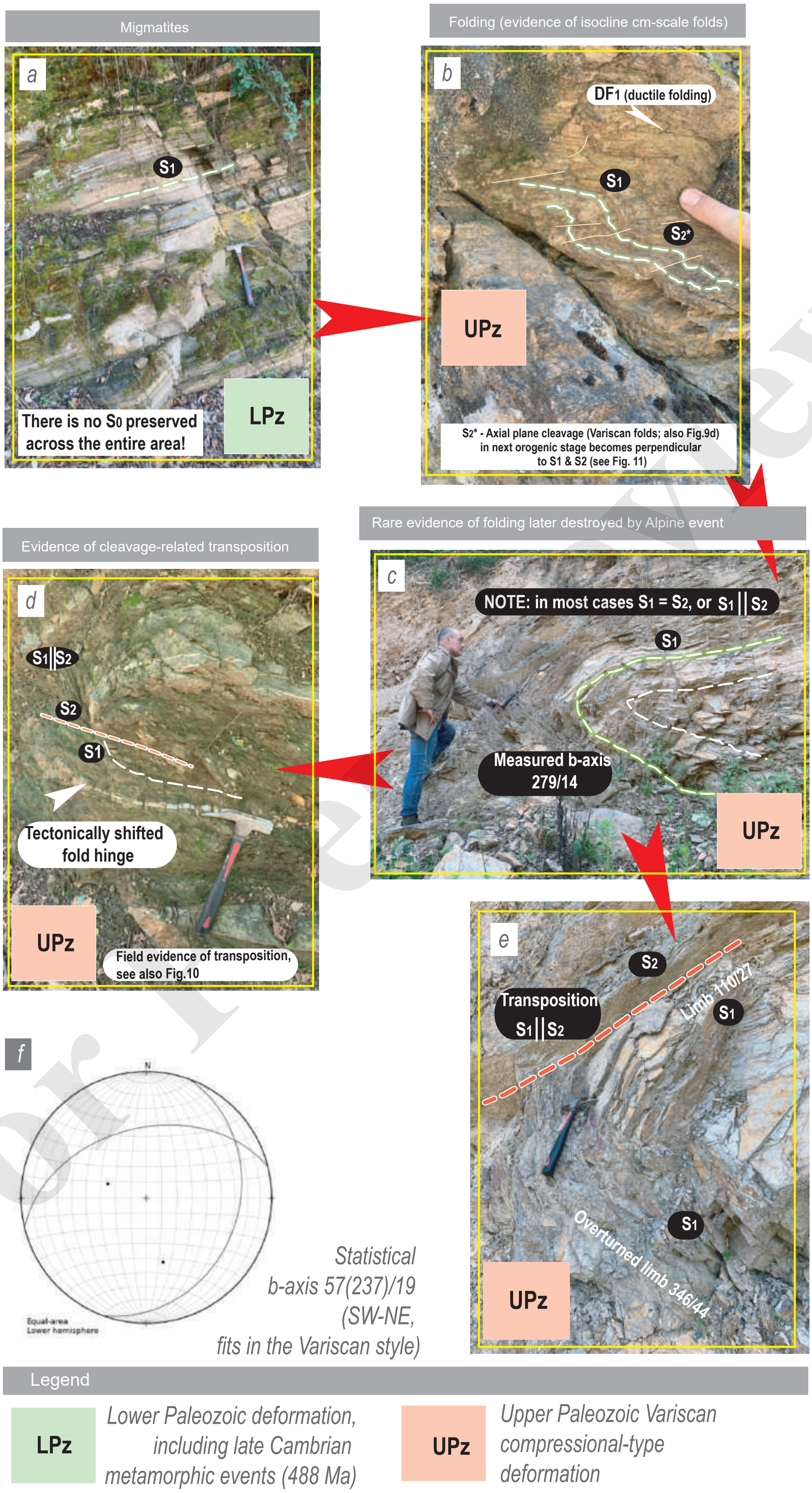

Migmatites
a
S1
There is no S0 preserved across the entire area!
LPz
Folding (evidence of isocline cm-scale folds)
b
DF1 (ductile folding)
S1
S2*
UPz
S2* - Axial plane cleavage (Variscan folds; also Fig.9d) in next orogenic stage becomes perpendicular to S1 & S2 (see Fig. 11)
Rare evidence of folding later destroyed by Alpine event
c
NOTE: in most cases S1 = S2, or S1 || S2
S1
Measured b-axis 279/14
UPz
Evidence of cleavage-related transposition
d
S1||S2
S2
S1
Tectonically shifted fold hinge
UPz
Field evidence of transposition, see also Fig.10
e
S2
Transposition S1||S2
Limb 110/27
S1
S1
Overturned limb 346/44
UPz
f
N
Equal-area Lower hemisphere
Statistical b-axis 57(237)/19 (SW-NE, fits in the Variscan style)
Legend
LPz
Lower Paleozoic deformation, including late Cambrian metamorphic events (488 Ma)
UPz
Upper Paleozoic Variscan compressional-type deformation

Fig. 9

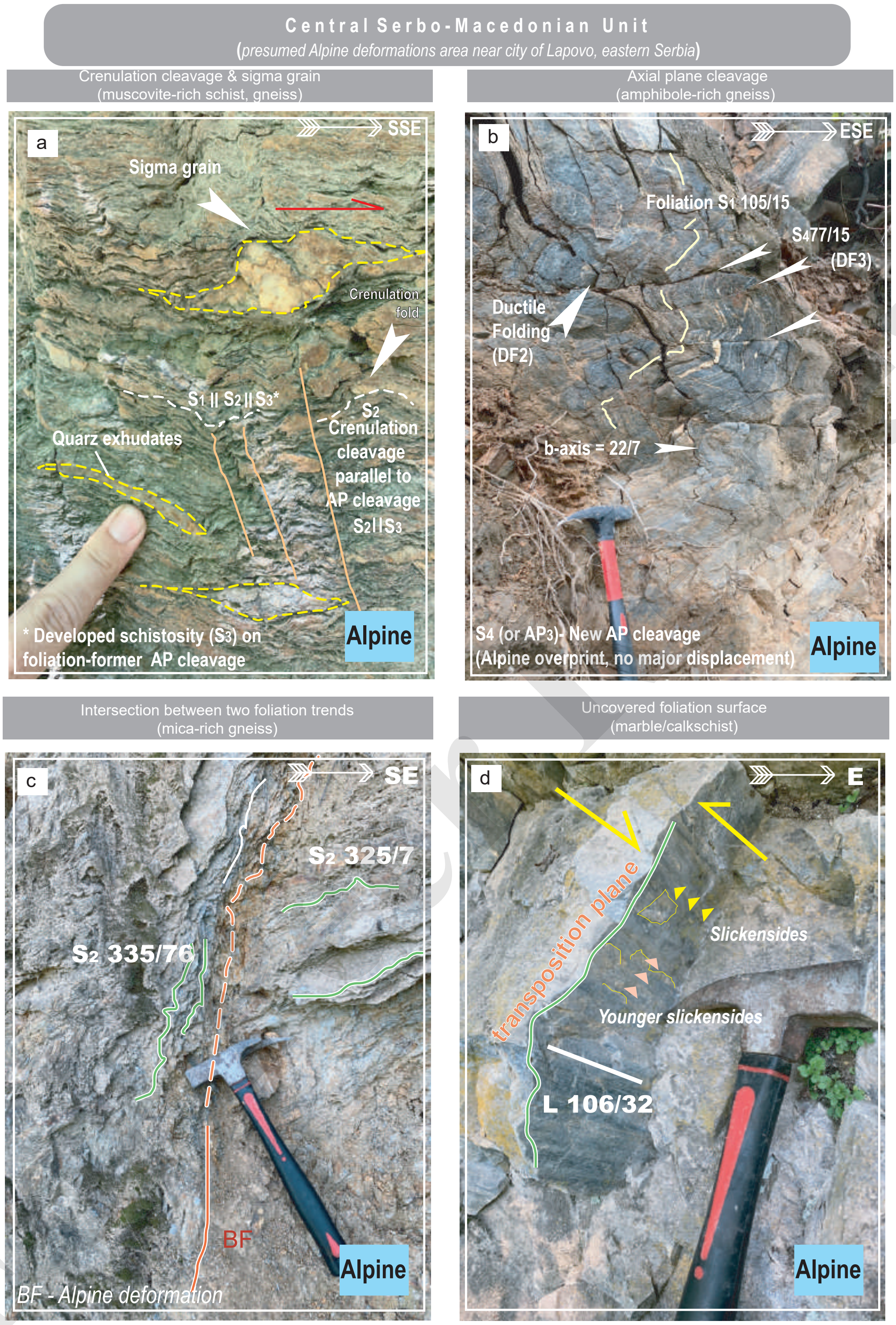
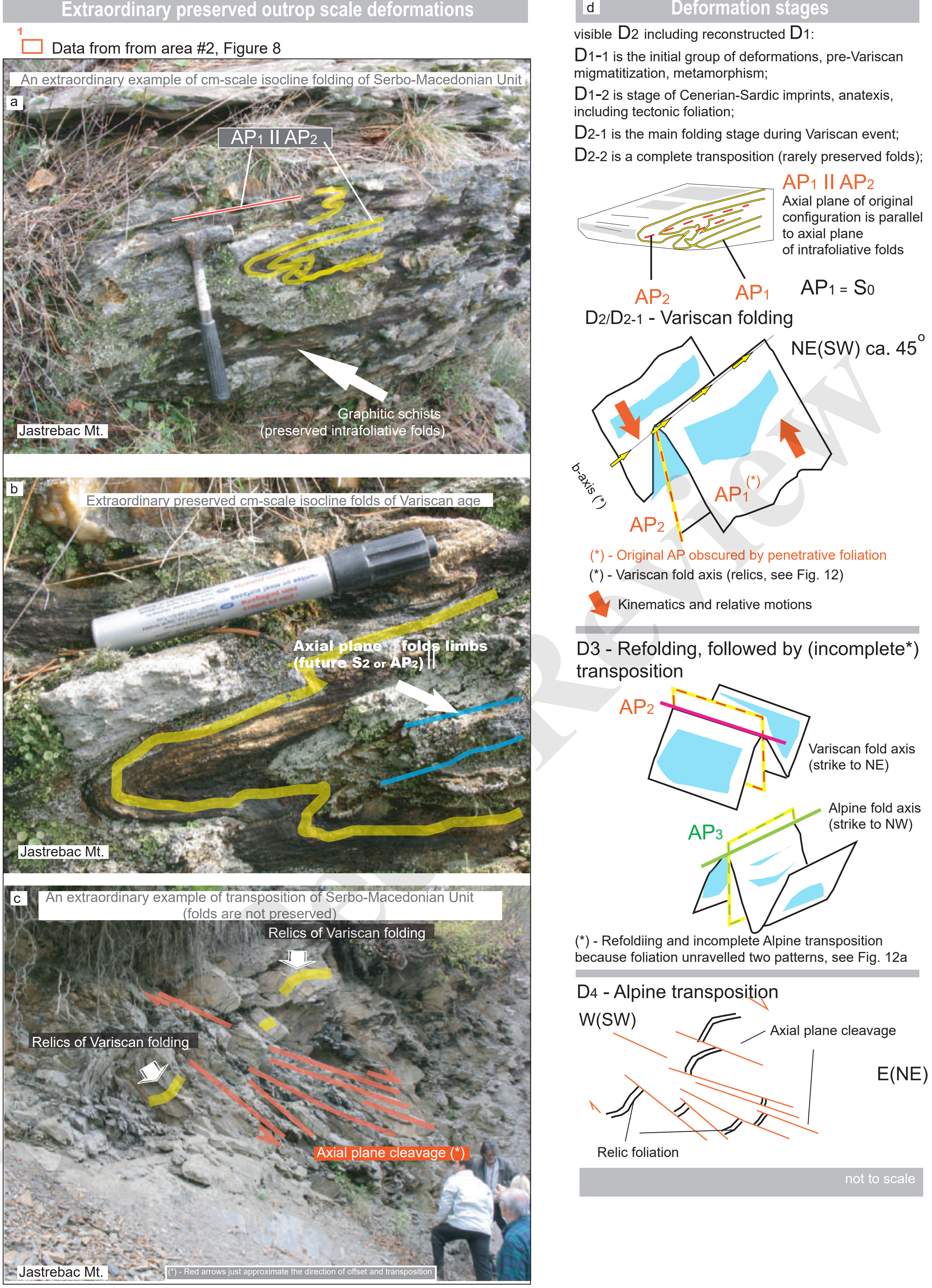

Central Serbo-Macedonian Unit
(presumed Alpine deformations area near city of Lapovo, eastern Serbia)
Crenulation cleavage & sigma grain
(muscovite-rich schist, gneiss)
Axial plane cleavage
(amphibole-rich gneiss)
a
SSE
Sigma grain
Crenulation fold
S_1 || S_2 || S_3*
Quarz exhudates
S_2 Crenulation cleavage parallel to AP cleavage S_2||S_3
* Developed schistosity (S_3) on foliation-former AP cleavage
Alpine
b
ESE
Foliation S_1 105/15
S_4 77/15
(DF3)
Ductile Folding (DF2)
b-axis = 22/7
S_4 (or AP_3)- New AP cleavage
(Alpine overprint, no major displacement)
Alpine
Intersection between two foliation trends
(mica-rich gneiss)
Uncovered foliation surface
(marble/calkschist)
c
SE
S_2 325/7
S_2 335/76
BF
BF - Alpine deformation
Alpine
d
E
transposition plane
Slickensides
Younger slickensides
L 106/32
Alpine

Fig. 10



visible D2 including reconstructed D1:

D1-1 is the initial group of deformations, pre-Variscan migmatitization, metamorphism;

D1-2 is stage of Cenerian-Sardic imprints, anatexis, including tectonic foliation;

D2-1 is the main folding stage during Variscan event;

D2-2 is a complete transposition (rarely preserved folds);

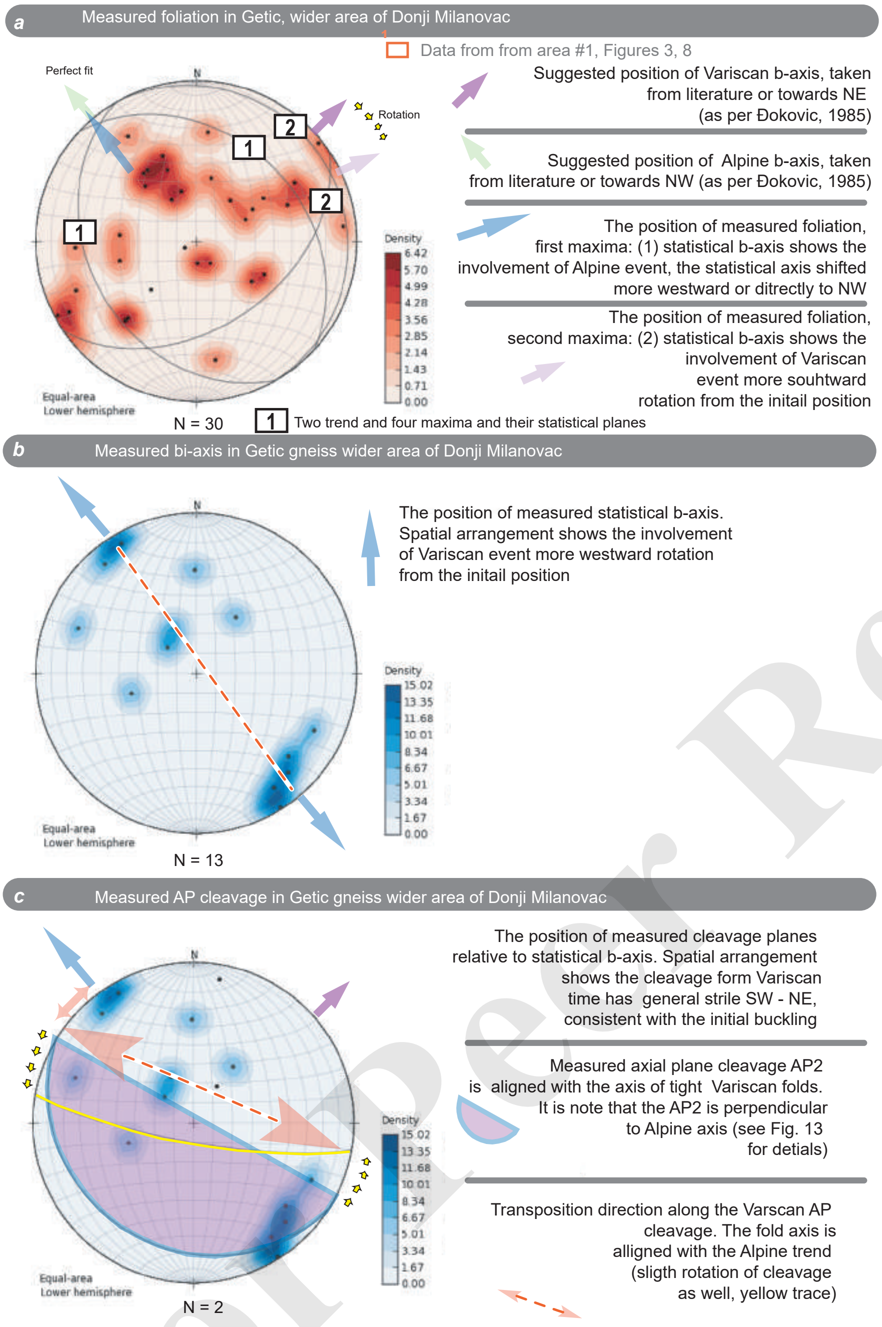
(*) - Original AP obscured by penetrative foliation

(*) - Variscan fold axis (relics, see Fig. 12)

Kinematics and relative motions

(*) - Refoldiing and incomplete Alpine transposition because foliation unravelled two patterns, see Fig. 12a

Fig. 11



Measured foliation in Getic, wider area of Donji Milanovac

Data from from area #1, Figures 3, 8

Suggested position of Variscan b-axis, taken from literature or towards NE (as per Đokovic, 1985)

Suggested position of Alpine b-axis, taken from literature or towards NW (as per Đokovic, 1985)

The position of measured foliation, first maxima: (1) statistical b-axis shows the involvement of Alpine event, the statistical axis shifted more westward or ditrectly to NW

The position of measured foliation, second maxima: (2) statistical b-axis shows the involvement of Variscan event more souhtward rotation from the initail position

1 Two trend and four maxima and their statistical planes

Measured bi-axis in Getic gneiss wider area of Donji Milanovac

The position of measured statistical b-axis. Spatial arrangement shows the involvement of Variscan event more westward rotation from the initail position

Measured AP cleavage in Getic gneiss wider area of Donji Milanovac

The position of measured cleavage planes relative to statistical b-axis. Spatial arrangement shows the cleavage form Variscan time has general strile SW - NE, consistent with the initial buckling

Measured axial plane cleavage AP2 is aligned with the axis of tight Variscan folds. It is note that the AP2 is perpendicular to Alpine axis (see Fig. 13 for detials)

Transposition direction along the Varscan AP cleavage. The fold axis is alligned with the Alpine trend (sligth rotation of cleavage as well, yellow trace)

Fig. 12

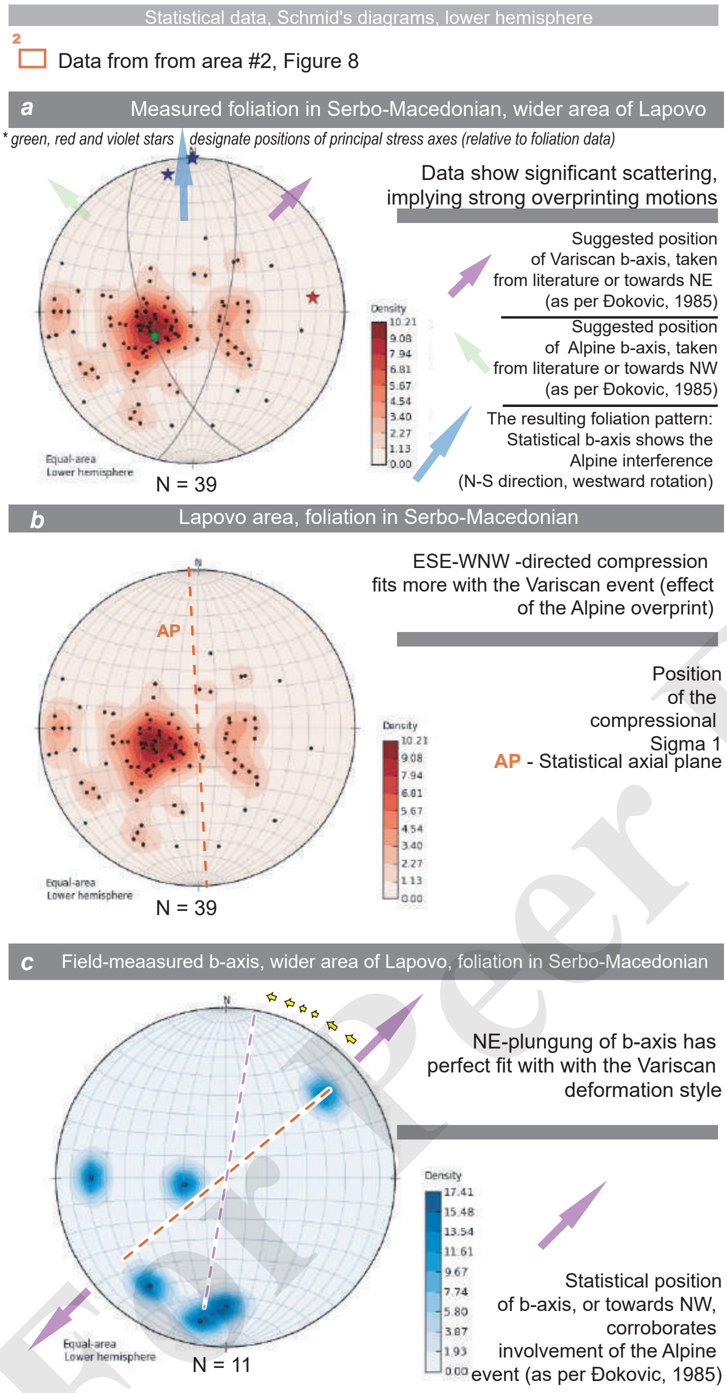

Statistical data, Schmid's diagrams, lower hemisphere
2
Data from from area #2, Figure 8
a
Measured foliation in Serbo-Macedonian, wider area of Lapovo
* green, red and violet stars designate positions of principal stress axes (relative to foliation data)
Data show significant scattering, implying strong overprinting motions
Suggested position of Variscan b-axis, taken from literature or towards NE (as per Đokovic, 1985)
Suggested position of Alpine b-axis, taken from literature or towards NW (as per Đokovic, 1985)
The resulting foliation pattern: Statistical b-axis shows the Alpine interference (N-S direction, westward rotation)
Density
10.21
9.08
7.94
6.81
5.67
4.54
3.40
2.27
1.13
0.00
Equal-area
Lower hemisphere
N = 39
b
Lapovo area, foliation in Serbo-Macedonian
N
AP
ESE-WNW -directed compression fits more with the Variscan event (effect of the Alpine overprint)
Position of the compressional Sigma 1
AP - Statistical axial plane
Density
10.21
9.08
7.94
6.81
5.67
4.54
3.40
2.27
1.13
0.00
Equal-area
Lower hemisphere
N = 39
c
Field-meaasured b-axis, wider area of Lapovo, foliation in Serbo-Macedonian
N
NE-plungung of b-axis has perfect fit with with the Variscan deformation style
Density
17.41
15.48
13.54
11.61
9.67
7.74
5.80
3.87
1.93
0.00
Statistical position of b-axis, or towards NW, corroborates involvement of the Alpine event (as per Đokovic, 1985)
Equal-area
Lower hemisphere
N = 11

Fig. 13

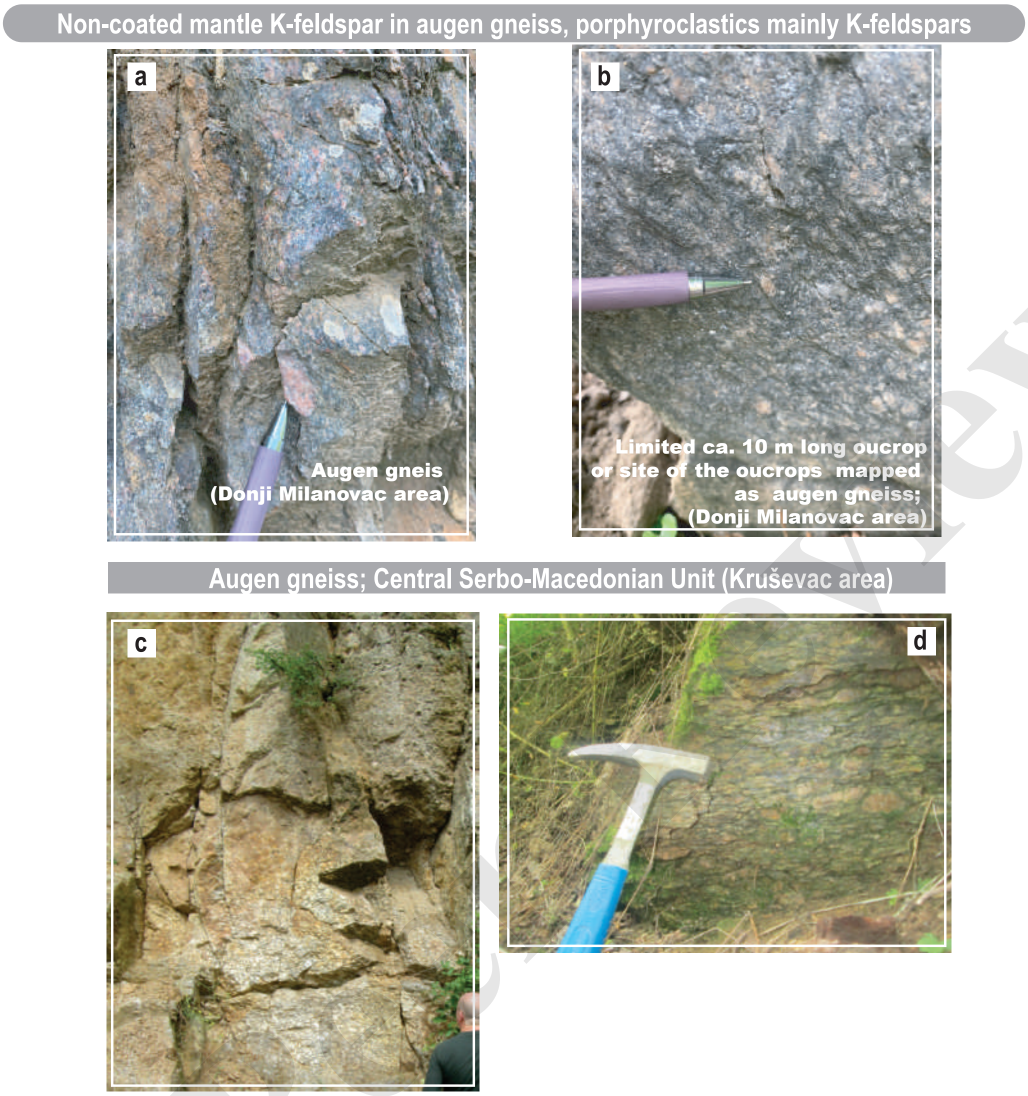

Non-coated mantle K-feldspar in augen gneiss, porphyroclastics mainly K-feldspars
a
Augen gneis
(Donji Milanovac area)
b
Limited ca. 10 m long oucrop
or site of the oucrops mapped
as augen gneiss;
(Donji Milanovac area)
Augen gneiss; Central Serbo-Macedonian Unit (Kruševac area)
c
d

Fig. 14

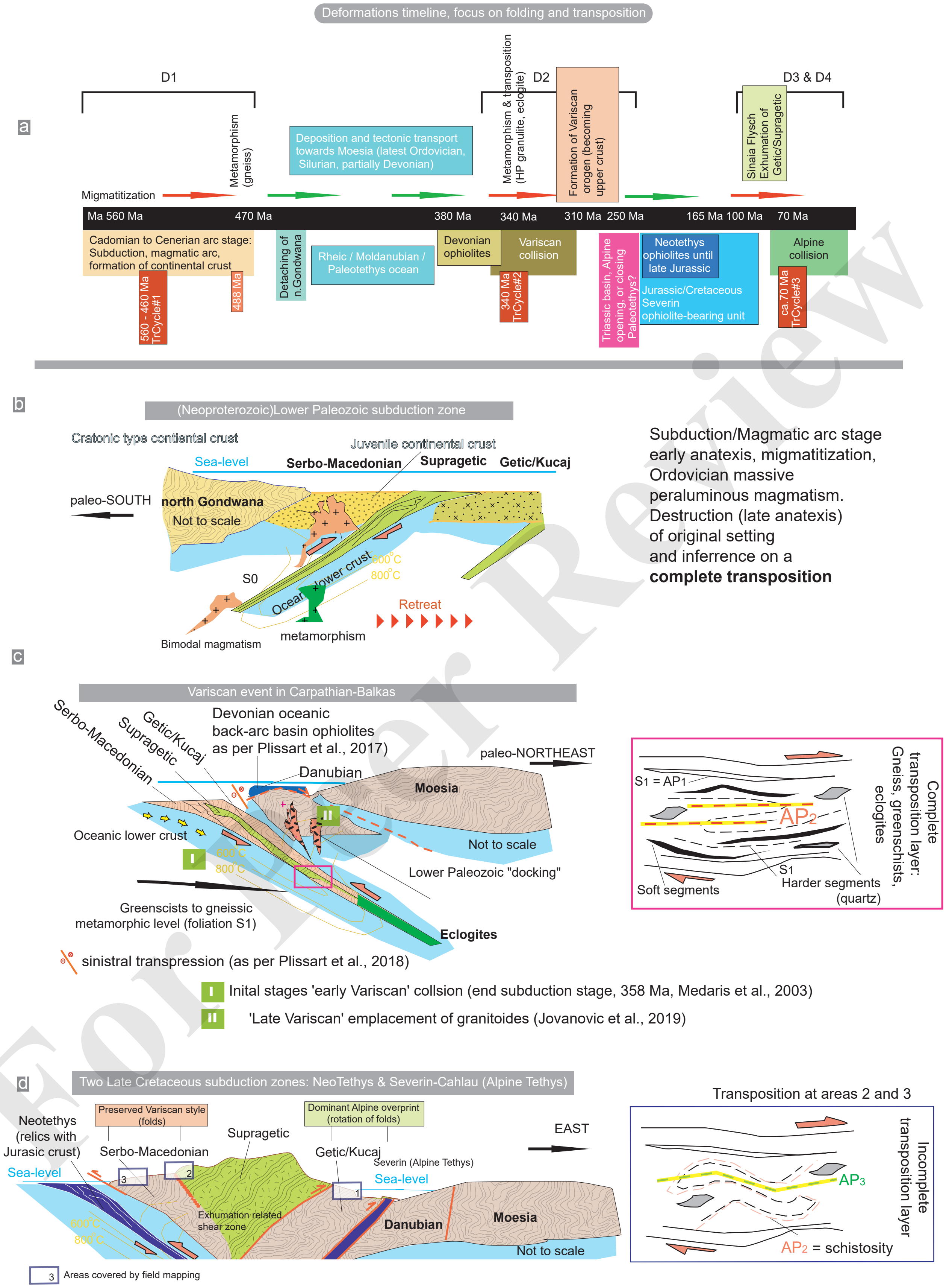

Deformations timeline, focus on folding and transposition
a
D1
D2
D3 & D4
Migmatitization
Metamorphism (gneiss)
Deposition and tectonic transport towards Moesia (latest Ordovician, Silurian, partially Devonian)
Metamorphism & transposition (HP granulite, eclogite)
Formation of Variscan orogen (becoming upper crust)
Sinaia Flysch Exhumation of Getic/Supragetic
Ma 560 Ma
470 Ma
380 Ma
340 Ma
310 Ma
250 Ma
165 Ma
100 Ma
70 Ma
Cadomian to Cenerian arc stage: Subduction, magmatic arc, formation of continental crust
560 - 460 Ma TrCycle#1
488 Ma
Detaching of n.Gondwana
Rheic / Moldanubian / Paleotethys ocean
Devonian ophiolites
Variscan collision
340 Ma TrCycle#2
Triassic basin, Alpine opening, or closing Paleotethys?
Neotethys ophiolites until late Jurassic
Jurassic/Cretaceous Severin ophiolite-bearing unit
Alpine collision
ca.70 Ma TrCycle#3
b
(Neoproterozoic)Lower Paleozoic subduction zone
Cratonic type contiental crust
Juvenile continental crust
Sea-level
Serbo-Macedonian
Supragetic
Getic/Kucaj
paleo-SOUTH
north Gondwana
Not to scale
S0
Ocean
lower crust
600°C
800°C
Retreat
Bimodal magmatism
metamorphism
Subduction/Magmatic arc stage early anatexis, migmatitization, Ordovician massive peraluminous magmatism. Destruction (late anatexis) of original setting and inferrence on a
complete transposition
c
Variscan event in Carpathian-Balkas
Serbo-Macedonian
Supragetic
Getic/Kucaj
Devonian oceanic back-arc basin ophiolites as per Plissart et al., 2017)
Danubian
paleo-NORTHEAST
Moesia
Oceanic lower crust
I
II
600°C
800°C
Not to scale
Lower Paleozoic "docking"
Greenscists to gneissic metamorphic level (foliation S1)
Eclogites
S1 = AP1
AP2
S1
Soft segments
Harder segments (quartz)
Complete transposition layer: Gneiss, greenschists, eclogites
sinistral transpression (as per Plissart et al., 2018)
I Inital stages 'early Variscan' collsion (end subduction stage, 358 Ma, Medaris et al., 2003)
II 'Late Variscan' emplacement of granitoides (Jovanovic et al., 2019)
d
Two Late Cretaceous subduction zones: NeoTethys & Severin-Cahlau (Alpine Tethys)
Neotethys (relics with Jurasic crust)
Preserved Variscan style (folds)
Serbo-Macedonian
Supragetic
Dominant Alpine overprint (rotation of folds)
Getic/Kucaj
Severin (Alpine Tethys)
EAST
Sea-level
Sea-level
3
2
1
600°C
800°C
Exhumation related shear zone
Danubian
Moesia
Not to scale
3 Areas covered by field mapping
Transposition at areas 2 and 3
AP3
AP2 = schistosity
Incomplete transposition layer

Fig. 15

Tectono-magmatic events	**Serbo-Macedonian Unit (gneiss; Serbia, North Macedonia, Greece)**	**Getic/Kučaj basement unit/Sredna Gora (sliced gneiss)**	**Danubian *s.l.***
Cadomian (Neoproterozoic)	• Pyrgadikia mylonitic granite 588 Ma (1) • granite 571 Ma (2)	Balintoni & Balica (2013), granites in orthogneiss (7); Sebeş unit, granites in orthogneiss: Balintoni et al., (2010a) (5)	N / A
Cenerian(Sardic) (Ordovician) /this study/	Granitic augen gneiss (1) , (11)	Lotru unit (6). Apuseni Mts. (7)	N / A
Variscan	Granite of the Arnea pluton, 300 Ma (1)	Brnjica, Neresnica, Ziman, Gornjane–Tanda–Blizna (Getic unit), (4); Variscan age of eclogites (8)	Aldinac, Janja, Ravno Bučje, Plavna, and Suvodol batholiths of mainly Variscan ages (4)
(Eo)Cimmerian /this study/	- Granitic Orthogneiss, 254 Ma(1); -meta-mafic rocks (9); - Skrut granitoid (10)	Leucocratic granites: Strelcha and Karavelovo (289.5±7.8 Ma (3)	N / A
Early Alpine	Numerous granitoid bodies (2)	Severin-Cehlau oceanic crust, Neubauer & Bojar (2013)	N / A
Late Alpine	Granite of Sithonia Peninsula, 65 Ma (1) and other numerous reports		

(1) Abbo et al. (2020); (2) Antić et al. (2016); (3) Balkanska et al., (2022); (4) Jovanović et al. (2019); (5) Balintoni et al., (2010a); (6) Balintoni et al., (2010b); (7) Balintoni & Balica (2013); (8) Medaris et al. (2003); (9) Bonev & Dilek, 2008; (10) Zidarov et al. (2007); (11) Spahić et al. (2021); (12) Neubauer & Bojar (2013). N / A – designates not studied or not existing tectonic stages.

Table. 1. Reports describing the main tectonic events imprinted into the Carpathian-Balkan basements. Blue colours are basements of Cadomian inheritance, and orange is Avalonian.

Variscan & Alpine deformation events imprinted *in Serbo-Macedonian Unit and analog units* (1)	Metamorphism	Exhumation (fission-track analysis)	Age of protoliths
Southern Serbia SMU[2,6, 11]	-	ca. 129 – 32 Ma, gradual cooling after 75 Ma (on apatites and zircons)	
	Greenschist-facies retrogression in the SMU probably occurred in the Early Jurassic (195 Ma)	Jurassic thermal event (^{40}Ar/^{39}Ar)	
	(1) Eclogite-type was in Neoproterozoic, whereas (2) medium amphibolitic facies was in Variscan time. (3) Latest Jurassic - Early Cretaceous greenschist-facies retrogressive stage (Supragetic)		Pelitic and psammitic sediments are usually considered protoliths of the felsic metamorphic rocks, and tholeiitic within-plate basalts and related tuffs as protoliths of the amphibolites. Parametamorphic protolith is of **569 Ma.**
Vertiskos unit[3,5]	[3]- Minor Neoproterozoic, mainly in Phanerozoic (U/Th). Rutile shows the latest 35 Ma stage.		Biotite gneiss E of Sochos, **468 Ma**
	[5]-Minor Triassic event, in connection to granitic bodies (single grain evaporation method)		
Sebeş-Lotru group (inclusive Supragetic and Getic)[4,6,8, 10, ,14]	ca. 300 Ma (Sm –Nd mineral – whole-rock isochrons for garnet amphibolite)		
		post-Variscan exhumation of the entire C-B system Supragetic, Getic, and Danubian basement units of the South Carpathians (330–300 Ma);	
	The event recorded by U/Pb La-ICP MS in orthogneiss of Campagna ca.549 Ma, and the same rocks of Lotru of 459 Ma		
	Study based on high-pressure relicts (eclogite, granulite): amphibole~quartz eclogites, metagabbro of probable Variscan age		
Central Serbia SMU[7,12]			Rb^{87}/Sr^{86}, on K-feldspar of **540 Ma**, the isochronal age of the entire rock sample is 475 Ma. Emplaced granite-gneiss is of 380 Ma.
	Rb/Sr and K/Ar, ^{87}Sr/^{86}Sr ratio yields temperatures above 500°C at 488 Ma	Resetting muscovite, biotite, and K-feldspar ages was a younger event that cooled below 145±15 °C 127.34.8 Ma age (Lower Cretaceous). A cooling rate of the muscovite and K-feldspar ages pinpoints the time interval from 150.6 Ma to 127.3 Ma	
Ograzhden supergroup[9]	Cadomian event on ca. 550 – 530 Ma) on gneiss-migmatitic supercomplex		Isotopic U-Pb, LA- ICP-MS on zircons show Ordovician to Silurian age on metagranites
Sredna Gora[13]	Variscan event 398 Ma – 336 Ma (to 333 Ma)	Early Alpine thermal event at about 140–138 Ma Late Alpine apatite FT dating 65 – 55 Ma	Paragneisses, metaigneous rocks, migmatites with minor garnet amphibolites, and high-pressure eclogites of continental and oceanic affinities

(1) – Serbo-Macedonian analog units: Ograzhden supergroup (Bulgaria), Vertiskos unit (Greece), Sebeş-Lotru terrane (Romania), “Eastern Veles Series” (North Macedonia); [2] - Antić et al., 2015; [3] – Abbo et al., 2020; [4] – Medaris et al., 2003; [5] – Himmerkus et al., 2009; [6] – Antić et al., 2017; 7 – Deleon et al., 1972; 8 - Balintoni et al., 2010; 9 – Zagorchev et al., 2012; 10 – Iancu et al., 1998; 11 – Antić et al., 2016; 12 – Balogh et al., 1994; Žak et al., 2020; 13 – Balkanska et al., 2022; 14 Dallmayer et al., 1996.

Table 2. Main age constraints on metamorphism and exhumation of Carpathian-Balkan metamorphic (C-B) assembly. Please see Figure 8 for the main sampling regions.