Acta Geologica Polonica, Vol. 71 (2021), No. 2, pp. 219–247
DOI: 10.24425/agp.2020.134558

Vestiges of Cambro-Ordovician continental accretion in the Carpathian-Balkan orogen: First evidence of the 'Cenerian' event in the central Serbo-Macedonian Unit

DARKO SPAHIĆ[1]*, ZORAN BOJIĆ[1], DANICA POPOVIĆ[1] and TIVADAR GAUDENYI[2]

[1] *Geological Survey of Serbia, Rovinjska 12, 11000 Belgrade, Serbia.*
[2] *Geographical Institute "Jovan Cvijić" of the Serbian Academy of Sciences and Arts, Djure Jakšića 9, 11000 Belgrade, Serbia.*
* *Corresponding author: darkogeo2002@hotmail.com; darko.spahic@gzs.gov.rs*

Darko Spahić: http://orcid.org/0000-0002-5832-0782
Tivadar Gaudenyi: https://orcid.org/0000-0002-1843-2384

ABSTRACT:

Spahić, D., Bojić, Z., Popović, D. and Gaudenyi, T. 2021. Vestiges of Cambro-Ordovician continental accretion in the Carpathian-Balkan orogen: First evidence of the 'Cenerian event' in the central Serbo-Macedonian Unit. *Acta Geologica Polonica*, **71** (2), 219–247. Warszawa.

In the Balkans, the Serbo-Macedonian Unit (SMU), Serbia, is thrust bounded by the composite Tethyan Vardar Zone and the Carpatho-Balkanides. The SMU actually emerges from beneath the Neoalpine Miocene–Pliocene deposits. Both provenance and geodynamic position of the SMU are poorly known and still debated. This paper reviews the data hitherto published and includes some new field data interpretations. The SMU is composed of a Neoproterozoic–Cambrian high-grade (para- and ortho-) gneiss with peraluminous magmatic arc components (560–470 Ma). The SMU is in the contact with Neoproterozoic upper Ordovician–Carboniferous low-grade metasedimentary succession of an accretionary wedge assembly represented by the Supragetic basement. The SMU basement became folded, sheared and metamorphosed around 490–450 Ma. Paleomagnetic data point to high southern latitudes and a peri-Gondwanan position of the SMU at that time, which concurs with glaciomarine evidence recorded from the upper Ordovician sediments at the base of an accretionary wedge succession. Based on the published data and field survey in the Stalać region, we correlate the SMU with the pre-Mesozoic gneiss terrane exposed in the Strona-Ceneri zone of the Alps. This terrane, identified as the Cenerian orogen of the Alaskan subduction type, developed at an active margin of Gondwana during middle Ordovician times. The SMU basement, with augen and migmatitic gneisses and arc-related peraluminous magmatic bodies, developed at this margin as part of the Cenerian belt or its equivalent. Such an orogenic edifice proved transient and in the earliest Silurian the SMU fragments drifted away being bound for Baltica (amalgamated Moesian microplate and Danubian terrane) to which they became accreted in the Carboniferous and included in the southern European branch of the Variscan orogen (Marginal Dacides/Carpatho-Balkanides). Despite considerable Variscan and Alpine reworking, the pre-Variscan, Cenerian-type crustal assembly along with an inferred boundary between the magmatic arc and the accretionary wedge, accompanied by back-arc/forearc deposits, are still decipherable in the Western Balkan countries.

Key words: 'Cenerian event'; North Gondwana; Serbo-Macedonian Unit; Supragetic basement; Lower Paleozoic paleosuture; Migmatites; Shear zones.

INTRODUCTION

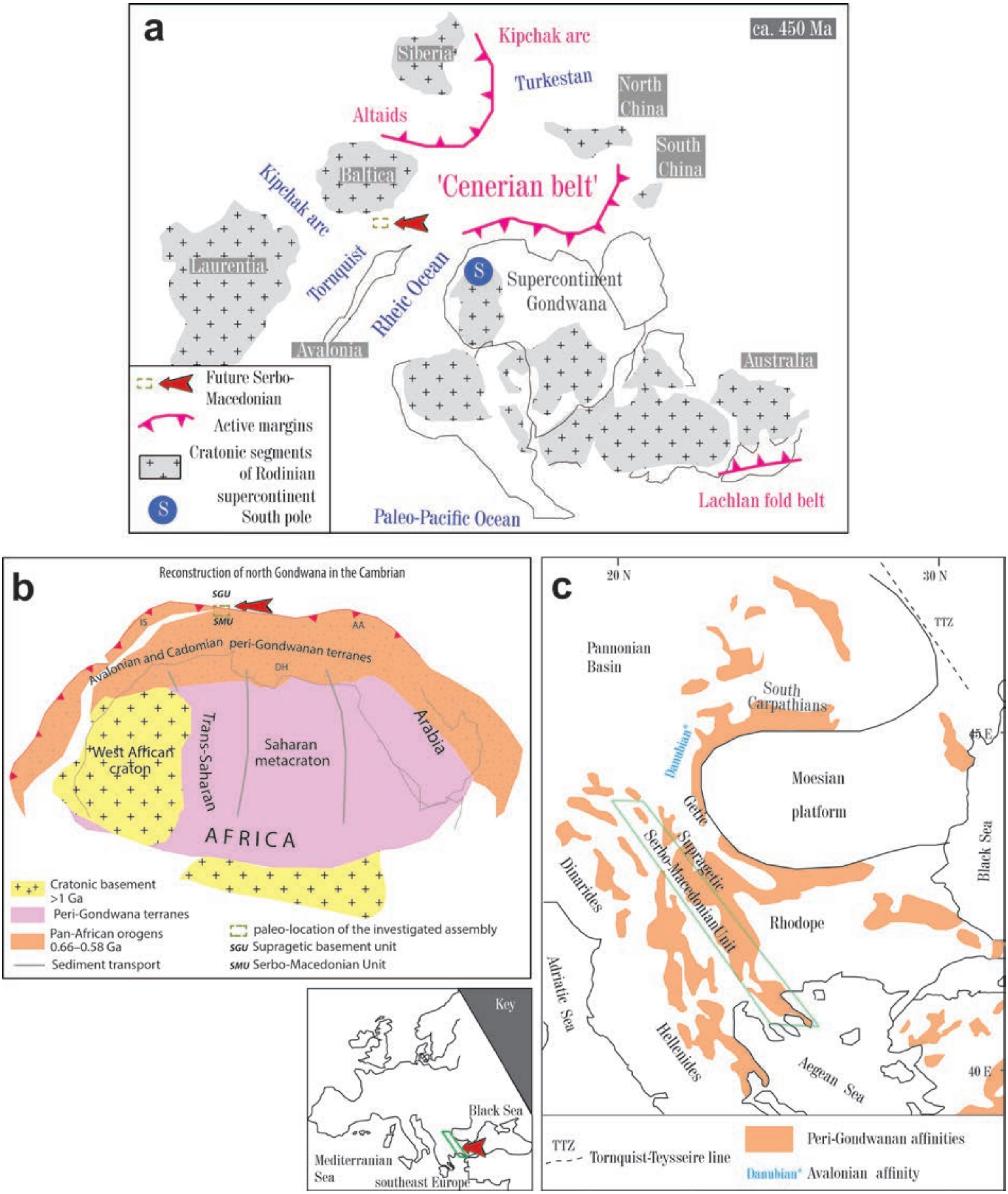
The ”Caledonian North African orogen” (Balintoni *et al.* 2011a) or “Cenerian-” i.e. “Sardic event” apparently contributed to important geodynamic assembly and amalgamation of the peri-Gondwanan lithosphere (Zurbriggen 2015; Text-fig. 1a, b). A significantly juvenile continental crust that developed along the northern peripheries of Gondwana (Text-fig. 1b) underwent progressive underthrusting and suturing which brought about a highly mobile Lower Paleozoic marginal orogenic belt (e.g., the eastern segment of the North Gondwana, sensu Stephan *et al.* 2019). It was composed of medium to high-grade gneiss-dominated terranes that were soon tectonically fragmented, detached and drifted away from their original locations in early Paleozoic times (Zurbriggen 2015). The breakup and dispersal of this vast marginal belt (Text-fig. 1a, b) resulted in the northward drift of several generations of peri-Gondwanan terranes (e.g., Murphy *et al.* 2001, 2006; Stampfli and Borel 2002; Murphy and Nance 2004; Nance and Linemann 2008; Nance *et al.* 2010; Franke *et al.* 2017; von Raumer *et al.* 2017; Spahić *et al.* 2019a, b). A complex group of microcontinents comprised of East Avalonian and Armorican domains with dominantly Cadomian tectonic elements drifted away and became basements for the terrane agglomeration that formed the European Variscan Belt from Iberia to the Balkans (e.g., Aleksić *et al.* 1988; Neubauer 2002; Franz and Romer 2006; Himmerkus *et al.* 2009; Meinhold *et al.* 2010; Oczlon *et al.* 2010; Zagorchev *et al.* 2012; Balintoni *et al.* 2010a, b, 2014; von Raumer *et al.* 2013; Keppie and Keppie 2014; Zurbriggen 2015; Antić *et al.* 2016; Spahić and Gaudenyi 2018; Abbo *et al.* 2019; Šoster *et al.* 2020; Text-figs 1c, 2). These Neoproterozoic–Lower Paleozoic vestiges carry the newly identified elements of the intra-Ordovician ‘Cenerian event’, which underwent significantly obliterating overprints and tectonic rearrangements during the Variscan and Alpine orogenies (e.g., Plissart *et al.* 2017, 2018; Antić *et al.* 2016, 2017; Spahić *et al.* 2019a, b; Text-figs 2, 3).

The Cenerian event (accretion of “continental” vs. oceanic lithospheres) corresponds somewhat to the well-recognized Ordovician convergence systems, likewise the east Australian Lachlan fold belt, Fammatian, Humberian, Taconic and Grampian orogenies (Balintoni *et al.* 2011a; Zurbriggen 2015, 2017a; Stephan *et al.* 2019; Meinhold *et al.* 2011 and references therein). All these Ordovician orogenic systems are characterized by recycled continental crust. In contrast, the ‘Cenerian event’ has important differences in the plate-tectonic context (Zurbriggen 2017a). The constraints for a recently described Ordovician “Cenerian orogeny” (Zurbriggen 2015, 2017a) are built upon the crystalline vestiges embedded within a pre-Variscan basement assemblage in the Swiss- and Italian Alps (Strona-Ceneri zone; Franz and Romer 2006; Zurbriggen 2015; Text-fig. 2). The Strona-Ceneri zone, interpreted as a terrane of northern Gondwanan descent, is comprised of (1) paragneiss having pelitic and greywacke protoliths, (2) banded amphibolites (metaandesites) and (3) abundant peraluminous orthogneisses. Both lithological contacts and foliation planes in the orthogneisses are moderately to steeply dipping and involved in km-scale folds with generally steep axial planes and fold axes. The vestiges of the Lower Paleozoic Cenerian orogeny in the Swiss and Italian Alps are interpreted as an analog of the modern-day Alaskan type accretionary orogen (Zurbriggen 2015, 2017a). The Alaskan model of the pre-Variscan geodynamic mechanism of encrustation and crustal growth offers an alternative to the well-established orogenic-type convergent plate margin model. The ‘Cenerian event’ illustrates a protracted amalgamation of an ancient continental crust above peri-Gondwanan subduction zones (overriding position; Text-fig. 1a, b). The culmination of crustal growth/amalgamation occurred during the Ordovician (defined as the “Intra-Ordovician event”; Text-fig. 1a).

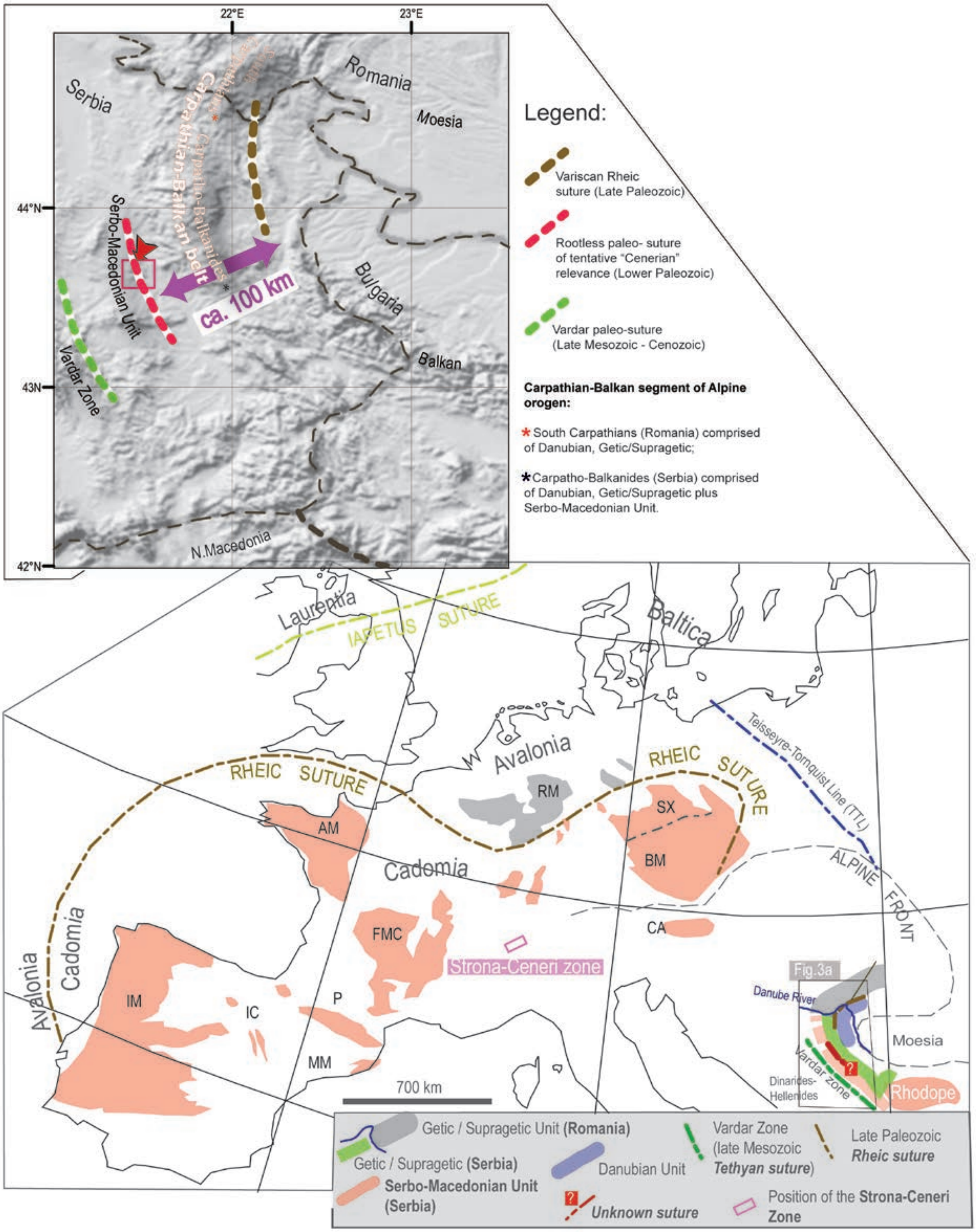
The aim of this work is to examine whether in the Western Balkans/Balkans/Northeast Mediterranean allochothonous crustal inlier, known as the “Serbo-Macedonian Massif” or Serbo-Macedonian Unit (SMU), which is mainly composed of gneisses with peraluminous magmatic signature and carries widespread records of Neoproterozoic–Ordovican magmatism and anatexis (Table 1), may be comparable to the Strona-Ceneri terrane as revealed in the Alps. The SMU arcuate gneiss-dominated terrane is exposed in Central Serbia, Bulgaria, North Macedonia, Greece (Text-figs 1, 2 and 3). The examination and tectonic reconstruction have been mainly based on literature sources and completed by field observations made in the Stalać region, Serbia.

THE ‘CENERIAN EVENT’

A cluster of Neoproterozoic peri-cratonic north Gondwana-derived microcontinents interacted with former Rodinian cratons up to early Paleozoic times (Unrug 1997; Murphy *et al.* 2004, 2006; Kearey *et al.* 2009; Text-fig. 1a). Erosion of the Neoproterozoic Pan-African orogenic hinterland coupled with a pro-



Text-fig. 1. a – Late Ordovician (ca. 450 Ma) configuration of continents redrawn after Zurbriggen (2014 and references therein). The 'Cenerian belt' is represented as a segment of a much larger Cambro-Ordovician active margin along the north Gondwana. Rodinian cratonic segments included. b – Reconstruction of Gondwana in the Cambrian showing the main Serbo-Macedonian Unit. Location of peri-Gondwana Terranes modified after Stampfli *et al.* (2002). Abbreviations: AA – Austro-Alpine, Ad – Adria, DH – Dinarides-Helenides, Is – Istanbul zone, SM – Serbo-Macedonian. SGU – Supragetic basement. c – Distribution of the peri-Gondwanan terranes within the European basements westward of the Trans European Suture zone (TESZ). Red arrow pinpoints the area of the Serbo-Macedonian Unit. Modified after Balintoni *et al.* 2014 and references therein.



Text-fig. 2. Distribution of Avalonian-Cadomian peri-cratonic microcontinents embedded into what is now Western-Central-southeast Europe, showing the basement units of the South Carpathians (inset from Draguşanu *et al.* 1997) and east Serbia. The Alpine-overprinted Carpathian-Balkan segment documents a section of the Rheic suture. The position of the investigated pre-Variscan suture is at a considerable distance relative to the main Variscan convergence system which is closer to western Moesia.

	'Cenerian event'	Strona-Ceneri zone	Serbo-Macedonian Unit *(for tectonic model and explanation see discussion chapter)*
1.	Clastic sediment sourcing and formation of "mud pile" (Paragneisses)	documented	documented
2.	Syntectonic extrusion of mixed magma sources (anatexis, presence of orthogneisses)	documented	documented
3.	Steeply structured pervasive amphibolite facies main schistosity of the orthogneisses (moderately to steeply oriented subduction-accretion complex)	documented	documented*
4.	Ductile deformation – folding (vicinity of accretionary wedge)	documented	documented
5.	Syntectonic extrusion of mixed magma sources (anatexis, presence of orthogneisses)	documented	documented
6.	Intermittent peraluminous magmatic imprints	documented	documented
7.	No over-thickened crust	documented	documented
8.	Different spatial position (regional scale) of the documented Variscan suture	not documented	documented
9.	Presence of Neoproterozoic–Ordovician oceanic crust (or downgoing plate)	not documented	documented
10.	Absence of stable craton	documented	documented

Table 1. Comparison between the Strona-Ceneri zone and the Serbo-Macedonian Unit. The numbers on the left indicate the essential features of the "Cenerian model" from Zurbriggen (2015). Point 3* indicates a high probability that foliation recorded within Serbo-Macedonian Unit is of Variscan age. In addition to the essential features of the model of Zurbrieggen (2015), the different spatial position (regional scale) of the documented Variscan suture is highlighted for the Serbo-Macedonian Unit. Moreover, the presence of Neoproterozoic–Ordovician oceanic crust (or downgoing plate) adjoining the Serbo-Macedonian Unit is documented.

tracted secondary erosion of exhumed metamorphic basements in the continental interior (e.g., north-central African cratons; Avigad *et al*. 2017; Text-fig. 1b) enabled voluminous clastic sediment supply into the adjoining proarc foredeep (subduction zones). Once transported and incorporated into a nearby subduction trench, huge inflows of clastic material ("mud pile"), were amalgamated to produce large-scale near-craton agglomerations of emerging Cambro-Ordovician continental crust (Zurbriggen 2017a). Unlike modern-day subduction processes, the ongoing Lower Paleozoic subduction was under the influence of the immense infill of clastic material. During the subduction of a downgoing slab, mantle-derived magmas were initially emplaced into the unconsolidated clastic matrix, which had an overriding position (accumulated on top of the subducting plate). This process allowed episodic emplacement of rising magma into the overriding clastic sequence, and amalgmation and piecemeal growth of juvenile continental crust. Thus, the peraluminous magmas compensated the ongoing underthrusting (Franz and Kroner 2006; Balintoni *et al*. 2011a) affecting thermally and spatially (anatexis) the overriding juvenile crust. Essentially, this process explains the upwards-directed magma flow and amalgamation of voluminous terrigenous detritus previously transported into a foredeep. This pallet of alternative crustal growth or encrustation processes yields a crustal reorganization ("cratonization") referred to as the "Cenerian Orogeny". Though the "Caledonian North African orogen" was recently proposed (Balintoni *et al*. 2011a), the terminology used (e.g., "cratonization", "orogeny"; Zurbriggen 2015) cannot be accepted, at least not in conventional use (something also pinpointed by Zurbriggen 2015). Namely, the investigated Cambro-Ordovician continental crust is not the nucleus of a continent and it was not stable because it was reworked and overprinted later on, during the Variscan and Alpine events. Therefore, instead "cratonized", we use "newly accreted". Because the term "Cenerian orogeny" does not fit perfectly, as there is no considerable wedging and crustal thickening reshaping the ancient landscapes, we rather prefer the use of the term 'Cenerian event'. These coalesced peripheral North Gondwana crystalline terranes are disconnected at the expense of protracted southward subduction of oceanic crust (Haydoutov *et al*. 2010; Nance and Linemann 2008; von Raumer and Stampfli 2008). The terrane detaching scenario offers a back-arc mechanism for rifting, successor oceanic embayment and eventual drifting off from north Gondwana.

REGIONAL TECTONIC FRAMEWORK AND PRE-ALPINE CONFIGURATION

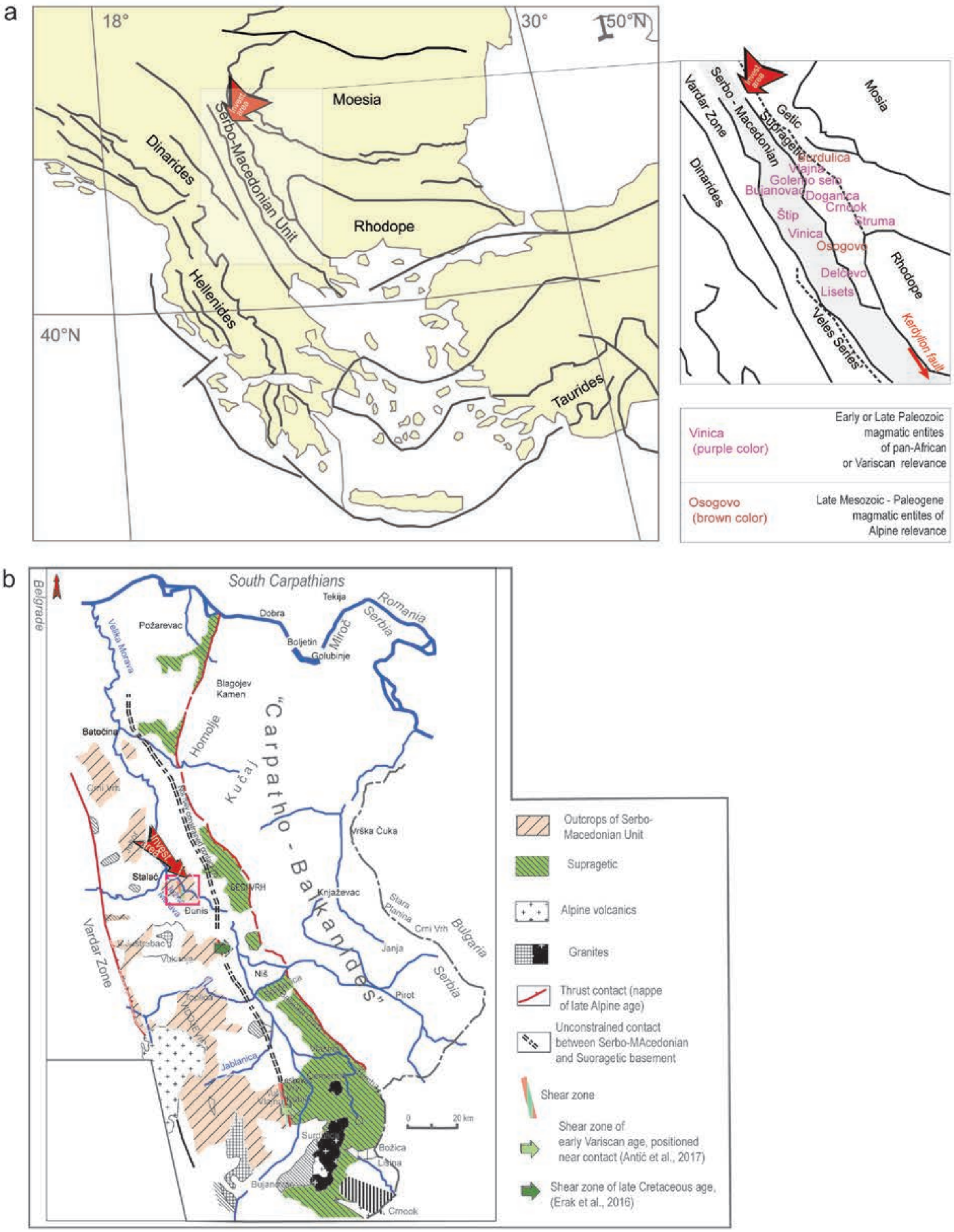
The geological configuration of southeast Europe (SEE) illustrates a complex plate-tectonic interplay of exotic peri-Gondwanan terranes and intervening Paleozoic and Mesozoic oceans. The north Gondwana terranes (Text-fig. 1a) subclassified as Avalonian- or Cadomian-type are embedded into what is now: (i) European Variscides (e.g., Franke 2006; Nance *et al*. 2008; Jastrzębski *et al*. 2013; Kroner and Romer

2013; Žák and Sláma 2017; Stephan *et al.* 2018, 2019; Golonka *et al.* 2019), (ii) south European Eo-Cimmerian Minoan terranes (Franz *et al.* 2005; Zulauf *et al.* 2007, 2014, 2018; Zlatkin *et al.* 2014; Dörr *et al.* 2015) including (iii) East Mediterranean basements (e.g., Ustaömer *et al.* 2011; Koralay *et al.* 2012). In between, (iv) a few considerably large segments of these late Pan African to Early Paleozoic terranes are incorporated in Alpine Europe – its central domain (e.g., Winchester *et al.* 2002; Scheiber *et al.* 2014; Zurbriggen 2015; Siegesmund *et al.* 2018; Arboit *et al.* 2019; Text-fig. 1). Alpine Europe includes the Southeast European (SEE) Carpathian-Balkan arc. Despite significant Variscan accretionary incorporation into the west Moesian (micro)craton (e.g., Plissart *et al.* 2017, 2018; Jovanović *et al.* 2019; Spahić *et al.* 2019) that was succeeded by the polyphase Alpine overprint, these SEE inliers host important yet undocumented evidence of a disputed plate-tectonic interval connecting the Cadomian orogeny in the Ediacaran–early Cambrian (Linnemann *et al.* 2007, 2014) with peculiar Lower Paleozoic events (Meinhold *et al.* 2011 and references therein).

The Mesozoic Alpine configuration is comprised of the following tectonic units/zones: the ALCAPA (Alps and West Carpathians), Southern Alps, Tisza, Pelagonides (i.e. External Hellenides) and South Carpathians/Carpatho-Balkanide terrane amalgamation (Supragetic/Getic or Supragetic/"Kučaj", Danubian and Moesian Euxinic craton; Text-figs 1c, 2, 3) including the NNW-SSE striking Serbo-Macedonian Unit (Text-fig. 3a). The latter basement inlier partially belongs to the Inner Hellenides, striking alongside the western Rhodopean Massif (divided by the Strymon fault/Kerdylion Detachment; e.g., Kydonakis *et al.* 2015). The opposite western side of the Serbo-Macedonian Unit occupies the Neotethyan composite paleosuture (Vardar Zone) and the Dinarides of the Adria microplate (e.g., Dimitrijević 1997, 2001; Csonotos and Vörös 2004; Text-fig. 3a). Any pre-Alpine correlation of the Carpathian-Balkan orogen is hampered as most of these inliers are concealed beneath a cluster of displaced Tethyan assemblages and overlain by late Alpine Neogene strata. Thus, despite a significant effort (Dimitrijević 1997; Neubauer 2002; Kräutner and Krstić 2003; Schmid *et al.* 2008, 2020; Jovanović *et al.* 2019), there is no comprehensive tectonic correlation capable of unambiguously connecting the Alpine units and their basement inliers between the Romanian South Carpathians, the Carpatho-Balkanides in eastern Serbia and western Bulgaria. Even the Alpine tectonic inheritance of the Serbo-Macedonian Unit remains unconstrained (for comments see Spahić and Gaudenyi 2018, 2020; Jovanović *et al.* 2019).

The Serbo-Macedonian basement inlier is now exposed externally as the upper allochton along strike of the arcuate Carpathian-Balkan basement amalgamation of the Alpine orogenic system (bent around the Moesian microcontinent once accreted to the southwestern Baltica margin (Text-figs 1c, 2 and 3a, b). That exotic Cadomian-type terrane (Antić *et al.* 2016; Spahić and Gaudenyi 2018), with widespread Neoproterozoic to Tertiary magmatic and metamorphic imprints, connects the South Carpathians in the north (Romania; e.g., Iancu *et al.* 2005; Balintoni *et al.* 2010a, b, 2014) and the Balkanides in the southeast (Ograzhden Unit; Bulgaria; e.g., Zagorchev *et al.* 2012, 2014, 2015; Text-fig. 1c). Its southern segment strikes across North Macedonia and Greece (Inner Hellenides; including its analog in the orthometamorphic Vertiskos Unit; Himmerkus *et al.* 2009; Meinhold *et al.* 2010; Abbo *et al.* 2019; Text-figs 1c, 2, 3). The investigated segment of the Serbo-Macedonian high-grade metamorphic agglomeration (Serbia; a combination of para- and orthometamorphics; Text-fig. 4) is in overprinted tectonic contact with a similar-aged subordinate greenschist-facies metamorphosed ocean-floor assembly (ancient olistostroms desposited on the ocean floor; Haydoutov *et al.* 2010) referred to as the Supragetic basement, the former "Vlasina Unit" (sensu Spahić *et al.* 2019b). An alternative interpretation of that unit as a separate terrane (Serbo-Macedonian vs. Supragetic) was discarded by earlier authors because of the transitional/gradational (non-tectonic) contact between the greenschist-facies rocks and gneisses observed in northeastern North Macedonia, area of the Kratovo sheet, 1: 100,000 (N-NE section of the map; Geološki zavod Skopje 1968; see explanation in Dimitrijević 1997). A similar opinion was reported much earlier, describing the gradual transition of the 'Lisina Series' to higher-grade gneisses near Vlasina, southern Serbia (Pavlović 1977).

In eastern Serbia and southwestern Romania, ancient vestiges of the Alpine basement inliers are classified as a collage of tectonometamorphic/tectonostratigraphic agglomerations or "terranes" docked onto the Moesian microplate of Amazonian-Avalonian provenence (Baltican promontory) (Text-fig. 3a). The Serbo-Macedonian Unit represents a high-grade crystalline unit comprised mainly of gneisses, biotite- and mica-schists, migmatites along with quartzites, quartzitic-graphitic schists, amphibolites, marbles, calc-schists and isolated occurrences of eclogites (Kalenić 2004; Text-fig. 4). Some recent authors place the high-grade metamorphic imprint in the Cadomian



Text-fig. 3. a – Main tectonic units surrounding western Moesia: Carpatho-Balkanides of Serbia/South Carpathians of Romania (Danubian, Getic/"Kučaj"-Supragetic), Serbo-Macedonian Unit, Vardar Zone, Dinarides, Hellenides, Pannonian basin (modified after Schmid *et al.* 2008; inset from Kounov *et al.* 2011). b – Location map, main outcrops of the Serbo-Macedonian Unit and Supragetic basement in Serbia (inset from Dimitrijević *et al.* 1967).

framework (Zagorchev *et al*. 2012), whereas the main process of migmatitization is placed within the protracted Variscan orogeny (Antić *et al*. 2017 and references therein).

The Supragetic basement (former "Vlasina Unit"), a greenschist-facies crystalline unit representing a mixture of sericite schists, calc-schists, and actinolite schists as remnants of basic ophiolite-bearing rocks, is accommodated at the opposite, eastern side (Text-fig. 3a, b) of the Serbo-Macedonian Unit (Spahić *et al*. 2019b). The questionable greenschist-facies retrogression supposedly occurred in the Early Jurassic (Antić *et al*. 2017). The contact between the two inliers of the Serbo-Macedonian Unit and the Supragetic basement is severely overprinted by the Variscan, Alpine and Neoalpine cycles (Dimitrijević 1997, pp. 114–115; Haydoutov and Yanev 1997; Erak *et al*. 2016; Spahić *et al*. 2019b and references therein). A Neoproterozoic (detrital zircons; Antić *et al*. 2016) to earliest Ordovician age of the Supragetic basement (southeastern segment in Serbia) is documented. Namely, the youngest documented age of the Supragetic basement (or "pre-Ordovician Vlasina Unit" of Antić et al. 2016) is Tremadocian, constrained by the remarkable discovery of an inarticulate colder climate *Obolus* and *Lingullela* brachiopod fauna ('Lisina Series'; Pavlović 1962; see also in Spahić *et al*. 2019b). More to the east, the Bulgarian analog of the Supragetic basement is the so-called Balkan terrane or "Morava Nappe". The Balkan/Thracian terrane concept describes the Lower Paleozoic interface zone investigated here as the "Thracian ophiolite suture". This suture (topic of this study) is characterized by an island-arc association (Neubauer 2002) comprised of a sedimentary and volcanic complex (Haydoutov *et al*. 2010, fig. 1).

To the north, basement units with a similar metamorphic overprint (like the Serbo-Macedonian Unit) exist in themore internal crystalline units of the Romanian South Carpathians. The Getic unit carries the Sebeş-Lotru terrane subdivided onto the Cumpăna and Lotru subunits (Balintoni *et al*. 2009, 2010b). These agglomerations are characterized by an Ordovician accretionary event comparable to the "Cenerian" (Balintoni *et al*. 2011a). The Danubian unit of Avalonian inheritance is comprised of much the older Făgeţel augen gneiss from the Drăgşan terrane basement of 803.2±4.4 Ma age (Balintoni *et al*. 2011b; Spahić and Gaudenyi 2018). These basement inliers continue into the east Serbian Carpatho-Balkanides (Text-figs 2, 3a). The most external Serbo-Macedonian crystalline agglomeration extends farther across western Bulgaria as the analog known as the Ograzhden unit (e.g., Zagorchev and Milovanović 2006; Zagorchev *et al*. 2012). The Serbo-Macedonian analog or the Ograzden unit/Thracian terrane of Bulgaria contains abundant anatectic granites (Zagorchev *et al*. 2014; for a configuration comparison see Spahić and Gaudenyi 2018). The Serbo-Macedonian Unit stretches further throughout North Macedonia and terminates in Greece as the Vertiskos basement (Himmerkus *et al*. 2009; Meinhold *et al*. 2010; Text-fig. 3a). In North Macedonia, in addition to the Serbo-Macedonian Unit, there is another peculiar Lower Paleozoic gneiss-dominated unit overthrust on top of the latter (Dimitrijević 1997; Antić *et al*. 2016; Šoster *et al*. 2020). This basement unit often referred to as the 'Eastern Veles Series' is nothing more than a displaced segment of the Serbo-Macedonian Unit during the late Alpine convergence (Savezni Geološki Zavod 1970; Robertson *et al. 2*013*;* Antić *et al*. 2016; Spahić *et al*. 2019a; Text-fig. 3a). The 'Eastern Veles Series' is a "segment" of the 'Veles Series' (sensu Spahić *et al*. 2019a; Šoster *et al*. 2020). In Greece, the age of this gneiss-dominated crystalline belt is growing younger to become of Upper Ordovician to Ordovician age (dominant orthogneiss with leucocratic two-mica gneiss; Abbo *et al*. 2019). This recently introduced Ordovician age is favorable in comparison to the previously imposed Silurian age (Himmerkus *et al*. 2009; Meinhold *et al*. 2010). The aforementioned age bracket has similarities with the Neoproterozoic–Silurian eastern South Alpine basement (explained by the up-section age variations due to a temporal change in provenance; Arboit *et al*. 2019). In the eastern Mediterranean, the rocks of similar age which include an almost complete pre-Variscan sedimentary sequence (from Ordovician) are referred to as the Istanbul terrane, whereas the Zonguldak terrane records a hiatus between Silurian and Devonian sequences (Ustaömer *et al*. 2011).

RESULTS

This chapter represents a stepwise compilation of the field structural observations (including lithostratigrahy) juxtaposed onto the documented Variscan paleosuture accommodated within the region. The outcropping areas of the Serbo-Macedonian Unit in Serbia expose several complexes of high-grade crystalline rock units (for a review see Dimitrijević 1997; Kalenić 2004; Spahić and Gaudenyi 2020 and references therein; Text-fig. 3a, b): (i) the Crni Vrh and Batočina area with dominant gneiss and mica schist, marbles, quartzite and amphibolite gneiss (Kalenić 2004), (ii) the Juhor area with dominant two-mica schist, gneiss and a zone of migmatites, Stalać (investigated area, see further in the text), (iii) the Crna Čuka and Jastrebac with high-grade metamorphic gneiss which include mylonites developed between the two gneiss-dominated segments of the Serbo-Macedonian Unit (Rakić *et al.* 1969). At localities Vidojevica-Pasjača and Jablanica, the Serbo-Macedonian Unit includes several metamorphic zones with migmatites, and the presence of kyanite-sillimanite with a dominance of fine-grained gneiss. An orthometamorphic protolith with a U-Pb age of ~500 Ma is reported in the Vučje gneiss (peraluminous granite; south of Leskovac; Zagorchev and Milovanović 1998; also in Vukanović *et al.* 1974, 1977; Text-fig. 3b). An overview of the magmatic episodes is available in Neubauer (2002), Antić *et al.* (2016) and a recent summary of Abbo *et al.* (2019).

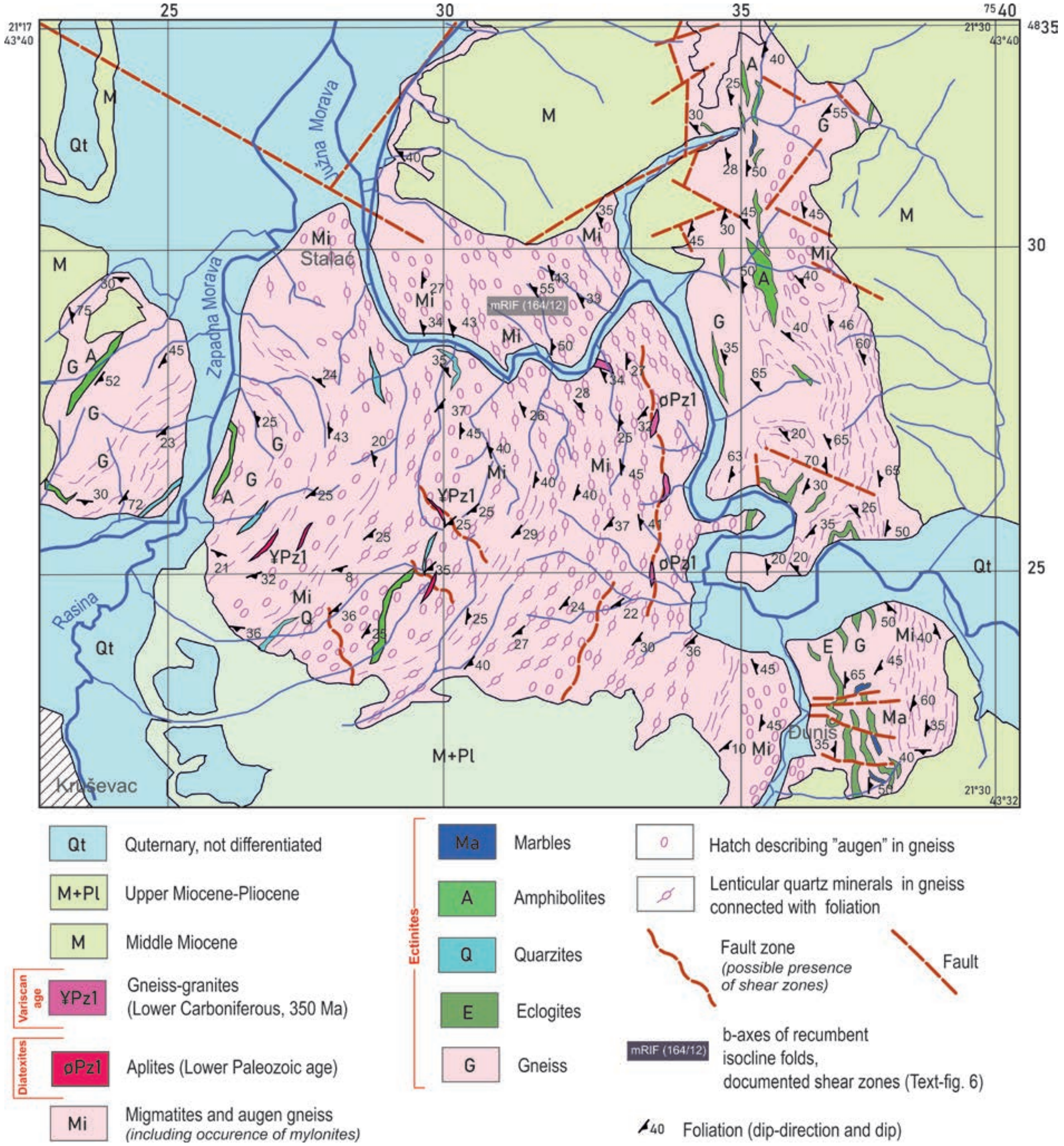
In most outcrops in Serbia, the rocks of the Serbo-Macedonian Unit represent metamorphosed psammitic-pelitic deposits (shallow to deep-water, probably of turbiditic origin/accretionary wedge). These mica-rich gneissic rocks ocassionaly record blastopsammitic texture (Cvetković 1992; also in Kalenić 2004) and alternate with orthogneisses being of Neoproterozoic to early Paleozoic age. Biotite gneiss is recorded with blastopsammitic texture comprised of poorly rounded granitoid, gneiss and quartz grains (Batočina area; Text-fig. 3). Accordingly, such texture marks short material transport within a highly mobile gneiss-granodiorite system (Cvetković 1992). The orthogneisses reveal different geochemical signatures (e.g., Zagorchev and Milovanović 2006; Antić *et al.* 2016; see details in chapter 3.2.3). In central Serbia, the Ediacarian–Cambrian transition is documented by the stratigraphically lower-positioned graphitic schists (fossil vesicles of algae *Archaeofavosina simplex* Naum; Kalenić *et al.* 1975; Kalenić 2004). The age of the Serbo-Macedonian Unit covers the earliest Neoproterozoic to early Cambrian time span (Kalenić *et al.* 1975; Deleon *et al.* 1972; Antić *et al.* 2016) reaching the Ordovician (documented in southern Serbia, also in Bulgaria as the Ograzhden unit; Zagorchev *et al.* 2015) and the Republic of North Macedonia.

Rock units over a considerably large area (ca. 30 km in width; Text-fig. 4) in the central segment of the Serbo-Macedonian Unit have been surveyed for deformation of Paleozoic i.e. pre-Alpine age. This area carries the evidence of (1) Neoalpine (Neogene) extensional episode, (2) Alpine (late Cretaceous–Paleogene) contractional episode inclusive nappe stacking, (3) late Paleozoic foliation and (4) a rootless paleosuture with no ophiolites. Nevertheless, a late Paleozoic, ophiolite-decorated Variscan suture is documented to the northeast of the investigated area (Plissart *et al.* 2018; Spahić *et al.* 2019; Text-fig. 1). In order to isolate the Variscan overprints from expectedly Cenerian features, the study defines the essential differences between the two Paleozoic paleosutures, which includes time-constraints on the formation of these two essential structural elements: (i) age of widespread penetrative foliation and (ii) indications for apparently rare pre-Variscan ductile deformation. The Variscan age of the former is also suggested for a more southern segment of the Serbo-Macedonian Unit in SE Serbia (Antić *et al.* 2017), and, in general, is accepted for the whole crystalline entity (Table 2).

Stalać area: Lithostratigraphy and paleosuture indicators

The core section of the exposed lower crust is accommodated toward the Supragetic unit (to the east). The basement geology is however obscured by several localized Neogene basins (Dimitrijević 1997) and a veneer of Quaternary deposits (Rakić *et al.* 1969; Krstić *et al.* 1974; see the geological map or Text-fig. 4 and following mapping units: Miocene (M), Miocene–Pliocene (M+Pl), and Quternary (Qt).

The investigated central segment of the Serbo-Macedonian Unit is comprised of gneisses and amphibolites, occasional augen gneisses, dominant two-mica paragneisses, sporadically occurring granite gneisses and locally exposed spectacular migmatites (Rakić *et al.* 1969; Dimitrijević 1997; in older literature these rocks are referred to as the "*ectinites*", sensu Levinson-Lessing and Struve 1963; Text-fig. 4). Sporadically, the gneiss-dominated matrix includes HP/HT eclogite lenses exposed with the associated structural imprint (Krstić *et al.* 1974; Text-figs 4, 5a–d, 6 and 7). The presence of metasedimentary quartzites and carbonates (marbles, calc-schists) documents the presence of the important parametamorphic sequences. On the contrary, the Serbo-Macedonian analog in Greece, referred to as the Vertiskos unit, is comprised entirely of orthometamorphites (Abbo *et al.* 2019). The protolith ages of Serbo-Macedonian crystalline rocks exposed in the Stalać area (Text-fig. 5a–d) or the Juhor-Stalać Mts. yield a lowermost Cambrian to Lower Ordovician age (541 to 475 Ma; Deleon *et al.* 1972). The dominantly clastic sequence probably belongs to an elongated marginal basin supplied with immense amounts of terrigenous material (with late Pan-African Cambrian–Ordovician sources; e.g., Bahlburg *et al.* 2009; Meinhold *et al.* 2013). The clastic material contains minor detrital in-



Text-fig. 4. Geological map of a wider area of the Stalać-Kruševac area, slightly modified after *Rakić et al.* 1969, sheet Kruševac, 1: 100,000; Krstić *et al.* 1974, sheet Aleksinac, 1:100,000). The position in the regional-scale shown in Text-Fig. 3b. The map exhibits an outcropping segment of the gneiss-dominated Serbo-Macedonian Unit surrounded by a Mio-Pliocene veneer. Explanation is in the text.

put from the remote cratonic basement (e.g., Saharan metacraton; Avigad *et al*. 2017; Text-fig. 1b). The documented presence of older North African cratonic elements suggests the northward paleodirection of sedimentary transport across the junction with the north Gondwanan realm (North Africa).

The stratigraphically higher marbles are reported to be of early Cambrian age (primitive marine fossil algae *Zonosphaeridium absolutum* Timofeev, *Protoleiosphaeridium sigillarium* Andreeva; Kalenić *et al*. 1975). The biostratigraphic age is similar to the aforementioned Rb-Sr data (Deleon *et al*. 1972). The

Sampling entitles	Lithology	Age	Ternary geotectonic discrimination	εHf values	A/CNK *vs*. A/NK classification plot
Golemo selo/Sijarinjska banja (SM250-2 and SM250-2-019)	paragneiss	562 Ma		−3.3 inherited core of 3.049 Ga indicates presence of Archean crust	
Doganica metagranitoid (Supragetic) (SM600-1)	granite	562 Ma	convergent setting	(+3.7 to +2.8) higher presence of crustal material	
Lisina gabbro (Supragetic) (SM352)	gabbro	550 Ma	within-plate	(+3.7 to +2.8) higher presence of crustal material	
Vlajna granitoid (SM02)	calc-alcaline granitoid	558 Ma	volcanic arc	juvenile magma source (+12.6 and −2.8)	peraluminous
Bosilegrad (Supragetic/Struma Unit) (SM236-1)	monzonite	522 Ma	volcanic arc	(+12.6 to +4.2) juvenile magma source	
Božica magmatic complex (Supragetic) (SM272-1)	granite and diorite	521 Ma	within-plate	(+12.6 to +4.2) juvenile magma source	peraluminous
Delčevo (Supragetic/Struma Unit) (SM140-1)	granite	536 Ma	magmatic arc	(+12.6 to +4.2) juvenile magma source	peraluminous
Vinica* (SM173-3)	leucocratic gneiss	490 Ma	volcanic arc (granites)	(+18. to +6.9) new crust	peraluminous
Maleševski Mts. (Ograzhden i.e. Serbo-Macedonian Unit) (SM184-1)	orthogniess (acidic and intermediate)	472 Ma	within-plate	(+4.3 to −6.2) juvenile magma source	peraluminous
Kukavica granites at Vrvi Kobila area (Sm01)	granodiorite (acidic and intermediate)	478 Ma	within-plate	(+4.3 to −6.2) juvenile magma source	peraluminous
bujanovac granite (SM377-2)	s-type granite	439 Ma	within-plate	(+4.3 to −6.2) mixed juvenile and continental crust	peraluminous
Štip magmatic complex (SM195-1)		304 Ma	late and post-collisional	(+4.3 to −6.2) mixed juvenile and continental crust signature of the melt	peraluminous
Novo Brdo schists (KOS02)	Micaschists	Maximum deposition at 255 Ma		For peak ca. 560 Ma: +3.7 to −2.8; higher presence of crustal material	

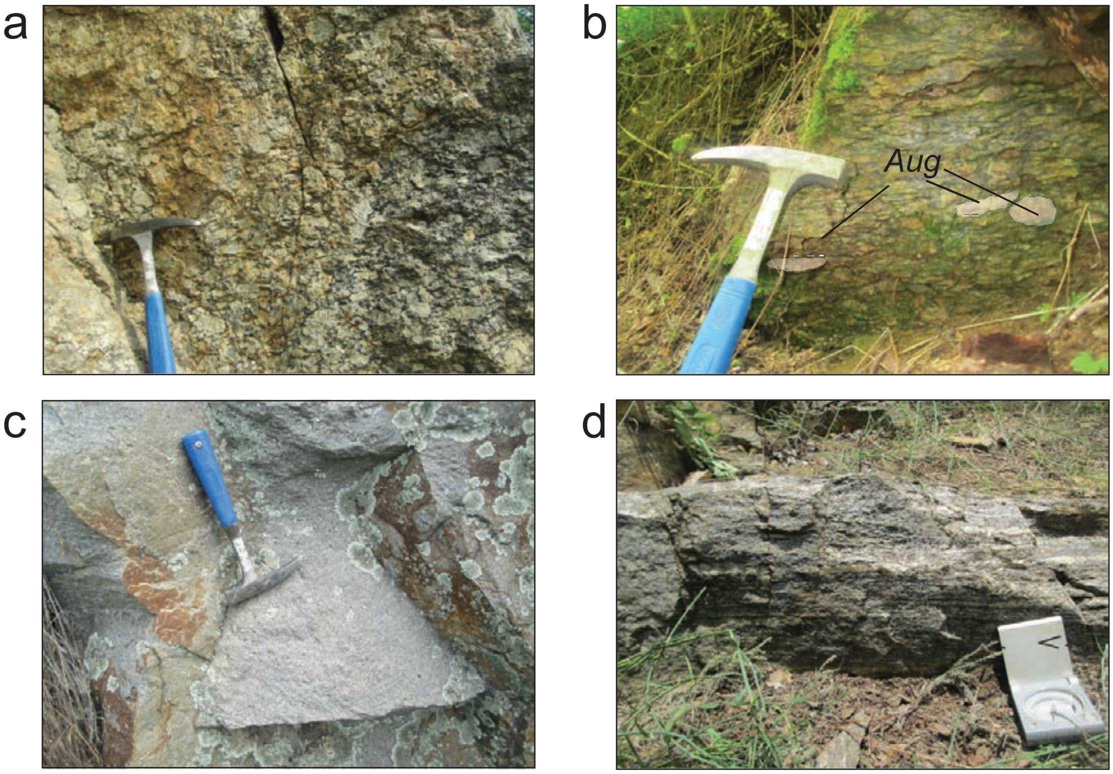
Table 2. Summary of the main peraluminous magmatic rocks of Cenerian relevance emplaced into the Serbo-Macedonian Unit (older vs. juvenile crust). Numeric data taken from Antić *et al*. (2016), reinterpreted. Color code indicates magmatism associated with each phase: light red (Neoproterozoic-lowermost Cambrian), blue-green (uppermost Cambrian–Ordovician), green (Silurian), light green (uppermost Carboniferous = Pennsylvanian).

metamorphic event occurred at temperatures ranging between 550 and 600°C and a pressure of ca. 6 kb (Batočina area; 488 Ma; Balogh *et al*. 1994). Another, similar age early Paleozoic metamorphic imprint is recorded within the Ograzhden unit, southwestern Bulgaria (Zagorchev *et al*. 2014). The *P-T* values in rocks of the Batočina segment are characterized by a garnet-staurolite-kyanite assemblage in gneisses and mica schists and by epidote-hornblende-garnet in amphibolites. According to the mineral assemblages, this part belongs to the deeper crust (garnet-kyanite level, Zurbriggen 2015).

Eclogites (E; Text-fig. 4) are locally distributed in lenses that crosscut local gneiss and migmatites (Rakić *et al*. 1969; Krstić *et al*. 1974; Text-fig. 4).

Migmatites (Mi; Text-fig. 4) occur as bodies and tectonic zones and as lenses. Their position interfingered with eclogite (the eastern edge towards the Supragetic unit) indicates that the highest pressure zone was later cut off by a principal Alpine fault (Kalenić *et al*. 1975). The migmatites are comprised of microcline-plagioclase gneiss. According to some authors, the migmatites of the Serbo-Macedonian Unit exhibit a retrogressive phase inferred from the emplacement of garnet-oligoclase-quartz veins and low-temperature quartz veins (Zagorchev and Milovanović 2006).

Gneisses (G; Text-fig. 4) are fine- to coarse-grained including spectacular augen gneisses (Text-fig. 5a). The former is more abundant and developed during the first phase of migmatitization (Krstić *et al*. 1974). Beside oval or lenticular feldspar porphyroblasts (also in Buriánek *et al*. 2009), the gneisses are composed of quartz, plagioclase (oligoclase to andesine), microcline and biotite. Feldspars are often albitized, sericitized and kaolinitized. In the Batočina area, augen gneisses are usually interlayered with host metasediments with occasional occurrences of bodies



Text-fig. 5. Example of rock formations within the investigated area: a, b – Augen gneiss. c – Granit-gneiss. d – Mica-rich gneiss with a penetrative foliation.

separated by sharp contacts (Balogh *et al*. 1992). The paragneiss sequence is characterized by a linear fabric on the foliation, defined by parallel quartz-feldspar rods set in a dominantly mica-rich matrix (Text-fig. 5d). The biotite content decreases in the gneiss bodies or gneiss-granites (Text-fig. 4, mapping unit ¥Pz2; Krstić *et al*. 1974). The main gneiss-dominating matrix is, however, crosscut by gneiss-granites of early Carboniferous age (*ca*. 350 Ma; Deleon *et al*. 1972; Text-figs 4, 5c). These Variscan gneiss-granites attest the Variscan interference in almost the entire Serbo-Macedonian Unit. Importantly, in a comparison with the main Serbo-Macedonian high-grade assembly, these Variscan gneiss-granites exhibit no developed foliation fabric (Text-fig. 4).

Pegmatite intrusions of early Paleozoic age (Text-fig. 4, mapping unit øPz1; Krstić *et al*. 1974) are abundant at the western realm of greater migmatitic bodies probably documenting progressively formed diatexites. A set of intruded pegmatite bodies illustrates rather steeply inclined syn-magmatic structures.

Amphibolites (A; Text-fig. 4) are not widespread. These rocks occur as elongated bands in the eastern segment of the Stalać complex, near the eclogites, and in the form of isolated ribbons. The protolith appears to be magmatic mafic rocks (Zagorchev and Milovanović 2006) set in a sandy-clayey matrix (Krstić *et al*. 1974). According to the SiO_2 and (K_2O+Na_2O) content in amphibolites of the Batočina area, these rocks were alkaline basalts (prior exposure to the metamorphic event) and correspond to subalkaline within-plate tholeiites (Cvetkovic 1992). The upper crustal level rocks represented by a mixture of quartzites, biotite gneisses, marbles and graphitic gneisses, were overprinted by low-pressure/high-temperature amphibolite facies metamorphism, very similar to that recognized in the much older Lainici-Păiuş Group (Lower Danubian; Liégeois *et al*. 1996 and references therein).

Plate boundaries late in the early Paleozoic and in late Paleozoic (Variscan) times

To specify and distinguish the imprints of the Variscan and the alternative lower Paleozoic paleosuture, a detailed comparison of the structures associated with late Paleozoic Variscan and early Paleozoic terrane amalgamations is provided. The paleogeography and pre-Alpine (dominantly Variscan) provenance of these terranes (e.g., Krstić *et al.* 1996; Winchester *et al.* 2006; Himmerkus *et al.* 2009; Haydoutov *et al.* 2010; Oczlon *et al.* 2010) were inferred from detailed petrology/geochemistry, biostratigraphic, structural and occasional radiometric age data (Aleksić 1977; Liégeois *et al.* 1996; Krstić *et al.* 2005; Iancu *et al.* 2005 and references therein; Haydoutov *et al.* 2010 and references therein; Jovanović *et al.* 2019; Antić *et al.* 2017; Plissart *et al.* 2018). Late Paleozoic reconstructions were also based on the occasionally discussed sedimentary provenance (Balintoni *et al.* 2009, 2010, 2013, 2014; Himmerkus *et al.* 2009; Antić *et al.* 2016; Abbo *et al.* 2019). The scarce paleomagnetic data of these stacked pre-Variscan exotic low- to high-grade Pan-African basement terranes show higher early Paleozoic Southern Hemisphere latitudes and lower latitudes during Carboniferous amalgamation (Milićević 1996; Ebner *et al.* 2010; for details see table 1 in Spahić *et al.* 2019).

A reconstruction of Paleozoic active margins in the Balkans is hindered by significant Alpine interference and nappe stacking. Nevertheless, the amalgamated Carpathian-Balkan basement terranes expose the position of the principal Variscan paleosuture (Liégeois *et al.* 1996; Haydoutov and Yanev 1997; Seghedi *et al.* 2005; Gerdjikov *et al.* 2010; Kounov *et al.* 2012; Iancu and Seghedi 2017; Plissart *et al.* 2018; Spahić *et al.* 2019b; Text-fig. 2). Moreover, the data indicate that prior to the well-documented Variscan amalgamation of the Carpathian-Balkan basement terranes, an older Ordovician thermometamorphic event occurred. Of particular importance are imprints recorded within the Neoproterozoic to Ordovician Sebeş-Lotru unit (South Carpathians; Balintoni *et al.* 2010b; U/Pb Concordia age of 550.7±1.7 Ma by Balintoni and Balica 2013; Text-figs 2 and 3a), Serbo-Macedonian Unit (Central Serbia; magmatic and detrital zircons including the numeric age by Antić *et al.* 2016; Text-fig. 3b), analog Ograzhden unit (south-western Bulgaria, Zagorchev *et al.* 2014) and a segment in Greece (magmatic and detrital zircons including numeric age by Meinhold *et al.* 2010; Abbo *et al.* 2019).

Variscan paleosuture

The evidence of HP-HT records in the SEE basement inliers may provide an insight into the deeper levels of the Variscan orogenic belt and its suture. Such data can also provide vital differences relative to the 'Cenerian event'. Vestiges of the dominant Variscan paleosuture are marked by (meta)mafic rocks scattered across (1) the peri-Moesian Variscan realm (Text-figs 2, 8b), (2) the west Moesian paleosuture or "Carpathian segment" (Kounov *et al.* 2012; Plissart *et al.* 2017, 2018; Spahić *et al.* 2019b and references therein) and (3) the Moesian microplate or "Balkan segment" that abuts against the Rhodopean Massif further south (e.g., Arkadakskiy *et al.* 2003; Carrigan *et al.* 2005; Plissart *et al.* 2018 and references therein).

In Serbia, records of regional thermal imprint, sampled from the central part of the Serbo-Macedonian Unit (apatite fission track), indicate a rapid cooling through the zircon and apatite partial annealing zones during the late early Cretaceous and early late Cretaceous (Antić *et al.* 2015). In the area of Vrvi Kobila (Text-fig. 3b), ^{40}Ar/^{39}Ar thermochronology on muscovite yields early Carboniferous (350.73±1.22 Ma) and Permian ages (250.913±1.07 Ma; numeric age by Antić *et al.* 2017). These exhumation data coupled with the structural observations constrain the Variscan involvement of the subordinate Supragetic basement and Serbo-Macedonian Unit. Importantly, the investigated 'Cenerian' paleosuture is positioned remotely relative to the Variscan front (Text-figs 2, 3a, 8b).

This configuration of Variscan event implies a paleo-northwards subducting plate beneath Moesia and closure of the Paleozoic ocean(s) (e.g., Haydoutov *et al.* 2010; Franke *et al.* 2017; Spahić *et al.* 2019a). The protracted Variscan suturing ultimately produced voluminous acidic syn- and post-orogenic imprints (Cherneva and Georgieva 2005; Haydoutov *et al.* 2010; Jovanović *et al.* 2019; Deleon *et al.* 1972; Antić *et al.* 2016; Text-fig. 8b). The Moscovian/Kasimovian latitude is 5°N (flora analyses by Pantić and Dulić 1991; paleo-latitudes by Milićević 1996). The Variscan paleosuture is ophiolite-decorated (Text-figs 1d, 2) associated with the Danubian Unit (Devonian ophiolites; Plissart *et al.* 2017). The nearby Osogovo-Lisets magmatic arc amalgamation (560–540 Ma; Kounov *et al.* 2012; Text-fig. 3a) is significantly older and consists of amphibolite, mica schists, muscovite-biotite and amphibole-biotite gneiss with ophiolitic protoliths (Frolosh Formation or "Diabase-Phyllitoid Complex"). The Osogovo-Lisets is intruded by gabbrodiorites and younger leucogranites belonging to the Strouma unit.

Lower Paleozoic subduction-accretion complex: The reactivated interface between the Serbo-Macedonian and Supragetic basement

Apart from the Stalać crystalline Serbo-Macedonian block investigated, another rare exposure of the contact between the Serbo-Macedonian Unit with the subordinate Supragetic basement is in the Jastrebac Mts. (Central Serbia). The reactivated disjunctive zone, composed of chloritic schists, mica schists, including quartzites, actinolitic schists, amphibolites and gneisses, was obliterated by a late Cretaceous extensional detachment (Erak *et al.* 2016). Severe Variscan and Alpine overprints elevated this ancient interface, which fits with the initially interpreted boundary between the 'Thracian' and 'Balkan' terranes (Haydoutov 1989; Haydoutov and Yanev 1997; Yanev *et al.* 2005; Haydoutov *et al.* 2010).

North of the Danube River (the administrative boundary between Serbia and Romania; Text-fig. 2), in more external segments of the South Carpathians, there is a continuation of this unconstrained paleosuture (Iancu and Seghedi 2017). The nearby Cumpăna unit (a segment of the Sebeş-Lotru terrane; Text-fig. 3a; sensu Iancu *et al.* 2005) consists of orthogneisses characterized by distinctive migmatitic structures, paragneisses, metabasites and meta-ultrabasic layers, including rare eclogites. The eclogites are of Variscan age (Medaris *et al.* 2003; Balintoni *et al.* 2010b and references therein). Two samples of orthogneiss from the Cumpăna unit yielded U-Pb zircon crystallization ages of 458.9±3.5 Ma and 466.0±4.2 Ma (Balintoni *et al.* 2010b). Migmatitic structures, augen gneisses and rodded gneisses are found together with eclogites that were derived from metabasic protoliths of unknown age (Medaris *et al.* 2003). High-pressure granulites and amphibolites may represent the overprinted eclogites. The relative depletion of Nb and Zr suggests a craton-proximate tectonic setting (Drăguşanu *et al.* 1997), similar to that proposed for the Cenerian system.

The investigated interface between the Serbo-Macedonian unit and the Supragetic basement steeply bends towards the southeast (Bulgaria), further striking to the east (Kraishte) and having the form of the aforementioned "Thracian ophiolite suture" (sensu Haydoutov *et al.* 2010). This suture is characterized by a mixture of sedimentary and volcanic complexes and illustrates the "Ordovician orogeny" (Haydoutov *et al.* 2010). In the Vertiskos terrane in northern Greece, early Silurian crystallization ages of the basement granites, based on the magmatic internal structure of the zircon grains coupled with trace-element and isotope geochemistry, show either a magmatic-arc setting with the presence of pre-existing Silurian continental crust (Himmerkus *et al.* 2009) or the grains were more recently introduced as a segment of Ordovician crust (zircon U-Pb LA-SF-ICP-MS zircon geochronology; Meinhold *et al.* 2010; U-Pb-Hf and rutile U\Pb data, Abbo *et al.* 2019). The presence of or the trace of Early Paleozoic welding in the Hellenic part of the Inner Hellenides (if any) remains unknown (and should not be expected).

*

The essential difference between the two different paleosutures is their modern-day locations. The one more internal is the peri-Moesian Variscan suture (with abundant Paleozoic ophiolite vestiges; Plissart *et al.* 2017, 2018)*,* whereas the 'Cenerian' rootless lithospheric scale boundary is positioned within the external flank of this Carpathian-Balkan nappe stack (Text-fig. 8b; see also Haydoutov *et al.* 2010). The modern-day distance between the two principal Paleozoic tectonic entities is ca. 100 km (Text-fig. 2). Despite the important Alpine interference in the Variscan configuration, there is no evidence of any "Caledonian" interference (unlike the situation within the Penninic pre-Alpine basement, sensu Scheiber *et al.* 2014).

Recycled continental crust of the Cenerian relevance

The more recent paleogeographic and deep crustal lithotectonic reconstructions are based on the Lu/Hf isotopic signatures from basement units and on ages and possible sources of detrital zircons in Neoproterozoic–Lower Paleozoic metamorphic rocks (e.g., Balintoni *et al.* 2010b; Antić *et al.* 2016; Abbo *et al.* 2019). The presence of late Neoproterozoic inherited zircon cores, detrital grains and xenocrysts with εHf values between +7.5 and −18.3 (694–580 Ma) within the Serbo-Macedonian Unit has been described as originating in a basement comprised of magmatic and sedimentary rocks comparable with a Neoproterozoic magmatic arc distributed along the length of the northeastern margin of Gondwana (Neubauer 2002; Antić *et al.* 2016). The transition into the postdated Ordovician juvenile crust is marked by the negative εHf values (εHf(t) = -3) from granitic augen gneiss and mylonitic granite gneiss (εHf(t) = (−7.9)-(−2.8) of ca. 460 Ma peak documented within the Greek segment of the Serbo-Macedonian Unit; Abbo *et al.* 2019). A moderate elevation in εHf(t) values is observed in the igneous basement rocks. The Serbo-Macedonian high-grade agglomeration carries a geochemical fingerprint marking reworked crust and depleted mantle-derived magmas. A mixed juvenile and continental crust signature of the melt is marked by the lower εHf values for the zircons, whose age range revolves around the Lower Ordovician (numeric values by Antić *et al.* 2016; Table 2). The Kukavica granite (478 Ma), the

Deformation age / Tectonic unit	Alpine and Neoalpine (Late Cretaceous–Paleogene and Early Miocene–today)	Variscan event (Early–Middle Carboniferous)	‘Cenerian event’ (Lower Paleozoic to Ordovician)
Serbo-Macedonian Unit (medium- to high-grade gneiss)	Dimitrijević 1997: Extensional faults	Antić *et al.* (2017): (1) The main foliation and migmatization are of Variscan age; D1 Initial Variscan imprint is related to isoclinal folding commonly preserved as up to decimeter-scale quartz-feldspar rootless fold hinges. D2 is associated with general south-eastward tectonic transport and refolding of earlier structures into recumbent meter- to kilometer-scale tight to isoclinal folds.Stages D1 and occurred in close sequence. The age of these two ductile deformation stages was constrained to the Variscan orogeny based on indirect geological evidence (ca. 408–ca. 328 Ma).	Spahić *et al.* this paper*:* (1) Foliation is of probably Variscan age (as by Antić *et al.* 2017). The pre-Variscan age of the main Cenerian-type matrix (ortho- and paragneiss) is attested by the emplacement of the Early Paleozoic pegmatites and gneiss-granites of Variscan age (Text-fig. 4); (2) Orthogneiss may have been sheared/mylonitized and then folded and migmatized; The foliation-parallel shear band, should be formed prior the foliation; (3) Documented presence of the “Cenerian” upper crust: Paragneiss, amphibolites, with the rare occurrence of the preserved ductile folds, shear zones. The vergence of the “Z-type” folds fits with the statistical b2 (Text-fig. 6c). The shear zone (Text-fig. 7a) is folded that might indicate the development prior the penetrative foliation; (4) Presence of large-sale folding (similar to Strone-Ceneri zone) can be attested by the documented sub-horizontal fold axis of “Z-type folds” or presence of sub-horizontal displaced shear zones;
Supragetic basement (greenschist-facies rocks)	(2) Dimitrijević 1997: Irregular foliation dips in all directions, presuming triclinic fabric. (*we presume the Alpine rearrangement of the foliative fabric*); Krstekanić *et al.* (2018): Foliation underwent Alpine restructuring in Lower Cretaceous; Dimitrijević 1997: Transposition of S-surfaces, folded axial cleavage, preserved remnants of fold hinge;		(5) Haydoutov *et al.* 2010: Within the “Thracian suture” (more internal segment of Carpathian-Balkan belt) explaining that the subduction zone was inclined to the SW under the Gondwana edge. This scenario is validated by the proposed Serbo-Macedonian Unit / Supragetic model). The volcanic rocks of the arc were formed at the onset of the Ordovician (490 Ma), while its earliest intrusions were in the beginning of the Cambrian (550–540 Ma). The results are fitting into the Cenerian interval.
Concluding remarks	Strong evidence of significant Alpine overprint of the Supragetic basement	Mild Alpine overprint of Serbo-Macedonian Unit (formation of large antiforms and synforms). Foliative fabric is of Variscan age.	Ductile imprint (shear zone / poorly preserved shear bends) precede dominant Variscan foliation within the Serbo-Macedonian Unit. The structural parameters (vergence of “Z-type folds) apparently favor the Variscan style.

Table 3. Summary of the three principal orogenic and imprinted deformations documented hitherto. Ductile imprint (shear zone / poorly preserved shear bends) precede the dominant Variscan foliation within the Serbo-Macedonian Unit. The structural parameters (vergence of “Z-type folds) apparently favor the Variscan style.

coarse-grained Bujanovac Qz-monzonite (439 Ma), and the Maleševski Mts. orthogneiss have lower εHf values (+4.3 to distributed within the fine-grained Bujanovac granite, the granite associated with the Štip magmatic complex; North Macedonia) including amphibolite from the Vinica area. However, the entire set of the latter markers is of Variscan and tentative Eocimmerian importance (sensu Zulauf *et al.* 2007, 2014, 2018). A recent study documented the repeated recycling of the Cadomian crust interfered with a minor juvenile crustal involvement (Serbo-Macedonian Unit in Greece; Abbo *et al*. 2019).

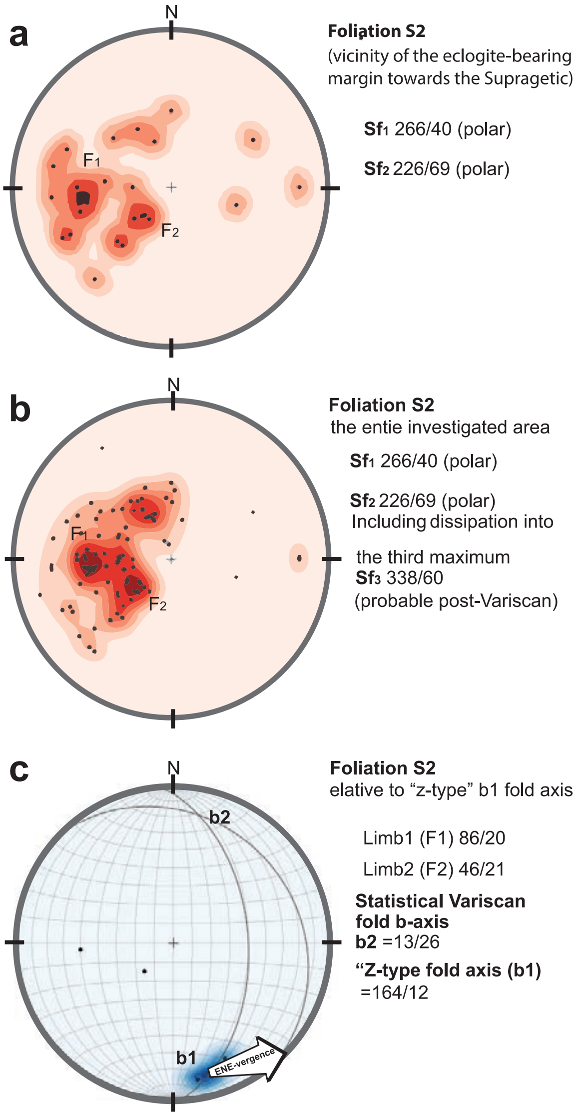
Structural record: distinguishing Variscan and Early Paleozoic imprints

Working in the highly complex Dinaric and Carpatho-Balkan orogenic areas which experienced multiple overprinting (orogenic) episodes, a pioneering geologist measured the folded and often transposed foliation fabric (i.e. its b- or fold axis as markers of the Variscan episode; Đoković 1985). Such pioneering work contributed to the deciphering of an overprinted structural style that included Alpine orogenic interference (Geological map of SFRY; 1:100.000). The Variscan (Đoković 1985; Antić *et al*. 2017; Plissart *et al*. 2018) and Alpine cycles are succeeded by Neogene or Neoalpine overprinting (see Table 3 for details). The Neoalpine stage is additionally marked by strike-slip tectonics (Fügenschuh and Schmid 2005; Marović *et al*. 2007; Burchfiel and Nakov 2015; Antić *et al*. 2017). Unfortunately, the possible imprints of the Cadomian Pan African event well-documented across the Eastern Mediterranean (e.g., Koralay *et al*. 2012 and references therein) and postdating the ‘Cenerian’ event have not been distinguished.

For the reconstruction of important pre-Variscan developments, it is of vital importance to emphasize the tectonic origin of the principal penetrative foliation embedded within the gneiss matrix. The basement units adjoining the Variscan suture (near the tip of western Moesia) are characterized by a dominant mylonitic foliation (Plissart *et al.* 2018). More externally from the Moesian Variscan front (Text-fig. 1c), in the Serbo-Macedonian Unit, folds in the foliation planes are reported to have a SW-vergence (Kalenić *et al.* 1975). Such a structural pattern with overprinted dominant foliation fits to the Alpine shortening framework. Variscan developments are suggested for a more southern segment of the Serbo-Macedonian Unit in SE Serbia, near Vrvi Kobila (Antić *et al.* 2017; Text-fig. 3b). In the vicinity of Leskovac, nevertheless, (Text-fig. 3b), there is locally documented evidence of two generations of foliation fabrics. The principal gneiss-dominated matrix is intruded by a ca. 500 Ma old peraluminous magmatic body (according to the protolith) exhibiting two generations of metamorphic foliations (Zagorchev and Milovanović 2006). The second, most likely younger foliation pattern (Variscan or Ordovician?) obliquely intersected the older system (Vučje gneiss).

Foliation

As mentioned earlier, the dominant structural record within the investigated gneiss-dominated succession is a well-developed penetrative foliation (Text-figs 4, 5, 6 and 7). The investigated area has a dominant penetrative foliation (S_2; Text-fig. 6) of the preferred ca. 90° dip-direction (in particular within its eastern flank; Text-figs 4, 6a). Analyses of Schmidt's diagram equal-area lower hemisphere projection exhibits a statistical gently plunging tight asymmetrical fold with differently oriented limbs, (Text-fig. 6a, b). Unlike the neighboring crystalline blocks (with an NNW-directed Alpine fabric), folds in the vicinity of Stalać exhibit the E-vergence thus fitting into the Variscan style. The observed foliation S_2 exposes scarce cm-scale folds including foliation-parallel shear bands (Text-fig. 7e, f, h). Presumably, the shearing (disrupted shear bands) preceded the foliation, whereas both structural elements were subsequently overprinted (likely in transitional brittle-ductile conditions; Text-fig. 7h, rC').



Text-fig. 6. Schmidt's diagram lower hemisphere projection of the foliative fabric and b-axis of minor folds, segment of Serbo-Macedonian Units (locations of data collected in Text-Fig. 4). a – Diagram exibits the two major peaks of foliation poles indicating the presence of folds (area in the vicinity of eclogites). b – Diagram exibits the three major peaks of foliation poles indicating probable Alpine interference. c – Diagram of the b-axis of the observed overturned folds. Rotation between the Variscan and Cenerian b-axes goes over 90°. Further explanation within the text.

This presence of a large overturned fold (Limb1 and Limb2; Text-fig. 6c) with the pole maximum of F_1/S_{f1} (266/40) indicates a moderate inclination towards the E-NE (Limb1 86/60). Another maximum can be connected to a shallow-dipping inclination of one of the limbs 226/69 or Limb2 46/31. The statistical fold axis (13/26) has a shallow-to-moderate dip angle, directed towards NNE (fits with the Variscan pattern). Such low-angle fold axis attests the presence of larger-scale regional folds. It should be noted that such a folding fabric is in line with the measurements across the southern realm of the Serbo-Macedonian Unit interpreted as an early Variscan involvement (Antić *et al.* 2017). However, the interpreted age of the deformation i.e. the penetrative foliation recorded within the Serbo-Macedonian Unit is tentative (Antić *et al.* 2017).

The third maximum (Sf3; Text-fig. 6b) illustrates a dissipation towards E-SE, indicating a probable rotation at the expense of subsequent brittle deformation events of Alpine age.

Shear zone and evidence of ductile folding

The crystalline rocks of the Serbo-Macedonian Unit in the Stalać area contain very rare evidence of folding in ductile conditions (flank towards the Supragetic unit). The position of the investigated ductile structures is remote relative to the Vrvi Kobila shear zone (Vrvi Kobila shear zone is of tentatative Variscan age; Antić *et al.* 2017; Text-fig. 3b). These folds (e.g., fold axis b1 = 164/12) represent exposed "Z-type" open folds, rootless hinges of parasitic folds (Text-fig. 7a, b). Apparently, these folds seem to be tectonically coupled with the folded shear zones. The rocks also include the presence of a naturally sectioned hinge area exposing folded leucocratic laminae within orthogneiss (Text-fig. 7c, d). The interpreted vergence of the "Z-type" folds is towards the ENE. The "Z-type" subhorizontal fold axis corroborates the presence of larger folds spatially rearranged during the subsequent deformational stage. Importantly, at the same outcrop (Text-fig. 4; point# mRIF), complete small-scale open folds are observed (Text-fig. 7e, f). These features are embedded into and within the gneiss-dominated matrix i.e. the foliation (Text-fig. 7h). The fold axes of these small-scale overturned folds are moderately inclined towards the SSE (Text-fig. 6c). The observed spatial arrangement seems to be a result of two compressional (folding) events. Alternatively, two single-stage compressional patterns were generated in ductile and near brittle-ductile transitional conditions (the fractures observed as in Text-fig. 7c indicate brittle-ductile conditions).

The shear zone(s) are observed along with small-scale "Z-type" parasitic folds which further include the presence of overturned folds. The tectonic conditions produced the foliation fabric that superimposes the small-scale shear bands. A narrow shear zone is marked by the opposite orientation of the limbs of the small-scale folds (green and yellow points or fold axes positioned inside small-scale overturned folds; Text-fig. 7a, b). Thus, these two ductile features could be regarded as precursory to the e.g. Variscan foliation, marking a tentative (initial) layering-parallel shearing associated with two discrete shortening episodes.

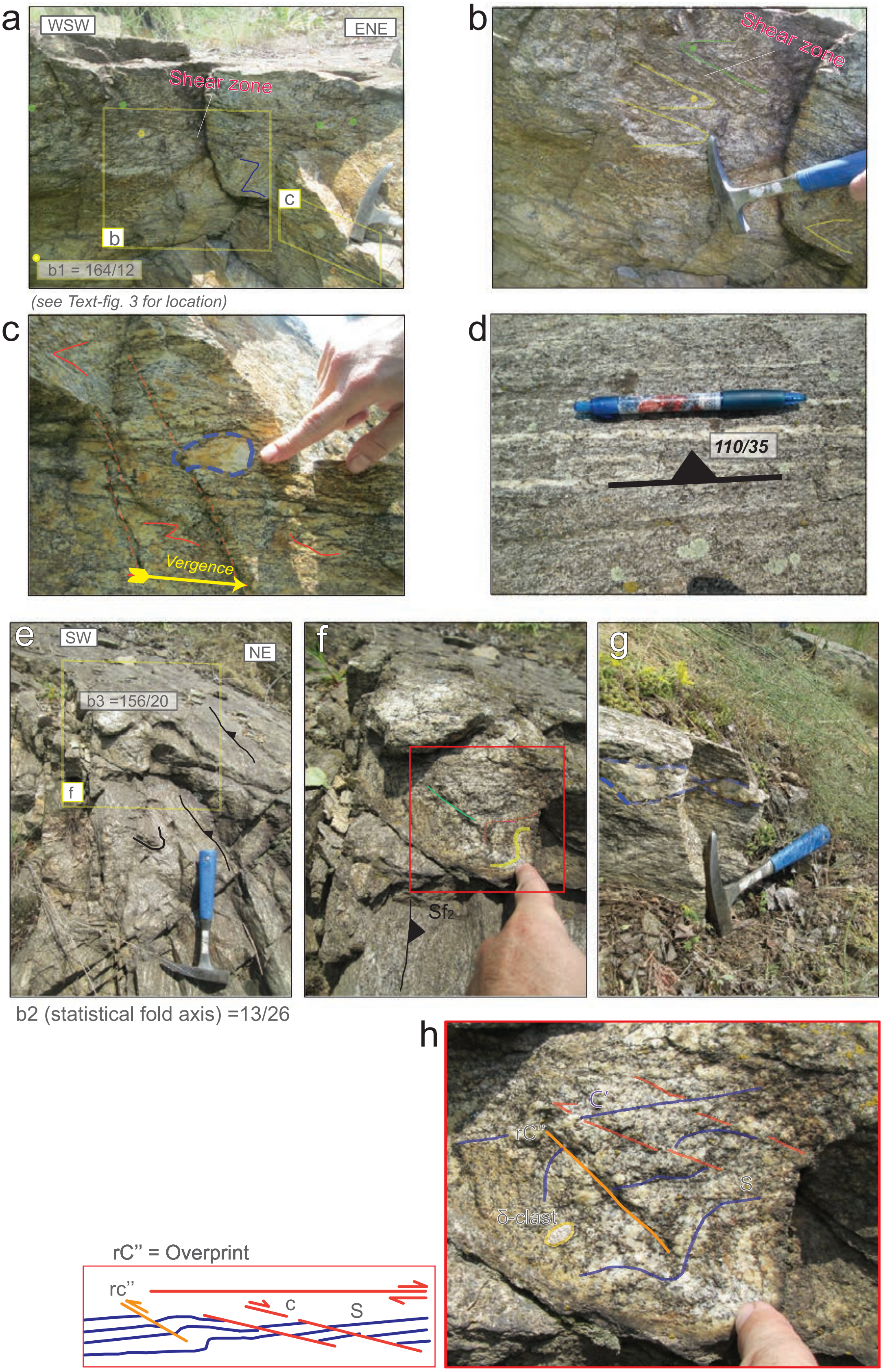
The regional shortening evident corroborates a compressional setting during the early Paleozoic (as suggested by Balintoni *et al.* 2011a; Zurbriggen 2015, 2017a; Stephan *et al.* 2019). The early Paleozoic age of the main Serbo-Macedonian matrix is well documented, hence comparable compressional configuration could also be interpreted as post-early Paleozoic orogen-parallel shearing (in both the Variscan and Alpine configurations; e.g. Antić *et al.* 2017; Table 3). To moderate uncertainty, the age of the local magmato-tectonic developments and its spatial relationship (crosscutting nature of pegmatites and Variscan gneiss-granites; Text-fig. 4) is further emphasized.

Lower Paleozoic pegmatites and upper Paleozoic (Variscan) granite gneisses

Despite ambiguous age of the investigated scarce ductile features, the emplacement of granite protoliths of gneisses (numeric age ca. 350 Ma by Deleon *et al.* 1972) attests to the pre-Variscan age of the main Serbo-Macedonian Unit. The best preserved intrusive contact relationships (Text-fig. 3) is within the investigated Stalać segment (Text-fig. 4). Another important analogy with the Cenerian subduction-accretion model is the well-documented early Paleozoic anatexis in the form of pegmatite intrusions (¥Pz1; Text-fig. 4). Magmatic foliation being concordant with the intrusive contacts and main schistosity (Zagorchev and Milovanović 2006) is the third reliable argument for a syntectonic intrusion. Nevertheless, further study of structural elements is highly recommended.

DISCUSSION

The following reconstruction is aimed at showing that lithospheric-scale models during the 'Cenerian' early Paleozoic interval can be tested against geological records preserved far from their original continental margins (Serbo-Macedonian Unit and Supragetic basement). To qualify the early Paleozoic paleogeographic and tectonic model that involved the 'Cenerian event', we integrated the rare local (i) Rb-Sr geochronological determinations (Deleon *et al.* 1972) with (ii) records of regional-scale Ordovician imprints (e.g., as in the Sebeş-Lotru metamorphic unit; Balintoni *et al.* 2010b). The study incorporated (iii) the already documented peraluminous character of some of the Neoproterozoic–Lower Paleozoic *S*-type granites (Antić *et al.* 2016). The reconstructed early Paleozoic paleosuture outlines a flanking peri-Gondwanan configuration of welded oceanic lithosphere (Supragetic basement) beneath newly "cratonized" crust (Serbo-Macedonian Unit; Text-fig. 1a).


a
WSW
ENE
Shear zone
b
c
b1 = 164/12
(see Text-fig. 3 for location)
b
Shear zone
c
Vergence
d
110/35
e
SW
NE
b3 =156/20
f
f
Sf₂
g
b2 (statistical fold axis) =13/26
h
C'
rC''
S
δ-clast
rC'' = Overprint
rc''
c
S

‘Cenerian’ North Gondwanan tectonic and paleogeographic framework

The ongoing debate considering an “intra-Ordovician orogeny” revolves around the so-called Cenerian or “Sardic” plate-tectonic event in North Gondwana. The ‘Cenerian event’ overlapped with the formation of the nearby Hirnantian ice sheet (ca. 443 Ma; Stephan *et al.* 2019). In addition to the Cadomian orogen (Neoproterozoic) and cratonic sources, erosion beneath the Hirnantian ice sheet apparently enabled another episode of voluminous supply of terrigenous detritus. The ‘Cenerian event’ has been interpreted as the result of: (1) a far-field effect due to the coeval collision of Baltica with Avalonia; (2) the “Cenerian Orogeny” (with Alaskan-type subduction-accretion as a modern analogue) or as (3) a localized compressional expression due to strain partitioning during the Cambro-Ordovician extension. Thus, the paleogeographic framework and mechanism of growth of these, later dislodged Peri-Gondwanan Avalonian- and Cadomian-type crustal fragments is validated (see Balintoni *et al.* 2011a, for a discussion; Text-fig. 1a). As presented, the magmatic and sedimentological, geochemical and age data (very similar to the Strona-Ceneri zone), rare field structural measurements, including the difference in position with regards the SEE segment of the Variscan paleosuture, show a strong fit with the ‘Cenerian event’.

The formation of the Serbo-Macedonian (continental) crust: Reconstruction of the ‘Cenerian event’

The following early Paleozoic (Cambro-Ordovician reference frame) paleotectonic and stratigraphic sections are tested by a stepwise comparison with the archetype model proposed by Zurbriggen (2015). The alternative Serbo-Macedonian encrustation model incorporates the important geochronological and geochemical data. The following early Paleozoic reconstruction further includes the scarce database of paleocontinental detrital sources. To facilitate tracking of the stepwise Cambro-Ordovician subduction setting proposed here, we suggest to use the location map or Text-fig. 3a, b of this paper, and fig. 2 of Antić *et al.* (2016).

Voluminous peri-Gondwanan clastic sediment sourcing (point#1, Zurbriggen 2015) is reflected by protoliths of Neoproterozoic–Cambrian metasedimentary rocks. The sedimentation age of 550–480 Ma proposed for the Strona-Ceneri zone (Zurbriggen 2017a) is also reported from the Serbo-Macedonian Unit (maximum depositional age of ca. 560 Ma with a prominent early Paleozoic peak at ca. 460 Ma). The presence of blastopsammitic structure with preserved poorly rounded grains (including gneiss grains themselves) indicates two important findings (Batočina series dated by *Archaeofavosina simplex* Naum; position in Text-fig. 3b). The pre-metamorphic sediment-sourcing event (protolith of the main gneiss-dominated matrix) unambigously occurred prior to the formation of the presumably Variscan foliation. Moreover, short sediment transport (Cvetkovic 1992; also in Kalenić 2004) from proximate Neoproterozoic sources can also be depicted. Abundant olistostroms (Haydoutov *et al.* 2010), including the postdated ‘Lisina Series’, piled up on the top of the Supragetic basement document the infill age of the subordinate Tremadocian trench (biostratigraphic age of the ‘Lisina Series’; Pavlović 1962, 1977). The Cumpăna metamorphic sequence (northern analog unit; paragneisses) exhibits approximately the same depositional maximum (Balintoni *et al.* 2010b). In the paleogeographic context, the peri-Gondwanan affinity is additionally documented by paleomagnetic data that revealed high latitudes in the early Paleozoic (Milićević 1996). Indeed, the cyclic sourcing of terrigeneous material restarted in the early Ordovician supplying tidal-controlled shallow Tremadocian deposition (metaconglomerates, metasandstones, metagreywacke, subgreywacke, all documented within the neighboring “Supragetic/Kučaj unit” or Supragetic/Getic; Banjac 2004; see Spahić *et al.* 2019b). Ongoing sourcing of clastic material shifted into very shallow

← Text-fig. 7. Rare ductile structural fabric of the investigated segment of the Serbo-Macedonian Unit. a, b – Examples of the first discovery of open small-scale “Z-type” folds in outcrop scale (point colors differentiate the opposite curvature around a shear zone. Dashed sense line implies that the observed shear zone possibly extends further towards the root of the outcrop and deeper. The subhorizontal axial planes additionally indicate the presence of larger-scale folding. The shear zone (between the green and yellow dots) underwent folding. The process of deformation of the orthogneiss (Text-fig. 4 a, b, position in Text-fig. 3) towards sheared/mylonitized and then folded and migmatized rock depicted on Text-fig. 6. c – An example of densely folded migmatitic gneiss exposing the hinge area in a leucocratic lamina. Red lines designate abundant “Z-type” folds, whereas pale red lines represent localized brittle-ductle fractures. d – An example of the foliation in gneiss-matrix. e, f, h – An example of the outcrop scale asymmetric small-scale open folds. The spatial elements of the axial plane fit with the heavily overprinted C-fabric (shear bend): The irregular foliation somewhat follows the S-fabric. The schematic diagram (to the left of h) indicates the shortening episode, i.e. the reactivation of the precursory shear zone (shear bend). The reactivated rC” fabric is in agreement with the syn-compressional development of the foliation. g – Transition of the penetrative foliation into the quartz augen and the presence of a quartz-bearing boudinage.

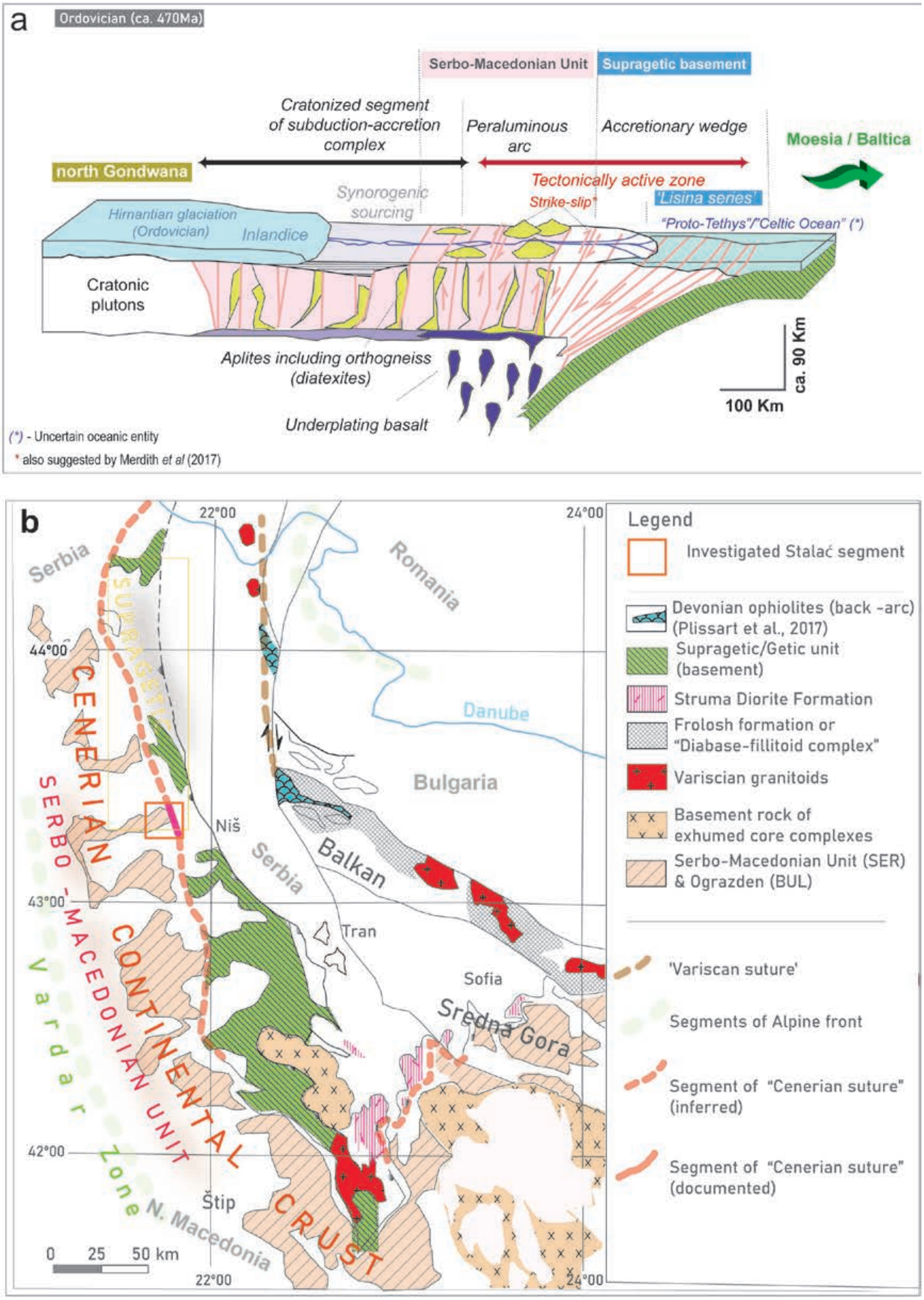
shore sedimentation, with a documented progradation to become fine-grained in the late Ordovician (effect of the Hirnatian inland ice). However, the Serbo-Macedonian segment records no lower to middle Ordovician rocks (unconformity; Spahić *et al.* 2019b; Text-fig. 4). The Upper Ordovician with its fine-grained deposition occupied deeper sections of the continental margin positioned in the present-day eastern Serbo-Macedonian Unit (Kučaj and Homolje, East Serbia; Krstić and Maslarević 1998; Banjac 2004 and references therein). Voluminous sourcing of sterile, non-fossiliferous clastites (in particular those of middle Ordovician age; age by Đajić 1996) may indicate an onset of high-latitude Ordovican glaciation in the hinterland (Text-fig. 8a). Likewise, the presence of 1.1–0.95 Ga detrital zircons in the Golemo Selo paragneisses and Izvor micaschists (North Macedonia; Antić *et al.* 2016) in the 'Eastern Veles Series' (an analog of Serbo-Macedonian Unit, Text-fig. 3a) marks the vicinity of Northeast African Gondwana sources (sensu Meinhold *et al.* 2013; Avigad *et al.* 2017).

As mentioned earlier, the first evidence of accretion underneath this steeply structured composite terrane (Serbo-Macedonian hanging wall) or deformation D_1 proposed by Zurbriggen (2015; Point #2) could somewhat be documented by the occurrence of rather scarce ductile imprints. The foliation planes in the vicinity of the amphibolite lenses dip steeply (Text-fig. 4). However, according to our opinion, the spatio-temporal relationship of the foliation and its origin recorded with the main gneiss matrix needs further investigation in both cases, the Strona-Ceneri zone and the Serbo-Macedonian Unit. Nevertheless, the overriding position (hanging wall) of the Serbo-Macedonian Unit can be documented by the additional HP/HT imprints: (i) the scarce ductile shear zones, overprinted relics of shear bends and (ii) the underthrusting position of the Supragetic ocean-floor assembly (see later in the text).

The Lu-Hf isotopic composition of Neoproterozoic to Cambrian zircons depicts a mixture of crustal- (Doganica granite and Lisina gabbro; Struma unit) and more juvenile Neoproterozoic–Lower Paleozoic magma sources (Vlajna, Bosilegrad, Božica, Delčevo; Text-fig. 3b). This combination marks the important fore-arc setting proposed by Zurbriggen (2015; Point #3; Ustaömer *et al.* 2005). Such bimodal magma sourcing can be associated with a segment of the late Cadomian active margin (earliest Cambrian). Mixing of basalts and crustal rocks in a volcanic system has been also documented within the Cumpăna sequence (Sebeş-Lotru terrane; sensu Drăguşanu *et al.* 1997).

The phase of dominant (latest Cambrian) pericratonic synorogenic sediment sourcing (Zurbriggen 2015; phase#4) is corroborated by a detrital zircon peak of ca. 488 Ma. Such timing corresponds to the tectonometamorphic episode and the initial metamorphic imprint (Serbo-Macedonian gneiss in the Batočina area; 488 Ma numeric age by Balogh *et al.* 1994). A second imprint occurred in the late Ordovician (454.2±2.1 Ma; numeric age by Zagorchev *et al.* 2014). The proposed "synorogenic magmatic activity" (meaning the peak of magmatism piercing newly amalgamated continental crust) is documented by the emplacement of within-plate tholeiitic basalts in middle–early late Ordovician times (Golemo Selo in Serbia, and the Vinica and Vlajna granite-gneiss; 450 Ma, Dimitrijević 1997). Importantly, similar crystallization ages of 458.9±3.5 Ma and 466.0±4.2 Ma are documented within the Cumpăna metamorphic unit (Balintoni *et al.* 2010b). Emplacement of mafic magmas preserved in the scarce amphibolites (in particular those located in the more southern Serbo-Macedonian segment) exhibits the involvement of intermediate magmatic rocks, gabbro diorites, within-plate tholeiites and within-plate alkali-basalts. The mixing of downgoing sedimentary/clastic material, protracted magmatic activity and anatexis contributed to the amalgamation of the new (peri)cratonic crust (sensu Zurbriggen 2015). The investigated Serbo-Macedonian block contains ribbons of amphibolite-facies metamorphic rocks and eclogite (similar to the Strona-Ceneri zone in the Swiss Alps). However, eclogites are not necessarily markers of the 'Cenerian event', but they are very likely good Variscan markers (as documented across the Balkans).

Because the suggested "cratonization processes" or the production of new continental crust do not form an over-thickened crust (no nappe-stacking of displaced crustal slices), there is no late- to post-orogenic exhumation of deeper crustal levels (Zurbriggen 2015; Point#5). Back-arc extension or in the Cenerian case extension of juvenile crust (Text-fig. 8a) eventually truncated, and finally dislodged a Serbo-Macedonian/Supragetic crustal accretionary assemblage from north Gondwana. A felsic early Silurian within-plate magmatic episode (quartz monzonite in the southwestern periphery of the Bujanovac, position in Text-fig. 3a) could represent the marker of the separation of the investigated subduction-accretion complex from the craton itself (North Gondwanan promontory). This event is probably connected with a late opening of the eastern Rheic Ocean (Stampfli and Borel 2002; Nance *et al.* 2010; Nance and Linemann 2012) or Paleotethys (Kroner and Romer 2013).



Text-fig. 8. a – Lower Paleozoic tectonic model of the Serbo-Macedonian Unit and Supragetic basement during the 'Cenerian event' (inset from Zurbriggen 2014, modified). The subduction-accretion setting was followed by separation from north Gondwana in the latest Ordovician-early Silurian. Further explanation within the text. b – The position of the 'Cenerian continental crust' (Serbo-Macedonian Unit) and its Ordovician suture (inset from Kounov *et al.* 2012, modified).

The proposed scenario is in accord with both the the "Cenerian Orogeny concept" or the option #2 (the Alaskan-type subduction-accretion model) and the regional geological configuration of the Carpatho-Balkanides. The fit of the regional configuration is further supported by the distant position (in present-day reference) of the documented Variscan suture front (Text-figs 2, 8b). The reliable paleotectonic/paleogeographic/sedimentary/magmatic markers of the recently constrained 'Cenerian event' are:

(i) The date of the culmination of lithospheric accretional growth (encrustation) is bracketed for the Cambrian–early to early middle Ordovician. The documented Tremadocian crustal-scale entanglement with the Supragetic basement (in addition to a widespread olistrome; Haydoutov *et al.* 2010) provides another piece of evidence for the proposed accretionary agglomeration/crustal configuration (Text-fig. 8b). The 'Cenerian-type' crustal growth process continued probably throughout the early middle and tentatively upper Ordovician. The Serbo-Macedonian/Supragetic early Paleozoic crustal agglomeration was eventually interrupted by the early Silurian separation from the back-arc position (relative to the Gondwanan hinterland). The proposed events and timing have a good fit with the 'Cenerian' Ordovician event (470 Ma; Balintoni *et al.* 2011a);

(ii) Dispersal (from the back-arc position) is additionally documented by a transgressive (Spahić *et al.* 2019b) deep-marine, continuous succession of latest Ordovician–Devonian age, deposited on the top the adjoining Supragetic/"Kučaj" (or Supragetic/Getic) crystalline basement (sensu Spahić *et al.* 2019b and references therein; also in Boncheva *et al.* 2010). Importantly, a Supragetic/"Kučaj" sedimentary pile unconformably overlies the Lower Ordovician Supragetic basement segment. Thus, the absence of the middle Ordovician is documented. Another important fact is that the U/Pb LA-ICP-MS zircon crystallization age (similar to the detrital age data from Greece; Abbo *et al.* 2019) yielded the middle–late Ordovician age (Darriwilian) of the Cumpăna metamorphic unit (Sebeş-Lotru terrane; numeric age by Balintoni *et al.* 2010b).

(iii) The disputed effect of the coeval early Paleozoic collision of Baltica with Avalonia can be ruled out on the ground of at least two following factors. As East Avalonia was in a drifting stage along with West Avalonia prior to 420 Ma (Keppie and Keppie 2014), there was no collision that would effect any developments along the North Gondwanan promontory. In addition, the slab-pull tectonic forces of the remote Laurentian southern margin could not profoundly affect the ongoing southwards-directed Cambrian–early Ordovician underplating and Cenerian-type lithospheric growth. Secondly, the effect of the remote collision of Baltica with (East) Avalonia at 420 Ma had no significance for the Cenerian lithosphere because the main compressional stage terminated there around 470 Ma. On the other hand, the precursory back-arc extension and ongoing spreading of the Rheic Ocean (ridge-push; Murphy *et al.* 2008; Keppie and Keppie 2014 and references therein) was likely to be affected by the 'Cenerian event' (the eastern Rheic aborted around 470 Ma; von Raumer *et al.* 2002; see Balintoni *et al.* 2011a, for a discussion).

(iv) The alternative interpretation that proposes localized compressional expression due to strain partitioning during the Cambro-Ordovician extension is not in agreement with the observed data in the Serbo-Macedonian Unit. Namely, the proposed model provides no explanation of the multiple early Paleozoic high-grade metamorphism (latest Cambrian–intra-Ordovician accretionary wedging) which occurred within this particular framework. It explains neither why the Cenerian-type terranes are deficient with oceanic crust, nor why there was no late early to middle Ordovician burial (which is expected to account for the proposed back-arc extension).

CONCLUSIONS

The stepwise in-depth comparison between the Serbo-Macedonian basement unit relative to the documented Cenerian imprints described in the Alps indicates affinities of the Carpathian-Balkan basement segment with the early Paleozoic 'Cenerian' orogeny. These are as follows:

- the Serbo-Macedonian Unit originated from the Early Paleozoic peri-cratonic segment of North Gondwana,
- protoliths of a variety of Neoproterozoic to lower Paleozoic metasedimentary clastic rocks reveal initial transport from North Gondwana sources (Cadomian orogeny and continental interior),
- the Serbo-Macedonian Unit is in tight connection with the wedged slices of Neoproterozoic–Ordovician oceanic lithosphere (Supragetic basement),
- the Serbo-Macedonian Unit is a carrier of voluminous syntectonic Neoproterozoic–Lower Paleozoic magmatism with a dominant continental crust component,
- mobilized diatexites, which rose as plutons and in-

truded metasediments, are common in the investigated Stalać region (dominant migmatites, gneisses and locally pegmatites) and all over the Supragetic basement (Haydoutov *et al.* 2010),

– the Serbo-Macedonian Unit contains no evidence of fragments of Precambrian cratons,

– the observed structures have moderately plunging fold axes and

– there is no exhumation of the lower crust until the Variscan event.

Our study enabled the distinguishing of the following early Paleozoic plate-tectonic processes revealed in the Serbo-Macedonian Unit:

- The superposition of the lithologies of the Strona-Ceneri zone (Zurbriggen 2015, table 1) vs. the Serbo-Macedonian Unit (Text-fig. 4) have an almost identical lithological input: the percentage of these sedimentary derived rocks is ca. 97% in area vs. mantle-derived occupying ca. 3% in area;
- The ‘Cenerian event’ connects the ongoing subduction of the Proto-Tethyan oceanic crust (Supragetic basement) underneath the newly accreted continental crust (Serbo-Macedonian Unit). Both lithospheric domains were distributed along the length of the North Gondwanan margin (Text-fig. 8). A comparable paleogeographic configuration is suggested by Abbo *et al.* (2019 and references therein);
- The age of the ‘Cenerian event’ in this part of southeastern Europe most likely spanned ca. the earliest Cambrian–middle Ordovician interval (similar as proposed Haydoutov *et al.* 2010; Balintoni *et al.* 2011a). In the case of the Serbo-Macedonian Unit (segment in Serbia), this mechanism connects a late Cadomian magmatic arc stage with the production of juvenile crust lasting during the Cambrian up to the Ordovician (the age of protolith ranging from 541 to 475 Ma; sensu Deleon *et al.* 1972). The maximum production of juvenile crust could have been associated with the widespread Ordovician magmatism and anatexis (similar to the proposition of Balintoni *et al.* 2011a; Zagorchev *et al.* 2014). According to the aforementioned arguments, the Cenerian setting has often been misinterpreted as being a magmatic arc tectonic inheritance (an intuitive continuation of the Cadomian arc);
- The distinction of the Serbo-Macedonian Unit as the pre-Mesozoic basement offers a unique opportunity to explore scarce, occasionally preserved Lower Paleozoic high-grade structures marking the lower crust. Despite the intense efforts presented by this paper, due to the significant subsequent Variscan and Alpine overprints, we would recommend further search for and investigation of rare and difficult-to-find records of pre-Variscan ductile features;
- The age of the metamorphic overprint (ca. 459 Ma) reported from the Sebeş-Lotru terrane (Getic; Text-fig. 3a) illustrates a possible involvement of the Cumpăna metamorphic unit in the suggested ‘Cenerian event’;
- The documentation of the ‘Cenerian event’ typifies an eastern bipartite shelf of North Gondwana (sensu Stephan *et al.* 2019). The results place (paleogeographically) the Serbo-Macedonian Unit along the length of its eastern shelf area. Such a position increases the likelihood of discovering Cenerian imprints over Cadomian tectonic elements;
- The geology of the investigated Carpathian-Balkan area (in particular of the Serbian segment) is of extreme complexity as it comprises the vestiges of at least three major Phanerozoic sutures (Text-fig. 8b).
- The “Caledonian North African orogen” (Balintoni *et al.* 2011a) is not a convenient term, instead we recommend to use the term ‘Cenerian event’.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors. The paper benefited from the constructive reviews of Prof. Dr. Franz Neubauer from the University of Graz and Prof. Dr. Andrzej Żelaźniewicz, Institute of Geological Sciences, Polish Academy of Sciences. Special thanks go to Prof. Dr. Andrzej Żelaźniewicz for detailed remarks on the manuscript content, as well as on the important continuous improvements of the early manuscript versions. The authors thank Editor-in-chief Piotr Łuczyński for impeccable guidance throughout the manuscript review process.

REFERENCES

Abbo, A., Avigad, D. and Gerdes, A. 2019. Crustal evolution of peri-Gondwana crust into present day Europe: The Serbo-Macedonian and Rhodope massifs as a case study. *Lithos*, **356–357**. https://doi.org/10.1016/j.lithos.2019.105295

Aleksić, V. 1977. Metamorphism. In: Petković, K. (Ed.), Geologija Srbije III-2 – Metamorfizam (Geology of Serbia III-2 – Metamorphism), 282 pp. Zavod za regionalnu geologiju i paleontologiju, RGF, Univerzitet u Beogradu; Belgrade. [In Serbian]

Aleksić, V., Dimitriadis, S., Kalenić, M., Stojanov, R. and Zagorchev, I. 1988. Serbo-Macedonian Massif. In: Zoubek, V., Cogné, J., Kozhoukharov, D. and Krautner, H. (Eds), Precambrian in Younger Fold Belts, 779–820. Wiley & Sons.

Antić, M., Peytcheva, I., von Quadt, A., Kounov, A., Trivić, B., Serafimovski, T., Tasev, G., Gerdjikov, I. and Wetzel, A. 2016. Pre-Alpine evolution of a segment of the North-Gondwanan margin: Geochronological and geochemical evidence from the central Serbo-Macedonian Massif. *Gondwana Research*, **36**, 523–544.

Antić, M.D., Kounov, A., Trivić, B., Wetzel, A., Peytcheva, I. and von Quadt, A. 2015. Alpine thermal events in the central Serbo-Macedonian Massif (southeastern Serbia). *International Journal of Earth Sciences (Geologishes Rundschau)*, **105**, 1485–1505.

Antić, M., Kounov, A., Trivić, B., Spikings, R. and Wetzel, A. 2017. Evidence of Variscan and Alpine tectonics in the structural and thermochronological record of the central Serbo-Macedonian Massif (south-eastern Serbia). *International Journal of Earth Sciences (Geologishes Rundschau)*, **106**, 1665–1692.

Arenas, R., Díaz Fernández, R., Sánchez Martínez, S., Gerdes, A., Fernández-Suárez, J. and Albert, R. 2014. Two-stage collision: exploring the birth of Pangea in the Variscan terranes. *Gondwana Research*, **25** (2), 756–763.

Arkadakskiy, S., Böhm, C., Heaman, L., Cherneva, Z., Stancheva, E. and Ovtcharova, M. 2003. Remnants of Neoproterozoic oceanic crust in the Central Rhodope metamorphic complex, Bulgaria. In: *The Geological Society of America Vancouver Annual Meeting*, GS3-62.

Arboit, F., Chew, D., Visoná, D., Massironi, M., Sciascia, F., Benedetti, G. and Rodani, S. 2019. The geodynamic evolution of the Italian South Alpine basement from the Ediacaran to the Carboniferous: Was the South Alpine terrane part of the peri-Gondwana arc-forming terranes? *Gondwana Research*, **65**, 17–30.

Avigad, D., Morag, N., Abbo, A. and Gerdes, A. 2017. Detrital rutile U-Pb perspective on the origin of the great Cambro-Ordovician sandstone of North Gondwana and its linkage to orogeny. *Gondwana Research*, **51**, 17–29.

Bahlburg, H., Vervoort, J.D. and DuFrane, S.A. 2009. Plate tectonic significance of Middle Cambrian and Ordovician siliciclastic rocks of the Bavarian Facies, Armorican Terrane Assemblage, Germany – U-Pb and Hf isotope evidence from detrital zircons. *Gondwana Research*, **17** (2-3), 223–235.

Balintoni, I. and Balica, C. 2013. Avalonian, Ganderian and East Cadomian terranes in South Carpathians, Romania, and Pan-African events recorded in their basement. *Mineralogy and Petrology*, **107**, 709–725.

Balintoni, I. and Balica, C. 2016. Peri-Amazonian provenance of the Euxinic Craton components in Dobrogea and of the North Dobrogean Orogen components (Romania): a detrital zircon study. *Precambrian Research*, **278**, 34–51.

Balintoni, I., Balica, C., Ducea, M.N., Chen, F., Hann, H.P. and Şabliovschi, V. 2009. Late Cambrian–Early Ordovician Gondwanan terranes in the Romanian Carpathians: zircon U-Pb provenance study. *Gondwana Research*, **16**, 119–133.

Balintoni, I., Balica, C., Ducea, M.N., Hann, H.P. and Şabliovschi, V. 2010b. The anatomy of a Gondwanan terrane: the Neoproterozoic–Ordovician basement of the pre-Alpine Sebeş-Lotru composite terrane (South Carpathians, Romania). *Gondwana Research*, **17**, 561–572.

Balintoni, I., Balica, C., Ducea, M.N. and Hann, H.-P. 2014. Peri-Gondwanan terranes in the Romanian Carpathians: A review of their spatial distribution, origin, provenance, and evolution. *Geoscience Frontiers*, **5** (3), 395–411.

Balintoni, I., Balica, C., Ducea, M.N. and Stremţan, C. 2011b. Peri-Amazonian, Avalonian-type and Ganderian-type terranes in the South Carpathians, Romania: The Danubian domain basement. *Gondwana Research*, **19**, 945–957.

Balintoni, I., Balica, C., Ducea, M.N., Zaharia, L., Fukun Chen, Cliveti, M., Hann, H.P., Li-Qiu Li and Ghergari, L. 2010a. Late Cambrian−Ordovician northeastern Gondwanan terranes in the basement of the Apuseni Mountains, Romania. *Journal of the Geological Society*, **167**, 1131–1145.

Balintoni, I., Balica, C. and Hann, H.-P. 2011a. About a peri-Gondwanan–North African enlarged acceptance of the Caledonian Orogeny. *Studia UBB, Geologia*, **56** (1), 29–32.

Balogh, K., Svingor, É. and Cvetković, V. 1994. Ages and intensities of metamorphic processes in the Batočina area, Serbo-Macedonian massif. *Acta Mineralogica-Petrographica*, **35**, 81–94.

Banjac, N. 2004. Stratigraphy of Serbia and Montenegro, 266 pp. Rudarsko-geološki fakultet, Institut za regionalnu geologiju i paleontologiju; Beograd. [In Serbian] (CD-ROM)

Boncheva, I., Lakova, I., Sachanski, V. and Koenigshof, P. 2010. Devonian stratigraphy, correlations and basin development in the Balkan Terrane, western Bulgaria. *Gondwana Research*, **17**, 573–582.

Burchfiel, B.C. and Nakov, R. 2015. The multiply deformed foreland fold-thrust belt of the Balkan orogen. *Geosphere*, **11**, 463–490.

Buriánek, D., Hrdličková, K. and Hanžl, P. 2009. Geological position and origin of augen gneisses from the Polička Unit, eastern Bohemian Massif. *Journal of Geosciences*, **54**, 201–219.

Carrigan, C.W., Mukasa, S.B., Haydoutov, I. and Kolcheva, K. 2005. Age of Variscan magmatism from the Balkan sector of the orogen, central Bulgaria. *Lithos*, **82**, 125–147.

Csontos, L. and Vörös, A. 2004. Mesozoic plate tectonic reconstruction of the Carpathian region. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **210**, 1–56.

Cvetković, V. 1992. Petrology of the metamorphic rocks from the norhtern parts of the Serbo-macedonian massif in the Batočina area, 132 pp. Unpublished Master Thesis. University of Belgrade; Beograd. [In Serbian]

Deleon, G., Dromnjak, M. and Lovrić, A. 1972. Sr age of the Stalać-Juhor metamorphic complex. In: VII Kongres geologa SFRJ. Predavanja održana u sekciji mineralogija i petrologija. Vol. II, 97–112. Zagreb. [In Serbo-Croatian, with English summary].

Dimitrijević, M. 1959. Geological column of the Serbo-Macedonian Mass, basic features. First Symposium of Serbian Geological Society, Belgrade (copy without pagination). [In Serbian]

Dimitrijević, M.D. 1997. Geology of Yugoslavia, 182 pp. Geological Institute-Gemini, Special Publication, Barex; Belgrade.

Dimitrijević, M.D. 2001. Dinarides and the Vardar Zone: a short review of the geology. *Acta Vulcanologica*, **13** (1-2), 1–8.

Dimitrijević, M. and Krstić, B. 1999. Geotectonic map in scale 1: 2,000,000. Ministry for Mining and Energetics of Serbia and Geomagnetic Institute; Belgrade. [In Serbian]

Dimitrijević, D., Grubić, A., Petrović, B., Aleksić, V., Babović, M., Divljan, S. and Kalenić, M. 1967. Metamorphic complexes if the Carpatho-Balkanic arch and adjacent areas. *Acta Geologica Academiae Scientiarurn Hungaricae*, **11** (1-3), 23–34.

Dörr, W., Zulauf, G., Gerdes, A., Lahaye, Y. and Kowalczyk, G. 2015. A hidden Tonian basement in the eastern Mediterranean: Age constraints from U-Pb data of magmatic and detrital zircons of the External Hellenides (Crete and Peloponnesus). *Precambrian Research*, **258**, 83–108.

Drăguşanu, C., Tanaka, T. and Iwamori, H. 1997. Metamorphosed Precambrian mafic rocks from the South Carpathians: island arc remnants? A geochemical caracterization of amphibolites fromthe Făgăraş Mountains, Romania. Schweiz. *Mineralogica Petrographica*, **77**, 419–437.

Đajić, S. 1996. Palinomorfe morskog paleozoika Kučajske zone istočne Srbije, 106 pp. Master Thesis. Faculty of Mining and Geology, University of Belgrade; Belgrade.

Đoković, I. 1985. Primena strukturne analize na rešavanje građe paleozojskih tvorevina Drinsko-Ivanjičke oblasti. *Geološki anali Balkanskoga poluostrva*, **49**, 11–160.

Ebner, F., Vozárová, A., Kovács, S., Kräutner, H.G., Krstić, B., Szederkényi, T., Jamićić, D., Balen, D., Belak, M. and Trajanova, M. 2010. Devonian–Carboniferous pre-flysch and flysch environments in the Circum Pannonian Region. In: Vozar, J., Ebner, F., Vozarova, A., Haas, J., Kovacs, S., Sudar, M., Bielik, M. and Pero, C. (Eds), Variscan and Alpine terranes of the Circum-Pannonian Region. *Geologica Carpathica*, **60** (1), 71–104.

Erak, D., Matenco, L., Toljić, M., Stojadinović, U., Andriessen, P.A.M., Wilingshofer, E. and Ducea, M.N. 2016. From nappe stacking to extensional detachments at the contact between the Carpathians and Dinarides – The Jastrebac Mountains of Central Serbia. *Tectonophysics*, **710**, 162–183.

Fügenschuh, B. and Schmid, S.M. 2005. Age and significance of core complex formation in a very curved orogen: evidencefrom fissiontrackstudiesintheSouth Carpathians (Romania). *Tectonophysics*, **404**, 33–53.

Franke, W. 2006. The Variscan orogen in central Europe: construction and collapse. In: Gee, D.G. and Stephenson, R.A. (Eds), European Lithosphere Dynamics. *Geological Society, London, Memoir*, **32**, 333–343.

Franke, W., Cocks, L.R.M. and Torsvik, T.H. 2017. The Palaeozoic Variscan oceans revisited. *Gondwana Research*, **48**, 257–284.

Franz, L., Okrusch, M., Seidel, E. and Kreuzer, H. 2005. Polymetamorphic evolution of pre-Alpidic basement relics in the external Hellenides, Greece. *Neues Jahrbuch für Mineralogie-Abhandlungen*, **181**, 147–172.

Franz, L. and Romer, R.L. 2007. Caledonian high-pressure metamorphism in the Strona-Ceneri Zone (Southern Alps of southern Switzerland and northern Italy). *Swiss Journal of Geosciences*, **100** (3), 457–467.

Friedl, G., Cooke, R.A., Finger, F., McNaughton, N.J. and Fletcher, I.R. 2011. Timing of Variscan HP-HT metamorphism in the Moldanubian Zone of the Bohemian Massif: U-Pb SHRIMP dating on multiply zoned zircons from a granulite from the Dunkelsteiner Wald Massif, Lower Austria. *Mineralogy Petrology*, **102**, 63–75.

Garfunkel, Z. 2015. The relations between Gondwana and the adjacent peripheral Cadomian domain – constrains on the origin, history, and paleogeography of the peripheral domain. *Gondwana Research*, **28**, 1257–1281.

Geološki zavod Skopje 1968. Geological map and Guide book for sheet Kratovo (K 34-69), Basic Geological Map of SFRY. Federal Geological Survey, SFRY; Belgrade. [In Macedonian with English abstract].

Gerdjikov, I., Ruffet, G., Lazarova, A., Angelov Vangelov, D., Balkanska, E. and Bonev, K. 2010b. ^{40}Ar/^{39}Ar geochronologic constraints of a Variscan transpression in Central Stara Planina Mountain. Proceedings “Geosciences 2010”, 109–110. Bulgarian Geological Society; Sofia.

Golonka. J., Porębski, S. J., Barmuta, J., Papiernik, B., Bębenek, S., Barmuta, M., Botor, D., Pietsch, K. and Słomka, T. 2019. Palaeozoic palaeogeography of the East European Craton (Poland) in the framework of global plate tectonics. *Annales Societatis Geologorum Poloniae*, **89** (4), 381–403.

Graf, J., von Quadt, A., Bernoulli, D. and Burg, J.-P. 1998. Geochemistry and geochronology of igneous rocks of the central Serbo-Macedonian Massif (Western Bulgaria). In: Carpathian-Balkan Geological Association, XVI Congress, Abstracts, 191. Geological Survey of Austria; Vienna.

Haydoutov, I., Pristavova, S. and Daieva, L. 2010. Some features of the Neoproterozoic–Cambrian geodynamics in South eastern Europe. *Comptes Rendus de l'Académie Bulgare des Sciences*, **63** (11), 1597–1608.

Himmerkus, F., Reischmann, T. and Kostopoulos, D.K. 2009. Serbo-Macedonian revisited: A Silurian basement terrane from northern Gondwana in the Internal Hellenides, Greece. *Tectonophysics*, **473**, 20–35.

Iancu, V., Berza, T., Seghedi, A. and Maruntiu, M. 2005. Palaeozoic rock assemblages incorporated in the south Carpathian Alpine thrust belt (Romania and Serbia): a review. *Geologica Belgica*, **8** (4), 48–68.

Iancu, V. and Seghedi, A. 2017. The South Carpathians: Tectono-Metamorphic Units related to Variscan and Pan-African inheritance. *Geo-Eco-Marina*, **2017**, 245–262.

Jastrzębski, M., Żelaźniewicz, A., Majka, J., Murtezi, M., Bazarnik, J. and Kapitonov, I. 2013. Constraints on the Devonian–Carboniferous closure of the Rheic Ocean from a multi-method geochronology study of the Staré Město Belt in the Sudetes (Poland and the Czech Republic). *Lithos*, **170-171**, 54–72.

Jovanović, D., Cvetković, V., Erić, S., Kostić, B., Peytcheva, I. and Šarić, K. 2019. Variscan granitoids of the East Serbian Carpatho-Balkanides: new insight inferred from U-Pb zircon ages and geochemical data. *Swiss Journal of Geosciences*, **112** (1), 121–142.

Kalenić, M. 2004. Geološki vodič kroz formacije Srpsko-makedonske mase, 18 pp. Geozavod-Gemini; Beograd.

Kalenić, M., Marković, V., Pantić, V. and Hadži-Vuković, M. 1975. Gornji proterozoik i stariji paleozoik u profilu – Resavski Visovi-Batočinska Straževica – selo Botunje. *Zapisnici SGD za 1974*, 3–39.

Karamata, S. 2006. The geodynamical framework of the Balkan Peninsula: its origin due to the approach, collision and compression of Gondwanian and Eurasian units. In: Robertson, A.H.F. and Mountrakis, D. (Eds), Tectonic Development of the Eastern Mediterranean Region. *Geological Society of London, Special Publication*, **260**, 155–178.

Kearey, P., Klepeis, K.A. and Vine, F.J. 2009. *G*lobal Tectonics, 496 pp. Wiley-Blackwell; Oxford-Chichester-Hoboken.

Koralay, O.E., Candan, O., Chen, F., Akal, C., Oberhänsli, R. Satır, M. and Dora, O.Ö. 2012. Pan-African magmatism in the Menderes Massif: geochronological data from leucocratic tourmaline orthogneisses in western Turkey. *International Journal of Earth Sciences (Geologishes Rundschau)*, **101**, 2055–2081.

Kounov, A., Burg, J.-P., Bernoulli, D., Seward, D., Ivanov, Z., Dimov, D. and Gerdjikov, I. 2011. Paleostress analysis of Cenozoic faulting in the Kraishte area, SW Bulgaria. *Journal of Structural Geology*, **33**, 859–874.

Kounov, A., Graf, J., von Quadt, A., Bernoulli, D., Burg, J.-P., Seward, D., Ivanov, Z. and Fanning, M. 2012. Evidence for a "Cadomian" ophiolite and magmatic-arc complex in SW Bulgaria. *Precambrian Research*, **212-213**, 275–295.

Keppie, J.D., Keppie, D.F. 2014. Ediacaran–Middle Paleozoic Oceanic Voyage of Avalonia from Baltica via Gondwana to Laurentia: Paleomagnetic, Faunal and Geological Constraints. *Geoscience Canada*, **41**, (1), 5–18.

Kräutner, H.G. and Krstić, B. 2002. Alpine and pre-Alpine structural units within the southern Carpathians and eastern Balkanides. *Proceedings of XVII Congress of Carpathian-Balkan Geological Association Bratislava, September 1–4. Geologica Carpathica*, **53**, Special Issue CD-R (without pagination).

Kräutner, H.G. and Krstić, B. 2003. Geological map of the Carpatho-Balkanides between Mehadia, Oravita, Niš and Sofia. CD-version provided at the XVIII Congress of the Carpathian-Balkan Geological Association, Belgrade 2006.

Kroner, U. and Romer, R.L. 2013. Two plates – Many subduction zones: The Variscan orogeny reconsidered. *Gondwana Research*, **24**, 298–329.

Krstekanić, N., Stojadinović, U., Kostić, B., Toljić, M. 2018. Internal structure of the Supragetic Unit basement in the Serbian Carpathians and its significance for the late Early Cretaceous nappe-stacking. *Geološki anali Balkanskoga poluostrva*,**78**, 1–15.

Krstić, B. and Karamata, S. 1992. Terani u Karpato-Balkanidima istočne Srbije (Terranes of the eastern Serbian Carpatho-Balkanides) Livre Jubilaire 1891–1991. *Zapisnici SGD za 1991*, 57–74.

Krstić, B., Karamata, S. and Milićević, V. 1996: The Carpatho-Balkanide terranes – a correlation. In: Knežević V. and Krstić B. (Eds), Terranes of Serbia, 71–76. Faculty of Mining Geology, University of Belgrade; Belgrade.

Krstić, B. and Maslarević, Lj. 1998. Ordovicijum Kučajskih planina (Istočna Srbija) (Ordovician rocks of Kučaj mountains, eastern Serbia). *Geološki anali Balkanskoga poluostrva*, **62**, 1–24.

Krstić, B., Maslarević, Lj. and Sudar, M. 2005. On the Graptolite Schists Formation (Silurian–Lower Devonian) in the Carpatho-Balkanides of eastern Serbia. *Geološki anali Balkanskoga poluostrva*, **66**, 1–8.

Krstić, B., Rakić, B., Veselinović, M., Dolić, D., Rakić, M., Anđelković, J. and Banković, V. 1974. Geological map and Guide book for sheet Kruševac (K 34-20), Basic Geological Map of SFRY. Federal Geological Survey, SFRY; Belgrade. [in Serbian with English abstract]

Kydonakis, K., Brun, J.-P., Sokoutis, D. and Gueydan, F. 2015. Kinematics of Cretaceous subduction and exhumation in the western Rhodope (Chalkidiki block). *Tectonophysics*, **665**, 218–235.

Levinson-Lessing, F.U. and Struve, E.A. 1963. Petrographic dictionary, 448 pp. Petrovym, R.P., Demynym A.M., Borsukom A.M., Ezhov, A.I. (Eds). Gosgeoltekhizdat; Moscow.

Linnemann, U., Gehmlich, M., Tichomirova, M., Buchmann, B. and Bombach, K. 1998. Tectonostratigraphic events of the peri-Gondwanan basement of the Saxo-Thuringian composite terrane (Central European Variscides). *Staatliches Museum für Mineralogie und Geologie Dresden*, **9**, 151–161.

Linnemann, U., Gerdes, A., Drost, K. and Buschmann, B. 2007. The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany. In: Linnemann, U., Nance, R.D., Kraft, P. and Zulauf, G. (Eds), The evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian–Variscan collision. G*eological Society of America Special Paper*, **423**, 61–96.

Linnemann, U., Gerdes, A., Hoffmann, M. and Marko, L. 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton – Constraints from U-Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). *Precambrian Research*, **244**, 236–278.

Marović, M., Toljić, M., Rundić, Lj. and Milivojević, J. 2007. Neoalpine tectonics of Serbia, 88 pp. Serbian Geological Society, Serbian Monographies, Belgrade.

Medaris, G., Ducea, M., Ghent, E. and Iancu, V. 2003. Conditions and timing of high-pressure Variscan metamorphism in the South Carpathians, Romania. *Lithos*, **70**, 141–161.

Meinhold, G., Arslan, A., Lehnert, O. and Stampfli, G.O. 2011. Global mass wasting during the Middle Ordovician: Meteoritic trigger or plate-tectonic environment? *Gondwana Research*, **19**, 535–541.

Meinhold, G., Kostopoulos, D., Frei, D., Himmerkus, F. and Reischmann, T. 2010. U-Pb LA-SF-ICP-MS zircon geochronology of the Serbo-Macedonian Massif, Greece: palaeotectonic constraints for Gondwana-derived terranes in the Eastern Mediterranean. *International Journal of Earth Sciences (Geologishes Rundschau)*, **99**, 813–832.

Meinhold, G., Kostopoulos, D., Reischmann, T., Frei, D. and BouDagher-Fadel, M.K. 2010. Geochemistry, provenance and stratigraphic age of metasedimentary rocks from the eastern Vardar suture zone, northern Greece. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **277**, 199–225.

Meinhold, G., Morton, A.C. and Avigad, D. 2013. New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U-Pb ages. *Gondwana Research*, **23**, 661–665.

Merdith, A.S., Collins, A.S., Williams, S.E., Pisarevsky, S., Foden, J.D., Archibald, D.B., Blades, M.L., Alessio, B.L., Armistead, S., Plavsa, D., Clark, C. and Müller, R.D. 2017. A full-plate global reconstruction of the Neoproterozoic. *Gondwana Research*, **50**, 84–134.

Milićević, V. 1996. Kučaj Terrane in Paleozoic time. In: Knežević, V. and Krstić, B. (Eds), Terranes of Serbia, 87–89. Faculty of Mining and Geology, Universty of Belgrade; Belgrade.

Milovanović, D., Marchig, V. and Dimitrijević, M.D. 1998. Petrology and chronology of Vučje gneiss, Serbo-Macedonian Massif, Yugoslavia. *Slovak Geological Magazine*, **4**, 29–33.

Murphy, J.B., Pisarevsky, S.A., Nance, R.D. and Keppie, J.D. 2001. Animated History of Avalonia in Neoproterozoic–Early Palaeozoic. In: Jessell, M.J. 2001. General Contributions: 2001. *Journal of the Virtual Explorer*, **3**, 45–58.

Murphy, J.B., Gutierrez-Alonso, G., Nance, R.D., Fernandez-Suarez, J., Keppie, J.D., Quesada, C., Strachan, R. and Dostal, J. 2006. Origin of the Rheic Ocean: Rifting along a Neoproterozoic suture? *Geology*, **34** (5): 325–328.

Murphy, J.B. and Nance, R.D. 2008. The Pangea conundrum. *Geology*, **36**, 703–706.

Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A. and Woodcock, N.H. 2010. Evolution of the Rheic Ocean. *Geoscience Frontiers*, **17**, 194–222.

Nance, R.D., Gutierrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A. and Woodcock, N.H. 2012. A brief history of the Rheic Ocean. *Geoscience Frontiers*, **3** (2), 125–135.

Nance, R. D. and Linnemann, U. 2008. The Rheic Ocean: Origin, evolution, and significance. *GSA Today*, **18** (12), 4–12.

Neubauer, F. 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. *Tectonophysics*, **352**, 87–103.

Oczlon, M.S., Seghedi, A. and Carrigan, C.W. 2007. Avalonian and Baltican terranes in the Moesian Platform (southern Europe, Romania, and Bulgaria) in the context of Caledonian terranes along the southwestern margin of the East European craton. In: Linnemann, U., Nance, R.D., Kraft, P. and Zulauf, G. (Eds), The evolution of the Rheic Ocean: From Avalonian-Cadomian active margin to Alleghenian-Variscan collision. *Geological Society of America Special Paper*, **423**, 375–400.

Pantić, N. and Dulić, I. 1991. Jungkarbonische Floren der Balkanhalbinsel und ihre palaeobiogeographische Bedeutung. *Proceedings of the Pan-European Palaeobotanical Conference, Vienna*, 371–375.

Pavlović, P. 1962. Über einige ordovizische inarticulaten brachiopoden im metamorphgesteinen bei Bosiljgrad (südöstliche Serbien), und über die bedeutung dieses fundes. *Geološki anali Balkanskoga poluostrva*, **39**, 99–112. [In Serbian with German abstract]

Pavlović, P. 1977. O "Gornjem (Vlasinskom) kompleksu" i podeli metamorfnih stena Srpsko-Makedonskog metamorfnog terena. *Zapisnici SGD za 1975. i 1976. godinu*, 123–132.

Petrović, B. and Karamata, S. 1972. Metaclastites – the basement of the upper complex of the crystalline shists of the Serbo-macedonian Mass. *Predavanja VII kongresa geologa SFRJ*, **2**, 301–316. [In Serbian]

Plissart, G., Diot, H., Monnier, C. and Mărunţiu, M. 2018. New insights into the building of the Variscan Belt in Eastern Europe (Romania, Serbia, Bulgaria). In: Ferrero, S., Lanari, P., Goncalves, P. and Grosch, E.G. (Eds), Metamorphic Geology: Microscale to Mountain Belts. *Geological Society, London, Special Publications*, **478**, 389–426.

Plissart, G., Monnier, C., Diot, H., Mărunţiu, M., Berger, J. and Triantafyllou, A. 2017. Petrology, geochemistry and Sm-Nd analyses on the Balkan-Carpathian Ophiolite (BCO − Romania, Serbia, Bulgaria): remnants of a Devonian back-arc basin in the easternmost part of the Variscan domain. *Journal of Geodynamics*, **105**, 27–50.

Rakić, M., Hadži-Vuković, M., Kalenić, M., Marković, V. and Milovanović, Lj. 1969. Geological map and Guide book for sheet Kruševac (K 34-19), Basic Geological Map of

SFRY. Federal Geological Survey, SFRY, Belgrade. [n Serbian with English abstract]

von Raumer, J.F. and Stampfli, G.M. 2008. The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. *Tectonophysics*, **461**, 9–20.

von Raumer, J.F., Stampfli, G.M., Borel, G. and Bussy, F. 2002. Organization of pre-Variscian basement areas at the north-Gondwanan margin. *International Journal of Earth Sciences (Geologishes Rundschau)*, **91**, 35–52.

von Raumer, J.F., Stampfli, G.M. and Bussy, F. 2003. Gondwana-derived microcontinents – the constituents of the Variscan and Alpine collisional orogens. *Tectonophysics*, **365**, 7–22.

von Raumer, J.F., Nesbor, H.-D. and Stampfli, G.M. 2017. The north-subducting Rheic Ocean during the Devonian: consequences for the Rhenohercynian ore sites. *International Journal of Earth Sciences (Geologishes Rundschau)*, **106**, 2279–2296.

Robertson, A.H.F., Trivić, B., Đerić, N. and Bucur, I.I. 2013. Tectonic development of the Vardar ocean and its margins: Evidence from the Republic of Macedonia and Greek Macedonia. *Tectonophysics*, **595-596**, 25–54.

Savezni Geološki Zavod (Federal Geological Survey) 1970. Geološka karta SFR Jugoslavije, 1:500000. Savezni Geološki Zavod; Beograd.

Scheiber, T., Berndt, J., Mezger, K. and Pfiffner, O.A. 2014. Precambrian to Paleozoic zircon record in the Siviez Mischabel basement (western Swiss Alps). *Swiss Journal of Geosciences*, **107**, 49–64.

Schmid S., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. and Ustaszewski, K. 2008. The AlpineCarpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, **101**, 139–183.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Georgiev, N., Kounov, A., Maţenco, L., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenović, B., Ustaszewski, K. and van Hinsbergen, D.J.J. 2020. Tectonic units of the Alpine collision zone between Eastern Alps and Western Turkey. *Gondwana Research*, **78**, 308–374.

Seghedi, A., Berza, T., Iancu, V., Mărunţiu, M. and Oaie, G. 2005. Neoproterozoic terranes in the Moesian basement and in the Alpine Danubian nappes of the South Carpathians. *Geologica Belgica*, **8** (4), 4–19.

Siegesmund, S., Oriolo, S., Heinrichs, T., Basei, M.A.S., Nolte, N., Hüttenrauch, F. and Schulz, B. 2018. Provenance of Austroalpine basement metasediments: tightening up Early Palaeozoic connections between peri-Gondwanan domains of central Europe and Northern Africa. *International Journal of Earth Sciences (Geologishes Rundschau)*, **107**, 2293–2315.

Spahić, D. and Gaudenyi, T. 2018. Primordial geodynamics of Southern Carpathian-Balkan Basements (Serbo-Macedonian Mass): Avalonian vs. Cadomian arc segments. *Proceedings of Geologists Association*, **130** (2), 142–156.

Spahić, D. and Gaudenyi, T. 2020. 60 years of the Serbo-Macedonian Unit concept: From Cadomian towards Alpine tectonic frameworks. *Geološki anali Balkanskoga poluostrva*, **81** (1), 41–66.

Spahić, D., Gaudenyi, T. and Glavaš-Trbić, B. 2019a. A hidden suture of the western Palaeotethys: regional geological constraints on the late Paleozoic "Veles Series" (Vardar Zone, North Macedonia). *Proceedings of Geologists' Association*, **130** (6), 701–718.

Spahić, D., Gaudenyi, T. and Glavaš-Trbić, B. 2019b. The Neoproterozoic–Paleozoic basement in the Alpidic Supragetic/ Kučaj units of eastern Serbia: a continuation of the Rheic Ocean? *Acta Geologica Polonica*, **69** (4), 531–548.

Spahić, D., Glavaš-Trbić, B., Đajić, S. and Gaudenyi, T. 2018. Neoproterozoic–Late Paleozoic evolution of the Drina Formation (Drina-Ivanjica Entity). *Geološki anali Balkanskoga poluostrva*, **79** (2), 57–68.

Stampfli, G.M. and Borel, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**, 17–33.

Šoster, A., Zavašnik, J., O'Sullivan, P., Herlec, U., Krajnc, B.P., Palinkaš, L., Zupancič, N. and Dolenec, M. 2020. Geochemistry of Bashibos-Bajrambos metasedimentary unit, Serbo-Macedonian massif, North Macedonia: Implications for age, provenance and tectonic setting. *Geochemistry*, doi: https://doi.org/10.1016/j.chemer.2020.125664

Stampfli, G.M., von Raumer, J.F. and Borel, G.D. 2002. Paleozoic R evolution of pre-Variscan terranes: from Gondwana to the Variscan Collision. *Geological Society of America Special Papers*, **364**, 263–280.

Stephan, T., Kroner, U. and Romer, R.L. 2018. The pre-orogenic detrital zircon record of the Peri-Gondwanan crust. *Geolological Magazine*, **156** (2), 281–307.

Stephan, T., Kroner, U., Romer, R.L. and Rösel, D. 2019. From a bipartite Gondwana shelf to an arcuate Variscan belt: The early Paleozoic evolution of northern Peri-Gondwana. *Earth-Science Reviews*, **192**, 491–512.

Torsvik, H.T. and Rehnström, E.F. 2003. The Tornquist Sea and Baltica-Avalonia docking. *Tectonophysics*, **362**, 67–82.

Unrug, R. 1997. Rodinia to Gondwana: The Geodynamic Map of Gondwana Supercontinent Assembly. *GSA Today*, **7** (1), 2–6.

Ustaömer, P.A., Ustaömer, T., Gerdes, A. and Zulauf, G. 2011. Detrital zircon ages from a Lower Ordovician quartzite of the Istanbul exotic terrane (NW Turkey): evidence for Amazonian affinity. *International Journal of Earth Sciences (Geologishes Rundschau)*, **100** (1), 23–41.

Ustaömer, P.A., Mundil, R. and Renne, P. 2005. U/Pb and Pb/ Pb zircon ages for arc-related intrusions of the Bolu Massif (W Pontides, NW Turkey): evidence for Late Precambrian (Cadomian) age. *Terra Nova*, **17**, 215–223.

Vavvasis, I., de Bono, A., Stampfli, G.M., Giorgis, D., Valloton, A. and Amelin, Y. 2000. U-Pb and Ar-Ar geochronological data from the Pelagonian basement in Evia (Greece): geodynamic implications for the evolution of Paleotethys. *Schweizerische mineralogische und petrographische Mitteilungen*, **80**, 21–43.

von Raumer, J.F., Stampfli, G.M. and Bussy, F. 2002. Organization of the pre-Variscan basement areas at the north Gondwanan margin. *Journal of Earth Sciences*, **91**, 35–52.

Vukanović, M., Karajičić, L., Dimitrijević, M.D., Možina, A., Gagić, N. and Jevremović, M. 1973. Pelagonian basement (Greece). Tumač za list Leskovac, Osnovna Geološka Karta 1:100000. Savezni Geološki Zavod; Belgrade.

Vukanović, M., Dimitrijević, M.D., Dimitrijević, M., Karajičić, L. and Rakić, M. 1977. Tumač za list Vranje, Osnovna Geološka Karta 1:100000. Savezni Geološki Zavod; Belgrade.

Winchester, J.A., Pharaoh, T.C. and Verniers, J. 2002. Palaeozoic amalgamation of Central Europe: an introduction and synthesis of new results from recent geological and geophysical investigations. *Geological Society London Special Publications*, **201** (1), 1–18.

Winchester, J.A., Pharaoh, T.C., Verniers, J., Ioane, D. and Seghedi, A. 2006. Palaeozoic accretion of Gondwana-derived terranes to the East European Craton: recognition of detached terrane fragments dispersed after collision with promontories. *Geological Society Memoirs*, **32**, 323–332.

Yanev, S., Lakova, I., Boncheva, I. and Sachanski, V. 2005. The Moesian and Balkan terranes in Bulgaria: Palaeozoic basin development, palaeogeography and tectonic evolution. *Geologica Belgica*, **8** (4), 185–192.

Zagorchev, I. 2015. Polyphase tectonometamorphism in Bulgaria: Some alternative interpretations and ideas. National Conferemce with International Particpation “Geosciences 2015” Abstracts, 99–100. Bulgarian Geological Society; Sofia

Zagorchev, I.S., Balica, C., Balintoni, I., Kozhoukharova, E., Săbău, G. and Negulescu, E. 2012. Palaeozoic evolution of the Ograzhden unit (Serbo-Macedonian Massif, Bulgaria and Macedonia). II Congress of Macedonian Geologists, 13–18. Macedonian Geological Society; Skoplje.

Zagorchev, I.S., Balica C., Bayanova, T.B., Kozhoukharova, E.S., Balintoni, I.C., Mitrofanov, F.P., Lyalina, B.V., Săbău, G. and Negulescu, E. 2014. Precambrian metabasic relicts in the Ograzhdenian supercomplex, Gorna Ribnitsa Village, Serbo-Macedonian massif, Southwest Bulgaria. Bul. Shk. Gjeol. 1/2014. *Special Issue Proceedings of XX CBGA Congress*, 24–26, Tirana.

Zagorchev, I. and Milovanović, D. 2006. Deformation and metamorphism in the eastern part of the Serbo-Macedonian Massif. *Proceedings ot the 18th Carpathian-Balkan Geological Association*, 670–672. Belgrade.

Žák, J. and Sláma, J. 2017. How far did the Cadomian ‘terranes’ travel from Gondwana during early Palaeozoic? A critical reappraisal based on detrital zircon geochronology. *International Geology Review*, **60** (3), 319–338.

Zlatkin, O., Avigad, D. and Gerdes, A. 2014. Peri-Amazonian provenance of the Proto-Pelagonian basement (Greece), from zircon U-Pb geochronology and Lu-Hf isotopic geochemistry. *Lithos*, **184-187**, 379–392.

Żelaźniewicz A., Buła Z., Fanning M., Seghedi A. and Żaba J. 2009. More evidence on Neoproterozoic terranes in Southern Poland and south eastern Romania. *Geological Quarterly*, **53** (1): 93–124.

Zulauf, G., Dörr, W., Fisher-Spurlock, S.C., Gerdes, A., Chatzaras, V. and Xypolias, P. 2014. Closure of the Paleotethys in the External Hellenides: Constraints from U-Pb ages of magmatic and detrital zircons (Crete). *Gondwana Research*, **28** (2), 642–667.

Zulauf, G., Romano, S.S., Dörr, W. and Fiala, J. 2007. Crete and the Minoan terranes: Age constraints from U-Pb dating of detrital zircons. In: Linnemann, U., Nance, R.D., Kraft, P. and Zulauf, G. (Eds), The evolution of the Rheic Ocean: From Avalonian–Cadomian active margin to Alleghenian–Variscan Collision. *Geological Society of America Special Paper*, **423**, 401–411.

Zulauf, G., Dörr, W., Marko, L. and Krahl, J. 2018. The late Eo-Cimmerian evolution of the external Hellenides: constraints from microfabrics and U-Pb detrital zircon ages of Upper Triassic (meta)sediments (Crete, Greece). *International Journal of Earth Sciences (Geologishes Rundschau)*, **107** (8), 2859–2894.

Zurbriggen, R. 2015. Ordovician orogeny in the Alps: a reappraisal. *International Journal of Earth Sciences (Geologische Rundschau)*, **104**, (2), 335–350.

Zurbriggen, R. 2017a. The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region. *International Journal of Earth Sciences (Geologishes Rundschau)*, **106** (2), 517–529

Zurbriggen, R. 2017b. Early Paleozoic orthogneisses in the Alps: products of a peri-Gondwanan peraluminous arc system. Abstract Volume 15th Swiss Geoscience Meeting. Davos, 17th–18th November 2017, 19–20. Swiss Geological Society; Bern

Zurbriggen, R., Kamber, B.S., Handy, M.R. and Nägler, T.F. 2004. Dating synmagmatic folds: a case study of Schlingen structures in the Strona-Ceneri Zone (Southern Alps, northern Italy). *Journal of Metamorphic Geology*, **16**, 403–414.

Manuscript submitted: 9th April 2020
Revised version accepted: 13th November 2020