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REVIEW PAPER

The Neoproterozoic–Paleozoic basement in the Alpidic Supragetic/Kučaj units of eastern Serbia: a continuation of the Rheic Ocean?

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ABSTRACT:

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This paper attempts to allocate a segment of the Paleozoic Ocean situated in what is now Southeastern Europe (SEE) into a regional geological and paleotectonic synthesis connecting the sedimentary, metamorphic and igneous records associated with the ocean's cycle. The Supragetic basement (external section of the Carpatho-Balkan arch) represents a tectonically reworked basement vestige of the Neoproterozoic–Lower Paleozoic oceanic floor system recrystallized under regional low temperature greenschist-facies conditions. The regional geological constraints associated with this low-grade basement are integrated with information from the overlying Silurian, Devonian and Lower Carboniferous cap-rocks of the "Kučaj Unit" to demonstrate the presence of a major Paleozoic ocean crossing this segment of SEE. In connection with the Lower Paleozoic north Gondwanan Pan-African processes, the low-grade Supragetic basement (including its Devonian cover) is in a complex relationship with the occasionally anchimetamorphic Silurian, Devonian, and Lower Carboniferous deep-water record of the polymetamorphic "Kučaj Unit". The Upper Devonian–Lower Carboniferous flysch and molasse of the "Kučaj Unit" are interposed with the Neoproterozic–Lower Paleozoic oceanic vestige or with the Supragetic basement with the corresponding Devonian Balkan-Carpathian back-arc ophiolite-bearing lithosphere and its carrier (Danubian Unit). This regional-scale synthesis demonstrates that a segment of the Rheic Ocean referred to as the Saxo-Thuringian seaway and its suture lay to the east, underneath the Permian red-bed overstepping sequence and to the west of the Danubian aggregation. Unlike many of the high-pressure rocks characterizing the segment of the Rheic suture in the Central European Variscides, the SEE zone described here has only a mild overprint.

Key words: Supragetic/"Kučaj Unit"; Carpatho-Balkanides; Rheic Ocean/seaways; Rheic suture.

INTRODUCTION

Recently, researchers have shown an increased interest in the better understanding of the inherited structures inferred to be present in the earliest, relatively unstable crustal mobile belts (Will and Frimmel 2018). After tectonic reactivation, crystalline remnants may host *in situ* or displaced fragments of major Paleozoic convergence centers. Thus, these are often classified as autochthonous or exotic basement aggregations, respectively. However, the presence of such components of a comparable deep crustal suture system and its Paleozoic paleogeography have just recently been investigated in this segment of Southeastern Europe (SEE; *e.g.*, Iancu and Seghedi 2017; Plissart *et al*. 2018).

The Alpine orogenic episode squeezed similar crystalline basement vestiges or ribbons of dismembered early Paleozoic Avalonian–Cadomian continents (Balintoni *et al*. 2011; Garfunkel 2015; Seghedi 2012; *sensu* Spahić and Gaudenyi 2018 and references therein; Stephan *et al*. 2018) along the length of the Carpathian-Balkan-Hellenic belt of SEE. Traditionally, this region has drawn much attention resulting in the fairly well-established paleogeography and tectonic history of the aggregated Alpidic Mesozoic systems (*e.g.*, Sandulescu 1984; Dimitrijević 1999; Kräutner and Krstić 2006). However, the presence of poorly dated ancient Pan-African Neoproterozoic to Devonian ophiolite- and flysch-bearing, magmatic- and continental-arc basement systems implies the interaction of formerly distant continental margins brought together by the early Paleozoic marine plate-tectonic conveyers.

The active widening of early Phanerozoic oceans had a dominant control on the S hemisphere throughout the Paleozoic epoch (*sensu* Cocks and Torsvik 2006; Gawęda and Golonka 2015; Linnemann *et al*. 2007; Nance *et al*. 2010, 2012; Winchester *et al*. 2002a, b, 2006). A number of the medium-size Avalonian–Cadomian arc segments drifted off north Gondwana and collided with the early Paleozoic Ocean and the northern-positioned Laurasia (*e.g.*, Balintoni *et al*. 2011; *sensu* Franke *et al*. 2017). The vestiges of these poorly constrained Paleozoic oceanic realms and seaways (*sensu* Moghdam *et al*. 2018) have been recognized in a 10,000 km-long segment of the Rheic suture (Nance and Murphy 2008) connecting Mexico to the Central European Variscides; Bohemian Massif, Saxo-Thuringia, Armorica, Carnic Alps, (*e.g.*, Boncheva *et al*. 2010 and references therein; Jastrzębski *et al*. 2013; Keppie *et al*. 2010). This suture very likely continued further, crossing the SEE segment of the Alpine orogen, East Mediterranean and Turkey (Nance *et al*. 2010, 2012; Text-fig. 1a).

The study presented here of the tentative Rheic Ocean, in addition to using the up-to-date summary of the paleocontinental inheritance of the regional basement units of Spahić and Gaudenyi (2018), compares the geological record of the two polycrystalline low- to very low pressure-temperature vestiges of the Paleozoic marine segment outboard the Avalonian–Cadomian margin with the paleogeographic models presented hitherto. This geological synthesis shows that the low-grade oceanic-floor assembly (Supragetic basement) and the peculiar, considerably conserved (meta)sedimentary flysch-bearing Paleozoic aggregation (segment of the "Kučaj Unit") signify the two principal vestiges of the Rheic Ocean and its seaways (*sensu* Franke *et al*. 2017). These are remarkably well-preserved in this part of SEE. The study connects the pre-Variscan paleogeographic interplay between formerly distant oceanic segments with the active widening of this segment of the Rheic Ocean and its seaways including the drift northwards, up to the late Variscan accretion with the former SW Laurentian, *i.e.* Moesian promontory (Upper and Lower Danubian).

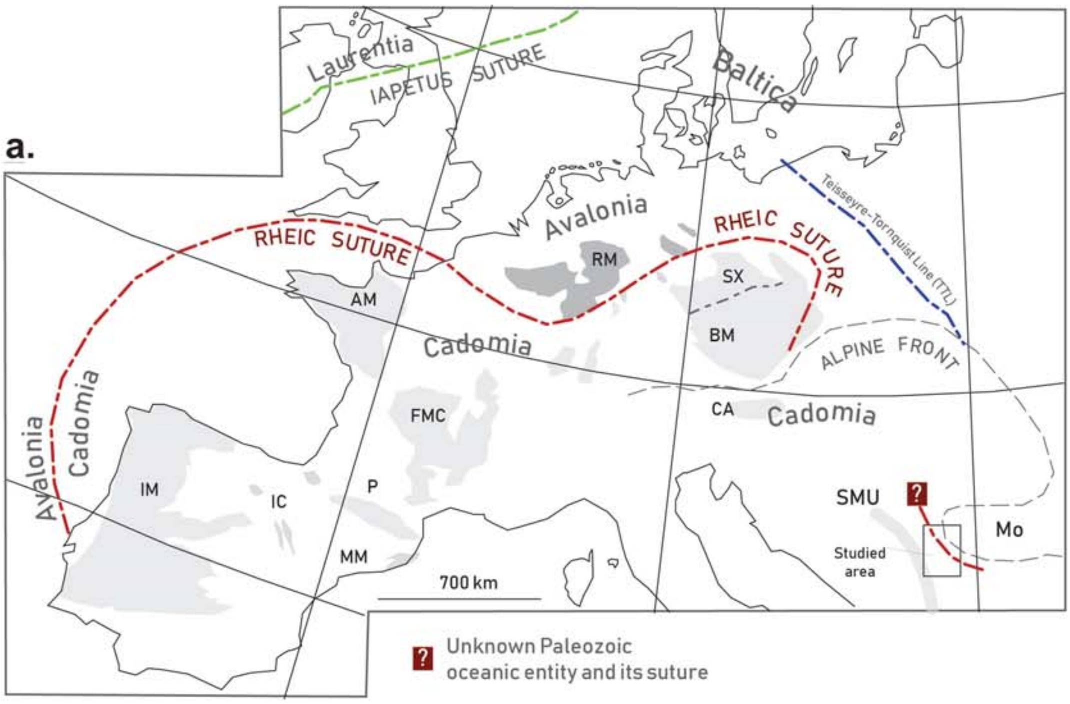
REGIONAL-TECTONIC FRAMEWORK (EXTERNAL SOUTH CARPATHIANS AND BALKAN)

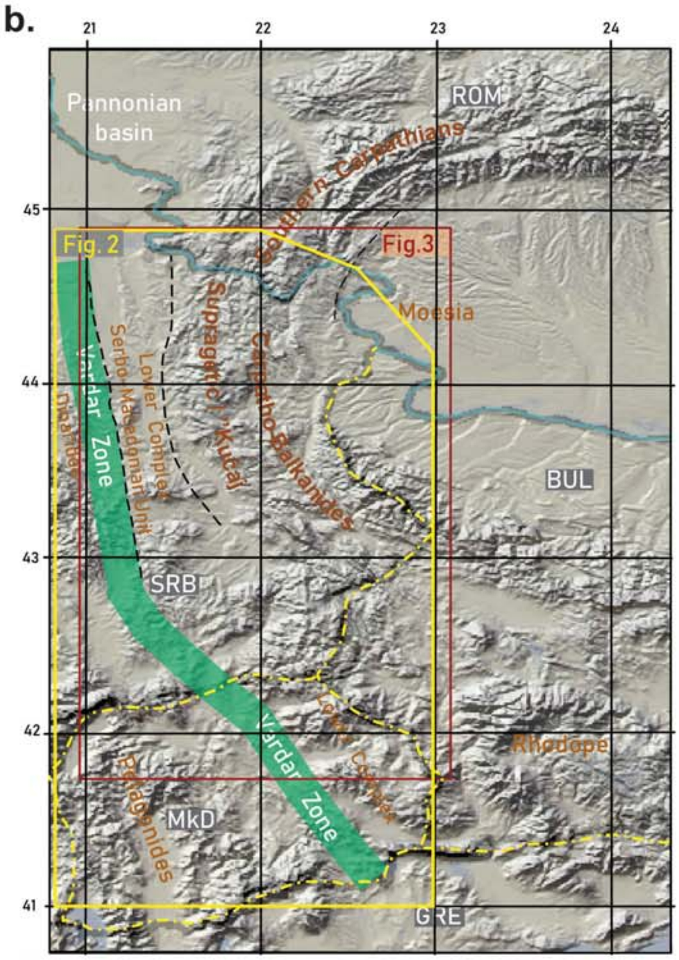
The Carpathian-Balkan arch consists of the medium-high mountains (1500–2500 m above sea level) abutting the Intra-Carpathian (*e.g.*, Csontos and Vörös 2004) or Pannonian Basin System (Text-fig. 1b). Geographically, the N South Carpathian arch stretches into Romania, continuing S into the prominent Carpatho-Balkan arch in Serbia (*e.g.*, Maksimović 1976b; Anđelković 1982, 1984; Text-figs 1b, 2) and the NW Morava-Rhodope zone in Bulgaria (*e.g.*, Boncheva *et al*. 2010).

The structural-tectonic events which elevated the Alpine-Carpathian-Balkan orogen have been the focal topic in SEE for over 40 years now (*e.g.*, Anđelković 1982; Săndulescu 1984, 1994; Dimitrescu 1985; Dallmeyer *et al.* 1996; Matenco and Schmid 1999; Kräutner and Krstić 2002, 2006; Iancu *et al*. 2005b; Moser *et al*. 2005; Schmid *et al*. 2008). The current Alpidic subdivision of the Carpathian-Balkan belt is based on the complex nappe imbrication of the mixed Mesozoic and pre-Mesozoic systems (Săndulescu 1994; Kräutner and Krstić 2002, 2003; Schmid *et al*. 2008; Vozár 2010).

Supragetic basement in the Alpidic context

In the Southern Carpathians and Balkans, the late Alpine evolution involved thrusting and exhumation in the course of two compressional episodes: (i) Upper Jurassic and (ii) latest Cretaceous involving the closure of the Severin-Cehlau oceanic basin (Iancu *et al*. 2005b). The Alpine polyphase compression inverted





Text-fig. 1. A. Cadomian and Variscan Massifs in SE and central Europe, model with a single Variscan suture of Rheic Ocean (modified after Linnemann *et al*. 2008 and references therein; Balintoni and Balica, 2016; Spahić and Gaudenyi, 2018). IM – Iberian Massif, IC – Iberian chains, RM – Rhenish Massif, AM – Armorican Massif, BM – Bohemian Massif, SX – Saxo-Thuringian Zone, MM – Maures Massif, P – Pyrénées, CA – Carnic Alps, Mo – Moesia (Avalonian, Peri-Amazonian inheritance), SMU – Serbo-Macedonian Unit, Lower Complex (Cadomian inheritance). B. Relief map showing the position of the Supragetic and "Kučaj Unit" within the Southern Carpathians (Romania) and its southern continuation – the Carpatho-Balkanides (Serbia). To the west is the Lower Complex Serbo-Macedonian Unit (basement unit), the intervening Mesozoic Vardar Zone (late Alpidic ophiolite-bearing accretionary assemblage) separating the latter from the Adria/Apulia microplate (Dinarides). The Pelaginic Unit is to the south of the Vardar Zone the preexisting basement configuration, which in its finite version override the Moesian system: the lowermost nappe is the Lower Danubian Unit, followed by the Upper Danubian, Severin, Getic, up to the uppermost Supragetic Unit (Kraütner and Krstić 2002, 2006).

The Supragetic basement unit has several names in use today. The term Getic/Supragetic Unit is coined in Romania (Săndulescu 1984); in Serbia the (tentative) equivalents are the "Upper Complex of the Serbo-Macedonian Unit" coined by Dimitrijević (1963, 1997) or the "Vlasina Complex" coined by Petrović (1969) or the newest set of the Carpatho-Balkan basement terranes in E Serbia (Kräutner and Krstić 2002, 2003, 2006). In Bulgaria, this greenschist unit is often referred to as the "Morava Nappe" (*e.g.*, Kounov *et al.* 2012), a segment of the larger "Balkan Terrane". According to our preliminary assessment of the configuration, the "Balkan Terrane" crosses over into eastern Serbia (Yanev *et al.* 2005) and is made up of the "Ranovac-Vlasina", "Kučaj" and "Lužnica" units.

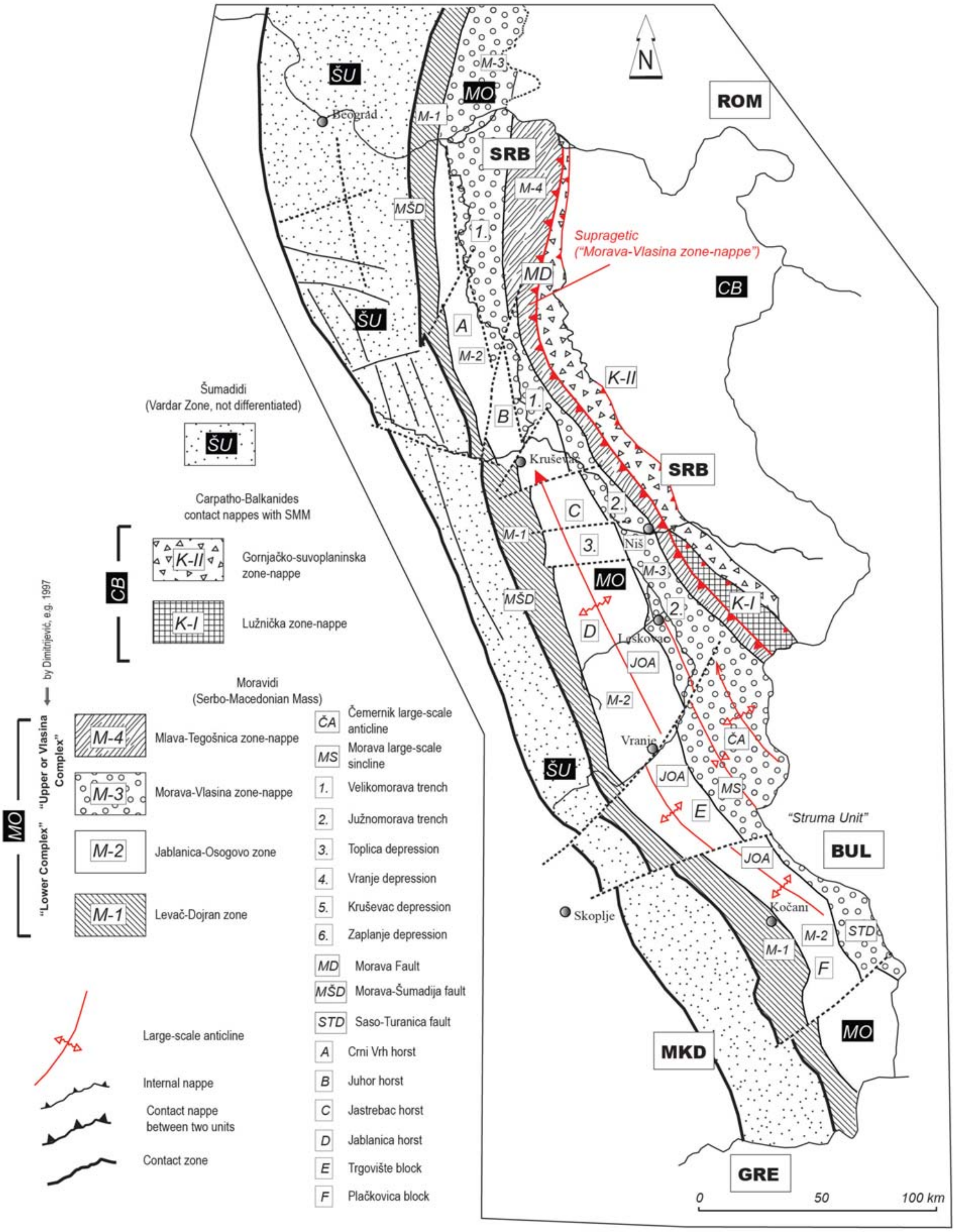
Pioneering authors exhibited profound understanding of the processes associated with the dominant Alpine tectonics of the Romanian Carpathians and Central Balkan Peninsula (Săndulescu 1984; Anđelković 1984; Dimitrescu 1985; Haydoutov 1989). Dimitrescu (1985) indicated that the Serbo-Macedonian Unit could either be a part of the Supragetic or belong to a more internal nappe system, and probably should be referred to the Internal Dacides (*sensu* Săndulescu 1984). Anđelković (1984) outlined the main tectonic phases and geotectonic units of the former Yugoslavia, connecting the eastern part of the country with the unit's extensions from Romania, Bulgaria, and stretching to the south, towards the East Mediterranean. The author subdivided the original Serbo-Macedonian Unit, separating the Moravides into four-nappe systems (Text-fig. 2). Approximately the "Mlava-Tegošnica zone-nappe" and a section of the "Morava-Vlasina nappe" in Serbia represent the continuation from the Romanian Supragetic Unit (Text-fig. 2).

In Serbia, within the most recent studies of the Carpatho-Balkanides, the Supragetic basement is subdivided into the "Lower" and "Upper Supragetic" referred to as the "Lužnica Terrane" and the Ranovac-Vlasina Terrane", respectively (Kräutner and Krstić 2002, 2003; Text-fig. 3). The contact between the two aforementioned entities is in the form of thrust faults (Kräutner and Krstić 2002; Krstić *et al.* 2005). The "Upper Supragetic" unit was additionally designated as the "Bocşa-Bukovik-Vlasina nappe", whereas the low-grade "Lower Supragetic" was referred to as the "Locva-Moniom-Ranovac-Poružnica nappe". Counterintuitively, the "Upper Supragetic" seems to be the older nappe, consisting of a mixture of gneiss, albite-porphyroblast schists, and Mesozoic sediments. The "Lower Supragetic" is comprised of Ordovician–Lower Carboniferous low-grade metamorphic rocks, structurally overlying the "Lužnica Unit" (or West Kraishte; Krstić *et al.* 2005). Recently, there has been a classification of the Supragetic basement dividing it into "pre-Ordovician" and the "post-Cambrian" (Antić *et al.* 2015). The latter has several similarities with the "Kučaj Terrane".

In Romania, the Middle Cretaceous shear zones separating the Supragetic and Getic units (Iancu *et al.* 1995b and references therein) are exposed in the W and central part of the South Carpathians. In contrast, in Romania, a Carboniferous to Permian shear zone (apatite fission track plato of ca. 351 Ma) is located in the vicinity of the contact between the Supragetic basement and the Lower Complex of the Serbo-Macedonian Unit (Antić *et al.* 2017). The W boundary stretches across central Serbia, *e.g.* in the vicinity of the Jastrebac tectonic window (Text-fig. 3). Here, the Supragetic greenschist rocks are in a tectonic relationship (Miocene shear zone) with the adjoining gneiss-dominated Lower Complex of the Serbo-Macedonian Unit (Erak *et al.* 2016).

Supragetic basement in the pre-Alpine context

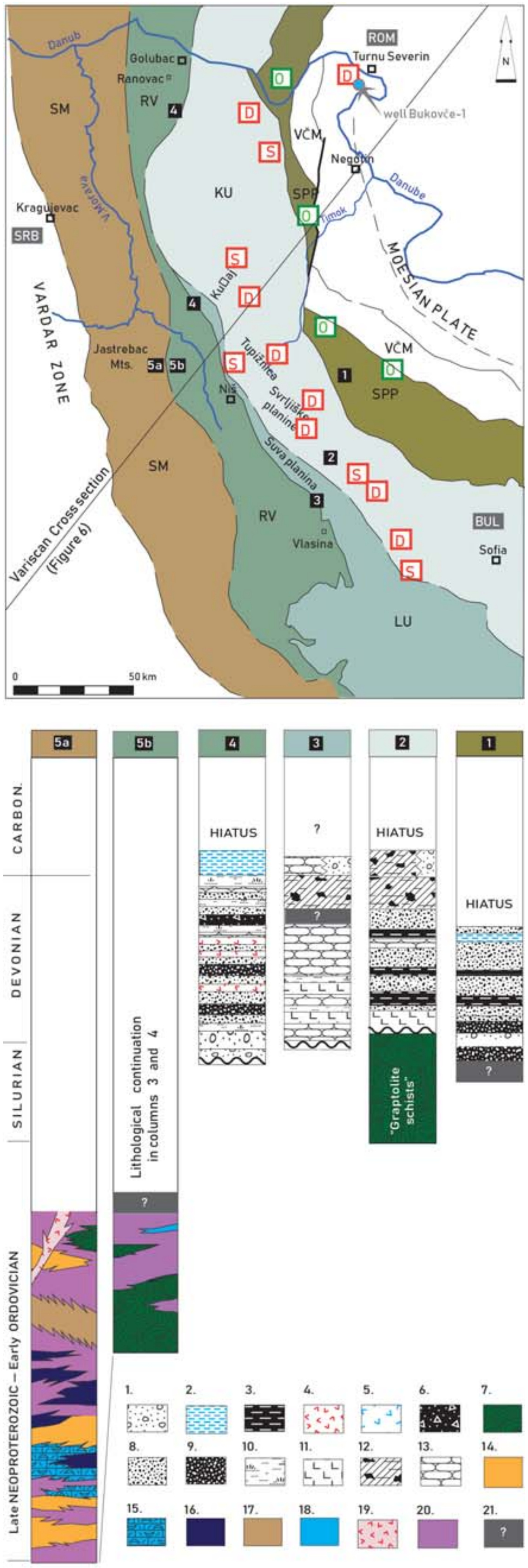
The Neoproterozoic–early Paleozoic rocks are collectively referred to as the Cadomian basement (Nance *et al.* 2007). In Romania, the basement units of the Getic/Supragetic containing eclogites and including Neoproterozoic igneous protoliths are referring to as the Sebeş-Lotru Terrane (Cumpăna and Lotru units, Balintoni *et al.* 2009). The basement fragments having neither eclogites nor Neoproterozoic igneous protoliths have been referred to as the Făgăraş, Leaota, Padeş and Caraş terranes (*sensu* Balintoni *et al.* 2010). The oceanic vestige named the Tişoviţa Terrane represents a segment of the Variscan suture in Romania (Balintoni *et al.* 2011) including its carrier, the Upper Danubian Unit (Plissart *et al.* 2018). Locally, a north-south trending belt of composite Variscan plutons (Balintoni *et al.* 2011; Jovanović *et al.* 2019 and references therein) marks the basement units of the South Carpathians as they cross over into the investigated part of E Serbia. However, there is no record of Variscan granitoid emplacement into the Supragetic basement (Jovanović *et al.* 2019). In contrast to the Romanian Getic medium-grade recrystallized basement segment, its southern "extension" in



Text-fig. 2. Obsolete tectonic map of the Alpidic Moravides (Lower- and "Upper Complex" Serbo-Macedonian Unit). The system is composed of four imbricated nappe slivers, including the extension of the Supragetic nappe in Serbia. The contact with the adjoining eastern unit or the Carpatho-Balkanides is always tectonic (modified after Anđelković 1982)

Serbia, the "Kučaj Terrane" (Text-fig. 3) is, however, partially composed of sedimentary to anchimetamorphic, well-preserved fossiliferous Paleozoic deposits positioned to the E of the Supragetic basement suite (*sensu* Kräutner and Krstić 2002; Krstić *et al*. 2005).

More to the west, the Supragetic basement/"Vlasina complex"/"Upper Complex of the Serbo-Macedonian Unit"/ is positioned to the E of the Lower Complex of the Serbo-Macedonian Unit or Ograzhen Unit in Bulgaria (Zagorchev 2001; Zagorchev *et al*. 2012). This is a north Gondwanan crustal relic of the Cadomian *i.e.* Neoproterozoic, Cambro-Ordovician (Antić *et al*. 2016; Balogh *et al*. 1994; Deleon *et al*. 1972; Zagorchev *et al*. 2015) to Silurian age (Himmerkus *et al*. 2006, 2007, 2009; Meinhold *et al*. 2010). Early authors argued that both systems are actually a single Neoproterozoic–Early Paleozoic complex (Pavlović 1977). Moreover, the juvenile contact (if any) is a matter of ongoing debate (*sensu* Antić *et al*. 2017; *sensu* Petrović and Karamata 1972). To make matters more complex, there is another tectonic suture positioned in the vicinity of the contact between the Supragetic basement and Serbo-Macedonian Unit (Iancu and Seghedi 2017). Popović (1995), however, highlighted a set of differences (age, the presence of mineralization that was not perceived within the Lower Complex of the Serbo-Macedonian Unit) arguing that the "Vlasina Complex"/Supragetic Unit/"Upper Complex" of the Serbo-Macedonian Unit signifies a discrete tectonic entity. As mentioned earlier, the highly complex Neoproterozoic–Paleozoic evolution of the entire set of the Carpathian-Balkan basement units including a review of their Avalonian–



Text-fig. 3. Basement terranes of eastern Serbia by Kräutner and Krstić (2002, 2006), inlet from Krstić *et al*. (2005). East Serbian terranes: VČM – Vrška Čuka-Miroč Unit (Lower Danubian), SPP – Stara Planina Poreč Unit (Upper Danubian), KU – Kučaj Unit (Getic); LU – Lužnica Unit (West Kraishte); RV – Ranovac-Vlasina Unit (Supragetic); SM – Serbian Macedonian Unit. Rectangles "S" and "D" mark the main outcrops of Silurian (Krstić *et al*. 2005) and Devonian (Veselinović, 1975). Rectangle containing "O" marks the position of the Balkan-Carpathian ophiolites of the Devonian age (Plissart *et al*. 2017). Below, set of lithostratographic columns: "Stara-Planina Poreč" (#1), "Ranovac Vlasina" (#2), "Lužnica" (#3) and "Kučaj" (#4) terranes (modified from Krstić *et al*. 2003). Columns modified and correlated, the columns #5b and #5a modified from Erak *et al*. (2016). Numbers in the legend: 1. Olistostrome, 2. Pelite, 3. Siltstone, 4. Acidic volcanic rocks, 5. Basic volcanic rocks, 6. Tuffaceous rocks, 7. Schists (greenschists), 8. Sandstone, 9. Conglomerates, 10. Shale, 11. Lydite, 12. Flysch, 13. Limestone, 14. Gneiss, 15. Marbles, 16. Amphibolites, 17. Migmatites, 18. Greenschist rocks, 19.Quarzites, 20. Younger magmatic rocks. Position of the well Bukovče-1 indicates the presence of the Devonian within the Moesian plate or the upper plate during the late Variscan collision (see further text for explanation)

Cadomian inheritance has been summarized recently (Spahić and Gaudenyi 2018).

The Supragetic basement in Serbia represents a highly heterogeneous system of greenschist-facies rocks, phyllites, quartzites (Text-fig. 3) controversially of Precambrian *i.e.* Ediacarian age (Maksimović 1976b). Microscale studies have confirmed the presence of a foliation produced by the growth of chlorite, sericite and muscovite recognized also at outcrop scale (Krstekanić *et al*. 2017). However, these authors ambiguously attribute this fabric to late Alpine upthrusting episodes. According to the crystallization parameters, in SE Serbia, the greenschist complex differentiates into "greenschists" and "progressively metamorphosed greenschists" with or without any mica content (Petrović 1965 in Aleksić 1977). The latter occasionally contains a variation of the greenschist facies with relics of recrystallized oceanic crust: actinolite-epidote schists, metagabbro, and serpentinites. In the NE and central part of Serbia, the Supragetic basement is composed of greenschist system rocks which are constituted of chlorite, epidote, actinolite, sericite schists. Here, the Supragetic basement is transgressively superseded by a Devonian volcano-sedimentary system (Kalenić *et al*. 1973; Text-fig. 3) which is again transgressively overlain by Lower Carboniferous conglomerates, sandstones and rhythmically alternating claystone and mudstone (Krstić 1975).

Relict amphibolite and transitional amphibolite-greenschist facies assemblages have been reported in the Vrvi Kobila area (SE Serbia; Petrović 1969), in the vicinity of the Božica magmatic complex (Babović *et al*. 1977; Krstić and Karamata 1992), N of the Surdulica pluton (Pavlović 1977) and E of Vranje (Babović *et al*. 1977; Vasković 1998; Vasković *et al*. 2003). In the literature, this controversial higher-grade metamorphism of the Supragetic Unit is connected with the "Baikalian" (850–650 Ma), or "Caledonian" orogenic events (Karamata and Krstić 1996). The age of the greenschist retrograde overprint has been tentatively placed in the early Carboniferous (Dimitrijević 1963; Petrović 1969; Krstić and Karamata 1992; Karamata and Krstić 1996; Graf 2001).

RESULTS: SYNTHESIS OF THE REGIONAL MAGMATO-SEDIMENTARY RECORD (SUPRAGETIC AND PALEOZOIC "KUČAJ" ANCHIMETAMORPHIC CAP-ROCKS)

In the Balkanides, the pre-Alpine Getic/Supragetic basement (the exact continuation of which is still ambiguous, *sensu* Spahić and Gaudenyi 2018; also see Jovanović *et al*. 2019) has a southern continuation in the form of an ophiolite-bearing basement system (the Struma-Frolosh volcanic arc system) composed of Neoproterozoic–Lower Paleozoic gneiss-dominated, greenschist rocks (Kounov *et al*. 2012). This juvenile ophiolite-bearing system predates the Devonian back-arc ophiolites of Tişoviţa -Iuti (Romania), and of Deli Jovan, Zaglavak and Crni Vrh situated to the N of the former within the Upper Danubian basement (*sensu* Balica *et al*. 2014; Plissart *et al*. 2017; Text-fig. 3).

End-Proterozoic calc-alkaline magmatism affecting the accreted Carpathian-Balkan basement blocks demonstrates their former location along the active margin of north Gondwana which is often referred to as the late Cadomian magmatic arc (562–522 Ma, Antić *et al*. 2016). Accordingly, their age suggests that the Supragetic basement was by that particular time already shifted away from the north Gondwanan shoreline. Early authors suggested that the age of the greenschist metamorphism predated the emplacement of the Vlajna granitoid (pre-450 Ma, in Petrović and Karamata 1972). More recently, the age of the Vlajna granitoid has been measured at ca. 558 Ma (Antić *et al*. 2016) placing the greenschist or medium-grade amphibolite-facies overprint into the Ediacaran. Krstekanić *et al*. (2017) indicated low greenschist conditions with temperatures reaching 300–350°C and the pressure reaching 0.3–0.5 GPa. Antić *et al*. (2017 and references therein), however, indicate peak metamorphic conditions of 450–500°C at 3–5 kbar (0.3–0.5 GPa). By accepting a pioneering greenschist-facies conditions/event (as suggested by the latter), we emphasize the issue of the disputable Variscan greenschist imprint as discussed earlier.

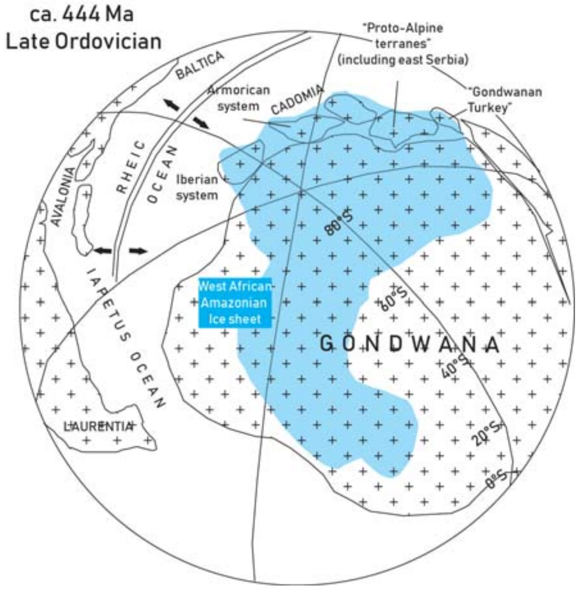
Ediacarian / Cambrian–Ordovician

The Paleozoic succession of the Central Balkan is situated above a Neoproterozoic ophiolite-bearing basement originating from an obducted intra-oceanic island arc system (*sensu* Haydoutov and Yanev 1997) and Cambrian calc-alkaline volcanic rocks. This intra-oceanic arc is the earliest ophiolite-bearing succession accommodated within the central segment of the S Carpatho-Balkan arch (W Bulgaria and E Serbia, Stara Planina ophiolite, Haydoutov *et al*. 2010). Typical N-MORB or "Normal MORB" features are characteristic of this ophiolite indicating a global paleo-ridge system distant from hot spots (*sensu* Gale *et al*. 2013). The ophiolite-bearing section has the following features: a layered cumulates unit (lowermost section), a metagabbro section and sheeted dykes, including pillow lava (Haydoutov *et al*. 2010). The scarce black shale and violet argillite have provided a late Neoproterozoic age – 563 ± 5 Ma (Haydoutov *et al*. 2010).

In Serbia, Maksimović (1976b) reported an Ediacarian age due to the Cambrian age of the overlying 400 m series of beds with *Ajacicyathus*. This is a Cambrian sequence which shows a vertical succession of Supragetic greenschists, amphibolite schists, and marbles (Vlasina area, Bukovik, Rožanj). In the "Kučaj Unit", *acritarchs* demonstrate the Upper Cambrian–Lower Ordovician age of the conglomerates which transgressively overly the greenschist rocks (Krstić and Maslarević 1990). Another name for the Supragetic is the "*Ramovac unit*" (almost certainly Ramovš (1989) named the "Ranovac Unit" after the settlement Ranovac in E Serbia). The "Ranovac Unit" is suggested to be of Neoproterozoic to Cambrian age, characterized by arkosic sediments, greywackes, porphyritic rocks accompanied by tuffs and keratophyres of Ordovician to Lower Carboniferous age. There is a documented record of isoclinal folds observed on the scale of the outcrop (Dimitrijević 1997).

The conglomeratic, quarzitic and metabasic and filitic volcano-sedimentary rocks of the "Turija series" (exposed in the vicinity of the settlement of Ranovac, Serbia) contain *Zonosphaeridium and Protoleiosphaeridium,* a set of Middle Cambrian spores (Anđelković 1975a). The continuation to a Lower Ordovician age of the Supragetic basement/Upper Complex of the Serbo-Macedonian Unit/"Vlasina Complex" is corroborated by the remarkable discovery of a lumachelle of inarticulate Brachiopods within presumed barren sericite schists (near Donja Lisina settlement in Serbia; Pavlović 1962). The inarticulate *Obolus* and *Lingullela* brachiopods discovered therein have common features with those discovered in the Tremadocian of Central Europe – "Armorican sandstone" (Pavlović 1975). *Cyclopyge prisca* discovered in shales overlain by Ashgill (Late Ordovician) diamictites documents a typical cold fauna for the peri-Gondwanan environment (Haydoutov and Yanev 1997; Hoffmann and Linnemann 2013; Text-fig. 4). During this time, Haydoutov *et al*. (2010), introduce the "Ordovician orogenic event".

The lowermost quarzitic conglomerates represent the Upper Ordovician system of the "Kučaj Zone". This sequence has grading towards quartz arenites, siltstones (Krstić and Maslarević 1990 and references therein). Another type of sedimentary Upper Ordovician strata is marked by the discovery of *Dalmanitina cf. proaeva* (Krstić 1960) which delineates the Caradocian level. This succession of deep basinal metapelites adjoins the shallow Ordovician siliciclastics (Krstić and Maslarević 1990). Deepwater metaarenites and metagreywackes mark the Ordovician–Silurian boundary.



Text-fig. 4. Ordovician glaciation also referred to as the "Sahara glaciation" (inlet from Hoffmann and Linnemann, 2013). The sketch marks the position of the "Proto-Alpine terranes" (including some of terranes accommodated modern-day Serbia) and "Gondwanan Turkey" relative to the widening Rheic Ocean

Silurian

Towards the far-SE parts of Serbia (Kučaj Mt. towards the Bulgarian border; Text-fig. 3), the low-grade greenschist system investigated marks a changeover towards fossiliferous Silurian schists and a slightly silicified sedimentary succession (Anđelković 1982; Krstić 1975b). Graptolite schists of Silurian age are documented in the "Kučaj Zone" and the "Lužnica Zone" (Krstić *et al*. 2005). This unit was previously described as the "Gornjačka Zone" (Maksimović 1976b). With respect to the Romanian Alpidic subdivision, the "Kučaj Zone" should be an analog of the Getic Unit (Krstić *et al*. 2005; Text-fig. 3). This folded Ordovician–Silurian succession (Krstić 1975b) is characterized by complete *graptolite* zones. The *acuminatus* Zone marks the Lower Silurian, whereas the graptolite *hercynicus* zone (Krstić *et al*. 2005) marks the transition from the Upper Silurian to the Lower Devonian. Graptolites coupled with low Cr/V (0.05–0.08) and Cr/Ni (0.7–

Terrane / Unit	Age	Latitude
Carpatho-Balcanic Terranes Locva-Ranovac-Vlasina Terrane (”Upper Supragetic”?)	Paleozoic–Lower Devonian	30/40˚S 39˚S
Ranovac Terranes (”Lower Supragetic”?)	Late Baschkirian–early Gzhelian	5˚N
Stara Planina Terrane	Early Devonian	4˚N
Kučaj Terrane	Ordovician Silurian Early Devonian Late Devonian Latest Moskovian–early Gzhelian	29–25˚S 20–14˚S 16˚S 5˚S 5˚N

Table 1. Summary of the paleolatitudes for a set of Southeast European tectonic units (terranes) (modified after Vozár 2010 and references therein). Moderately high latitudes in the Ordovician indicate the drift stage, detaching away from the north Gondwana active margin. The age and latitude comparison of all tectonic units clearly indicate low latitudes in the late Carboniferous (5˚N)

0.8) ratios are typical deep-water deposition markers (Krstić *et al*. 2005).

Towards the present-day E-NE Serbia (the area of Dunavski ključ), according to the data of a deep borehole drilled in a vicinity of Kladovo settlement (E Serbia; Text-fig. 3), the paleontological analyses (Pantić and Šećerov 1977) indicate a possibility that this western edge of the Moesian micro-plate was also under a subaqueous environment during the Ordovician. Silurian *Acritarchs* are documented at depths from 1597 m to 1604 m. Thereby, a vast oceanic space from N Gondwana, towards the proto-Moesia throughout the Ordovician, Silurian including the Devonian marine termination is unraveled by the presence of this flora.

According to the paleomagnetic data from the Serbian part of the “Balkan Terrane” (the Supragetic basement) this was situated during the Ordovician at a palaeolatitude of 38°S–39°S, whereas was during the Middle Devonian the palaeolatitude was ca. 10–15°S (Yanev 2000). The measured paleolatitudes (Table 1) of Ordovician age indicated that the Supragetic- (“Ranovac-Vlasina terrane”) and the adjacent basement units of Serbia occupied the southern hemisphere at moderately high latitudes.

Devonian

The Devonian in SE Serbia can be divided into two different successions. There is the Devonian succession transgressively overlying the Supragetic crystalline basement, consisting of a variety of facies (Text-fig. 3). Occasionally this succession is in direct connection with the Upper Silurian (Krstić *et al.* 2003).

The other Devonian succession belongs to the “Kučaj Unit” (Mts. Rtanj, Kučaj, Devica, Tupižnica, etc.). The Devonian of the “Kučaj Unit” has a wide distribution across E Serbia (Text-fig. 3). As mentioned earlier, the Devonian record extends towards the east, Devonian strata having been located underneath the western Moesian micro-plate in Serbia (well Bukovče-1, depth of 1192–1198 m; Anđelković 1975b; Pantić and Šećerov 1977; Text-fig. 3). Lower, Middle and Upper Devonian sediments are confirmed in SE Serbia (Veselinović 1975). Marine Lower Devonian continues up from the Upper Silurian, transitioning to neritic, occasionally terrigenous Middle Devonian, whereas the presence of largely terrigeneous Upper Devonian is demonstrated by the rare occurrence of the conodont *Palmatolepis perlobata schindewolfi*, (Veselinović 1975). The following Devonian facies are summarized below according to the Graptolite zone present (Maksimović 1976a):

(i) Graptolite schists with lenses of limestone extending up from the Silurian and containing *Monograptus uniformis,* (ii) Limestone facies with black limestones at the base, with abundant *Kionoceras originale* (Barr), *Platyceras complanatum* (Barr), *Geinosoceras*, etc. These are overlain by coralliferous limestones with *Favosites* sp., brachiopods, etc.

Siltstone with sandstones with the Middle Devonian *Psilophyton* sp., *Calamophyton primaverus* (Kučaj, Svrljiške planine, Suva planina) and the Upper Devonian *Cyclostigma ursinum*, *Cyclostigma herynium*, *Stigmaria devonica* (Rtanj, Stara Planina, Crn Vrh, Zvonačka banja). In Bulgaria, the complete Devonian succession occurs in the Morava nappe, containing a mixture of shales, limestones, sandstones, and siltstones with conodonts in the Lower Devonian Vrapcha Formation. Above comes the Carboniferous Beraintsi Formation (Boncheva *et al.* 2010). However, the Devonian in NE Serbia is represented by a volcano-sedimentary formation (Text-fig. 3; Kalenić *et al*. 1973; Krstić *et al*. 2003).

Kalenić and Aleksić (1976) explain that the entire system of pre-Carboniferous rocks is unconformably blanketed by a molasse sequence (area near Ranovac settlement, towards Plažane, Bukovik, Seličevica and

Babička Gora in E Serbia). The system of E Serbian molasses is of terrestrial to shallow marine inheritance probably marking the one-time foreland basin of the Variscan Moesian promontory (molasse material derived from the Eurasian promontory?).

Carboniferous and Permian

These sediments are situated E of the Supragetic basement within Carpatho Balkanides. In the Capatho-Balkanides of Serbia, Carboniferous sediments referred to as the "*šarena serija*" ("variegated series") have been documented at several locations: Stara Planina, Miroč Mt., Mlava and Pek rivers (see Text-figs 1b and 3 for geographical reference), mostly accompanied by the Permian to Mesozoic cover (Anđelković 1975a). In Bulgaria, the Lower Carboniferous of the Balkan Terrane (Beraintsi Formation) is characterized by the deep-water outer shelf margin of the peri-Gondwana platform (Boncheva *et al.* 2010 and references therein). The Lower Carboniferous or Kulm of NE Serbia is characterized by a separate volcano-sedimentary formation and a flysch-like siliciclastic formation of conglomerates, sandstones, black platy limestones that include *Crinoides*, *Brachiopodes*, and an abundant microfauna (Pantić 1975). In E Serbia (Niška Banja, Koritnik), the Lower Carboniferous Kulm system is in direct connection with the Upper Devonian sediments probably marking an occasional transition to flysch-dominated deposition (tentative analog of the Upper Devonian–Lower Carboniferous Beraintsi Formation in Bulgaria). The Middle and Upper Carboniferous is characterized by continental deposition dominated by coal-bearing sediments (Pantić 1975). Recently a set of granitoids distributed along the Carpatho-Balkanides of E Serbia yielded a very late Variscan age (Jovanović *et al*. 2019; Text-fig. 5). The emplacement of the Variscan granitoids of Gornjane-Tanda-Blizna, Neresnica-Ziman, was across the Getic unit ("Kučaj"), whereas the Janja, Ravno Bučje, and Stara Planina granitoids pierced the Upper Danubian system (or SPP unit; Text-fig. 3) and the Plavna, Suvodol Lower Danubian Unit (Jovanović *et al*. 2019 and references therein). Despite significant shifts in the regional configuration, the main emplacement time has no significant variations, ranging 319–281 Ma.

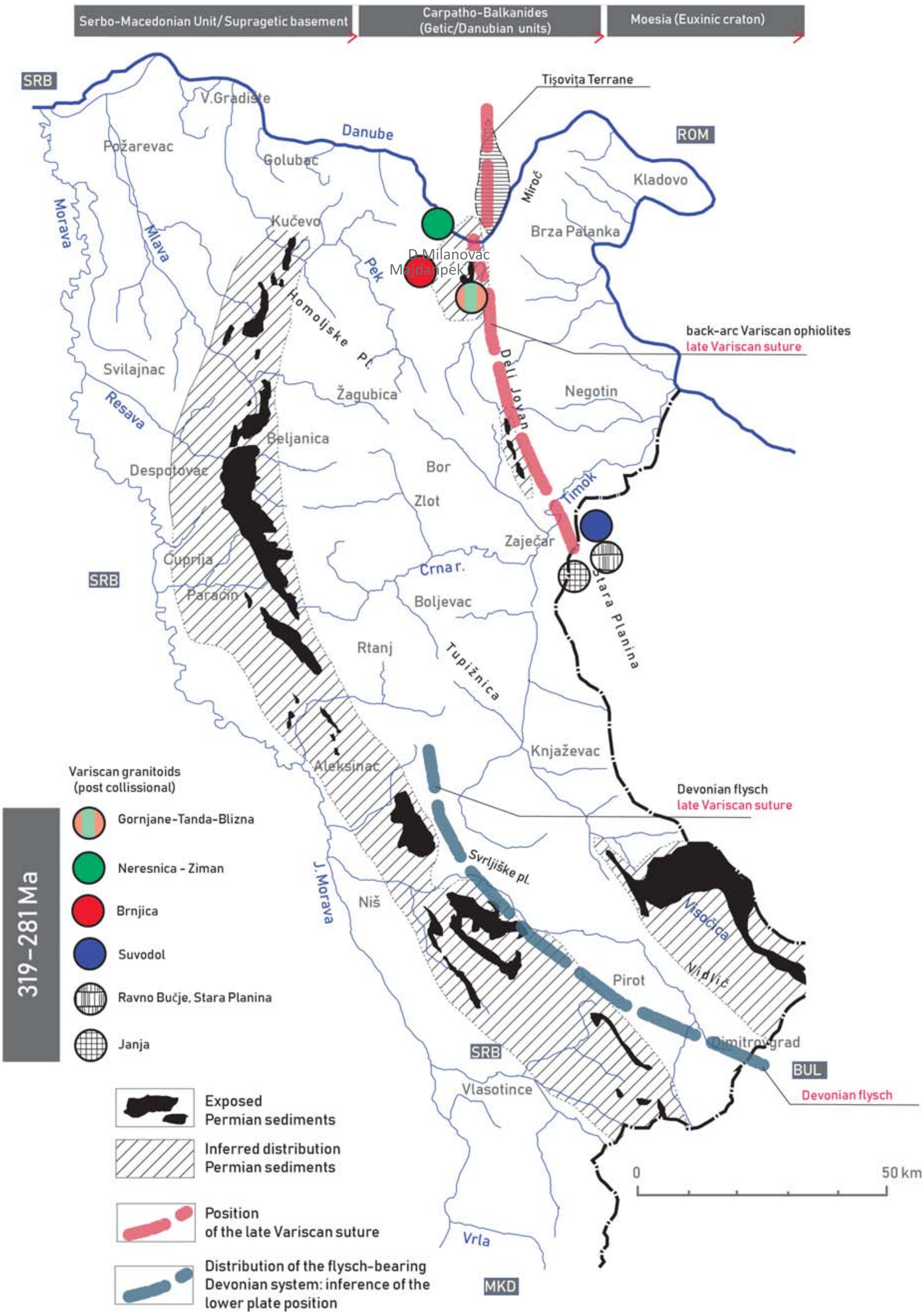
Post-Variscan red-bed deposits in Romania unconformably overstep different Precambrian– Cambrian and low-grade Lower Paleozoic crystalline rock complexes, as well as the Variscan nappe structures (Seghedi *et al*. 2001). In Serbia, the Permian overstep sequence or "Permian red sandstones" (Maslarević and Protić 1975) or molasse sediments (Ramovš 1989) is distributed in the form of "internal" and "external" belts distributed around the E Serbian Carpatho-Balkanides. In between the two Permian "belts", there is an N-S-directed Permian gap (Text-fig. 5). It appears that the Permian continental deposition was not on top of the Supragetic, suggesting pre-Permian burial which may conditionally be validated by the development of a high-strain Permian shear zone in Vrvi Kobila (numeric age of the shear zone determined by Antić *et al*. 2017).

The "Red Permian Sandstone" in the "internal belt" is situated on top of the Serbo-Macedonian Unit and the W Carpatho-Balkanides ("Kučaj Unit", former the "Gornjak-Suva Planina zone" of Anđelković 1975a). The Permian sandstones are tentatively allocated to the Rotlingend and Zechstein because their contact with the underlying Carboniferous "*šarena serija*" ("variegated series") (Anđelković 1975a) is gradual. The thickness is estimated to range from 50 to 700 m indicating a highly differentiated paleorelief and intensive erosion of the former Permian soil.

RECONSTRUCTION OF THE PALEOZOIC PALEOGEOGRAPHY: A SEGMENT OF CARPATHO-BALKANIDES IN THE CONTEXT OF THE RHEIC OCEAN AND ITS SEAWAYS

A number of recent reports have dealt with the European Neoproterozoic–Upper Paleozoic paleo-

Text-fig. 5. Distribution of the late Variscan suture, a segment in eastern Serbia. Position of the Variscan suture, position of the late Variscan suture inferred from the back-arc ophiolites and Variscan granitoids (red line). Blue line displays the position of the Devonian flysch. Permian sediments in Serbia (modified after Anđelković and Protić in Maslarević and Protić, 1975). Numeric age of the granitoid emplacement from Jovanović *et al*. 2019. The Permian overstep sequence corroborates the inferred late Variscan (Upper Carboniferous) accretion. Distribution of the Permian sediments in eastern Serbia (inlet from Anđelković and Protić, in Maslarević and Protić 1975). The Permian overstep sequence (western or "external belt") marks once again the late Variscan (Carboniferous) accretion of the Supragetic. Permian red beds are distributed additionally in the Carpatho-Balkanides of Serbia (internal or "eastern belt") having a prominent gap towards the Supragetic basement and Serbo-Macedonian Unit. Therein, the Devonian outcrops (modified after Veselinović 1975) are distributed, including those of the Carboniferous age that are positioned more easterly, in the vicinity of the Devonian back-arc ophiolites (modified after Pantić, 1975; see Text-fig. 3). The restored collision *i.e.* docking depicts the underplating position directed to the NE in modern-day reference (or NW in Devonian reference; as suggested by Nance *et al*. 2012); consequently the reconstruction depicts a 90° clockwise post-Devonian rotation of the suture/thrust front →



Serbo-Macedonian Unit/Supragetic basement
Carpatho-Balkanides (Getic/Danubian units)
Moesia (Euxinic craton)
SRB
ROM
BUL
MKD
Tişoviţa Terrane
back-arc Variscan ophiolites
late Variscan suture
Devonian flysch
late Variscan suture
Devonian flysch
Danube
Morava
Mlava
Pek
Resava
Timok
Crna r.
J. Morava
Visočica
Vrla
V.Gradište
Požarevac
Golubac
Kučevo
D.Milanovac
Majdanpek
Kladovo
Miroč
Brza Palanka
Homoljske Pl.
Svilajnac
Žagubica
Deli Jovan
Negotin
Beljanica
Despotovac
Bor
Zlot
Zaječar
Ćuprija
Paraćin
Boljevac
Stara Planina
Rtanj
Tupižnica
Knjaževac
Aleksinac
Svrljiške pl.
Niš
Pirot
Vidlič
Dimitrovgrad
Vlasotince
319–281 Ma
Variscan granitoids (post collissional)
Gornjane-Tanda-Blizna
Neresnica - Ziman
Brnjica
Suvodol
Ravno Bučje, Stara Planina
Janja
Exposed Permian sediments
Inferred distribution Permian sediments
Position of the late Variscan suture
Distribution of the flysch-bearing Devonian system: inference of the lower plate position
0
50 km

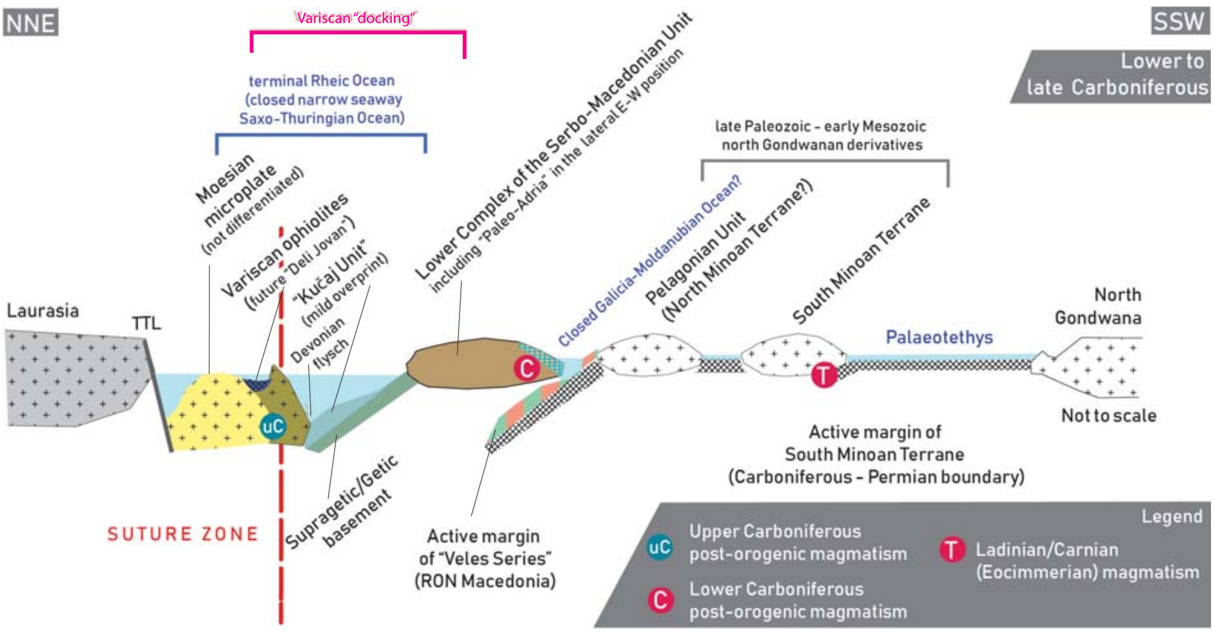
geography (Balintoni *et al.* 2014; Cocks and Torsvik 2006; Li *et al.* 2017; Nance *et al.* 2007, 2010, 2012; Oczlon *et al.* 2007; Pharaoh 1999; Stampfli *et al.* 2002; Stampfli *et al.* 2013; von Raumer *et al.* 2003; Winchester *et al.* 2006). According to most authors, the Avalonian–Cadomian rift-drift mechanism is governed by a Neoproterozoic (Cadomian) active continental margin with a back-arc basin followed by the ridge-trench collision and slab break-off. Accordingly, new accommodation space for the development of the retroarc basin in the late Ediacaran–early Cambrian emerges. A contemporaneous southward oblique underplating affected the transition into the transform margin and the posterior back-arc closure (Linnemann *et al.* 2007; Nance *et al.* 2012). Such oblique kinematics contributed to the detaching of the ribbon-like north Gondwanan lithosphere segments. However, key authors include an "Eo-Variscan event" occurring between 400 and 380 Ma, referring to the collision of an intra-oceanic arc with the eastern portion of the Gondwana margin (Haydoutov *et al.* 2010; von Raumer and Stampfli 2008 and references therein).

The Early Paleozoic history of the modern-day SEE region began with the accretion of initial Avalonian segments onto the Baltican promontory during the Cambro-Ordovician drift and the Silurian closure of the Iapetus/Tornquist Sea (*sensu* Nance *et al.* 2012). Despite the significant Alpidic overprint, this primordial accretion within the promontory of SW Baltica is still demonstrated by the modern-day configuration of the Carpatho-Balkanides (Text-fig. 3). Onwards are the Avalonian terranes (closest to the Baltican promontory; Text-fig. 6), including the anterior 570–547 Ma Moesian microplate or Euxinic craton (Balintoni *et al.* 2013, 2014; Balintoni and Balica 2016; Spahić and Gaudenyi 2018; Żelaźniewicz *et al.* 2009; Text-fig. 3). Similar to the Moesia is the Malopolska Massif (Żelaźniewicz *et al.* 2009).

The initiation of the Rheic Ocean took place after the protracted Cambrian back arc – retroarc process (Linnemann *et al.* 2007). These processes occurred either in the mid- to late Cambrian (Nance *et al.* 2012) or in early Ordovician (Nance *et al.* 2010; Winchester *et al.* 2002a). This Pan-African scenario is locally authenticated by the Ediacarian–Cambrian *Ajacicyathus* marker (Maksimović 1976b) and by the Lower Ordovician inarticulate brachiopod fauna (Pavlović 1962). Based on the detrital cratonic sources, the suggested inception place of some of the SEE Cadomian segments should be a paleo-Asian far-east section of the north-Gondwanan active margin referred to as the "Galatian cluster" (Antić *et al.* 2016; Balintoni *et al.* 2014; *sensu* Stampfli *et al.* 2013). Based on these remote initial far-east Cadomian continental positions (relative to the reconstructed accretionary Variscan locations; von Raumer and Stampfli 2008) the suggested paleotransport towards the Baltican craton would rather be E-W directed, instead of the NW direction proposed earlier (*sensu* Nance *et al.* 2012). To make matters more complex, the proposed drift route is parallel to the paleo-Equator thus suggesting a detrital input from the dislocated Asian blocks (Hunia) distributed along the Cambrian north-Gondwanan margin (von Raumer and Stampfli 2008). Another scenario connects the Cadomian segments of the Carpatho-Balkanides with the eastern Rheic Ocean developed on the account of the Proto-Tethys S-directed subduction (Balintoni *et al.* 2014).

During the Silurian epoch, growing extension produced a voluminous ocean of ~4000 km in width (Nance *et al.* 2010, 2012). The deep water environment has authentication in the SEE region in the form of (i) Silurian graptolite schists in central-E Serbia (Text-fig. 3) and (ii) by the population of Silurian *Acriratcha* discovered in the deeper sections of the Moesian Paleozoic (Dunavski ključ, E Serbia). There are similarities in the Upper Silurian concerning the Ossa Morena Zone (Robardet and Gutiérrez-Marco 2004). Silurian *Graptolite* schists are documented on top of the "Lužnica Unit" (West Kraishte; Krstić *et al.* 2005). A continuous Ordovician to early Carboniferous section (Ramovš 1989) in a vicinity of the SE Supragetic basement/"Kučaj Unit" demonstrates that the Devonian basin was inherited from an Ordovician shelf margin basin (Boncheva *et al.* 2010). In global terms, already in the Lower Devonian there began the closure of the Rheic Ocean which terminated in the Lower Carboniferous (Nance *et al.* 2010). Nevertheless, deep-water Lower Devonian sediments cover large areas of E-SE Serbia (Krstić *et al.* 2003; Maksimović 1976b; Veselinović 1975; Text-fig. 5) including Srednegorie of NW Bulgaria (Boncheva *et al.* 2010).

The numerous uncertainties associated with the Rheic closure led to the suggestion that the ocean closure was driven by intra-oceanic subduction (Nance *et al.* 2012). In the investigated segment of SEE, however, the final stage of the Rheic Ocean could be marked by the Lower Carboniferous siliciclastic series (Serbia; description in Pantić 1975) connected to the Givetian to Lower Carboniferous flysch (Bulgaria; Boncheva *et al.* 2010 and references therein). This late Paleozoic flysch including the molasse sequences can be interpreted as reflecting a typical (shallow slab) underplating typifying Gondwana as the Variscan foreland (*e.g.*, southern margin of the Rheno-Hercynian



Text-fig. 6. Plate kinematic model for the assembly of minor plates in the east Serbian segment of the later overprinted Variscides (position of the section on Text-fig. 3). Variscan "docking" of the Supragetic basement and "Kučaj Unit" in the underplated position inferred by the response of the back-arc ophiolites crosscutting the Danubian Unit. Numeric age data (magmatic rocks) from Antić *et al*. (2016); Jovanović *et al*. (2019), Zulauf *et al*. (2014, 2018). Tentative Galicia-Moldanubian seaway closure inferred from the "Veles Series" (RON Macedonia). See text for details

or Saxo-Thuringian basin; Franke, 2006). However, the position and the ages of the Lower Complex, Supragetic basement and "Kučaj Unit" rather indicate the aggregation of a continental arc assembly prior to the arrival of the late Paleozoic north Gondwanan derivates (Text-fig. 6). In addition, similar synorogenic flysch-bearing systems may correspond to the flyschoid and molassic deposits of the Late Devonian and Early Carboniferous Ossa Morena Zone (Robardet and Gutiérrez-Marco 2004). The suggested configuration marks the NE direction (present-day reference) of the descending Rheic/Saxo-Thuringian oceanic lithosphere underneath the Danubian basement (Text-fig. 6). The proposed underplating scenario is in line with the inferred Rheic system as the lower plate (*e.g.*, Jastrzębski *et al*. 2013) having as its counterpart the opposite (upper plate) back-arc ophiolite obduction emplacement (Plissart *et al*. 2018) of the now neighboring Tişoviţa mafic-ultramafic complex (ca. 405 Ma; Plissart *et al*. 2017). Moreover, the set of ductile deformation and petrological markers in the Upper Danubian (Plissart *et al*. 2018) and granitoid bodies in E Serbia documents the collisional-post-collisional sequencing marked by the very late (or post)Variscan emplacement age of ca. 320–290 Ma (numeric age by Jovanović *et al*. 2019) penetrating the former Variscan footwall and hanging wall.

The Upper Devonian–Lower Carboniferous flysch trough, molasse and continental Upper Carboniferous terrestrial systems (Serbia and this part of SEE) may mark the age and the position of the Rheic suture, its Saxo-Thuringian seaway (*sensu* Franke *et al*. 2017) (Text-fig. 5). The Supragetic oceanic crust including the slightly recrystallized Devonian cover sequence laid down in an inner shelf environment (Boncheva *et al*. 2010) is a vestige of the early Paleozoic oceanic crust, whereas the "Kučaj Unit" represents the deep-water system of the Rheic *i.e.* Saxo-Thuringian Ocean. The investigated section of the Rheic suture can be placed to the W of the tentative "Kulm flysch" of Serbia (to the S of the Tişoviţa oceanic lithospheric fragment, across the Danube River). The suture is partially blanketed by the Permian red-bed overstep sequence (Text-fig. 5). The exhumation of the Getic-Supragetic basement in Romania has an Upper Carboniferous age ($^{40}Ar/^{39}Ar$ ages of 320–295 Ma, Dallmeyer *et al*. 1998) implying the peak convergence of this Rheic/Saxo Thringian segment with the tentative involvement of the Galicia-Moldanubian seaway closure (Text-fig. 6) and the Pangea assembly.

In the Alpine phase, these Rheic/Saxo-Thuringian/Galicia-Moldanubian Ocean(?) sutures were overprinted by a major strike slip system (*sensu* Plissart *et al.* 2018) which was reactivated several times after the Variscan docking initially involved rifting of this new southern European foreland. The Carnian western Palaeotethys closure (*e.g.*, Csontos and Vörös 2004; Text-Fig. 6) affected the early Alpine extension whereas the terminal Alpine nappe stacking rearranged late Mesozoic configuration (Kräutner and Krstić 2002). The inherited oblique rotation accounted for the Alpine orogen-parallel dextral transtension along the Timok fault system and its analogs (Kräutner and Krstić 2002). Latest reactivation can be attributed to the clockwise rotations of the northern segments throughout the Neogene (Marović *et al.* 2001).

CONCLUSIONS

In E Serbia, the Supragetic Unit (basement section) consisting of the underlying Ediacarian–Lower Ordovician with its lateral continuation into the "Kučaj Unit" (tentative Getic) which include the Upper Ordovician/Silurian and include a Devonian sealing sequence. The Devonian overlapping between these two terranes documents their probable nearby position under similar sedimentary environments (also in Boncheva *et al.* 2010) during the Paleozoic plate-tectonic drift.

The synthesis provides a few significant clarification points regarding the presence of the Rheic Ocean/Saxo-Thuringian seaways in SEE:

- This suggested SEE Rheic (Saxo-Thuringian) closure scenario can be validated by (i) short-time Devonian back-arc ophiolite formation (Balica *et al.* 2014; Plissart *et al.* 2017, 2018) within the Upper Danubian (upper plate), (ii) Lower Carboniferous "Kulm flysch", (iii) the age of Variscan granitoids, (iv) late-staged Upper Carboniferous accretion (ca. 352 Ma) between the investigated section(s) of the N Gondwana and SEE segment of the SW Laurussian promontory (Moesian microplate including the already accreted Avalonian terranes likewise Danubian);
- The Rheic suture including its seways consequently lies to the E and along the Lower Carboniferous "Kulm flysch" (E-NE Serbia) and along the Devonian (SE Serbia) to Lower Carboniferous Beraintsi Formation in NW Bulgaria;
- The question of the paleocontinental positioning and the age of the greenschist facies metamorphism of the Supragetic basement remains an open issue;
- The Supragetic basement is currently differentiated as the system accommodated on top (upthrusted sequence) of the Getic Unit. Such systematization favors the Alpine structural style (overprint) rather than an original depositional configuration;
- It remains unclear where is the original contact (if any) between the two polymetamorphic basement entities;
- The Supragetic basement or the "Ranovac-Vlasina unit" adjoins the "Kučaj unit" and "Lužnica Unit" or "West Kraishte Unit". The continuation in the sedimentary Silurian succession between the "Kučaj" and "Lužnica" or "West Kraishte unit" indicates a maximum width of Silurian Ocean.

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