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Early Paleozoic Cenerian (Sardic) geodynamic relationships of peripheral eastern north Gondwana affinities: revisiting the Ordovician of the Getic/Kučaj nappe (eastern Serbia)

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Regional tectonic synthesis suggests that a segment of the bipartite eastern Gondwana-type Carpathian-Balkan nappe-stacked Getic/Kučaj/Supragetic basement (eastern Serbia) experienced Cambro-Ordovician Cenerian (Sardic) accretionary-type deformation. The Ordovician basement of the Alpine Getic/Kučaj nappe exposes an earlier-mapped shallow-marine transgressive-type Fe-silicate-rich ironstone sequence. The Ordovician ironstone is used as second-order evidence of a hitherto untraceable tectonically-driven unconformity. Early Paleozoic compression is consistent with the controversial latest Cambrian to intra-Ordovician Cenerian (Sardic) interval, documented by (i) a 488 Ma metamorphic event and available detrital zircon data (Serbo-Macedonian gneissic unit), (ii) a deformed Lower Ordovician Getic/Kučaj brachiopod assembly, and (iii) an intra-Ordovician unconformity dividing the Supragetic basement/"Vlasina complex". The data further imply that mafic gabbro-dominating sills, cropping out in the northern Getic/Kučaj unit, are consistent with Ordovician back-arc activity. The Getic/Kučaj gabbro is Ordovician in age, piercing a Neoproterozoic–Cambrian (Lower Ordovician) Supragetic/"Vlasina complex", overlain by a transgressive Silurian–Devonian sedimentary sequence. The emergence of Ordovician mafic intrusions reflects submarine volcanism, while deep-water redox conditions were capable of a sustained supply of Fe (similar to Sardinia). In terms of tectono-palaeogeographic reconstructions, the origin of Ordovician shortening and mafic volcanism is often challenged. The latter is broadly analogous with the embryonic eastern Rheic Ocean, corresponding additionally to the Armorican spur and related intra-continental magmatism.

Key words: eastern north Gondwana, Ordovician ironstones, Cenerian (Sardic) event, glacio-eustatic changes, eastern Serbia.

INTRODUCTION

Displaced supercontinental margins are places capturing imprints of past tectonothermal activities, often consistent with peripheral orogenic-type zoning, recurrent back-arc lithospheric fragmentation and terrane dispersal (e.g., Murphy et al., 2001; van Staal and Hatcher, 2010; Meinhold et al., 2013; Merdith et al., 2017). The Lower Paleozoic bipartite north Gondwana periphery may be either genetically linked with a Cambro-Ordovician active margin (Zurbriggen, 2017a, b) or simply with back-arc extension (Stephan et al., 2019). The Cambro-Ordovician interval was, however, tectonically critical for north Gondwana, characterized by a complex interplay of plate tectonic processes: Ordovician arc-supercontinent collisions, rifting, (palaeo)northwards drift of peri-Gondwanan terranes, formation of unconformities, metamorphism, (bimodal) igneous activity, inclusive development of high-strain deformation (e.g., Murphy et al., 2008; van Staal and Hatcher, 2010; Balintoni et al., 2010, 2011, 2014; Abu-Alam et al., 2013; Zurbriggen, 2015, 2017a, b; Cocco and Funneda, 2019; Maino et al., 2019; Stephan et al., 2019; Spahić et al., 2021; Cocco et al., 2022). In addition to a number of overlapping lithospheric-scale processes, the Ordovician of north Gondwana is further complicated as it combines (i) astronomically induced Earth-scale cooling episodes with the rather localized Middle and Late Ordovician north Gondwanan glaciations (Young, 1989; Fang et al., 2019), (ii) a phase of massive ironstone production (Guerrak, 1988, Young, 1992; Trela, 2008; Pufahl et al., 2020; Dunn et al., 2021, and references therein), and (iii) the immense inflow of Pan-African orogen-derived clastic material indicating transport from a distant hinterland (e.g., Bahlburg et al., 2009; Meinhold et al., 2013; Avigad et al., 2017; Benayad et al., 2019).

The post-Cadomian (e.g., Linnemann et al., 2007) and post-Pan-African (Kröner and Stern, 2005) dominantly shelf-controlled bipartite north Gondwanan Cambrian–Ordovician overstep sequence, experienced transient Cenerian (Sardic) shortening. The tectonothermal event involved bimodal magmatism with an intervening "convergence" culminat-

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ing in the Ordovician (e.g., Kroner and Romer, 2013; Zurbriggen, 2015, 2017a, b; Álvaro et al., 2021; Oriolo et al., 2021, Avigad et al., 2022; Cocco et al., 2022). The Cenerian (Sardic) contraction was either influenced by transpressional movements along the extensive shelf (Stephan et al., 2019) or, in an alternative palaeogeographic reconstruction, is consistent with reattachment of near-shore laterally transferred peri-Gondwanan ribbon-like arc terrane(s) (Stampli and Borel, 2002; von Raumer et al., 2002; van Staal and Hatcher, 2010). The contraction and subsequent uplift of the shelfal area produced an angular Ordovician unconformity, best recorded in Sicily, the Alps and the Pyrenees (Martini et al., 2001; Zagorevski et al., 2006; Casas, 2010; Oggiano et al., 2010; Cocco and Funneda, 2019; Puddu et al., 2018; Maino et al., 2019; Hollocher et al., 2022). Other than in southern Europe, the Cenerian (Sardic) unconformity has received little attention in the literature. The flanking Cenerian (Sardic) underexplored involvement likely affected the North African cratonic basins (e.g., Tawadros, 2012; Le Heron et al., 2013), and the rest of the drifted Central European basement terranes (e.g., Brittany, Saxo-Thuringia and the Teplá Barrandian Unit, as well as basement terranes incorporated into the Alpine orogen; Fig. 1A, B – green-grey colour, blue colour, respectively). In addition, field evidence of a Cenerian (Sardic) compressional record in Central Variscan European basements is either absent, or is in a high strain domain likely occurring as orthogneisses with Ordovician 480–450 Ma protolith (e.g., Abalos et al., 2002; Franz et al., 2005; Kroner and Romer, 2013; Avigad et al., 2022). A similar situation is present in the incorporated Carpathian-Balkan pre-Variscan and Variscan basement edifices of Alpine orogen (e.g., Yanev et al., 2000; Kräutner and Krstić, 2002; Iancu et al., 2005; Seghedi et al., 2005; Krstić et al., 2008; Balintoni et al., 2009, 2014; Kounov et al., 2012; Bonev et al., 2013; Antić et al., 2016; Plissart et al., 2017, 2018; Spahić and Gaudenyi, 2018; Spahić et al., 2018, 2019a, 2021; Žák et al., 2021; Ferretti et al., 2022; Figs. 1C, 2 and 3).

The Lower Paleozoic tectonic perturbations of (eastern) peripheral north Gondwana generated three stages of the Cenerian (Sardic)-related volcanism (a typical location is Sardinia; Oggiano et al., 2010; Maino et al., 2019; Stephan et al., 2019; Oriolo et al., 2021; Avigad et al., 2022):

- intermediate and felsic volcanic rocks (491–479 Ma) bounded at the top by the Sardic unconformity;
- calc-alkalic rhyodacites of ~465 Ma, corroborating the presence of bimodal Mid-Ordovician arc volcanism;
- alkalic metaepiclastites recorded within the post-Caradocian transgressive sequence (440 Ma), related to the rifting and collapse of the Mid-Ordovician volcanic arc.

In this respect, the Getic/Kučaj and Supragetic nappes investigated, i.e., basement units of eastern Serbia, may include relevant evidence of here tested:

- link between the geodynamic evolution of recently identified dominantly peraluminous Cenerian (Sardic) type gneisses of the Serbo-Macedonian Unit (Spahić et al., 2021), and the nearby Getic/Kučaj/Supragetic Cambro-Ordovician basement units;
- evidence of Cambrian–Ordovician contraction and uplift may include the tectonically deformed brachiopod assembly earlier discovered within a meta-clastic sequence (Krstić and Maslarević, 1998). These deformed brachiopods are consistent with a Lower Ordovician age, positioned stratigraphically beneath Mid-Ordovician intra-layered ironstone, chemically described also by Mrvaljević (1956), and stratigraphically by Ferretti et al. (2022). The ironstone sequence led to the idea to use it as an auxiliary marker of unconformity, which can be dated from the latest Cambrian to the Middle Ordovician or the pre-Hirnantian interval (previously mapped by Zavod za geološka i geofizička istraživanja, 1961–1968; Barjaktarović, 2007; also recorded in the analogous Svoge unit, western Bulgaria; Gutierrez-Marco et al., 2002; 2003; Ferretti et al., 2022, and references therein);
- Ordovician back-arc extension or an inner cratonic Ordovician opening of a semi-restricted Gondwanan seaway (gabbroic rocks of pre-Silurian age recorded in the northern Getic/Kučaj zone; near the Danube River; Bogdanović et al., 1978).

However, the magnitude of the extensional back-arc opening of the eastern Rheic/Moldanubian/Palaeotethys Ocean, or the actual amount of displacement from the Gondwana mainland, remains unknown (Žák and Sláma, 2018). To make matters more difficult, the Neoproterozoic–Cambro-Ordovician Getic/Kučaj/Supragetic sequences investigated underwent both Variscan and Alpine tectono-metamorphism (Figs. 3 and 4).

In this review paper, by applying conventional regional geological and stratigraphic methods in combination with the available literature sources, we test a Cambro-Ordovician palaeogeographic and tectonic relationship between a segment of far-travelled peri-Gondwanan terranes and the Gondwana mainland. The Gondwanan Armorican inheritance of the Getic/Kučaj unit is documented exclusively within its regional Carpathian-Balkan Ordovician analogue referred to as the Svoge unit in Bulgaria (Gutierrez-Marco et al., 2003; Yanev et al., 2006; Chatalov, 2017; Georgiev et al., 2021, 2022). A limited number of regional studies have not discussed Fe-chlorite (i.e. chamosite) and siderite authigenesis and diagenesis-related unconformity, and their linkage to the north Gondwana shelf (e.g., Matheson et al., 2022). Commonly, the stratigraphic distribution of the Ordovician ironstones of North Africa correlate with the intervals between higher sea levels, separating transgressive systems tracts which overlie maximum flooding surfaces i.e., marine transgression as accommodation increased from lowstand conditions (Young, 1992; also in Pufahl et al., 2020). Thus, the frequent occurrence of Middle–Upper Ordovician chamosite- and siderite-bearing ironstones within the Getic/Kučaj/Svoge nappes of the Carpathian-Balkan belt (Veselinović, 1975; Krstić and Maslarević, 1998; Gutierrez-Marco et al., 2003; Yanev et al., 2006; Figs. 2 and 3) is alternatively used as a proxy for (i) unconformities (transgressive initial deposit above an unconformity; Young, 1992); and (ii) together with evidence of Ordovician mafic magmatism supplying ferruginous water as a possible source of iron (e.g., Mücke and Farshad, 2005; Oggiano et al., 2006; Pufahl et al., 2020; Matheson et al., 2022), as an alternative palaeogeographic and tectonic reconstruction of the Getic/Kučaj nappe in further portraying a narrow palaeoceanic seaway.

REGIONAL-TECTONIC OUTLINE

The entire region of south-east Europe and the north-east-East Mediterranean, including its Carpathian-Balkan-Hellenic sector (Fig. 1B, C), illustrates a very complex interaction of several orogenic accretionary-type events (e.g., Dimitrijević, 1997; Kräutner and Krstić, 2002; Iancu et al., 2005; Seghedi et al., 2005; Karamata, 2006; Schmid et al., 2008; Zulauf et al., 2015). The youngest late Alpine or Neoalpine, of extensional-type, occurred in the Oligo-Miocene (Marović et al., 2007). Oligo-Miocene extension followed a precursor (i) Eoalpine event (Late Cretaceous–Paleogene; Dimitrijević,

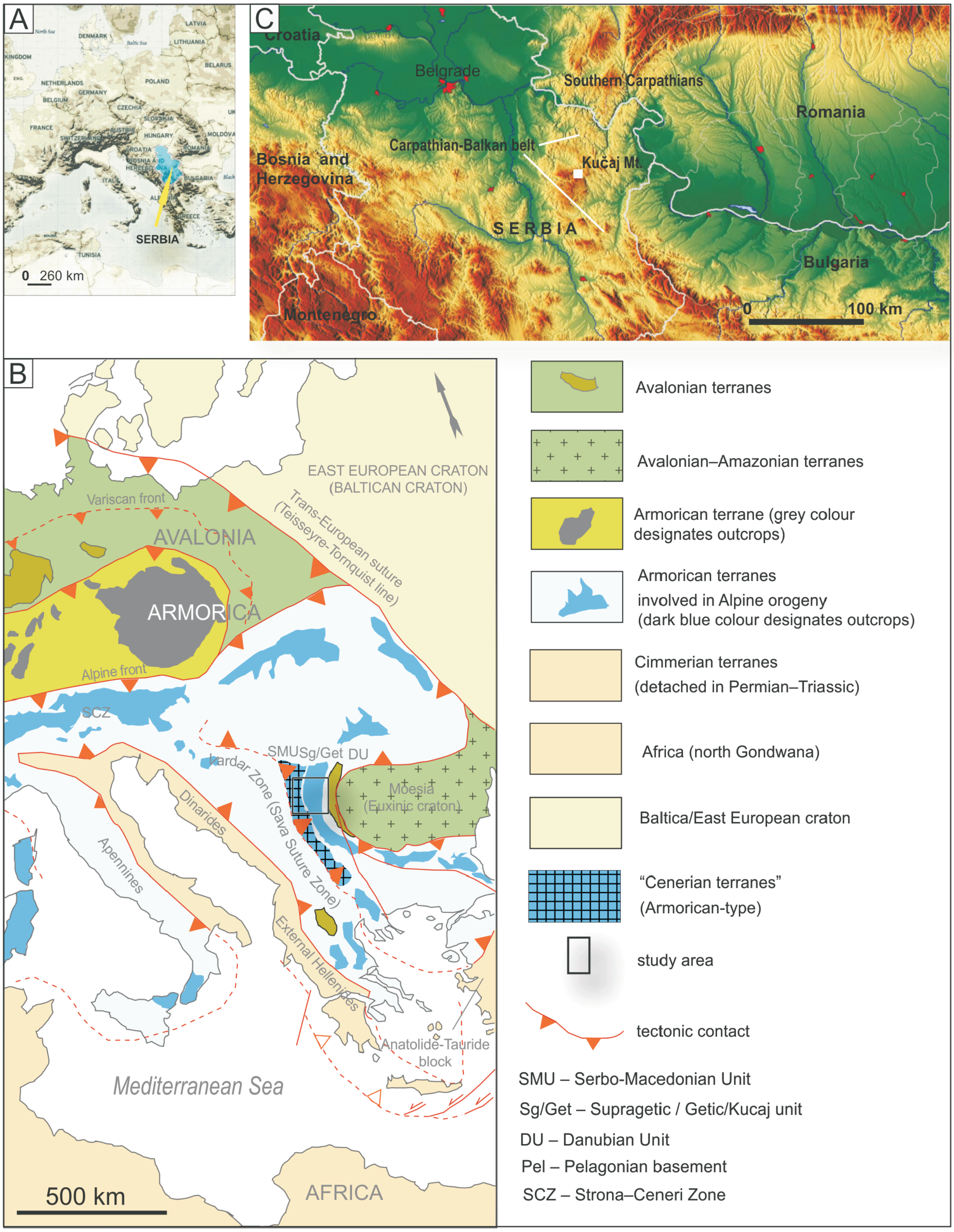


Fig. 1A – the Alpine domain of Europe (Gauss–Krüger to WGS84 coordinate transformations (svemir.co); B – distribution of Avalonian vs. Cadomian vs. Cimmerian microcontinents, embedded into what is now Western, i.e, Central and South-east Europe (Spahić, 2022a, b), respectively (inset from Topuz et al., 2021, significantly modified). Modification includes detrital zircon data taken from Zlatkin et al. (2014, 2017); Spahić and Gaudenyi (2018, and references therein). The Alpine orogeny, in particular Eoalpine compression, reworked the precursor Variscan configuration of the Carpathian-Balkan sector that include the exposed north Gondwanan Armorican basement elements. The exposed polymetamorphic terranes include the Serbo-Macedonian Unit as a segment of the dispersed Lower Paleozoic Cenerian margin (similar to the Alps i.e., basement belonging to the Strona–Ceneri zone). The Kučaj area investigated and its sedimentary Ordovician sequence are to the east of the documented Cenerian terrane or Serbo-Macedonian Unit; C – a relief map of the Kučaj Mt. area and Carpathian-Balkan fold-and-thrust belt (Relief Map – maps-for-free.com)

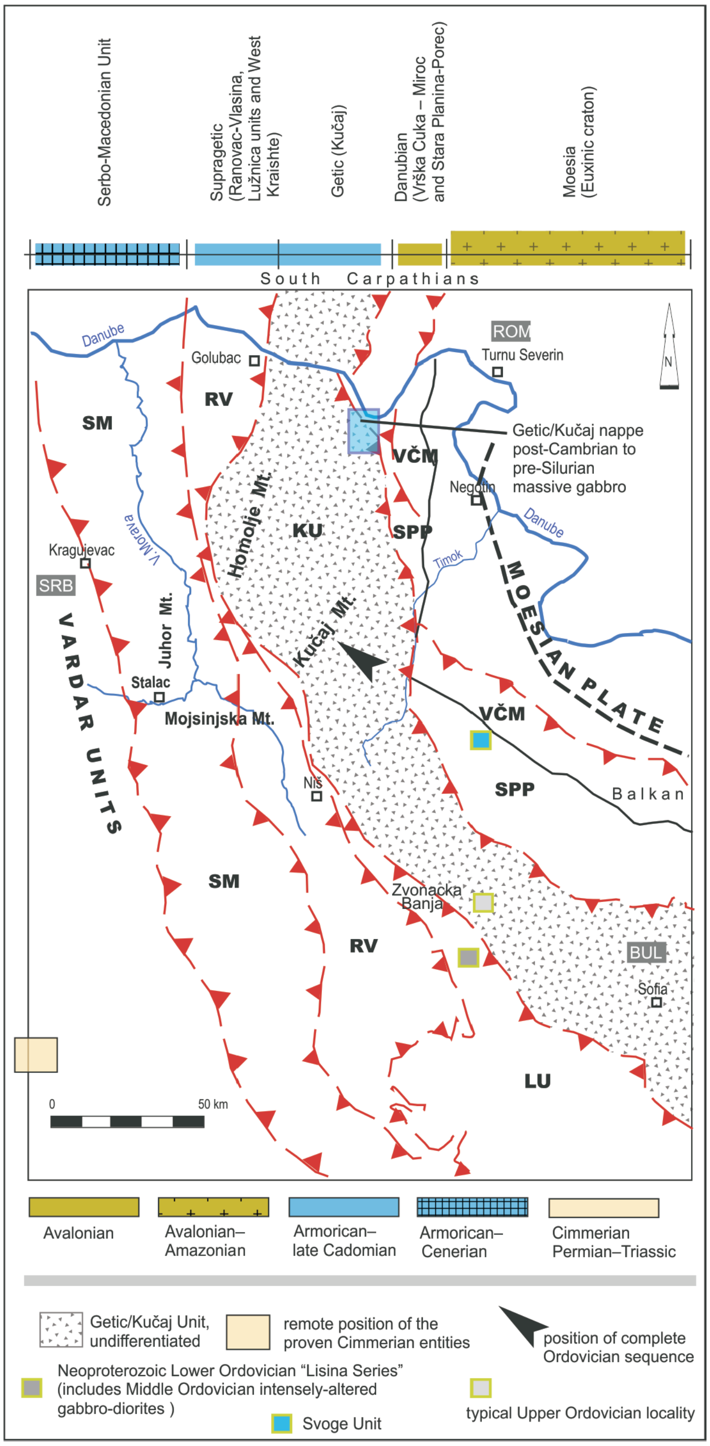


Fig. 2. Main tectonic units surrounding western Moesia (Kräutner and Krstić, 2002), with documented Peri-Gondwanan inheritance (data taken from Spahić and Gaudenyi, 2018, and references cited therein)

Moesia/Euxinic craton (Avalonian–Amazonian), VČM – Vrška Čuka-Miroč Unit (Lower Danubian, Avalonian), SPP – Stara Planina Poreč Unit (Upper Danubian, Avalonian), KU – Kučaj Unit (Getic, late Cadomian); LU – Lužnica Unit (West Kraishte, Cadomian), RV – Ranovac-Vlasina Unit (Supragetic, Cadomian), SM – Serbo-Macedonian Unit (Cadomian/Cenerian)

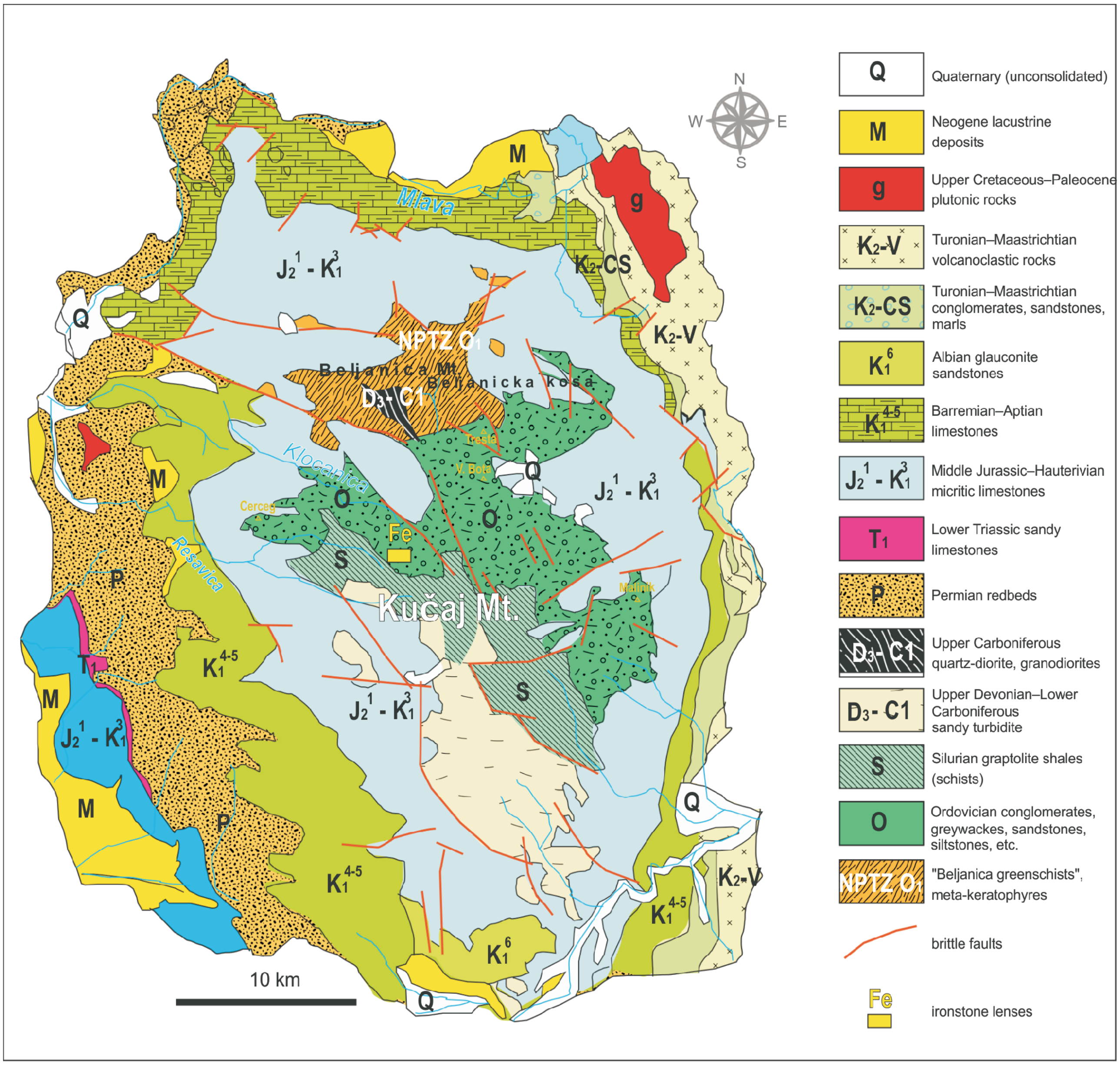
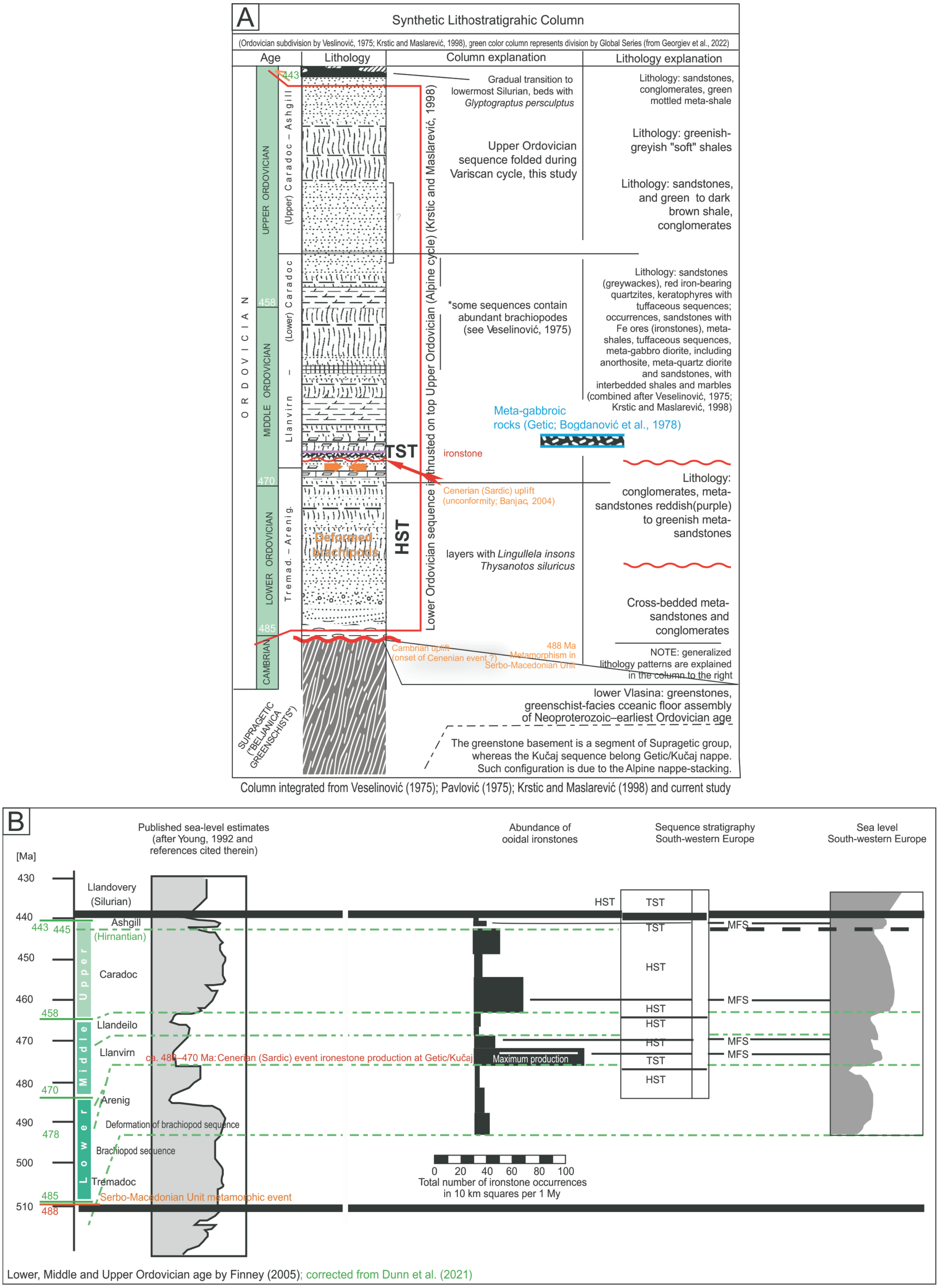


Fig. 3. Geological map of the wider area of the Kučaj Mt. (inset from Petrović et al., 2020; redrawn from Kräutner and Krstić, 2002)

The position in the "Beljanica greenschist" which are of the same age as the Supragetic basement (i.e. underlying the Ordovician sequence investigated). The main Ordovician sedimentary sequence gradually passes into the Silurian, which is not the case in NE Serbia (Bogdanović et al., 1978). Spatial position of the ironstone beds. Further explanations are within the text

1997; Spahić and Gaudenyi, 2022), preceded by (ii) "Eocimmerian docking" or an "Early Cimmerian" compressional event in the Late Triassic (Zulauf et al., 2015; Spahić et al., 2019b; Spahić, 2022a, b). (iii) The early Alpine event was an extensional episode (latest Permian–Triassic–Jurassic) that appeared after (iv) protracted Variscan amalgamation, linking late Carboniferous events with igneous activity in the Early Permian (Medaris et al., 2003; Winchester et al., 2006; Jovanović et al., 2019). (v) The Variscan precursor is (vi) the Cenerian or "Sardic" event (*sensu* Zurbriggen, 2015, 2017a, b, Stephan et al., 2018, 2019) which reached its peak (peraluminous igneous activity, high strain deformation, and anatexis) during latest Cambrian–Ordovician (Serbo-Macedonian Unit; Zagorchev et al., 2012; Spahić et al., 2021). Caledonian involvement has not yet been recorded. Cenerian involvement was initially suggested for the Serbo-Macedonian Unit gneisses, imprinted by a very interesting latest Cambrian 488 Ma metamorphism (Balogh et al., 2004).

The involvement of a Mid-Ordovician compressional event within the wider Carpathian-Balkan basement terranes was first suggested by Golonka et al. (2005), Haydoutov et al. (2010), and Balintoni et al. (2011). This Mid-Ordovician event was originally referred to as the "early Caledonian orogeny" (Balintoni et al., 2011). The Carpathian-Balkan basement terranes which were exposed to Cambro-Ordovician accretion or "orogeny" underwent tectonic transport to become an exotic Variscan basement collage in the aftermath (e.g., Żelaźniewicz et al., 2004; Carrigan et al., 2005; Oczlon et al., 2007; Kroner and Romer, 2013; Zulauf et al., 2015; Antić et al., 2017; Žák and Sláma, 2018; Fig. 1A, B). As a result, a large segment of north Gond-



A
Synthetic Lithostratigrahic Column
(Ordovician subdivision by Veslinović, 1975; Krstic and Maslarević, 1998), green color column represents division by Global Series (from Georgiev et al., 2022)
Age
Lithology
Column explanation
Lithology explanation
O R D O V I C I A N
UPPER ORDOVICIAN
MIDDLE ORDOVICIAN
LOWER ORDOVICIAN
CAMBRIAN
443
458
470
485
(Upper) C a r a d o c – A s h g i l l
(Lower) C a r a d o c – L l a n v i r n
T r e m a d. – A r e n i g.
Gradual transition to lowermost Silurian, beds with *Glyptograptus persculptus*
Upper Ordovician sequence folded during Variscan cycle, this study
Lower Ordovician sequence inthrusted on top Upper Ordovician (Alpine cycle) (Krstic and Maslarević, 1998)
*some sequences contain abundant brachiopodes (see Veselinović, 1975)
Lithology: sandstones, conglomerates, green mottled meta-shale
Lithology: greenish-greyish "soft" shales
Lithology: sandstones, and green to dark brown shale, conglomerates
Lithology: sandstones (greywackes), red iron-bearing quartzites, keratophyres with tuffaceous sequences; occurrences, sandstones with Fe ores (ironstones), meta-shales, tuffaceous sequences, meta-gabbro diorite, including anorthosite, meta-quartz diorite and sandstones, with interbedded shales and marbles (combined after Veselinović, 1975; Krstic and Maslarević, 1998)
Meta-gabbroic rocks (Getic; Bogdanović et al., 1978)
TST
ironstone
Cenerian (Sardic) uplift (unconformity; Banjac, 2004)
HST
Deformed brachiopods
layers with *Lingullela insons Thysanotos siluricus*
Lithology: conglomerates, meta-sandstones reddish(purple) to greenish meta-sandstones
Cross-bedded meta-sandstones and conglomerates
Cambrian uplift (onset of Cenenian event ?)
488 Ma Metamorphism in Serbo-Macedonian Unit
NOTE: generalized lithology patterns are explained in the column to the right
SUPRAGETIC ("BELJANICA GREENSCHISTS")
lower Vlasina: greenstones, greenschist-facies cceanic floor assembly of Neoproterozoic–earliest Ordovician age
The greenstone basement is a segment of Supragetic group, whereas the Kučaj sequence belong Getic/Kučaj nappe. Such configuration is due to the Alpine nappe-stacking.
Column integrated from Veselinović (1975); Pavlović (1975); Krstic and Maslarević (1998) and current study
B
Published sea-level estimates (after Young, 1992 and references cited therein)
Abundance of ooidal ironstones
Sequence stratigraphy South-western Europe
Sea level South-western Europe
[Ma]
430
440
450
460
470
480
490
500
510
443 445
458
470
478
485
488
Upper
Middle
Lower
Llandovery (Silurian)
Ashgill
(Hirnantian)
Caradoc
Llandeilo
Llanvirn
Arenig
Deformation of brachiopod sequence
Brachiopod sequence
Tremadoc
Serbo-Macedonian Unit metamorphic event
ca. 480–470 Ma: Cenerian (Sardic) event ironestone production at Getic/Kučaj
Maximum production
0 20 40 60 80 100
Total number of ironstone occurrences in 10 km squares per 1 My
HST
TST
TST
HST
HST
HST
HST
TST
HST
MFS
MFS
MFS
MFS
Lower, Middle and Upper Ordovician age by Finney (2005); corrected from Dunn et al. (2021)

wana was embedded within the eastern Variscan orogen to become a western Moesian Dacides/Southern Carpathian or Carpathian-Balkan sector (e.g., Balintoni and Balica, 2013, 2016; Balintoni et al., 2014; Antić et al., 2016, 2017; Chatalov, 2017; Spahić and Gaudenyi, 2018; Abbo et al., 2019; Ferretti et al., 2022; Figs. 1B, C and 2). Following the involvement of the Variscan basement in the Alpine-Himalayan orogeny, this lithospheric-scale fragment was structurally rearranged to become a collage of basement components of the western Alpine–Himalaya collisional orogen (Dimitrijević, 1997; Kräutner and Krstić, 2002; Iancu et al., 2005; Karamata, 2006; Schmid et al., 2008; Plissart et al., 2018). The western Carpathian-Balkan inliers were structurally stacked into a sliced Alpine basement system placed to the west of the Moesian micro-continent (e.g., Săndulescu, 1984; Yanev et al., 2006; Plissart et al., 2018; Spahić and Gaudenyi, 2018; Spahić et al., 2019a, b; Žák et al., 2021). These inliers of pre-Alpine basement terranes crop out across the Danube River from the Southern Carpathians of SW Romania into eastern Serbia (Kräutner and Krstić, 2002; Iancu et al., 2005; Fig. 2). These include (*sensu* Kräutner and Krstić, 2002; Fig. 2): the Vrška Čuka-Miroč Unit (Lower Danubian); the Stara Planina Poreč Unit (Upper Danubian); the Kučaj Unit (Getic); the Lužnica Unit (West Kraishte); the Ranovac-Vlasina Unit (Supragetic); and the Serbo-Macedonian Unit. Towards the east of the central Serbo-Macedonian Unit is the Rhodope Massif, which records imprints comparable to those of the Ordovician Cenerian/Sardic bimodal Middle–Late Ordovician (Bonev et al., 2013).

The Getic/Kučaj nappe/unit (in Alpine configuration) investigated incorporates a sedimentary cover of Ordovician to Carboniferous age (Kräutner and Krstić, 2002; Antić et al., 2016). However, the presence or surface exposure of the Ordovician sequence is not consistent across eastern Serbia; in most cases Ordovician sequences are absent. Limited in size yet widespread gabbroic rocks of the post-Cambrian and pre-Silurian (likely of late Lower Ordovician age) were previously mapped across the northern Getic/Kučaj zone (near Danube River; Bogdanović et al., 1978; Fig. 2). The central segment of the Getic/Kučaj Ordovician sequence (Fig. 3) includes coarsely crystalline gabbros (likely Mesozoic in age; Mrvaljević, 1956).

APPROACH, METHODOLOGY AND (EASTERN) NORTH GONDWANAN AFFINITY

In the literature of the last 50 years, a few papers consider the complex issue of the Ordovician (bio)stratigraphy and, in particular, the Early Paleozoic palaeogeography and tectonics, of the Alpine Carpathian-Balkan sector. Earlier authors collected dominantly biostratigraphic data, comparing the Ordovician succession with documented global examples, often of local character. Nevertheless, important field observations including of the Kučaj Mt. ironstone and its position near Klencuški potok is taken from the available local literature (Mrvaljević, 1956; Krstić and Maslarević, 1998; also in Ferretti et al., 2022; Fig. 3): namely, irregular lenses of chamosite and siderite several meters thick, sandwiched between underlying sandstones and overlying metapelitic rocks (Krstić and Maslarević, 1998). The ironstone is commonly associated with dolomite, calcite, sheridanite, and in places quartz sand. The chamosite is green and occurs in micronodular aggregates (Krstić and Maslarević, 1998). Accumulations resembling pseudo-ooids are rare, whereas siderite occurs as cryptocrystalline aggregates, locally in the form of spherolites. The Kučaj Mt. ironstone has a granular Fe-silicate-rich structure, with dominant iron and manganese, and with trace tungsten (Mrvaljević, 1956). Some recent studies (Chatalov, 2017; Georgiev et al., 2021; and for the Serbo-Macedonian Unit; Antić et al., 2016, 2017) have indicated an “Armorican Terrane Assemblage” inheritance, hinting at Cenerian (Sardic) involvement (Spahić et al., 2021). In addition to revisited stratigraphy and available tectonic-palaeogeographic models, scarce Lower Paleozoic magmatic and detrital zircon record data (e.g., Deleon et al., 1972; Antić et al., 2016; Siegesmund et al., 2018; Abbo et al., 2021; Georgiev et al., 2021, 2022) are reassessed in our study.

In the Kučaj Mountain, vertical and lateral facies changes characterizing a complete Ordovician succession are described from several rather poor exposures. Lithofacies composing these presumably Armorican edifices were logged in detail in road cuts and quarry walls (Barjaktarović, 2007), and are described in the following section. However, a large part of the central Ordovician Getic/Kučaj Mt. sequence is unfossiliferous. Thus, in addition to reassessment of the superpositional relationships of displaced strata (Krstić and Maslarević, 1998; Fig. 4A), we use the position of the ironstone as (i) an auxiliary intra-formational tectonic marker (Veliki Malinik area of Kučaj Mt.; Krstić and Maslarević, 1998; Fig. 3). The presence of the ironstones within the early Middle Ordovician sequence further indicates (ii) shallow or subaerial reworking of large amounts of underlying Fe-bearing rocks (e.g., Matheson et al., 2022). Thus, the ironstone sequence was also used (iii) to provide constraints on possible mafic oceanic crustal Fe-sources, which are consistent with the development of Ordovician near-marginal north Gondwanan seaways (e.g., Sardinia – Oggiano and Mameli, 2006; Matheson et al., 2022). Finally, we discuss the two main tectono-palaeogeographic Cambrian–Ordovician scenarios (Zurbriggen, 2015, 2017a, b vs. that of Stephan et al., 2019).

Fig. 4A – a synthetic stratigraphic column of the complete Ordovician sequence compiled from Veselinović (1975), Krstić and Maslarević (1998) and the current study. Age in green outlines the stratigraphic constraints relative to Lower, Middle and Upper Ordovician stratigraphy *sensu lato* (also in Finney, 2005). The lithostratigraphic column highlights the position of the regional-scale Cenerian unconformity, best observed in a greenstone Supragetic basement unit. On top of the Supragetic is the Kučaj Mt. Ordovician sequence; B – a selected eustatic curve for the Ordovician, including relative abundance of ooidal ironstones. Graph shows the sequence stratigraphic interpretation of successions on the “Western European Platform” in SW Europe (inset from Young, 1992, modified). The interpretation includes the latest Cambrian–Ordovician transgressive (TST) and following highstand (HST) systems tracts. In this study, we juxtaposed the TST and HST with a more recent Ordovician bulk stratigraphy *sensu lato*, further correlating the sequence stratigraphic tracts with the Carpathian-Balkan Ordovician framework (original numbers are black, updated age numbers are in green, taken from Dunn et al., 2021 and references therein). The extracted relative sea-level curve for the Ordovician of SW Europe is to the right (lowstand in sea-level consistent with the palaeogeographic position/shallow water of the Getic/Kučaj area). The Getic/Kučaj ironstone production correlates with the “maximum production stage”, including a late Lower Ordovician fall of sea level (LST at 478 Ma). The “maximum production stage” was succeeded by a HST. The graph also shows a shallow Cambro-Ordovician environment with the stratigraphic position of a deformed brachiopod assemblage

NORTH GONDWANAN STRATIGRAPHIC AND STRUCTURAL INHERITANCE OF THE ORDOVICIAN GETIC/KUČAJ SUCCESSION: A BRIEF SYNOPSIS

THE AGE OF THE SUPRAGETIC BASEMENT

To oldest Neoproterozoic rocks in the area lie to the west of the Getic/Kučaj unit, represented by a complex Supragetic greenschist-grade submarine mafic volcano-plutonic and sedimentary succession (Spahić et al., 2019a). The Supragetic basement unit of eastern Serbia correlates with regional analogues, such as at West Kraishte, and the "Morava nappe" of western Bulgaria (former "Vlasina unit"; Antić et al., 2016; Žák et al., 2021). This unit comprises a lower greenschist-facies basement unit (Popović, 1993; Vasković, 2002; Kräutner and Krstić, 2002; Spahić et al., 2019a), which is the carrier of phosphates as indicators of a reducing environment (Pavlović, 1975, 1977; for a phosphatic ironstone environment see Dunn et al., 2021). The Neoproterozoic–Lower Ordovician age of these rocks is confirmed by stratigraphically lowermost graphitic schists (fossil vesicles of the alga *Archaeofavosina simplex* Naum; Kalenić et al., 1975; Ferretti et al., 2022). The age of the sequence is constrained by the inarticulate brachiopods *Lingulobolus hawkei*, *Pseudobolus*? *salteri* and *Thysanobolus*? *sp.*, spanning the Early Ordovician *sensu lato* (Gutierrez-Marco et al., 1999; Krstić et al., 2008). The locally analogous unit is referred to as the "Beljanica green schists" (Getic/Kučaj nappe; Fig. 3), which was tectonically displaced from the parental succession during the pervasive tectonometamorphic Variscan and Alpine events. On top of the "Beljanica series" is the Ordovician metasedimentary succession investigated (Fig. 3). The biostratigraphical synopsis of dominantly Cambro-Ordovician palynomorphs below (based on Veselinović, 1972a, b; Ercegovac et al., 1995; Ercegovac and Đajić, 1996; Đajić, 1996) provides additional data regarding the development of the Ordovician Armorican successions and their Gondwanan inheritance (Gutierrez-Marco et al., 1999; Krstić et al., 2008; Antić et al., 2016; Žák et al., 2021; see Ferretti et al., 2022, for a discussion).

AGE CONSTRAINTS ON THE ORDOVICIAN METASEDIMENTARY SUCCESSION OF EASTERN SERBIA

In general, the Lower Paleozoic Getic/Kučaj sequence along with its east Serbian analogues, including the Svoge unit of SW Bulgaria (Krstić and Maslarević, 1998; Krstić et al., 2008; Georgiev et al., 2022), comprise metasandstone beds, tens of meters thick (reflecting shallow shelf seas; Krstić and Maslarević, 1998; Fig. 4A). The oldest preserved lower Paleozoic record associated with the Getic/Kučaj unit (Fig. 2) is within the Homolje Mt. (Đajić, 1996; Krstić et al., 2003; Banjac, 2004). The Homolje succession largely resembles that of the Getic/Kučaj Mt., with some specific features (Banjac, 2004). The Homolje Mt. area reveals a gneiss-dominated Alpine nappe, positioned above the Neoproterozoic–lowermost Paleozoic greenschist-facies nappe (Banjac, 2004). The lowermost Paleozoic sedimentation was interrupted by a regional hiatus (Banjac, 2004). After the hiatus, the Ordovician sequence accumulated a thickness of over 1000 m. The lowermost section comprised of meta-sandstones includes *Protosphaeridium* sp., *Leiosphaeridia* sp., *Lophosphaeridium* sp., *Leiomarginata simplex*, *Granomarginata prima* and *Verzchachium reductum* (Ercegovac and Đajić, 1996; also in Banjac, 2004). The anchimetamorphic siliciclastic succession represents an initial stage of deposition, conditionally designated to the stratigraphically lowermost Ordovician. This element of the lower Paleozoic succession contains also rare *Sphaeromorphitae* (*Leiospheridia* and *Lophosphaeridium*) and *Polygonomorphitae* (*Veryhachiuk reductum* type). However, *Eomycetopsis crassiusculum, Vendotenia* sp. (recorded in the Neoproterozoic of Scotland and in schists of Alberta; Đajić, 1996) indicate the probable presence of rocks of older, Cambrian age (presence of gradual Cambrian–Ordovician transition). The second cycle, characterized by quartzitic sandstones, has palynolomorphs dominated by the family Sphaeromorphitae: *Granomarginata prima, Leieomarginata simplex, Uniporata* sp., *Bacispheridium* sp. and cf. *Symplasosphaeridium* sp., and includes chitinozoan fragments (Đajić, 1996). This association suggests the stratigraphically lowermost Ordovician. According to the brachiopod fauna – *Thysanotos siluricus* Eichw., *Obolus* sp., *Lingullela* sp., *Orbiculoidea* sp. – the age is Tremadocian (location Ćerček; Veselinović, 1972b; Fig. 3). An earlier study (Krstić and Maslarević, 1998) identified a highly deformed assemblage of the brachiopods *Obolus (Lingulobolus) feistmanteli* (Barr.), *Obolus bamindei* from the Czech Tremadoc, *Obolus complexus* Barr., and *Orbiculoidea* sp. Veselinović (1972) recorded *Thysanotos siluricus* (Eichw.), a marker fossil characterizing the Lower Ordovician (Tremadocian–Arenig) of Europe. The upper part of the Lower Ordovician sequence is characterized by grey, greenish and purple laminated, medium- to fine-grained, rarely coarse, quartz metasandstones to subarkoses. The Alpine nappe-stacked structure resulted in the displacement of the Upper Ordovician sequence, placing the latter underneath the Lower Ordovician (Krstić and Maslarević, 1998; Fig. 4A). Primary bedding planes are still observable in this metasedimentary succession (Figs. 4A and 5A,B). However, the types of contact between the component Ordovician sequences are poorly constrained, and may be either erosional or non-erosional, or gradual and without hiatuses (Krstić and Maslarević, 1998).

Regarding the suggested Middle Ordovician (inner shelf; Fig. 6A), the sequence exposed at Kučaj Mt. lacks fossils (Krstić and Maslarević, 1998). The ironstone sequence was recognized earlier and mapped as of Middle Ordovician age (Krstić and Maslarević, 1998; Fig. 4A). Such a stratigraphic position is consistent with sequence stratigraphic interpretations and associated Ordovician sea-level reconstructions (Young, 1987), in particular with the maximum production stage (Young, 1992; Fig. 4B). Nevertheless, we have updated the stratigraphic constraints on the local Ordovician, in particular the Lower Ordovician *sensu lato* (cf. the chart in Dunn et al., 2021; Fig. 4B). Lithologically, it is a highly heterogeneous sequence of rocks composed of metapsammite and metapelite, which alternate both laterally and vertically (Krstić and Maslarević, 1998). The metasandstones are white to pale grey and are well-sorted. The chamosite and siderite beds investigated are several metres thick, and form irregular lenses overlying quartz sandstones that in turn overlie metapelite (upper segment of the Kločanica River; Fig. 3). Chamosite and siderite are the principal constituents of these rocks and are associated with dolomite, calcite, sheridanite, and occasionally quartz. Chamosite is green in micro-nodular aggregates fine flakes in streaks. Accretions resembling pseudo-ooids are rare. Siderite forms cryptocrystalline aggregates, in places in the form of spherulites. There are several Fe-bearing Ordovician localities (Krstić and Maslarević, 1998; Gutierrez-Marco et al., 2003). These "oolitic ironstones" are of pre-Hirnantian age (Krstić and Maslarević, 1998; Yanev et al., 2006), being of middle Berounian, and lower and upper Orenitian age (Grohoten Formation; Gutierrez-Marco et al., 2003). This barren Middle Ordovician sequence of the Kučaj Mt. includes abundant magnetite, scarce zircon, apatite, pyroxene, green amphibole, epidote and chlorite (Krstić and Maslarević, 1998).

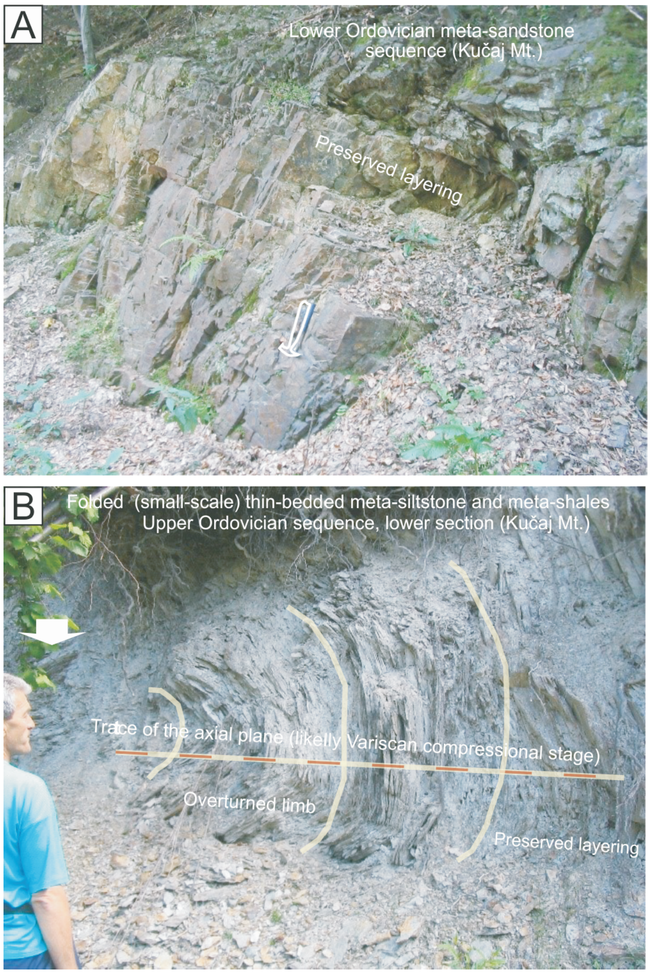


Fig. 5. Ordovician exposures in the Kučaj Mt.

A – a Lower Ordovician metasandstone sequence; **B** – folded Upper Ordovician metapelites

At a regional scale, a typical Upper Ordovician age (meta-sandstone, Zvonačka Banja locality; 14 samples, Đajić, 1996) is indicated by *Lophosphaeridium citrinum*, *L.* sp. (aff. Pervarerum), *L.* cf. *papillatum, Leiosphaeridium* sp. (cf. *Le. minuta*). A metaclaystone (Mali Malinik, Bauca) contains *Mirchystridium varians*, *Leiosphaeridia* sp., *Priscogalea* sp., *Veryhachium* sp. (type – breve), *Lophosphaeridium* cf. *pervarerum* and *Mirchystridium radinas.* The entire succession comprises Caradocian shallow-marine siliciclastic rocks of the Homolje Mt. (Krstić and Maslarević, 1990). This succession has, according to earlier palynological studies, a Middle–Upper Ordovician age, whereas a recent study indicated an Upper Ordovician to Silurian age span (*Acanthomorphitae*, *Polygonomorphitae*, *Sphaeromorphitae*, *Netromorphitae* and *Hercomorphitae;* Đajić, 1996; Fig. 4A). According to the authors, these palynomorph associations are equivalent to those in Belgium (*sensu* Martin, 1968; Đajić, 1996). The Upper Ordovician of the Kučaj Mt. area reveals a dark grey to black thin-layered, laminated sandstone, and metamudstone, which includes graphitic matter (Fig. 5B). In the Kučaj Mt. area, a green-mottled metashale is documented (equivalent to the Cerecel Formation of the Svoge unit; Krstić and Maslarević, 1998). Despite indications that later Variscan interference has not influenced this presumed eastern Gondwana fragment (Stephan et al., 2019), compressional deformation structures are visible in the field. A number of folds affecting the Upper Ordovician sequence was observed in the fieldwork; Fig. 5B). The presence of nappe-stacked, displaced Upper over Lower Ordovician (Fig. 4A), indicates that the post-Variscan Alpine compression had largely a brittle deformation character (e.g., Vangelov et al., 2013; Plissart et al., 2018; Balkanska et al., 2021). The uppermost Ordovician succession (Hirnantian layer with *Glyptograptus persculptus*) is overlain by Lower Llandovery deposits (Krstić et al., 2005). There is a transgressive relationship between the Hirnantian (glaciomarine) metasandstones (Kučaj Mt.; Krstić and Maslarević, 1998; Barjaktarović, 2007; Fig. 4A), and pebbly sandstones of the Svoge unit (Cerecel beds of western Bulgaria; Gutierrez-Marco et al., 2003) and the underlying Upper Ordovician sequence. The Hirnantian sequence is followed by earliest Silurian grey-green foliated to thin-bedded phyllites (Kučaj Mt.; Krstić et al., 2005). The Llandovery comprises grey-green foliated to thin-bedded phyllites, equivalent to the Cerecel beds of Bulgaria. The metasandstones contain Upper Ordovician acritarchs: *Lophosphaeridium citrinum*, *L. parverarum, L. cf. papilatum, Lophosphaeridium p.*, *Brochopsophosphera* cf. *uralica*, *Trachipsophosphaera* sp., *Leiosphaeridia* sp. type C, *Leiomarginata simplex*, *Priscogallea* sp., ?*Tylotopallia* sp. and *Michrystridium pallidum* (Ercegovac and Đajić, 1996). In the uppermost section of the metasandstone beds, there are fragments of older Ordovician rocks: metasandstones, metasiltstones and metashales. The metasandstones are overlain by graphitic metapelites (0.5 m), characterized by the graptolite *Glyptograptus* sp., including graphitic metapelites and lydites of the *acuminatus* graptolite Biozone (marking the lowermost Silurian; Krstić et al., 2005). The late Llandovery was a period of global sea-level rise, indicated by the presence of black graptolitic shales (e.g., Sachanski et al., 2010, and references cited therein).

THE ORDOVICIAN “CENERIAN OROGENY” AND BACK-ARC CRUSTAL PROCESSES: GETIC/KUČAJ AND SUPRAGETIC INFERENCES

EVIDENCE OF CENERIAN (SARDIC) COMPRESSION

Recent reconstructions of former Cambro-Ordovician peripheral terranes relative to north Gondwana (Armorican-type basement units in the Carpatho-Balkanides; Getic/Kučaj/Sredna Gora, Supragetic/Serbo-Macedonian/Ograzhden/Morava basement; e.g., Kräutner and Krstić, 2002; Balintoni et al., 2010, 2014; Kounov et al., 2012; Zagorchev et al., 2012; Antić et al., 2016; Iancu and Seghedi, 2017; Spahić and Gaudenyi, 2018) imply lithospheric-scale accretionary processes led by accretionary-type subduction and an episode of crustal growth in the hanging-wall position (e.g., Crook, 1980; Martini et al., 1991; McKerrow et al., 1991; *sensu* Cawood et al., 2009; Zurbriggen, 2015, 2017a, b; Moghadam et al., 2018; Oriolo et al., 2021; Siegesmund et al., 2021; Spahić et al., 2021; Fig. 7A). However, some more recent palinspastic reconstructions impose a transcurrent faulting episode affecting the Gondwanan stable platform or passive margin also referred to as the Armoric spur (Garfunkel, 2015; Franke et al., 2017; Puddu et al., 2018; Stephan et al., 2019). In the case of the Carpathian-Balkan belt, scarce data indicate latest Cambrian high-strain deformation (shear zones, migmatites; Spahić et al., 2021) and metamorphism, recorded in the nearby Cambrian gneissic Serbo-Macedonian Unit (Rb/Sr method on whole-rock samples from paragneiss yield 488 Ma, Balogh et al., 2004). The latest Cambrian event likely represents the initial stage of the north Gondwanan collision.

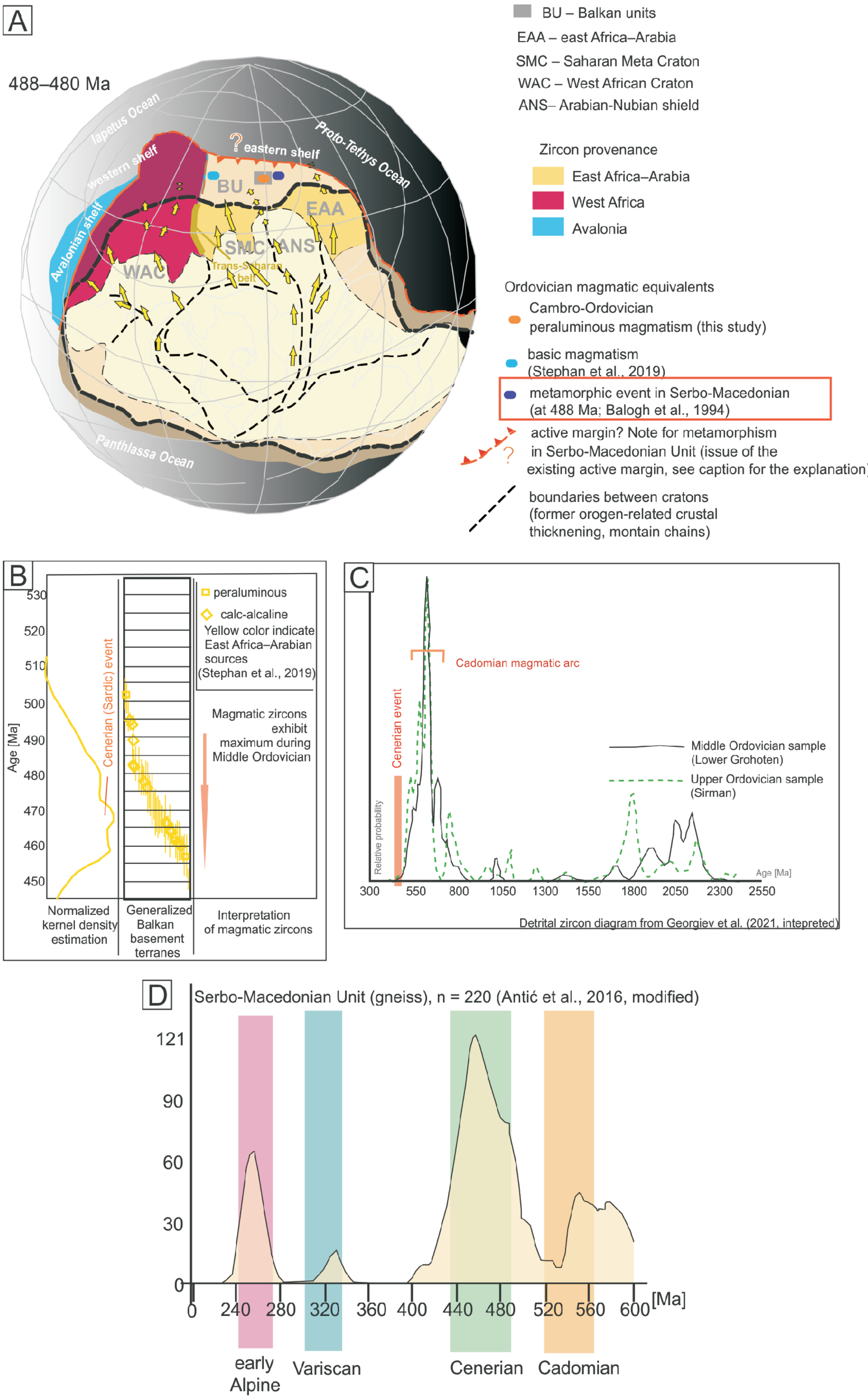


Fig. 6A – an Ordovician palaeogeographic reconstruction, exposing the Carpathian-Balkan Getic/Kučaj basement, which underwent the Cenerian (Sardic) event (inset from Stephan et al., 2019, significantly modified). There are two Cenerian (Sardic) explanations or palinspastic options: (i) no Ordovician active margin (e.g., Stephan et al., 2019) or (ii) the Cenerian (Sardic) active margin having the polarity of subduction directed southwards (Zurbriggen, 2015). The Getic/Kučaj unit experienced compressional lifting in the Cenerian (Sardic) followed by ironstone formation (after the late Lower Ordovician transgressive episode); B – magmatic ages across Balkan basements (data from Stephan et al., 2019); C – relative probability plots from sampled Middle and Upper Ordovician sequences (data taken from Georgiev et al., 2021, modified). The peak exhibiting the Cadomian maximum accords with a voluminous sourcing episode imprinted by detrital ages spanning 0.54 to 0.44 Ga (Bahlburg et al., 2009). The second and third peaks are visible in both samples, pinpointing the decreasing magmatic activity related to back-arc opening; D – detrital zircon data of the gneissic Serbo-Macedonian Unit (data from Antić et al., 2016, slightly modified). The data undoubtedly show the Cenerian (Sardic) peak

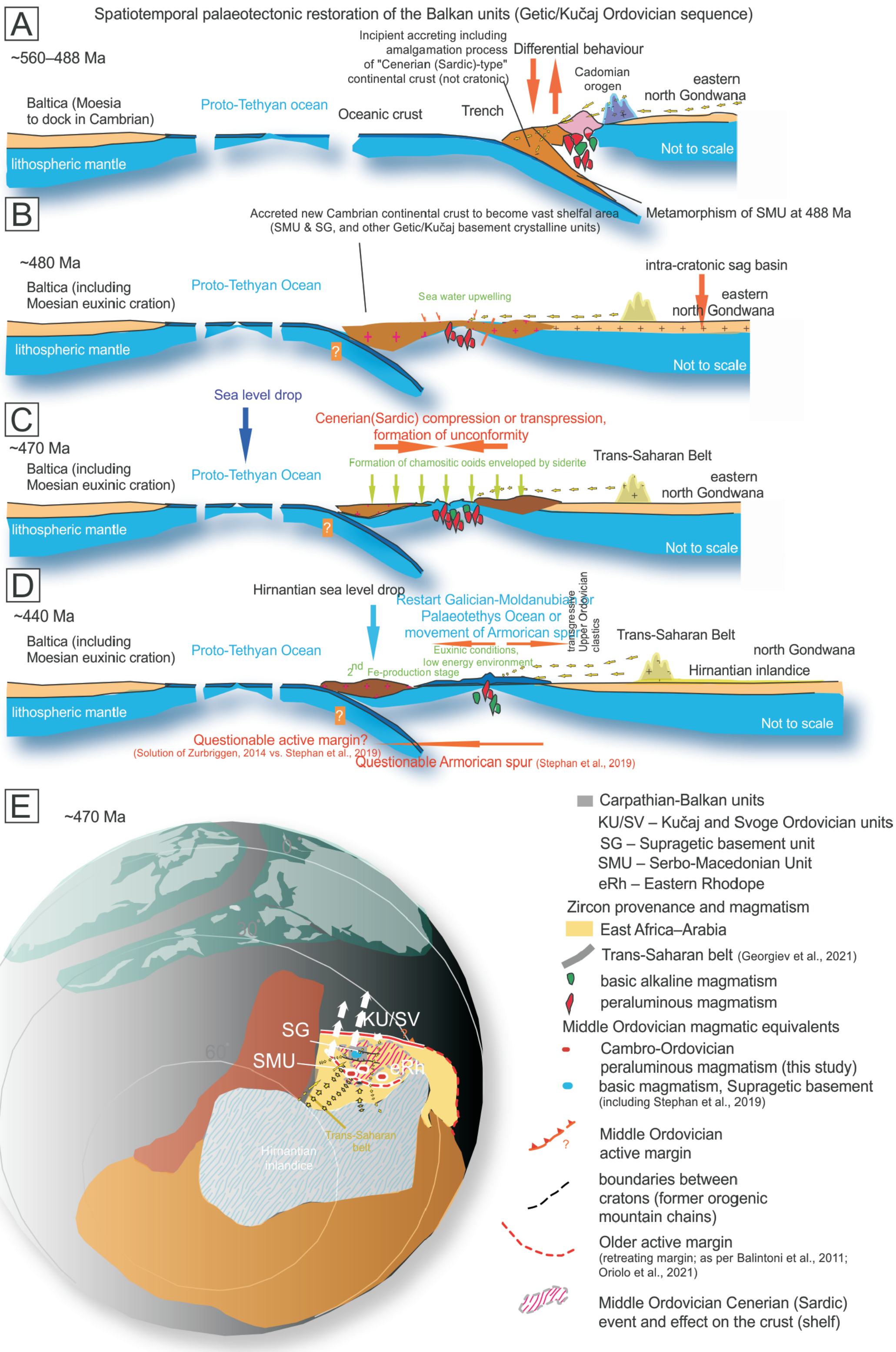


Fig. 7. Tectonic-palaeogeographic model of the Ordovician Kučaj sequence, including the Supragetic basement during the Lower Ordovician Cenerian (Sardic) "orogeny" (Fig. 7C – inset from Stephan et al., 2019, with significant modification)

A – formation of Cadomian–late Cadomian magmatic arc during the Neoproterozoic–Cambrian, onset of peripheral crustal thickening. The age of metamorphism is according to Balogh et al. (2004); **B** – subduction beneath a stabilized Gondwanan shelf produced extension and emplacement of limited mafic melts in the incipient back-arc rift valley (Lower to beginning of Middle Ordovician); **C** – the peak of the Cenerian (Sardic) event, mild compression, a shallow sea, and opening of the incipient back-arc rift valley. Opening produced mafic volcanic rocks, allowing the formation of Fe-rich minerals; **D** – Late Ordovician transgression (see Fig. 4B) followed by regional extension (likely at the expense of the active margin), and the terminal Silurian detachment and dispersal of peripheral mini-continents towards western Moesia (Baltica); E – palaeogeographic reconstruction of the Cenerian (Sardic) event; the model includes a questionable active margin/subduction-accretion stage (the model of Stephan et al., 2019 proposes a passive margin). The presence of a volcanic arc (as in the Ordovician Getic/Kučaj sequence investigated herein) pinpoints an active margin positioned along the eastern north Gondwanan craton. Locations of mafic and calc-alkaline magmatism are in blue, i.e., red colours. The process likely restarted in the earliest Silurian, allowing separation of Carpathian-Balkan peripheral terranes from eastern north Gondwana (as per Bonev et al., 2013; Maino et al., 2019; Spahić et al., 2021; Topuz et al., 2021)

This event was succeeded by a transgression and a Lower Ordovician high-systems-tract (Fig. 4) marking new, widespread deposition across this segment of the north Gondwanan shelf. Importantly, the actual age of the "Lower Ordovician" of east Serbia ends with the Tremadocian Stage (Fig. 4A). By comparison with global Ordovician stratigraphy (Fig. 4), the end of the Tremadocian actually represents the middle section of the Middle Ordovician of the Global Series (see Georgiev et al., 2022, for details). In this Middle Ordovician compression episode are placed the deformed Tremadocian brachiopods, further indicating immediately post-Tremadocian crustal shortening. In addition, a major regression episode is documented at the end of "Lower Ordovician" (Banjac, 2004) or at the end of Middle Ordovician of the Global Series. Further evidence of Middle Ordovician compression and uplift is a 1600 m-thick "upper part of the Vlasina complex". This upper sequence unconformably overlies the Arenigian terminal succession belonging to the "lower unit" (Krstić et al., 2003). To summarize, the Getic/Kučaj Ordovician sequence exposes clear evidence of Cenerian (Sardic) compression, showing an eastern north Gondwana inheritance (according to Stephan et al., 2019, exclusively the eastern north Gondwanan segment experienced the latter event):

- pre-Variscan Cenerian (Sardic) compression caused deformation of a brachiopod assembly within the Lower Paleozoic Getic/Kučaj clastic sequence, succeeded by the formation of the ironstone sequence investigated (transgressive systems tract; Fig. 4);
- in addition, data of Stephan et al. (2019) show a clear correlativity of magma generation across the Carpathian-Balkan basements and its involvement with the Cenerian (Sardic) events (magmatic zircons; Fig. 6B, C);
- detrital zircon data include a Cenerian peak (~480–440 Ma), documented within the gneiss-bearing Serbo-Macedonian Unit (see Antić et al., 2016: fig. 9, "Lower Complex"; Fig. 6D).

ORDOVICIAN FE-BEARING IRONSTONES AS MARKERS OF A BACK-ARC SEAWAY

Ordovician oolitic ironstones of the "Paleozoic North African Ironstone Belt" extend along the margin of the Gondwana craton (Guerrak, 1988), thus being present across western and central European basement terranes (Young, 1992; Trela, 2008). The most common occurrence of chamosite and siderite is in banded iron formations, representing the principal iron-bearing minerals in ironstones, often associated with underlying fine-grained lithified claystone sequences (Deer et al., 2013a). In addition to the Ordovician ironstone maximum production stage (Oggiano and Mameli, 2006; Dunn et al., 2021), banded iron formations are documented across most Precambrian continental regions, together being a principal source of iron and phosphates (e.g., Żelaźniewicz et al., 2009; Dunn et al., 2021), such as that of the Supragetic basement unit. Oolitization is a sedimentary process of accretion developed in a quiet environment (Guerrak, 1988) with low sedimentation rates, and thus has often been described as part of a transgressive initial deposit above an unconformity (Young, 1992). The ironstone sediment is also ascribed to the formation of aggradational parasequence on a storm-dominated shelf characterized by recurrent coastal upwelling (Dunn et al., 2021). Ordovician ironstones may also be correlated with the bottom of fining-upwards sequences on shallow shelves (transgressive conditions; Guerrak, 1988; Pufahl et al., 2020). Such a restricted near-shore environment that was semi-connected with inconsistently oxygenated Ordovician oceans provided a suitable anoxic hydrothermally-enriched habitat for the appearance of ferruginous bottom water (Dunn et al., 2021; Li et al., 2021).

In the oolitic Jurassic ironstones of the English Midlands, siderite represents the principal ore mineral appearing along with chamosite and hydrated iron oxides. The origin of this particular ironstone deposits is not fully comprehended; theoretically, iron is a derivative extracted from continental sources (processes of weathering), transported as the bicarbonate and precipitated once captured CO_2 was absent to keep iron as the soluble bicarbonate. For example, weathering of erosion-exposed (oceanic) mafic rocks and related epiclastic rocks contributes to enrichment of iron, the process indispensable for the deposition of chloritic oolitic claystone (Oggiano and Mameli, 2006). Much siderite results from the carbonation of chamosite, and it may likewise be formed by the contemporaneous replacement of calcite by $FeCO_3$ (Deer et al., 2013a). Siderite has appeared as a hydrothermal mineral in metallic veins, in paragenesis with manganese; the iron-rich carbonates of the Coeur d'Alene district of Idaho are associated with Pb, Ag and Zn sulfide orebodies. Siderite occurrence in the Ivigtut cryolite deposit is well-documented (table 58, analysis 4 in Deer et al., 2013a); however, this cryolite deposit is linked to a pegmatitic pneumatolytic origin. Interestingly, Fe-chlorite is a dominant clay mineral in Arctic Sea sediments, whereas montmorillonite and kaolinite indicate mid-latitude seas, depending on the weathering intensity in the source areas (Martini et al., 2001).

The Getic/Kučaj granular Fe-silicate-rich ironstone has 35.72% Fe, 1–2% Mn, and locally traces tungsten (Mrvaljević, 1956). Chamosite and siderite, as the principal constituents of these rocks, are associated with dolomite, calcite, sheridanite, and sometimes quartz (Krstić and Maslarević, 1998). The chamosite is green colour, forming micro-nodular aggregates or as fine flakes, having the form of streaks, whereas pseudo-ooids are scarce. Siderite occurs in the form of cryptocrystalline aggregates, occasionally having the shape of spherulites. Chamosite, siderite, and sheridanite were identified by differential thermal (DTA) and XRPD analyses (Krstić and Maslarević, 1998). A close inspection of the XRPD pattern (diffraction lines) corroborates the presence of siderite ($FeCO_3$; Deer et al., 2013a; ICDD-PDF: 83-1764), including the components of the solid-solution series of the chlorite group (between clinochlore, $(Mg_{10}Al_2)[Al_2Si_6O_{20}](OH)_{16}$ and chamosite, $(Fe^{2+}{}_{10}Al_2)[Al_2Si_6O_{20}](OH)_{16}$; Deer et al., 2013b). However, reevaluation shows that it is difficult to confirm any presence of chamosite and sheridanite (without chemical analysis), because these minerals are constituents of the chlorite group with exceptionally similar XRPD patterns. With regards to the abundant chlorite, this is a very common mineral in a widespread low- to medium-grade metamorphic assemblage (Supragetic basement, "Beljanica series"; Figs. 2 and 3). Chlorite is formed at temperatures reaching ~400°C and pressures of ~0.3 GPa. Chlorites are also a common constituent of igneous rocks due to the hydrothermal alteration of the embedded primary ferromagnesian minerals. Notably, chlorites are a common by-product of weathering and appear in many argillaceous rocks, including some iron-rich deposits (Deer et al., 2013b).

The presence of pervasive bioturbation, coupled with the ironstone sequence, likely indicates a low-energy coastal habitat, which allows fallout from suspension in a low-oxygen offshore setting (Pufahl et al., 2020, and references cited therein). Such conditions (Krstić and Maslarević, 1998) indicate the presence of a shallow inner shelf consistent with the "Oxygen Minimum Zone" (Mathesson et al., 2022; Fig. 7C–E). The shallow environment is consistent with the Cambro-Ordovician high-stand systems tract (Fig. 4). This high-stand systems tract at Cambrian–Lower Ordovician sea level prevented subaerial exposure of the Gondwanan shelf. The inner shelf or tidal flat was in a very shallow environment lasting up to the ca. Early–Middle Ordovician boundary (or beggining of the Middle Ordovician), the formation of unconformity and onset of a transgressive systems tract (Guerrak, 1988; Pufahl et al., 2020; Fig. 4). The suggested Early–Middle Ordovician regional uplift and shallow setting is consistent with the underlying deformed brachiopod fauna. The ironstone accumulated by compensating the precursory low-stand conditions (Fig. 7C, D).

BRIEF COMPARISON WITH REGIONAL BASEMENT ANALOGUES: EVIDENCE OF BACK-ARC IMPRINTS

The presence of post-Ordovician to pre-Silurian (or Ordovician age) gabbro intrusions belonging to the northeastern Getic/Kučaj nappe (Bogdanović et al., 1978; Fig. 2) suggests the presence of an Ordovician magmatic arc or intraplate intrusive equivalents (Fig. 7E). Another regional example of back-arc activity is inferred within the Rhodopean massif of the Carpathian-Balkan thrust belt (Bulgaria). Back-arc north Gondwanan activity is constrained by Ordovician low-Ti tholeiitic to calc-alkaline gabbros/basalts and plagiogranite of MORB-IAT MORB-type with a back-arc basalt signature (Bonev et al., 2013; Fig. 7E). Back-arc developments most likely contributed to delivering east-west opening of either the Rheic Ocean (McKerrow et al., 1991; Nance et al., 2010, 2012; Kounov et al., 2012; Linnemann et al., 2011; Şen, 2021a) or the onset of the eastern Rheic (e.g., Bonev et al., 2013; Chatalov, 2017; Maino et al., 2019; Şen, 2021b). The peripheral fragmentation of north Gondwana is further indicated by an early Silurian felsic episode emplaced and documented within the Serbo-Macedonian Unit (476–433 Ma and 439 ±2 Ma; Antić et al., 2016; Fig. 7D). Silurian detachment of Carpathian-Balkan peripheral terranes triggered the onset of Silurian, Devonian, and Lower Carboniferous deposition (e.g., Krstić et al., 2003, 2005, Spahić et al., 2019a, b; Šoster et al., 2020). Such a conclusion is additionally supported by the fact that the entire cluster of Carpathian-Balkan basement terranes experienced Variscan deformation (e.g., Iancu et al., 2005; Antić et al., 2017; Spahić et al., 2021). Variscan deformation is not predicted for peripheral eastern North Gondwanan terranes (terranes positioned to the east of the Armorican spur; Stephan et al., 2019).

CONCLUDING REMARKS

The displaced pre-Mesozoic Variscan terranes of the Carpathian-Balkan basement units incorporate several high-grade crystalline down to meta-sedimentary basement branches of early Phanerozoic age, in particular, the Getic/Kučaj basement (Kräutner and Krstić, 2002; Getic/Kučaj nappe; Iancu et al., 2005; Seghedi et al., 2005; Antić et al., 2016; Spahić and Gaudenyi, 2018; Fig. 2). The regionally largest Getic/Kučaj nappe (Fig. 2) was either derived from the periphery of the east northern Gondwanan shelf (Stephan et al., 2019) or most likely detached from the Ordovician active margin (Zurbriggen, 2015; Fig. 7E). Other inferences are as follows:

- Ordovician contraction and back-arc activity determined the following bipartite eastern Gondwana-related peripheral events: (i) transient Early Ordovician Cenerian (Sardic) compression affecting the Lower Ordovician Getic/Kučaj sequence and nearby basements (represented by the 488 Ma metamorphic event, and detrital zircon data in the Serbo-Macedonian Unit, and also by an assemblage of highly distorted brachiopods of Lower Ordovician age; Krstić and Maslarević, 1998), (ii) the hitherto unexplained inner-Supragetic unconformity (“lower vs. upper Vlasina unit”; Krstić et al., 2003; Antić et al., 2016), including (iii) the presence of mafic-type Ordovician magmatism;
- ironstone production was likely supported by the underlying Supragetic-Getic greenschist basement, including the “Beljanica greenstones”. The Ordovician model proposed provided conditions capable of a sustained supply of Fe into a clast-supported underlying lithified sedimentary level to become hard ironstone;
- Ordovician mafic volcanic rocks of the NE Getic/Kučaj nappe likely reflect the onset of Rheic ocean lithosphere production, along its eastern flank;
- The new constraints on the Cenerian (Sardic) event in Balkans are consistent with the well-documented Ordovician developments recorded across southern European basements. In the Balkans, Cenerian (Sardic) accretionary interference is of (early) Middle Ordovician age.

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