Geological Quarterly, 2023, 67: 4
DOI: http://dx.doi.org/10.7306/gq.1675

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

Darko SPAHIĆ[1, *], Pavle TANČIĆ[2] and Dejan BARJAKTAROVIĆ[1]

[1] Geological Survey of Serbia, Rovinjska 12, 11000 Belgrade, Serbia; ORCID: 0000-0002-5832-0782 [D.S.]

[2] University of Belgrade, Institute of Chemistry, Technology and Metallurgy, Department for Catalysis and Chemical Engineering-National Institute of the Republic of Serbia, Njegoševa 12, 11000 Belgrade, Serbia; ORCID: 0000-0002-4024-710X [P.T.]

Spahić, D., Tančić, P., Barjaktarović, D., 2023. Early Paleozoic Cenerian (Sardic) geodynamic relationships of peripheral eastern north Gondwana affinities: revisiting the Ordovician of the Getic/Kučaj nappe (eastern Serbia). Geological Quarterly, 67: 4, doi: 10.7306/gq.1675

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 avilable 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; Zurbriggen, 2014, 2017a,b; Cocco and Funneda, 2017; 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 indicates 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-

* Corresponding author, e-mail: darkogeo2002@hotmail.com

Received: November 29, 2022; accepted: January 11, 2023; first published online: XXXX

ing in the Ordovician (e.g., Kroner and Romer, 2013; Zurbriggen, 2015, 2017a,b; Álvaro et al., 2020; 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, 2017; 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., 2012), 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., 2017; 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., 2018; 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., 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., 2021; 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; Krstić and Kräutner, 2003; 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,

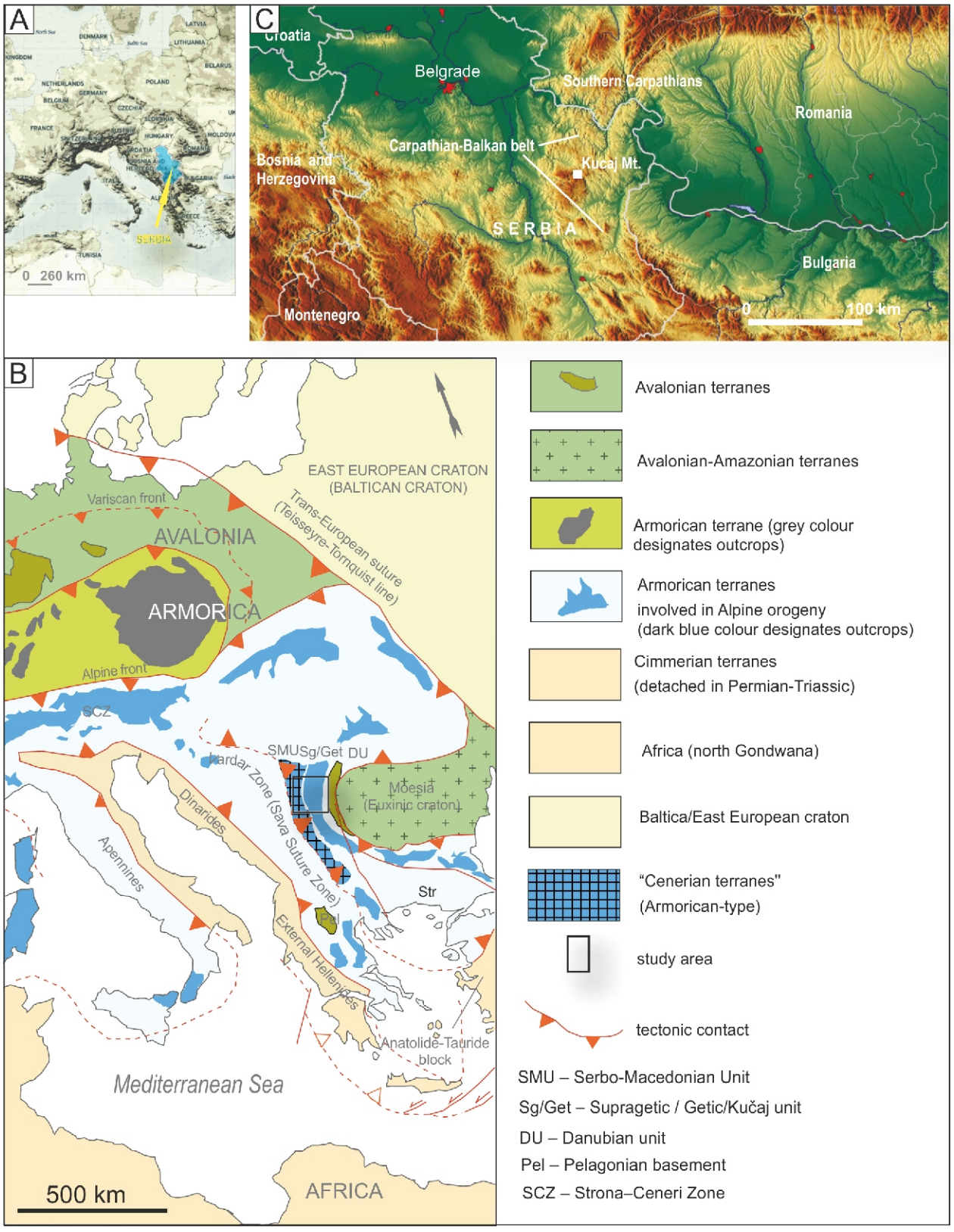


Fig. 1A – the Alpine domain of Europe (Gauss–Krüger to WGS84 coordinate transformations (svemir.co); B – distribution of Avalonian vs. Cadomian vs. Cimmerian microcontinents, embedded into what is now Western, i.e, Central and South-east Europe (Spahić, 2022a, b), respectively (inset from Topuz et al., 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)

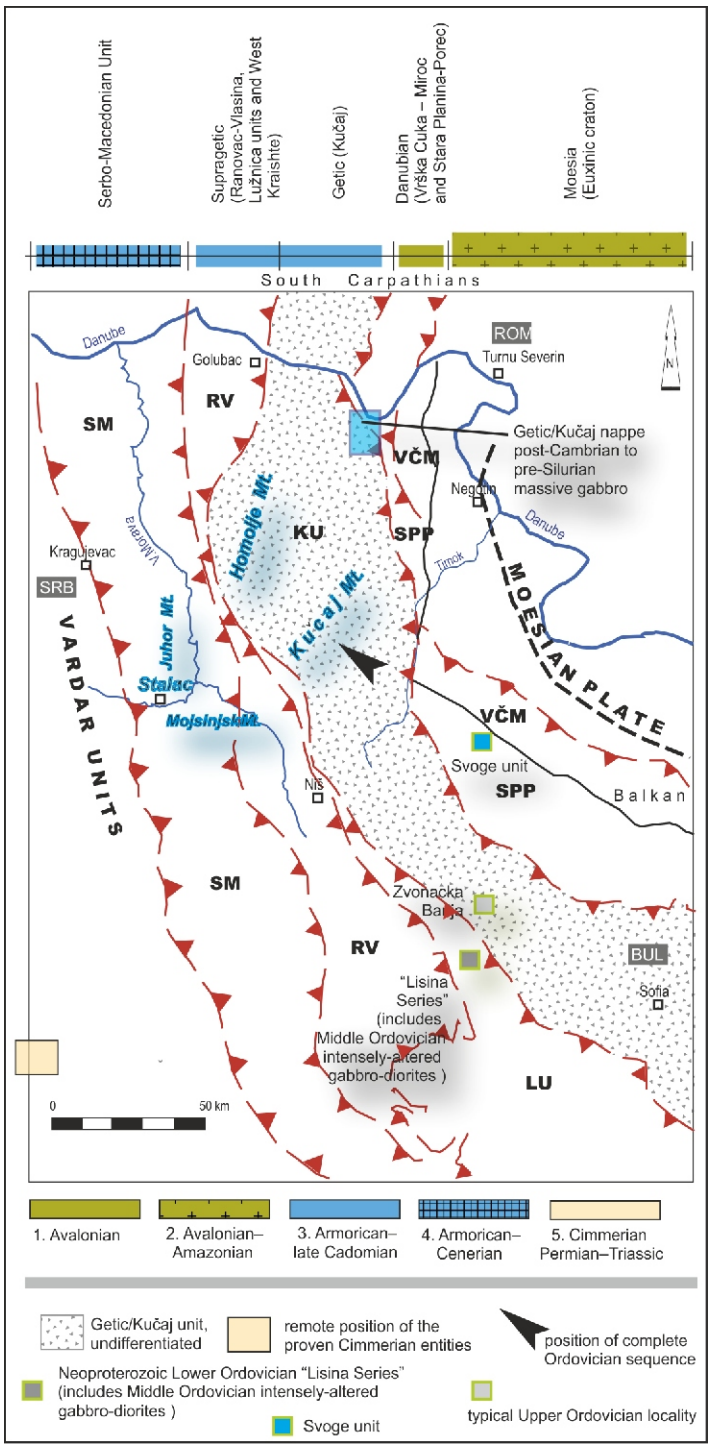


Fig. 2. Main tectonic units surrounding western Moesia (Kräutner and Krstić, 2002), with documented Peri-Gondwanan inheritance (data taken from Spahić and Gaudenyi, 2018, and references cited therein)

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)

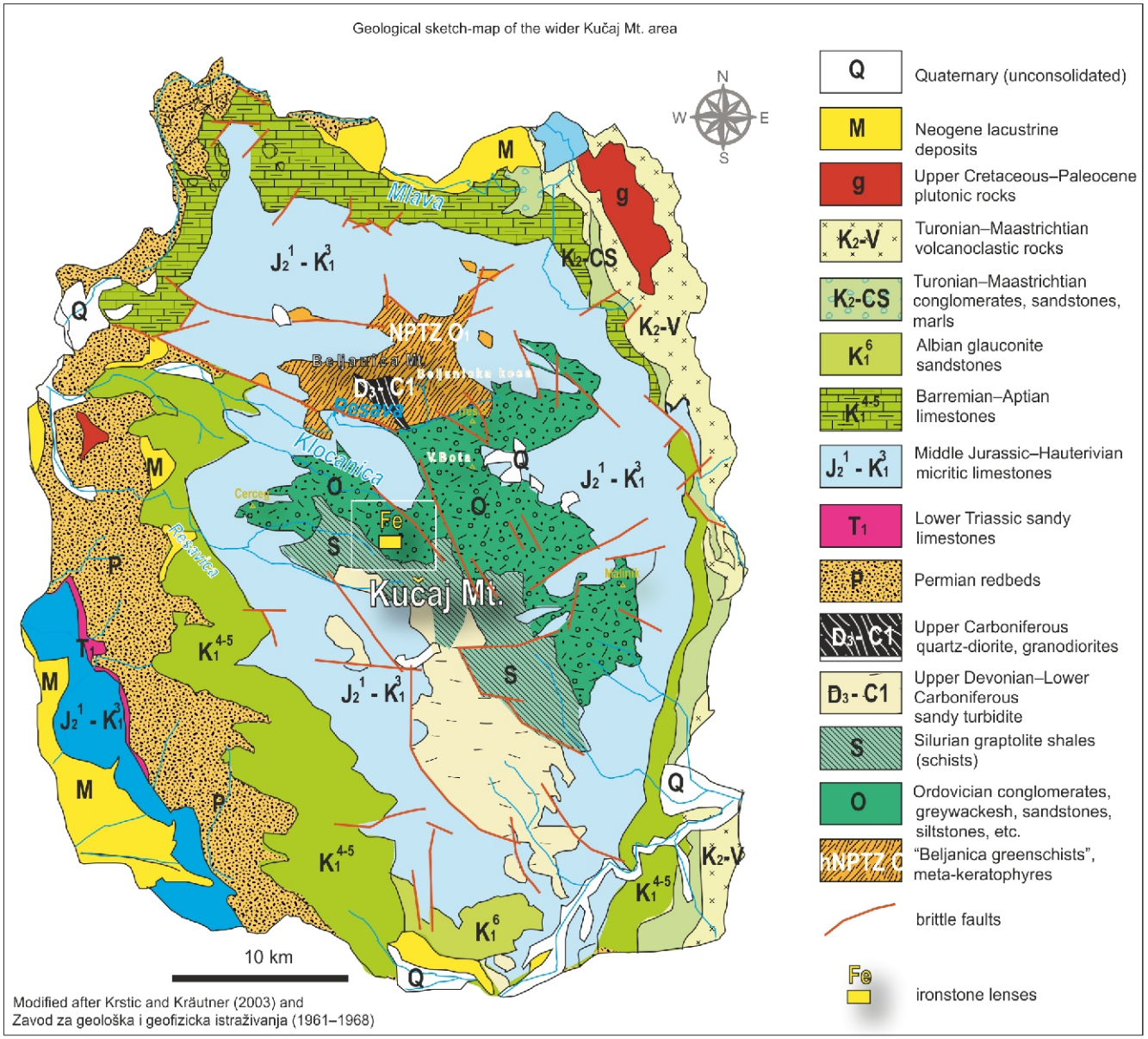
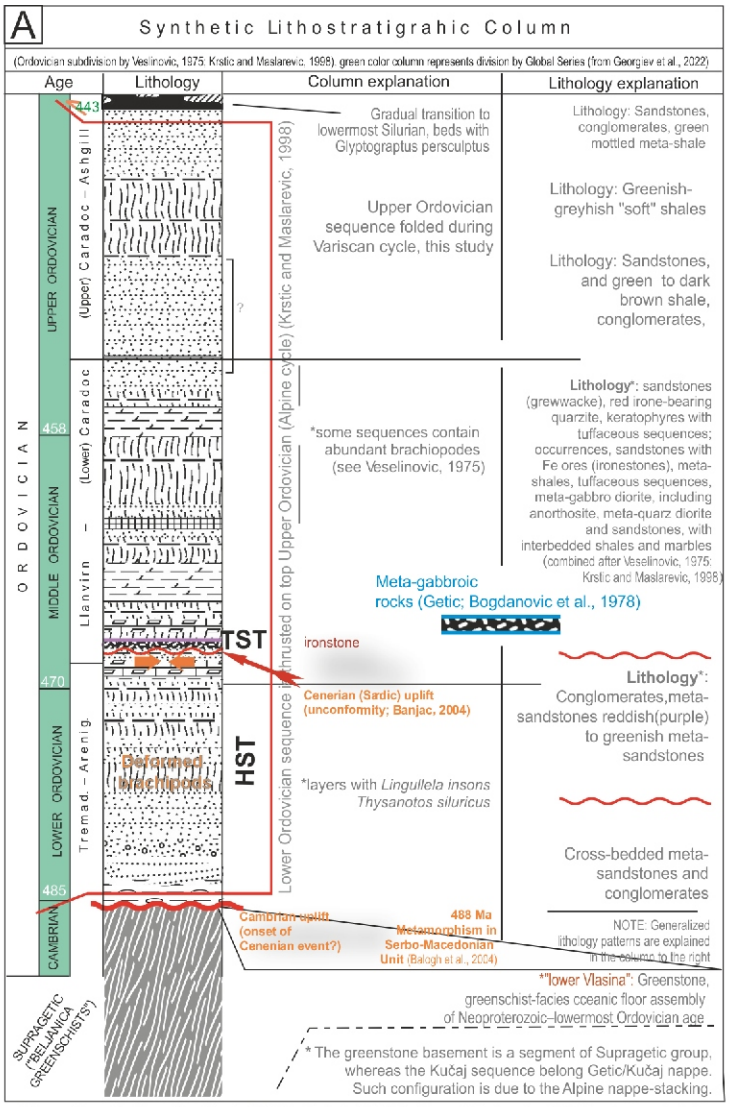


Fig. 3. Geological map of the wider area of the Kučaj Mt. (inset from Petrović et al., 2020; redrawn from Kräutner and Krstić, 2002)

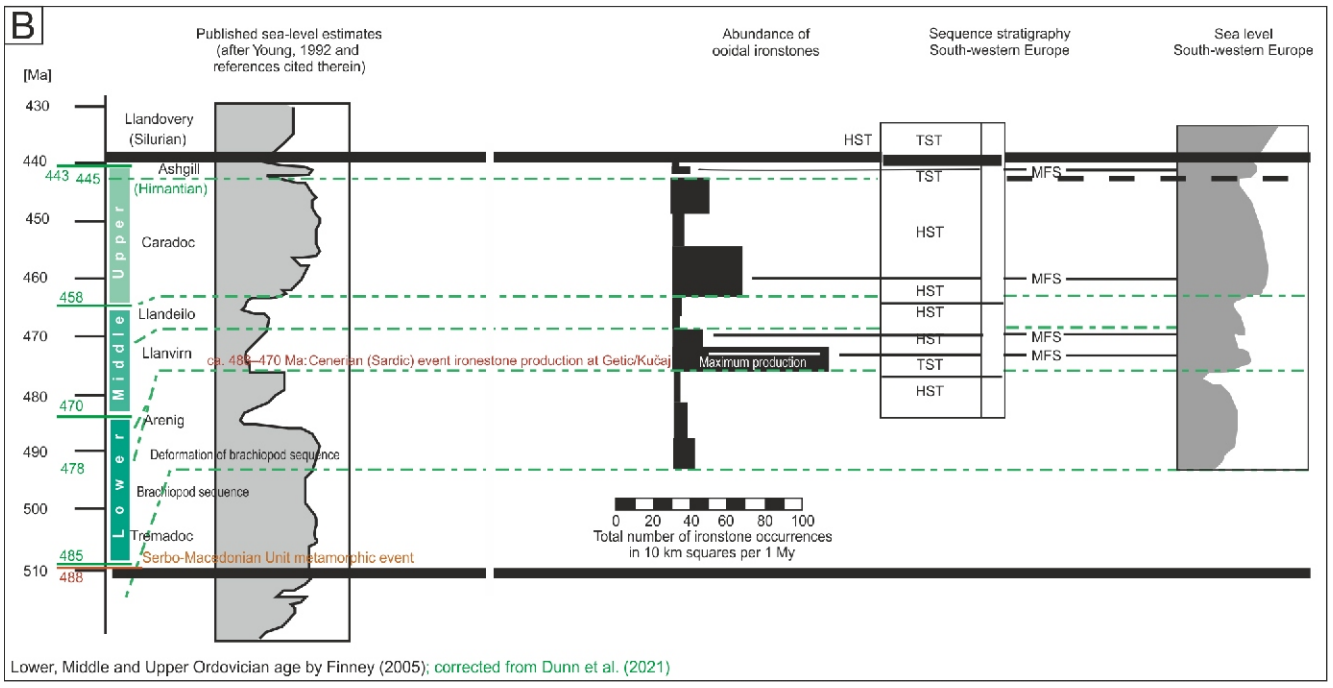
The position in the "Beljanica greenschist" which are of the same age as the Supragetic basement (i.e. underlying the Ordovician sequence investigated). The main Ordovician sedimentary sequence gradually passes into the Silurian, which is not the case in NE Serbia (Bogdanović et al., 1978). Spatial position 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, 2020a, 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 lastest 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., 2014; Antić et al., 2017; Žák and Sláma, 2017; Fig. 1A, B). As a result, a large segment of north Gond-



Column integrated from Veselinovic (1975); Pavlovic 1975; Krstic and Maslarevic, (1998) and current study



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; 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; Krstić and Kräutner, 2003; 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 (Krstić and Kräutner, 2003; Iancu et al., 2005; Fig. 2). These include (*sensu* Krstić and Kräutner, 2003; 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 (Krstić and Kräutner, 2003; 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, 2014, 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, 2003; 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., 1999; 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).

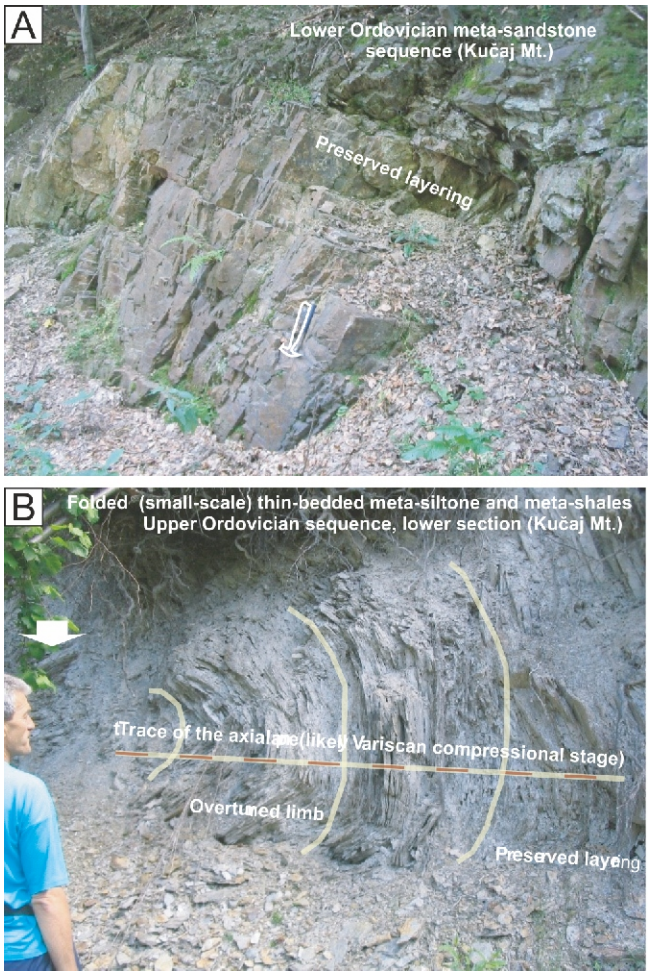


Fig. 5. Ordovician exposures in the Kučaj Mt.

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. *L. 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. 5A, B). 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., Krstić and Kräutner, 2003; 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.

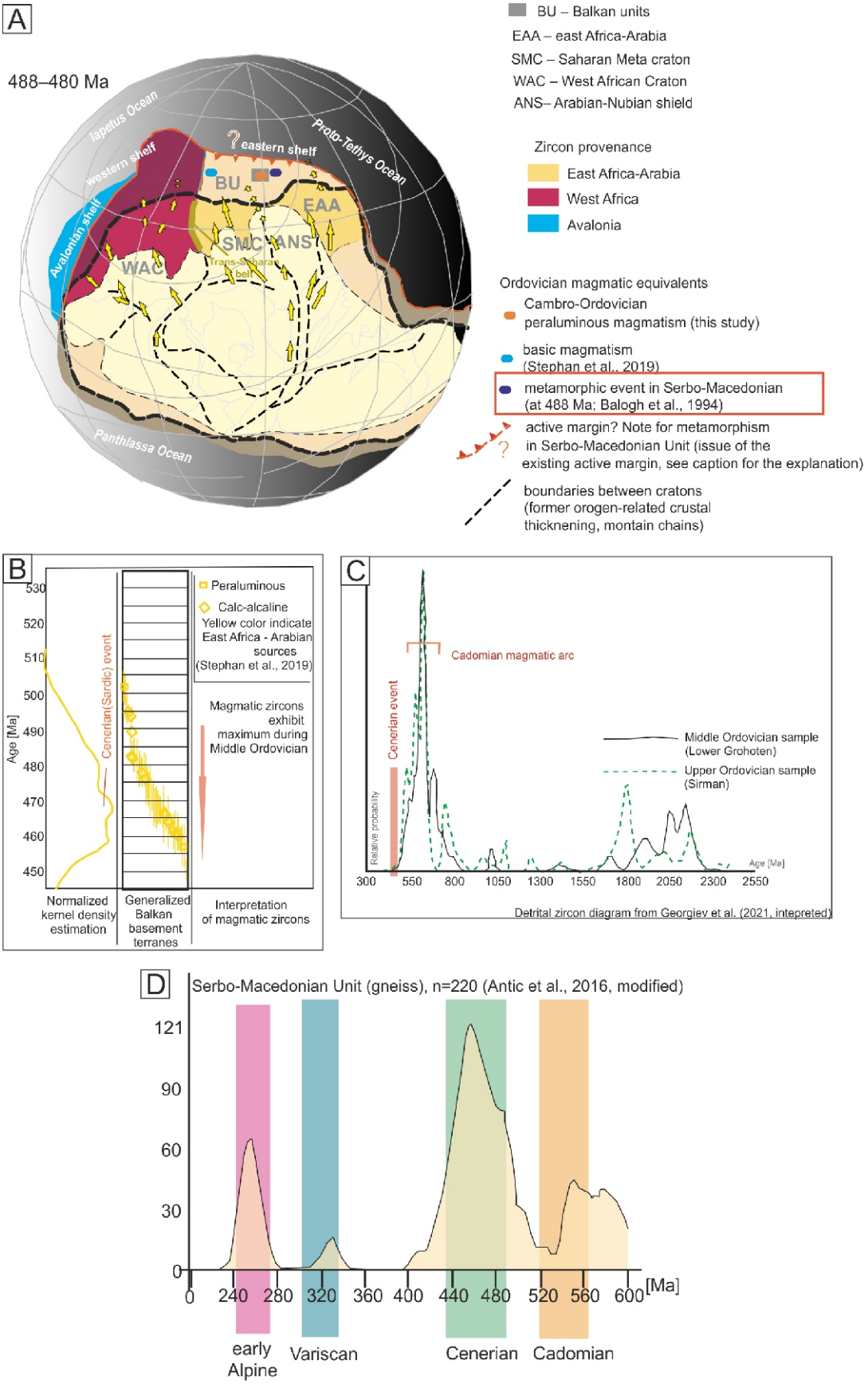


Fig. 6A – an Ordovician palaeogeographic reconstruction, exposing the Carpathian-Balkan Getic/Kučaj basement, which underwent the Cenerian (Sardic) event (inset from Stephan et al., 2019, significantly modified). There are two Cenerian (Sardic) explanations or palinspastic options: (i) no Ordovician active margin (e.g., Stephan et al., 2019) or (ii) the Cenerian (Sardic) active margin having the polarity of subduction directed southwards (Zurbriggen, 2014). 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

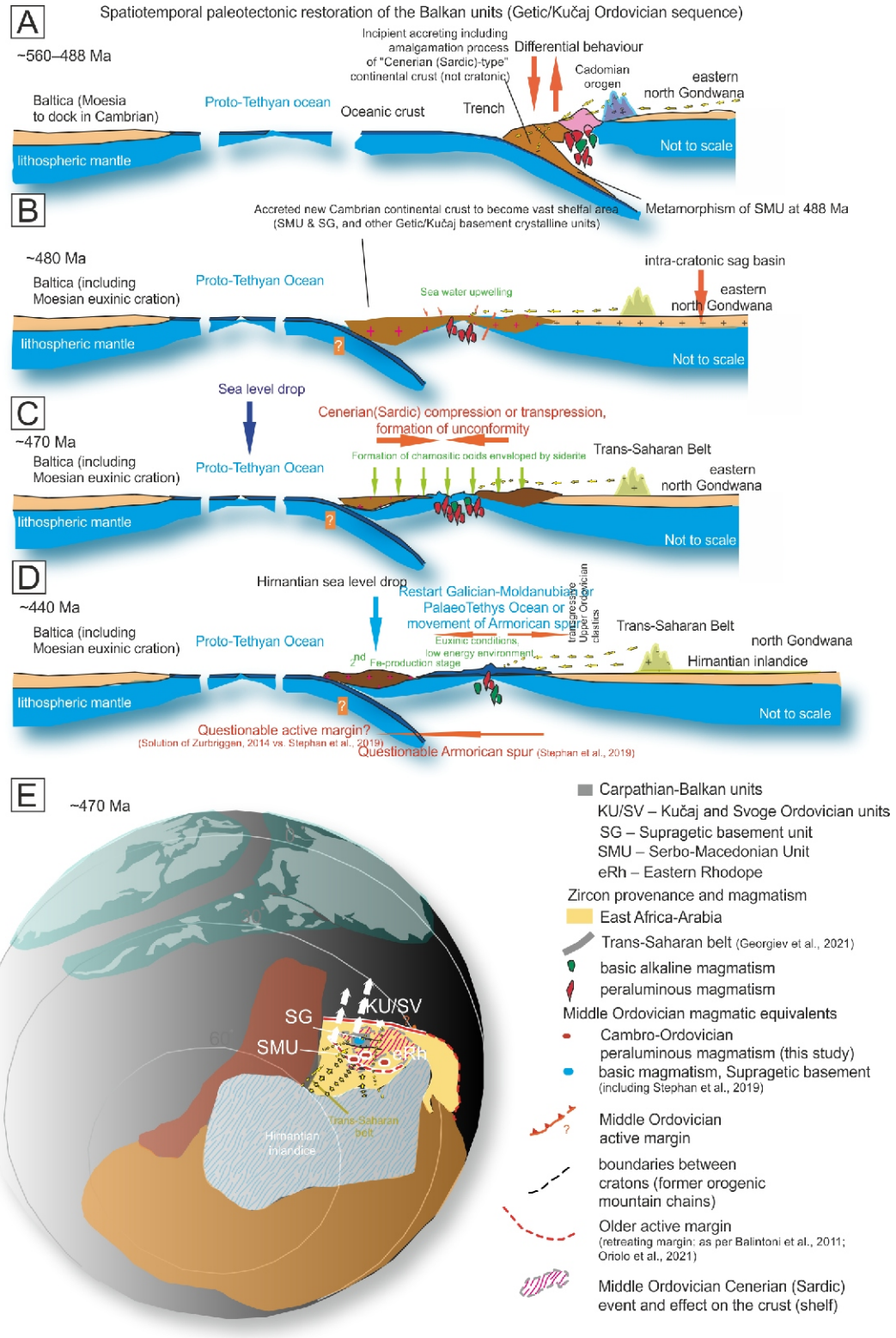


Fig. 7. Tectonic-palaeogeographic model of the Ordovician Kučaj sequence, including the Supragetic basement during the Lower Ordovician Cenerian (Sardic) "orogeny" (Fig. 7C – inset from Stephan et al., 2019, with significant modification)

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. 4A, B) 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. 4A, B), 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. 4A, B);
- 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., 2019). 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., 2019, 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 shal-

low environment is consistent with the Cambro-Ordovician high-stand systems tract (Fig. 4A, B). 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., 2019; Fig. 4A, B). 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., 2014; 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 (Krstić and Kräutner, 2003; 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 to (early) Middle Ordovician age.

Acknowledgements. This work was partially financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-68/2022-14/200026). The paper benefited from the constructive review by anonymous reviewer.

REFERENCES

Ábalos, B., Carreras, J., Druguet, E., Viruete, J.E., Pugnaire, M.T.G., Alvarez, S.L., Gil-Ibarguchi, J.I., 2002. Variscan and pre-Variscan tectonics. In: The Geology of Spain (eds. W. Gibbons and T. Moreno): 155–183. The Geological Society of London. https://doi.org/10.1144/GOSPP.9

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

Abu-Alam, T.S., Santosh, M., Brown, M., Stüwe, K., 2013. Gondwana collision. Mineralogy and Petrology, **107**: 631–634. https://doi.org/10.1007/s00710-013-0283-5

Álvaro, J.J., Casas, J.M., Quesada, C., 2021. Reconstructing the pre-Variscan puzzle of Cambro-Ordovician basement rocks in the southwestern European margin of Gondwana. Geological Society Special Publications, **503**: 531–562. https://doi.org/10.1144/SP503-2020-89

Antić, M., Peytcheva, I., von Quadt, A., Kounov, A., Trivić, B., Serafimovski, T., Tasev, G., Gerdjikov, I., Wetzel, A., 2016. Pre-Alpine evolution of a segment of the North-Gondwanan

margin: geochronological and geochemical evidence from the central Serbo-Macedonian Massif. Gondwana Research, **36**: 523–544. https://doi.org/10.1016/j.gr.2015.07.020

Antić, M., Kounov, A., Trivić, B., Spikings, R., Wetzel, A., 2017. Evidence of Variscan and Alpine tectonics in the structural and thermochronological record of the central Serbo-Macedonian Massif (south-eastern Serbia). International Journal of Earth Sciences, **106:** 1665–1692. https://doi.org/10.1007/s00531-016-1380-6.

Avigad, D., Morag, N., Abbo, A., Gerdes, A., 2017. Detrital rutile U-Pb perspective on the origin of the great Cambro-Ordovician sandstone of North Gondwana and its linkage to orogeny. Gondwana Research, **51**: 17–29. https://doi.org/10.1016/j.gr.2017.07.001

Avigad, D., Abbo, A., Gerdes, A., Schmitt, A.K., 2022. Crustal evolution of Western Europe: constraints from detrital zircon U-Pb-Hf-O isotopes. Gondwana Research, **106**: 379–396. https://doi.org/10.1016/j.gr.2022.02.006

Bahlburg, H., Vervoort, J.D., DuFrane, S.A., 2009. Plate tectonic significance of Middle Cambrian and Ordovician siliciclastic rocks of the Bavarian Facies, Armorican Terrane Assemblage, Germany – U–Pb and Hf isotope evidence from detrital zircons. Gondwana Research, **17**: 223–235. https://doi.org/10.1016/j.gr.2009.11.007

Balintoni, I., Balica, C., 2013. Avalonian, Ganderian and East Cadomian terranes in South Carpathians, Romania, and Pan-African events recorded in their basement. Mineralogy and Petrology, **107**: 709–725. https://doi.org/10.1007/s00710-012-0206-x

Balintoni, I., Balica, C. 2016. Peri-Amazonian provenance of the Euxinic Craton components in Dobrogea and of the North Dobrogean Orogen components (Romania): a detrital zircon study. Precambrian Research, **278**: 34–51. https://doi.org/10.1016/j.precamres.2016.03.008

Balintoni, I., Balica, C., Ducea, M.N., Chen, F., Hann, H.P., Şabliovschi, V., 2009. Late Cambrian–Early Ordovician Gondwanan terranes in the Romanian Carpathians: zircon U-Pb provenance study. Gondwana Research, **16**: 119–133. https://doi.org/10.1016/j.gr.2009.01.007

Balintoni, I., Balica, C., Ducea, M.N., Hann, H.P. Şabliovschi, V., 2010. The anatomy of a Gondwanan terrane: the Neoproterozoic–Ordovician basement of the pre-Alpine Sebeş-Lotru composite terrane (South Carpathians, Romania). Gondwana Research, **17**: 561–572. https://doi.org/10.1016/j.gr.2009.08.003

Balintoni, I., Balica, C., Hann, H.P., 2011. About a peri-Gondwanan-North African enlarged acceptance of the Caledonian Orogeny. Studia UBB Geologia, **56**: 29–32. DOI: 10.5038/1937-8602.56.1.3

Balintoni, I., Balica, C., Ducea, M.N., Hann, H.-P., 2014. Peri-Gondwanan terranes in the Romanian Carpathians: A review of their spatial distribution, origin, provenance, and evolution. Geoscience Frontiers, **5**: 395–411. https://doi.org/10.1016/j.gsf.2013.09.002

Balkanska, E., Gerdjikov, I., Georgiev, S., Lazarova, A., Dörr, W., Kounov, A., 2021. Structural and geochronological constraints on the magmatic and tectonic events in the pre-Alpine basement of the central parts of the Balkan fold–thrust belt (Central Stara Planina Mountains, Bulgaria). International Journal of Earth Sciences, **110**: 1181–1211. https://doi.org/10.1007/s00531-021-02011-1

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

Banjac, N., 2004. Stratigrafija Srbije i Crne Gore. Rudarsko-geološki fakultet, Belgrade. 551.73/.76(497.11+497.16)(075.8)(0.034.2)

Barjaktarović, D., 2007. Report for the Geological Map of Serbia, 1: 50 000, sheet Žagubica-4. Unpublished material, Geological Survey of Serbia.

Benayad, S., Ysbaaa, S., Chaouchia, R., Haddouche, O., Kacimi, A., 2019. Sedimentological characteristics and reservoir quality prediction in the Upper Ordovician glaciogenic sandstone of the In-Adaoui-Ohanet gas field, Illizi basin, Algeria. Journal of Petroleum Science and Engineering, **179**: 159–172. https://doi.org/10.1016/j.petrol.2019.04.037.

Bogdanović, P., Marković, V., Dolić, D., Dragić, D., Rakić, M. Babović, M., Rajčević, D., Popović, V., Milošević, Lj., 1978. Geological map of SFRY, scale 1:100,000, sheet Donji Milanovac. Federal Geological Survey. https://geoliss.mre.gov.rs/OGK/RasterSrbija/OGKWebOrig/listovi.php?karta=Donji_Milanovac

Boncheva, I., Lakova, I., Sachanski, V., Koenigshof, P., 2010. Devonian stratigraphy, correlations and basin development in the Balkan Terrane, western Bulgaria. Gondwana Research, **17**: 573–582. https://doi.org/10.1016/j.gr.2009.11.012

Bonev, N., Ovtcharova-Schaltegger, M., Moritz, R., Marchev, P., Ulianov, A., 2013. Peri-Gondwanan Ordovician crustal fragments in the high-grade basement of the Eastern Rhodope Massif, Bulgaria: evidence from U-Pb LA-ICP-MS zircon geochronology and geochemistry. Geodinamica Acta, **26**: 207–229. https://doi.org/10.1080/09853111.2013.858942

Carrigan, C.W., Mukasa, S.B., Haydoutov, I., Kolcheva, K., 2005. Age of Variscan magmatism from the Balkan sector of the orogen, central Bulgaria. Lithos, **82**: 125–147. https://doi.org/10.1016/j.lithos.2004.12.010

Casas, J.M., 2010. Ordovician deformations in the Pyrenees: new insights into the significance of pre-Variscan ('sardic') tectonics. Geological Magazine, **147**: 674–689. https://doi.org/10.1017/S0016756809990756

Chatalov, A., 2017. Sedimentology of Hirnantian glaciomarine deposits in the Balkan Terrane, western Bulgaria: Fixing a piece of the north peri-Gondwana jigsaw puzzle. Sedimentary Geology, **350**: 1–22. https://doi.org/10.1016/j.sedgeo.2017.01.004

Crook, K.A.W., 1980. Fore-arc evolution and continental growth-general-model. Journal of Structural Geology, **2**: 289–303. 0191-8141/80/0901-0289

Deer, W., Howie, R., Zussman, J., 2013a. Siderite. In: An Introduction to the Rock-Forming Minerals, 3rd ed. The Mineral Society, London, UK, 461-462. ISBN 978-0903056-33-5

Deer, W., Howie, R., Zussman, J., 2013b. Chlorite group. In: An Introduction to the Rock-Forming Minerals, 3rd ed. The Mineral Society, London, UK, 208–215. ISBN 978-0903056-33-5

Deleon, G., Dromnjak, M., Lovrić, A., 1972. Sr age of the Stalać-Juhor metamorphic complex (in Serbo-Croatian with English summary). In: VII Kongres geologa SFRJ: Predavanja održana u sekciji mineralogija i petrologija, **2**: 97–112, Zagreb.

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

Dunn, S.K., Pufahl, P.K., Murphy, J.B., Lokier, S.W., 2021. Middle Ordovician Upwelling-Related Ironstone of North Wales: Coated Grains, Ocean Chemistry, and Biological Evolution. Frontiers of Earth Sciences, **9**. 669476. https://doi.org/10.3389/feart.2021.669476

El Bahariya, G.A., 2006. Petrology, mineral chemistry and metamorphism of two pan-African ophiolitic metagabbro occurrences, Central Eastern Desert, Egypt. Magallat al-''Ulum al-Giyulugiyyat li-l-Gumhuriyyat al-''Arabiyyat al-Muttahidat/United Arab Republic Journal of Geology, **50**: 183.

Erak, D., Matenco, L., Toljić, M., Stojadinović, U., Andriessen, P.A.M., Wilingshofer, E., Ducea, M.N., 2016. From nappe stacking to extensional detachments at the contact between the Carpathians and Dinarides – The Jastrebac Mountains of Central Serbia. Tectonophysics, **710**: 162–183. https://doi.org/10.1016/j.tecto.2016.12.022

Ercegovac, M., Đajić, S., 1996. Lower Paleozoic Acritarchs of Kučaj zone, Eastern Serbia. Geološki Anali Balkanskog Poluostrva, **60**: 185–202.

Ercegovac, M., Đajić, S., Krstić, B., 1995. Palynomorph in marine Paleozoic of the Carpatho-Balkanides, Eastern Serbia. Proceedings of the XV Congress of Carpatho-Balkan Geological Association; Geological Society of Greece, Special Publications, **4** : 181–185.

Ercegovac, M., Krstić, B., Kiselinov, H., Zagorchev, I., Kalenić, Đ., 2011. New data on the age of the low-grade metamorphic complexes in Stara planina Mts., NW Bulgaria and Eastern Serbia. In Proceedings of National conference with international participation "Geosciences 2012". Bulgarian geological society,

National Conference with international participation "Geosciences 2011": 85–86.

Fang, Q., Wua, H., Wanga, X., Yang, T., Li, H., Zhang, S., 2019. An astronomically forced cooling event during the Middle Ordovician. Global and Planetary Change, **173**: 96–108. https://doi.org/10.1016/j.gloplacha.2018.12.010

Ferretti, A., Schönlaub, H.P., Sachanski, V., Bagnoli, G., Serpagli, E., Battista V.G., Yanev, S., Radonjić, M., Balica, C., Bianchini, L., Colmenar, J., Gutiérrez-Marco, J.C., 2022. A global view on the Ordovician stratigraphy of south-eastern Europe. Geological Society Special Publications, **532**. https://doi.org/10.1144/SP532-2022-174

Finney, S., 2005. Global series and stages for the Ordovician System: A progress report. Geologica Acta, **3**: 309–309. https://raco.cat/index.php/GeologicaActa/article/view/82381

Franke, W., Cocks, L.R.M., Torsvik, T.H., 2017. The Palaeozoic Variscan oceans revisited. Gondwana Research, **48**: 257–284. https://doi.org/10.1016/j.gr.2017.03.005

Franz, L., Okrusch, M., Seidel, E., Kreuzer, H., 2005. Polymetamorphic evolution of pre-Alpidic basement relics in the external Hellenides, Greece: Neues Jahrbuch für Mineralogie-Abhandlungen, **181**: 147–172. doi: 10.1127/0077-7757/2005/0013

Garfunkel, Z., 2015. The relations between Gondwana and the adjacent peripheral Cadomian domain—constrains on the origin, history, and paleogeography of the peripheral domain. Gondwana Research, **28**: 1257–1281. https://doi.org/10.1016/j.gr.2015.05.011

Georgiev, S., Sachanski, V., Andreeva, P., Kiselinov, H., Balkanska, E., Lakova, I., Tanatsiev, S., 2021. Paleogeographic position of the Ordovician rocks from the Svoge Unit, Western Balkan-preliminary results. Review of the Bulgarian Geological Society: **82**. 49–51.

Georgiev, S., Sachanski, V., Andreeva, P., Kiselinov, H., Balkanska, E., Lakova, I., Tanatsiev, S., 2022. Trans-Saharan Belt Provenance: A potential source for the Ordovician succession of the Balkan Terrane (Svoge Unit)-Clues from LA-ICP-MS detrital zircon dating analysis. Proceedings of the Bulgarian Academy of Sciences, **75**: 237–247.

Ghienne, J.F., Benvenuti, A., El Houicha, M., Girard, F., Kali, E., Khoukhi, Y., Langbour, C., Magna, T., Míková, J., Moscariello, A., Schulmann, K., 2018. The impact of the end-Ordovician glaciation on sediment routing systems: a case study from the Meseta (northern Morocco). Gondwana Research, **63**: 169–178. https://doi.org/10.1016/j.gr.2018.07.001

Golonka, J., Gahagan, L., Krobicki, M., Marko, F., Oszczypko, N., Slaczka, A., 2005. Plate tectonic evolution and paleogeography of the circum-Carpathian region. AAPG Memoir, **84**: 11–46. DOI:10.1306/985606M843066

Guerrak, S., 1988. Ordovician ironstone sedimentation in Ougarta ranges: North Western Sahara (Algeria). Journal of African Earth Sciences, **7**: 657–578. https://doi.org/10.1016/0899-5362(88)90116-9

Gutiérrez-Marco, J.C., Robardet, M., Rábano, I., Sarmiento, G.N., San Hose Lancha, M.A, Herranz, M.A., Pidal, A.P., 2002. Ordovician. In: The Geology of Spain (eds. W. Gibbons and T. Moreno): 31–49. Geological Society of London. https://doi.org/10.1144/GOSPP.4

Gutierrez-Marco, J.C., Yanev, S.N., Sachanski, V.V., 1999. Braquiopodos inarticulados del Ordovicico Inferior de la Unidad Ranovac-Vlasina („Supragethicum") y paleobiogeografia de las unidades tectonicas balcanides de Serbia oriental (Yugoslavia). Temas Geologico-Mineros ITGE, **I** (26): 566–574. Inst. Tecnol. Geomin. Espana, Madrid. ISBN: 84-7840-381-7.

Gutierrez-Marco, J.C., Yanev, S., Sachanski, V., Rabano, I., Lakova, I., San Hose Lancha, M.A, Diaz Martinez, E., Boncheva, I., Sarmiento, G., 2003. New biostratigraphical data from the Ordovician of Bulgaria. INSUGEO, Serie Correlación Geológica, **17**: 79–85. http://dgisrv15.unt.edu.ar/fcsnat/insugeo/geologia_17/11.htm

Haydoutov, I., Pristavova, S., Daieva, L. 2010. Some features of the Neoproterozoic–Cambrian geodynamics in South eastern Europe. Comptes rendus de l'Académie bulgare des Sciences, **63**: 1597–1608.

Hollocher, K., Bull, J., Robinson, P., 2002. Geochemistry of the metamorphosed Ordovician Taconian magmatic arc, Bronson Hill anticlinorium, western New England. Physics and Chemistry of the Earth, Parts A/B/C, **27**: 5–45. https://doi.org/10.1016/S1474-7065(01)00002-X

Iancu, V., Berza, T., Seghedi, A., Marunţiu, M., 2005. Palaeozoic rock assemblages incorporated in the south carpathian alpine thrust belt (Romania and Serbia): a review. Geologica Belgica, **8**: 48–68. https://popups.uliege.be/1374-8505/index.php?id=772

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

ICDD-PDF 83-1764, 1981. Siderite, Elfenberger, H., Mereiter, K., Zemann, J. Zeitschrift für Kristallographie, **156**: 233.

Jovanović, D., Cvetković, V., Erić, S., Kostić, B., Peytcheva, I., Šarić, K., 2019. Carpatho-Balkanides of eastern Serbia. Variscan granitoids of the East Serbian Carpatho-Balkanides: new insight inferred from U-Pb zircon ages and geochemical data. Swiss Journal of Geosciences, **112**: 121–142. https://doi.org/10.1007/s00015-018-0325-4

Kalenić, M., Marković, V., Pantić, V., Hadži-Vuković, M., 1975. Gornji proterozoik i stariji paleozoik u profilu – Resavski Visovi-Batočinska Straževica – selo Botunje (in Serbo-Croatian). Zapisnici SGD za 1974 godinu: 3–39.

Karamata, S., 2006. The geodynamical framework of the Balkan Peninsula: its origin due to the approach, collision and compression of Gondwanian and Eurasian units. Geological Society Special Publications, **260**: 155–178. doi: 10.1144/GSL.SP.2006.260.01.07

Kounov, A., Graf, J., von Quadt, A., Bernoulli, D., Burg, J.-P., Seward, D., Ivanov, Z., Fanning, M., 2012. Evidence for a "Cadomian" ophiolite and magmatic-arc complex in SW Bulgaria. Precambrian Research, **212–213**: 275–295. https://doi.org/10.1016/j.precamres.2012.06.003

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

Kröner, U., Romer, R.L., 2013. Two plates — Many subduction zones: The Variscan orogeny reconsidered. Gondwana Research, **24**: 298–329. https://doi.org/10.1016/j.gr.2013.03.001

Kröner, A., Stern, R. J., 2005. Africa. Pan-African orogeny. Encyclopedia of Geology, **1**: 1–12. Elsevier, Amsterdam.

Krstić, B., Maslarević, Lj., 1990. Depositional environments of the marine Paleozoic in the Hercynid Kučaj Zone Eastern Serbia. Bulletin de l' Academie Serbe des Sciences et des Arts, Classe Science Mathematiques et Naturelles, Sciences Naturelles, **32**: 29–29.

Krstić, B., Maslarević, L., Sudar, M., Ercegovac, M., 2008. Paleozoic and Lower Triasic Formations in the SE part of the East Serbian Carpatho–Balkanides. Bulletin de l'Académie serbe des sciences et des arts – Classe des sciences Mathématiques et Naturelles, Sciences Naturelles, **44**: 9–28.

Krstić, B., Maslarević, Lj., 1998. Ordovician rocks of Kučaj mountains, eastern Serbia. Geološki anali Balkanskoga poluostrva, **62**: 1-24.

Krstić, B., Maslarević, L.J., Ercegovac, M., Djajić, S., 2003. Devonian of the Serbian-Carpatho Balkanides. Académie Serbe des Sciences et des Arts, Classe des Sciences Mathématiques et Naturelles, Sciences Naturelles, **4**: 7–16.

Krstić, B., Maslarević, Lj., Sudar, M., 2005. On the Graptolite Schists Formation (Silurian–Lower Devonian) in the Carpatho–Balkanides of eastern Serbia. Geološki anali Balkanskoga poluostrva, **66**: 1–8. https://doi.org/10.2298/GABP 0566001K.

Le Heron, D.P., Meinhold, G., Bergig, K.A., 2013. Neoproterozoic–Devonian stratigraphic evolution of the eastern Murzuq Basin, Libya: a tale of tilting in the central Sahara. Basin Research, **25**: 52–73. https://doi.org/10.1111/j.1365-2117.2012.00555.x

Li, N., Li, C., Algeo, T. J., Cheng, M., Jin, C., Zhu, G., Fan, Y., Sun, Z., 2021. Redox changes in the outer Yangtze Sea (South China) through the Hirnantian Glaciation and their implications for the end-Ordovician biocrisis. Earth-Science Reviews, **212**. 103443. https://doi.org/10.1016/j.earscirev.2020.103443

Linnemann, U., Gerdes, A., Drost, K., Buschmann, B., 2007. The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany. GSA Special Paper, **423**: 61–96. Doi: 10.1130/2007.2423(03)

Linnemann, U., Gerdes, A., Hoffmann, M., Marko, L., 2011. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal gowth and orogenic zoning along the periphery of the West African Craton—Constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Research, **244**: 236–278. https://doi.org/10.1016/j.precamres.2013.08.007.

Maino, M., Gaggero, L., Langone, A., Seno, S., Fanning, M., 2019. Cambro-Silurian magmatisms at the northern Gondwana margin (Penninic basement of the Ligurian Alps). Geoscience Frontiers, **10**: 315–330. https://doi.org/10.1016/j.gsf.2018.01.003

Marović, M., Toljić, M., Rundić, Lj., Milivojević, J., 2007. Neoalpine Tectonics of Serbia. Serbian Geological Society.

Martini, P., Tongiorgi, M., Oggiano, G., Cocozza, T., 1991. Alluvial fan to marine shelf transition in SW Sardinia, Western Mediterranean Sea: tectonically ("Sardic Phase") influenced clastic Ordovician sedimentation. Sedimentary Geology, **72**: 97–115. https://doi.org/10.1016/0037-0738(91)90125-W

McKerrow, W.S., Dewey, J.F., Scotese, C.R., 1991. The Ordovician and Silurian development of Iapetus Ocean. Special Papers in Palaeontology, **44**: 165–178. https://doi.org/10.1144/gsjgs.143.1.0185

Medaris, G., Ducea, M., Ghent, E., Iancu, V., 2003. Conditions and timing of high-pressure Variscan metamorphism in the South Carpathians, Romania. Lithos, **70**: 141–161. https://doi.org/10.1016/S0024-4937(03)00096-3

Meinhold, G., Morton AC, Avigad D, 2013. New insights into peri-Gondwana paleogeography and the Gondwana super-fan system from detrital zircon U–Pb ages. Gondwana Research, **23**: 661–665. https://doi.org/10.1016/j.gr.2012.05.003

Merdith, A.S., Collins, A.S., Williams, S.E., Pisarevsky, S., Foden, J.D., Archibald, D.B., Blades, M.L., Alessio, B.L., Armistead, S., Plavsa, D., Clark, C., Müller, R.D., 2017. A full-plate global reconstruction of the Neoproterozoic. Gondwana Research, **50**: 84–134. https://doi.org/10.1016/j.gr.2017.04.001

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

Mrvaljević, N., 1956. Ergebnisse der geologischen Untersuchungen in Gebiete des Kločanica-Fluesses (Ost Serbien) (in Serbian with German summary). Zapsinici Srpskog geološkog društva za 1954: 75–77. Beograd.

Mücke, A., Farshad, F., 2005. Whole-rock and mineralogical composition of Phanerozoic ooidal ironstones: Comparison and differentiation of types and subtypes. Ore Geology Reviews, **26**: 227–262. https://doi.org/10.1016/j.oregeorev.2004.08.001

Murphy, J.B., Gutiérrez-Alonso, G., Fernández-Suárez, J., Braid, J.A., 2008. Probing crustal and mantle lithosphere origin through Ordovician volcanic rocks along the Iberian passive margin of Gondwana. Tectonophysics, **461**: 166–180. https://doi.org/10.1016/j.tecto.2008.03.013

Murphy, J.B., Pisarevsky, S., Nance, R.D., 2013. Potential geodynamic relationships between the development of peripheral orogens along the northern margin of Gondwana and the amalgamation of West Gondwana. Mineralogy and Petrology, **107**: 635–650. https://doi.org/10.1007/s00710-012-0207-9

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

Nance, R.D., Gutiérrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2010. Evolution of the Rheic Ocean. Gondwana Research, **17**: 194–222. https://doi.org/10.1016/j.gr.2009.08.001

Nance, R.D., Gutierrez-Alonso, G., Keppie, J.D., Linnemann, U., Murphy, J.B., Quesada, C., Strachan, R.A., Woodcock, N.H., 2012. A brief history of the Rheic Ocean. Geoscience Frontiers, **3**: 125-135. https://doi.org/10.1016/j.gsf.2011.11.008

Oczlon, M.S., Seghedi, A., Carrigan, C.W., 2007. Avalonian and Baltican terranes in the Moesian Platform (southern Europe, Romania, and Bulgaria) in the context of Caledonian terranes along the southwestern margin of the East European craton. GSA Special Paper, **423**: 375–400. doi: 10.1130/2007.2423(18)

Oggiano, G., Mameli, P., 2006. Diamictite and oolitic ironstones, a sedimentary association at Ordovician–Silurian transition in the north Gondwana margin: new evidence from the inner nappe of Sardinia Variscides (Italy). Gondwana Research, **9**: 500–511. https://doi.org/10.1016/j.gr.2005.11.009

Oriolo, S., Schulz, B., Geuna, S., González, P.D., Otamendi, J.E., Sláma, J., Druguet, E., Siegesmund, S., 2021. Early Paleozoic accretionary orogens along the Western Gondwana margin. Geoscience Frontiers, **12**: 109–130. https://doi.org/10.1016/j.gsf.2020.07.001

Pavlović, M., 1975. Precambrian and Paleozoic In: Geologija Srbije ii-1 – Prekambrijum i paleozoik (ed. K. Petković). Zavod za regionalnu geologiju i paleontologiju, RGF, Univerzitet u Beogradu, Belgrade.

Pavlović, P., 1977. Oberer (Vlasina) komplex" und Teilung der metamorphen Gesteine des Serbo-Mazedonichen metamorphen Terrain (in Serbo-Croatian with German summary). Zapisnici SGD za 1975. i 1976. godinu: 123–132.

Petrović, A., Nikolić, D., Trnavac Bogdanović, D., Crević, I., 2020. Assessment of karst geomorphosites on Kucaj and Beljanica mountains as a resource for the development of karst-based geopark. Acta Carsologica, **49**: 179–190. Doi: 10.3986/ac.v49i2-3.8748

Plissart, G., Diot, H., Monnier, C., Mărunţiu, M., 2018. New insights into the building of the Variscan Belt in Eastern Europe (Romania, Serbia, Bulgaria). Geological Society Special Publications, **478**: 389-426. https://doi.org/10.1144/SP478.1

Plissart, G., Monnier, C., Diot, H., Marunţiu, M., Berger, J., Triantafyllou, A., 2017. Petrology, geochemistry and Sm-Nd analyses on the Balkan-Carpathian Ophiolite (BCO – Romania, Serbia, Bulgaria): remnants of a Devonian back-arc basin in the easternmost part of the Variscan domain. Journal of Geodynamics, **105**: 27–50. https://doi.org/10.1016/j.jog.2017.01.001

Popović, R., 1993. Lithostratigraphic relationship within Morava massif based on the borehole VG-3 drilled in Vranjska Banja 1990/1991 (in Serbian). Proceedings of the Geoinstitute, **28**: 27–33.

Puddu, C., Álvaro, J.J., Casas, J.M., 2018. The Sardic unconformity and the Upper Ordovician successions of the Ribes de Freser area, Eastern Pyrenees. Journal of Iberian Geology, **44**: 603–617. https://doi.org/10.1007/s41513-018-0084-0

Pufahl, P.K., Squires, A.D., Murphy, J.B., Quesada, C., Lokier, S.W., Álvaro, J.J., Hatch, J., 2020. Ordovician ironstone of the Iberian margin: Coastal upwelling, ocean anoxi.a and Palaeozoic biodiversity. The Depositional Record, **6**: 581–604. https://doi.org/10.1002/dep2.113

von Raumer, J.F., Stampfli, G.M., 2008. The birth of the Rheic Ocean — Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. Tectonophysics, **461**: 9–20. https://doi.org/10.1016/j.tecto.2008.04.012

von Raumer, J.F., Stampfli, G.M., Borel, G., Bussy, F., 2002. Organization of pre-Variscian basement areas at the north-Gondwanan margin. International Journal of Earth Sciences, **91**: 35–52. https://doi.org/10.1007/s005310100200

Săndulescu, M. 1984. Geotectonics of Romania (in Romanian). Editura Tehnică, Bucharest.

Sachanski, V., Göncüoglu, M.C., Gedik, I. , 2010. Late Telychian (early Silurian) graptolitic shales and the maximum Silurian highstand in the NW Anatolian Palaeozoic terranes. Palaeoge-

ography, Palaeoclimatology, Palaeoecology, **291**: 419–428. https://doi.org/10.1016/j.palaeo.2010.03.011

Schmid, S., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer S., Schuster, R., Tischler, M., Ustaszewski, K., 2008. The Alpine Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences, **101**: 139–183. https://doi.org/10.1007/s00015-008-1247-3

Seghedi, A., Berza, T., Iancu, V., Mărunţiu, M., Oaie, G., 2005. Neoproterozoic terranes in the Moesian basement and in the Alpine Danubian nappes of the South Carpathians. Geologica Belgica, **8**: 4–19. https://popups.uliege.be/1374-8505/index.php?id=746

Şen, F., 2021a. Age and implication of Late Ediacaran dykes in the Istanbul-Zonguldak Tectonic Unit (NW Turkey): implications for the rifting of the Rheic Ocean. International Geology Review, **64**: 2416–2435. https://doi.org/10.1080/00206814.2021.1904296

Şen, F., 2021b. U-Pb zircon geochronology and geochemistry of mafic and intermediate dykes in the Istanbul–Zonguldak Tectonic Unit (NW Turkey): evidence for Devonian and Carboniferous magmatism and the north-subducting Rheic Ocean in Far East Avalonia. International Journal of Earth Sciences, **110**: 1899–1920. https://doi.org/10.1007/s00531-021-02046-4

Siegesmund, S., Oriolo, S., Heinrichs, T., Basei, M.A.S., Nolte, N., Hüttenrauch, F., Schulz, B., 2018. Provenance of Austroalpine basement metasediments: tightening up Early Palaeozoic connections between peri-Gondwanan domains of central Europe and Northern Africa. International Journal of Earth Sciences, **107**: 2293–2315. https://doi.org/10.1007/s00531-018-1599-5.s

Siegesmund, S., Oriolo, S., Schulz, B., Heinrichs, T., Basei, M.A.S., Lammerer, B., 2021. The birth of the Alps: Ediacaran to Paleozoic accretionary processes and crustal growth along the northern Gondwana margin. International Journal of Earth Sciences, **110**: 1321–1348. https://doi.org/10.1007/s00531-021-02019-7

Šoster, A., Zavašnik, J., O'Sullivan, P., Herlec, U., Krajnc, B.P., Palinkaš, L., Zupančič, N., Dolenec, M., 2020. Geochemistry of Bashibos-Bajrambos metasedimentary unit, Serbo-Macedonian massif, North Macedonia: implications for age, provenance and tectonic setting. Geochemistry, **80**: 125664. https://doi.org/10.1016/j.chemer.2020.125664

Spahić, D., 2022a. Towards the Triassic configuration of western Paleotethys. Journal of Earth Science, **33**: 1–19. https://doi.org/10.1016/j.lithos.2019.105295

Spahić, D., 2022b. Missing link on the western Paleotethys configuration: Stratigraphic constraints on the truncated Triassic "Gornjak" sequence (eastern Serbia, Balkan/Carpathian hinterland). Italian Journal of Earth Sciences, **141**: 278–292. https://doi.org/10.3301/IJG.2022.14

Spahić, D., Gaudenyi, T., 2018. Primordial geodynamics of Southern Carpathian-Balkan Basements (Serbo-Macedonian Mass): Avalonian vs. Cadomian arc segments. Proceedings of Geologists' Association, **130**: 142–156. https://doi.org/10.1016/j.pgeola.2018.10.006

Spahić, D., Gaudenyi, T., 2022. On the Sava Suture Zone: Post-Neotethyan Oblique Subduction and the Origin of the Late Cretaceous Mini-Magma Pools. Cretaceous Research, **131**: 105062. https://doi.org/10.1016/j.cretres.2021.105062

Spahić, D., Glavaš-Trbić, B., Đajić, S., Gaudenyi, T., 2018. Neoproterozoic - Late Paleozoic evolution of the Drina Formation (Drina–Ivanjica Entity). Geološki anali Balkanskoga poluostrva, **79**: 1–12. https://doi.org/10.2298/GABP1802057S

Spahić, D., Glavaš-Trbić, B., Gaudenyi, T., 2019a. The Neoproterozoic–Paleozoic basement in the Alpidic Supragetic/Kučaj units of eastern Serbia: a continuation of the Rheic Ocean? Acta Geologica Polonica, **69**: 531–548. Doi: 10.24425/agp.2019.126446

Spahić, D., Gaudenyi, T., Glavaš-Trbić, B., 2019b. A hidden suture within the northern Paleotethyan margin: paleogeographic/paleo-tectonic constraints on the late Paleozoic 'Veles Series' (Vardar Zone, North Macedonia). Proceedings of the Geologists' Association, **130**: 701–718. https://doi.org/10.1016/j.pgeola.2019.10.008

Spahić, D., Gaudenyi, T., Bojić, Z., Popović, D., 2021. Vestiges of Cambro-Ordovician continental accretion in the Carpathian-Balkan Orogen: first evidence of the Cenerian Event in the Central Serbo-Macedonian Unit. Acta Geologica Polonica, **71**: 219–247. https://doi. org/10.24425/agp.2020.134558

Stampfli, G.M., Borel, G.D., 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. Earth and Planetary Science Letters, **196**: 17–33. https://doi.org/10.1016/S0012-821X(01)00588-X

Stephan, T., Kroner, U., Romer, R.L., 2018. The pre-orogenic detrital zircon record of the Peri-Gondwanan crust. Geological Magazine, **156**: 281–307. Cambridge University Press. doi:10.1017/S0016756818000031

Stephan, T., Kroner, U., Romer, R.L., Rösel, D., 2019. From a bipartite Gondwana shelf to an arcuate Variscan belt: the early Paleozoic evolution of northern Peri-Gondwana. Earth-Science Reviews, **192**: 491–512. https://doi.org/10.1016/j.earscirev.2019.03.012

Tawadros, E., 2012. Geology of North Africa. Taylor & Francis, London.

Trela, W., 2008. Sedimentary and diagenetic environments of Middle Ordovician iron-rich limestones (Pobroszyn Formation) in the northern Holy Cross Mountains, Poland. Geological Quarterly, **52**: 199–212.

Topuz, G., Candan, O., Wang, J.-M., Li, Q.-L., Wu, F.-Y., Yýlmaz, A., 2021. Silurian A-type metaquartz-syenite to -granite in the Eastern Anatolia: implications for Late Ordovician-Silurian rifting at the northern margin of Gondwana, Gondwana Research, **91**: 1–17. https://doi.org/10.1016/j.gr.2020.12.005

van Staal, C.R., Hatcher Jr., R.D., 2010. Global setting of Ordovician orogenesis. Global Ordovician earth systems: GSA Special Paper, **466**: 1–11. Doi: 10.1130/2010.2466(01)

Vangelov, D., Gerdjikov, Y., Kounov, A., Lazarova, A., 2013. The Balkan Fold-Thrust Belt: an overview of the main features. Geologica Balcanica, **42**: 29–47.

Vasković, N.J., 2002. Petrology and PT condition of white mica-chlorite schists from Vlasina series-Surdulica, SE Serbia. Geoloski anali Balkanskoga poluostrva, **64**: 199–220. https://doi.org/10.2298/GABP0264199V

Veselinović, M., 1972a. Prilozi poznavanju starijeg paleozoika istočne Srbije (in Serbian). Zapisnici srpskog geološkog društva za 1968, 1969, 1970 godinu: 253–255. Beograd.

Veselinović, M., 1972b. Ordovijumski cistoidi iz roda *Heliocrinites* Eichwald, 1840 u paleozoiku istočne Srbije (in Serbian). Zapisnici srpskog geološkog društva za 1972 godinu: 130–133.

Veselinović, M. 1975. Ordovician, Eastern Serbia (in Serbian). In: Geologija Srbije, II-1 Stratigrafija – Prekambrijum i Paleozoik: 47–49. Zavod za Regionalnu geologiju i paleontologiju Rudarsko-geološkog fakulteta, Beograd.

Winchester, J.A., Pharaoh, T.C., Verniers, J., Ioane, D., Seghedi, A., 2006. Palaeozoic accretion of Gondwana-derived terranes to the East European Craton: recognition of detached terrane fragments dispersed after collision with promontories. Geological Society Memoirs, **32**: 323–332. https://doi.org/10.1144/GSL.MEM.2006.032.01.19

Yanev, S., 2000. Palaeozoic terranes of the Balkan Peninsula in the framework of Pangea assembly. Palaeogeography, Palaeoclimatology, Palaeoecology, **161**: 151–177. https://doi.org/10.1016/S0031-0182(00)00121-8

Yanev, S., Goncuoglu, M.C., Gedik, I., Lakova, I., Boncheva, V., Sachanski, Okuyucu, C., Timur, E., Maliakov, Y., Saydam. G., 2006. Startigraphy, correlations and paleogeography of Paleozoic terranes of Bulgaria and NW Turkey: a review of recent data. Geological Society Special Publications, **260**: 51–67. https://doi.org/10.1144/GSL.SP.2006.260.01

Young, S.A., Saltzman, M.R., Foland, K.A., Linder, J.S., Kump, L.R., 2009. A major drop in seawater $^{87}Sr/^{86}Sr$ during the Middle Ordovician (Darriwilian): links to volcanism and climate? Geology, **37**: 951–954. https://doi.org/10.1130/G30152A.1

Young, T.P., 1992. Ooidal ironstones from Ordovician Gondwana: a review. Palaeogeography, Palaeoclimatology, Palaeoecology, **99**: 321–347. https://doi.org/10.1016/0031-0182(92)90021-V

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

Zagorevski, A., Rogers, N., Van Staal, C.R., McNicoll, V., Lissenberg, C.J., Valverde-Vaquero, P., 2006. Lower to Middle Ordovician evolution of peri-Laurentian arc and backarc complexes in Iapetus: Constraints from the Annieopsquotch accretionary tract, central Newfoundland. GSA Bulletin, **118**: 324–342. https://doi.org/10.1130/B25775.1

Žák, J., Sláma, J., 2018. How far did the Cadomian terranes' travel from Gondwana during early Palaeozoic? A critical reappraisal based on detrital zircon geochronology. International Geology Review, **60**: 319–338. https://doi.org/10.1080/00206814.2017.1334599

Žák, J., Svojtka, M. Gerdjikov, I. Kounov, A. Vangelov., D., 2021. The Balkan terranes: a missing link between the eastern and western segments of the Avalonian–Cadomian orogenic belt? International Geology Review, **64**: 1–27. https://doi.org/10.1080/00206814.2020.1861486

Zavod za geološka i geofizička istraživanja, Beograd, 1961–1968. Basic Geological Map of SFRY, scale 1:100,000. Sheet Žagubica. Federal Geological Survey. https://geoliss.mre.gov.rs/OGK/RasterSrbija/OGKWebOrig/listovi.php?karta=zagubica

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

Żelaźniewicz, A., Dörr, W., Bylina, P., Franke, W., Haack, U., Heinisch, H., Schastok, J., Grandmontagne, K., Kulicki, C., 2004. The eastern continuation of the Cadomian orogen: U-Pb zircon evidence from Saxo-Thuringian granitoids in south-western Poland and the northern Czech Republic. International Journal of Earth Sciences, **93**: 773–781. https://doi.org/10.1007/s00531-004-0418-3

Zou, C., Qiu, Z., Poulton, S.W., Dong, D., Wang, H., Chen, D., Lu, B., Shi, Z., Tao, H., 2018. Ocean euxinia and climate change "double whammy" drove the Late Ordovician mass extinction. Geology, **46**: 535–538. https://doi.org/10.1130/G40121.1

Zulauf, G., Dörr, W., Fisher-Spurlock, S.C., Gerdes, A., Chatzaras, V., Xypolias, P., 2015. Closure of the Paleotethys in the External Hellenides: Constraints from U-Pb ages of magmatic and detrital zircons (Crete). Gondwana Research, **28**: 642–667. https://doi.org/10.1016/j.gr.2014.06.011

Zurbriggen, R., 2015. Ordovician orogeny in the Alps: a reappraisal. International Journal of Earth Sciences, **104**: 335–350. https://doi.org/10.1007/s00531-014-1090-x

Zurbriggen, R., 2017a. The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region. International Journal of Earth Sciences, **106**: 517–529. Doi 10.1007/s00531-016-1438-5

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