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RESEARCH ARTICLE

Tithonian limestone as a marker of early contraction of NeoTethyan Vardar Ocean: structural constraints on the latest Jurassic–earliest Cretaceous “docking” (Dobroljupci, Kuršumlija, Jastrebac Mt., Serbia)

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Abstract
The Jurassic–Cretaceous East Vardar Zone (EVZ) is a NNW–SSE-directed NeoTethyan back-arc crustal amalgamation that passes through Romania, Serbia, Bulgaria, North Macedonia, and Greece. This somewhat elongated Jurassic back-arc ocean underwent early compression, “docking” and nappe-stacking in the latest Jurassic–earliest Cretaceous. The Tithonian(Berriasian) limestones, which stratigraphically overlie the Middle Jurassic oceanic crust, are not only crucial markers of the latest Jurassic contraction and exhumation but also bear significant implications for the NeoTethyan Vardar developments (evidence of paleokarstification). During the latest Jurassic–earliest Cretaceous compressional event, the oceanic crust belonging to the EVZ interacted with the Dacia Mega-Unit and its Serbo-Macedonian continental margin. By introducing new structural observations, this study covers the interference character between the EVZ periphery and the western Serbo-Macedonian Unit. Supported by previous mapping results, new structural data are extracted from several key outcrops distributed across central Serbia (Dobroljupci, Kuršumlija, Jastrebac Mt.). The analyses of geodynamic implications related to the NeoTethyan Vardar contraction have outlined the latest Jurassic-earliest Cretaceous accretionary-type deformation embedded in the peripheral units (Tithonian-Berriasian limestones, mélanges, Serbo-Macedonian gneiss). These findings are significant as they provide a deeper understanding of the geological processes that shaped this region during the mid-Mesozoic. Despite Late Alpine overprinting, the latest Jurassic arc-type “soft collision” or “docking” (no evidence of significant crustal thickening with a very limited obduction) produced the newly observed NNE-SW oriented folds. The folds are observed within the Jurassic carbonate rocks and greenschist-facies rocks of likely similar age and origin (train of steeply plunging synforms, D_1). The tectonic resetting and initiation of post-collisional progressive subduction remobilized the stalled remnant of the Vardar marine corridor after the short-term Berriasian exposure and palaeokarstification. Such tectonic developments triggered a foreland-type subsidence and accumulation of the clastic-carbonate Lower Cretaceous “paraflysch” on top of the EVZ ophiolites/mélange/Tithonian limestones. However, the new depositional cycle and the oldest Lower Cretaceous paraflysch sequence remain devoid of ophiolite inclusions.

Keywords Tithonian limestones · Paleotectonic reconstruction · Jurassic ophiolites · Vardar Zone · East Vardar Zone · Serbo-Macedonian Unit · Latest Jurassic–earliest Cretaceous collision

Introduction

Remnants of ancient oceans recognized as on-land ophiolites and deeper recrystallized equivalent magmatic suites are often observed along exhumed continental margins. Such a combination of crustal fragments indicates a formerly active oceanic margin or suture zone and is often referred to as the subduction-accretion complex (e.g., Bonev and Stampfli 2011; Festa et al. 2019; Mposkos et al. 2024; Okay et al. 2022; Bonev et al. 2023; Spahić et al. 2023a). The three contrasting rock assemblages can be recognized

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as composite deep water oceanic-continental accretionary amalgamations of former active margins: (a) sliced cut-off fragments frequently accompanied by shallow-water carbonates (oceanic crust that is obducted onto a continental margin), or the ophiolitic part, (b) dominantly clastic or turbiditic rocks, which often constitute a trench assembly, and (c) their deeper, often exhumed igneous crustal domains that are frequently exposed to a variety of metamorphic conditions. Between the Carpathian-Balkan and Dinaric-Hellenic Mesozoic accretionary ophiolite-turbidite assemblage lies the composite collisional Vardar Zone (Fig. 1a–c). The Vardar Zone represents the westernmost relic of oceanic NeoTethyan affinity embedded into Alpine-Mediterranean-Himalaya mountain system. The geodynamic context of the NeoTethyan Vardar Ocean discussed in terms of subduction-accretionary history has the protracted tectono-metamorphic evolution spanning the Late Jurassic–earliest Cretaceous event, lasting until the Late Cretaceous-Paleogene collision (Anders et al. 2005; Saccani et al. 2008a, b; Meinhold et al. 2009; Šarić et al. 2009; Bonev and Stampfli 2011; Marroni et al. 2014; Spahić et al. 2023a; Kydonakis et al. 2015; Richards 2015; Putiš et al. 2019; Table 1). The latter collisional event corresponds to its slab pull-driven “terminal closure” (van Hinsbergen et al. 2015, and references therein), giving rise to the Dinaride-Carpathian-Balkan-Rhodope-Hellenide segments of the Alpine orogen (e.g., Ricou et al. 1998; Karamata 2006; Schmid et al. 2008; Maffione and van Hinsbergen 2018; Fig. 1a–c; Table 1).

The Jurassic Neo-Tethys has a composite oceanic length exceeding 3000 km (e.g., Robertson 2012; Jolivet 2023). The exposed Jurassic lithospheric fragments of the (western) Balkan Peninsula represent the northwestern segment of the NeoTethyan Vardar Ocean. Larger Jurassic lithosphere belts are widespread across a number of mountain ranges (Fig. 1a–c, e.g., in Serbia, Zlatibor Mt—ZLA, Maljen Mt.—MA), whereby smaller size fragments are exposed in the eastern Kopaonik Block, Belgrade, Levač/Ždraljica/Dobroljupci, and Kuršumlijska banja areas (Fig. 1, EVZ ophiolites; KB, BG, L/ŽD/Dlj, KB, Fig. 2a, b). The residual geometry and geochemical fingerprints are compatible with either an obduction-driven single NeoTethyan Vardar ocean on the Dinarides or with multiple Jurassic paleo-oceanic developments (see, e.g., Schefer et al. 2010; Robertson et al. 2013; Bortolotti et al. 2013; Spahić and Gaudenyi 2020a, b; Kukoč et al. 2024; Jolivet 2023, for discussion; Tables 1, 2; Fig. 1).

To the east of the Dinarides is the NNW-SSE striking a discrete East Vardar Zone (hereinafter EVZ; Figs. 1c, 2a, b). The studied east-vergent EVZ (in Jurassic reference frame) stretching across central Serbia is composed of shallow intrusive-type gabbro-diabase with minor involvement of the Jurassic volcanics of the acidic to intermediate compositions (subduction-related volcanic arc magmatism; Resimić-Šarić et al. 2005; Šarić et al. 2009; Boev et al. 2018; Figs. 1c, 2, 3a). The EVZ assembly is frequently overlain by Tithonian limestone. The EVZ segment in Romania can be interpreted as an island arc affinity obducted on top of the Dacia unit (Apuseni Mt., Romania; see Gallhofer et al. 2017, for a discussion; Fig. 1). During the latest Jurassic–earliest Cretaceous, already subducting Western Vardar Zone (WVZ) oceanic lithosphere was presumably tectonically transported and contemporaneously with the marginal EVZ ophiolites were obducted on top of the continental margin (eastward-directed obduction accounting for the flip of subduction polarity; Gallhofer et al. 2017; Fig. 1c, yellow arrow; Fig. 2a, c, d; Fig. 3a–c). On the other hand, mainly earlier reports (e.g., Rakić et al. 1969, 1976; Dimitrijević 1997) inclusive a few more recent contributions (e.g., Šarić et al. 2009; Boev et al. 2018; Petrović et al. 2015; Spahić and Gaudenyi 2019; Maleš et al. 2023), pointed out somewhat different latest Jurassic–earliest Cretaceous crustal motions observed in central Serbia. The proposed lithospheric motions between the elements of the NeoTethyan ophiolite sequences and the Serbo-Macedonian continental margin have rather a descending lower oceanic plate configuration. The following discussion revisits these supra-crustal inconsistencies revolving around the late Jurassic plate configuration. The field observation focus are the spatial orientation of oceanic and continental plates and deformations embedded into the Tithonian limestone, inclusive configuration of their equivalents exposed across central Serbia.

To investigate the puzzling latest Jurassic–Cretaceous NeoTethyan paleogeographic and structural configuration of central Serbia (Table 2), we examine a rarely exposed tectonic contact between the EVZ (Tithonian limestone) and the gneissic high-grade Serbo-Macedonian basement (Figs. 1, 2, 3). The study aims to find out if there is any field evidence of the upward (**e**astward)-directed obduction-type hanging wall motions imprinted on top of the Jurassic microcontinent (Fig. 1, yellow arrow). The kinematic observations were not intended to characterize the entire deformation history of the contact under study but to focus on the central Serbian Jurassic developments characterized by Tithonian limestone. We thus reevaluate the finite configuration, analyze regional geodynamic setting, and discuss the genesis and tectonic involvement of the EVZ Jurassic ophiolites. Several transects crosscutting these two interacting NeoTethyan lithospheric-scale systems are structurally mapped during several field campaigns. The collected field data provided new geometrical constraints on the orientation of the overprinted Jurassic foredeep and accompanied limestone relative to the Serbo-Macedonian overriding plate (Figs. 3, 4). We studied several exposed outcrops in central Serbia (Fig. 2b), looking for the exposed NeoTethyan Vardar marginal configuration: (i) the contact

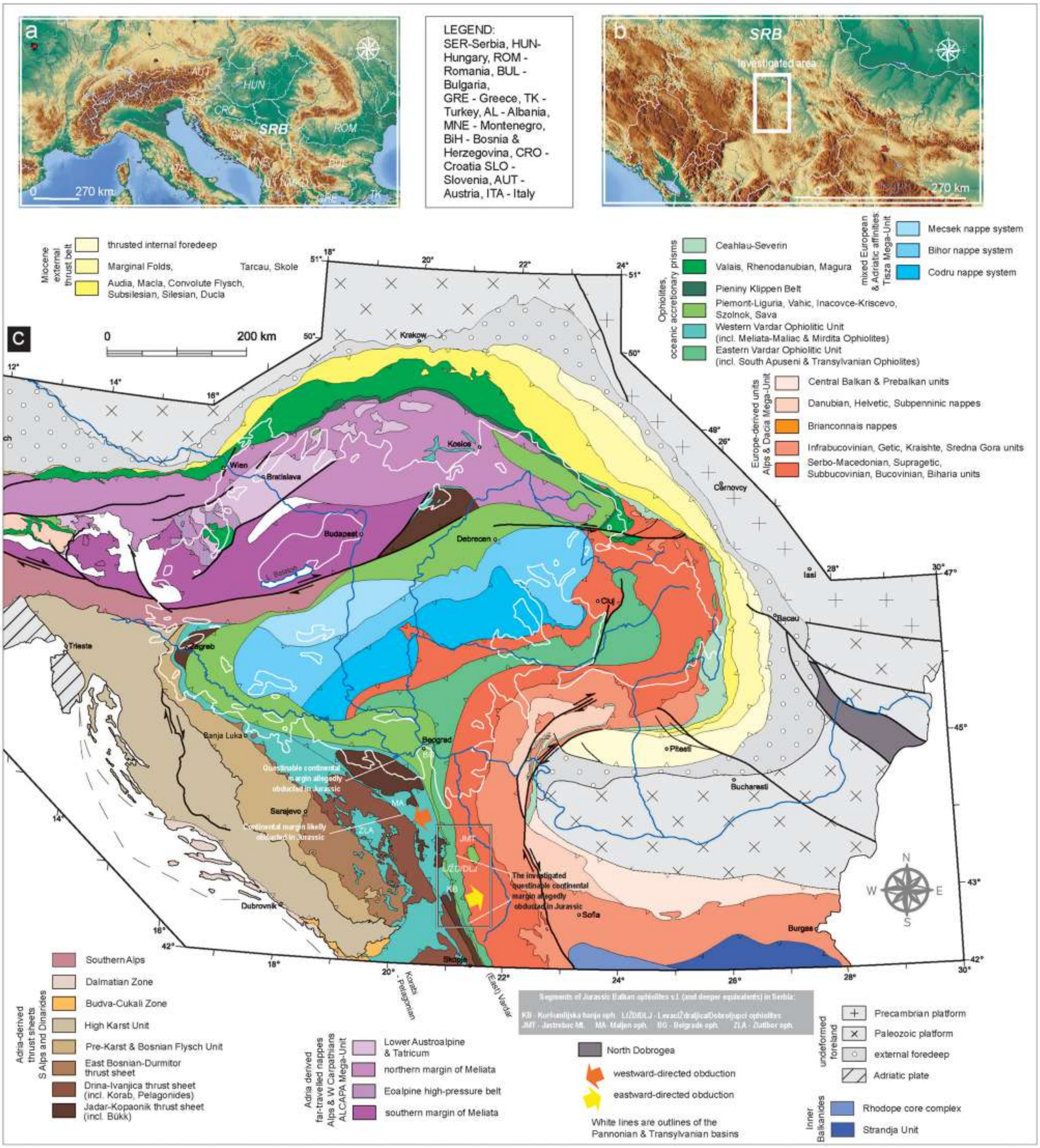


Fig. 1 Central tectonic units of the Alps, Carpathians, and Dinarides (modified after Schmid et al. 2008). The sketch map illustrates the Jurassic obduction on top of the Jadar and Drina-Ivanjica nappes and the Serbo-Macedonian margin). The investigated obduction-related tectonic boundary is towards the Serbo-Macedonian Unit (yellow-blue rectangle). Abbreviations: *SER* Serbia, *ROM* Romania, *BiH* Bosnia & Herzegovina, *CRO* Croatia, *NMKD* North Macedonia, *GRE* Greece, *AL* Albania, *ITA* Italy, *TK* Turhey, *SPA* Spain

between the Jurassic EVZ assembly (mainly basic type rocks and Tithonian limestones) and Serbo-Macedonian Unit, cropping out at the Dobroljupci area (Fig. 2b#1), (ii) the Neogene core-complex, which exposes tectonically exhumed metamorphosed NeoTethyan crustal segments at the Jastrebac Mt. (Fig. 2b#2), whereby in the (iii) Kuršumlijska banja area we observed evidence of mid-Mesozoic nappe-stacking (involving the Kopaonik Mt.

Table 1 NeoTethan research in a number of publications. The table shows the authors and principal conclusions

Publications (author's)	Country	Type of the study/approach	General results on NeoTethys/Vardar	Interpretation of the East Vardar Zone
Anđelković (1973)	SER	Regional geology	Emphasizes the Upper Cretaceous magmatism	Separates "Šumadidi" as the turbidite belt (EVZ)
Karamata et al. (1994, 2000)	SER, NMKD, GRE, BiH	Petrology, paleogeography	There is a relic "Vardar Ocean" in Cretaceous	The Eastern subzone closed in Jurassic
Dimitrijević (1997, 2001)	SER, NMKD, BiH, CRO	Regional Alpine tectonics	Vardar and Dinaric Tethys are separated oceans, Jadar block in the Vardar zone	Internal Vardar subzone, tectonically reworked during early Alpine events (Jurassic)
Karamata (2006)	SER, NMKD, BiH, CRO	Regional paleogeography and tectonics	Vardar and Dinaric Tethys are separated oceans, Main Vardar Zone	Main Vardar Zone; closed during the Late Jurassic and represents suture
Stampfli and Kozur (2006)	SER, NMKD, GRE, BiH, CRO, TR, AL	Regional paleogeography and tectonics	Multiple Oceans model	Late Jurassic collision of the Vardar plate with the Rhodope and Balkans,
Hrvatović and Pamić (2005)	BiH, CRO	Regional Alpine tectonics	Alpine nappes configuration	–
Pamić (2002)	BiH, CRO	Regional Alpine tectonics	(Re)introduction of "Sava-Vardar zone"	Part of "Sava-Vardar zone"
Csontos and Vörös (2004)	SER, BiH, CRO	Regional paleogeography	Paleogeography based on single ocean model	Vardar subducted by the end of Jurassic, causing the Bihor –Getic –Serbo –Macedonian microcontinent to collide with the internal Dinaric –Western Carpathian margin
Resimić-Šarić et al. (2005)	SER	Magmatic age and geochemical signatures	168.4 ± 6.7 Ma on quartzdiorite	East Vardar Zone ophiolites and their maximum age
Šarić et al. (2009)	SER	Magmatic age and geochemical signatures	major, trace and Sr–Nd–Pb data concerning Upper Jurassic granitoid rocks	Emplacement of the East Vardar ophiolites in the Upper Jurassic was followed by high-temperature collision
Schmid et al. (2008, 2020)	SER, NMKD, BiH, CRO	Regional Alpine tectonics from Upper Triassic	Paleogeography and nappe-stacked configuration based on single ocean model	Late Jurassic emplacement of the Eastern Vardar Ophiolitic Unit onto at least parts of the Biharia nappe system and its lateral equivalent, the Serbo-Macedonian Massif, is probably related to the obduction of the Eastern Vardar ophiolites onto parts of the Dacia Mega-Unit
Gallhofer et al. (2017)	ROM	Magmatic age and geochemical signatures	Paleogeography and tectonics	East Vardar Zone ophiolites are obducted on Dacia
Mikes et al. (2008)	BiH	Regional Alpine tectonics	First detrital zircon data – there is another turbidite section of Cretaceous age	–
Grubić et al. (2009, 2010)	BiH	Regional Alpine tectonics	Age of Sava Zone magmatic equivalents	–

Table 1 (continued)

Publications (author's)	Country	Type of the study/approach	General results on NeoTethys/Vardar	Interpretation of the East Vardar Zone
Robertson et al. (2013)	SER, NMKD, BiH, CRO	Review of Regional Alpine tectonics	Comparison between single and multiple ocean models	
Bazylev et al. (2009)	BiH	Magmatic age and geochemical signatures	There are multiple Vardar oceans	
Ustaszewski et al. (2009, 2010)	BiH, CRO	Exhumation fission track analyses	Age of Sava Zone exhumation and magmatic equivalents	–
Robertson (2012)	SER, NMKD, BiH, CRO	Review of Regional paleogeography	Paleogeography of entire Tethys	
Bortolotti et al. (2013)	SER, NMKD, BiH, CRO	Review of Regional paleogeography and number of oceans	Comparison between single and multiple ocean models (favor single ocean model)	
Faul et al. (2014)	BiH, CRO	Magmatic age and geochemical signatures		–
Petrović et al. (2015)	SER	Gravimetric geophysical data	There is slab beneath Serbo-Macedonian Unit	EVZ ophiolites subducted underneath Serbo-Macedonian
Menant et al. (2016)	SER, NMKD, GRE,	Reconstruction of regional paleogeography	Paleogeography and nappe-stacked configuration based on single ocean model, no Sava Zone	–
Prelević et al. (2017)	NMKD	Magmatic age and geochemical signatures	Upper Cretaceous age of Sava Zone basalts	–
Maffione and van Hinsbergen (2018)	SER, BiH	Magmatic age and regional tectonics	Provides all ages of the ophiolites, mainly Jurassic	
Gawlick et al. (2016)	SER, BiH	Stratigraphy and paleogeography	Triassic developments in Dinarides	–
van Hinsbergen et al. (2020)	SER, NMKD, GRE, BiH, CRO, ITA, TK; SPA	Regional paleogeography	Regional paleogeography based on single ocean model	EVZ ophiolites are formed at a spreading center located in a forearc position above a N-S trending subduction zone
Toljić et al. (2018, 2019, 2020)	SER	Regional tectonics	Sava zone is fore-arc basin	–
Boev et al. (2018)	SER, NMKD	Overview of magmatic age and geochemical signatures	Juxtaposition of geochemical signatures	East Vardar Zone has peculiarities in Central Serbia
Dilek et al. (2007)	GRE, AL	Overview of magmatic age and geochemical signatures	Juxtaposition of geochemical signatures	The Vardar Zone ophiolites separate the Pelagonian microcontinent from the Serbo-Macedonian Zone to the east, which represents the Jurassic–Early Cretaceous active margin of Eurasia
Sokol et al. (2019)	SER	New magmatic ages and regional tectonics	Sava Zone	–
Scherreiks and BouDagher-Fadel (2021)	GRE	Stratigraphy and paleogeography	Favor single-ocean model	During Middle Jurassic time a 1200-km slab of west Vardar lithosphere subducted beneath the supra-subduction, "Eohellenic" arc

Table 1 (continued)

Publications (author's)	Country	Type of the study/approach	General results on NeoTethys/Vardar	Interpretation of the East Vardar Zone
Spahić and Gaudenyi (2020b, 2022); Spahić (2022b)	SER, BiH, CRO, NMKD	Overview of regional paleogeography	Jurassic ophiolites, Sava Suture Zone	East Vardar Zone interacted in a strike-slip mode with Serbo-Macedonian
Yu et al. (2022)	ITA	Overview of regional paleogeography	New data bauxites	–

Country key as in Fig. 1

and EVZ ophiolites and southern segment of Tithonian limestones; Fig. 1). There at Kuršumlijska banja, the latest Jurassic–earliest Cretaceous relationship between the two supra-crustal ophiolite systems is also observed (Western Vardar beneath East Vardar; Fig. 2b#3). The new outcrop-scale structural mapping campaign in scale 1:50,000, sheet Kruševac 4 allowed us to reconstruct and extrapolate these puzzling NeoTethyan Vardar affinities, particularly the latest Jurassic–earliest Cretaceous configuration of the EVZ.

Geology

Jurassic paleogeography, NeoTethyan ophiolites and continental margin

The investigated NeoTethyan paleosuture system of central Serbia involves the rocks of the Paleozoic, Jurassic, and Cretaceous–Paleogene ages (Figs. 2a–c, 3a–c, 4a). The NeoTethys represents either a rift or a Paleotethys-related oceanic affinity that subducted (paleo)northwards (in Permian–Triassic reference) underneath the Laurasian/Eurasian/Eocimmerian margin (former Paleotethyan mega-bay; Vavvasis et al. 2000; Zulauf et al. 2015; Spahić and Gaudenyi 2021; Spahić 2022a, c). The landlocked northwestern NeoTethyan oceanic basin or branch, which developed within the previously amalgamated Variscan-Cimmerian basement framework, strikes W-E linking Central Europe, the Balkan Peninsula and the Hellenides with the eastern Mediterranean region. The latest Jurassic–earliest Cretaceous oceanic closure of the latter landlocked basin is connecting the investigated northwestern NeoTethys with the compressional and metamorphic event, well-documented in the Balkan-Hellenic, Intra-Pontide Suture Zone, striking further across Sanandaj-Sirjan Zone in Iran (e.g., Anders et al. 2005; Mposkos et al. 2024; Şen 2024; Shabanian and Neubauer 2024).

Across the Balkan Peninsula, the initial latest Jurassic–earliest Cretaceous ophiolite obduction, "docking", "soft collision", including the latest Jurassic–Lower Cretaceous thrusting was overprinted by the latest Cretaceous–Paleogene west-vergent nappe stacking and tectonic exhumation of the three ophiolite-bearing zones (Table 2): (i) Inner Dinaric Zone, located within the northeastern margin of Apulia/Adria and west of the Pelagonide Massif (e.g., Ilić and Neubauer 2005; Mikes et al. 2008; Schmid et al. 2008; Srećković-Batoćanin et al. 2012), (ii) Western Vardar Zone ultramafic rock distributed along the Apulia/Adria northeastern edge (on top of former passive margin or Jadar and Drina-Ivanjica nappes; Pamić 2002; Pamić et al. 2002a, b; Karamata 2006; Faul et al. 2014; Schmid et al. 2008; Yu et al. 2022), and here investigated (iii) the NNW-SSE striking trench-parallel the EVZ, which plunges into Aegean sea; e.g., Zachariadis et al. 2006; Šarić et al. 2009; Gallhofer et al. 2017; Boev et al. 2018; Mposkos et al. 2024; Tables 1, 2). A segment of the southern EVZ limb strikes as the Circum-Rhodope belt (e.g., Spahić et al. 2020a, b; Bonev et al. 2022) and abuts around the south of Rhodopean massif (Figs. 1, 2a, b). To the north of the Rhodope is the adjoining early Paleozoic gneiss-bearing Serbo-Macedonian Unit of central Serbia. Together with the Rhodopean massif, the Serbo-Macedonian Unit represents a western realm of the Mesozoic continental margin (e.g., Bonev and Stampfli 2008; Michail et al. 2016; Maleš et al. 2023; Table 1). The Serbo-Macedonian Unit was a segment of the latest Jurassic–earliest Cretaceous southern Euroasian continental margin. This position was succeeded by the developing rift/back-arc Triassic Meliata-Maliac oceans (e.g., northern Greece, eastern Bulgaria, Bonev and Stampfli 2008; Ferriére et al. 2012, 2016; Spahić and Gaudenyi 2021; Spahić 2022c). This Alpine extension is consistent with the rest of the peri-Moesian Variscan basement units, including the opening of the southern limb of Alpine Tethys (eastern Serbia; Kräutner and Krstić 2002; Antić et al. 2017; Spahić and Gaudenyi 2018; Figs. 1, 2d, 3b). During the latest Cretaceous–Paleogene collisional late Alpine wedging and crustal thickening event, the previously amalgamated Serbo-Macedonian Unit and EVZ had the overriding plate position (e.g., Schmid et al. 2008; Fig. 1).

Central segment of the East Vardar Zone (Serbia and surroundings)

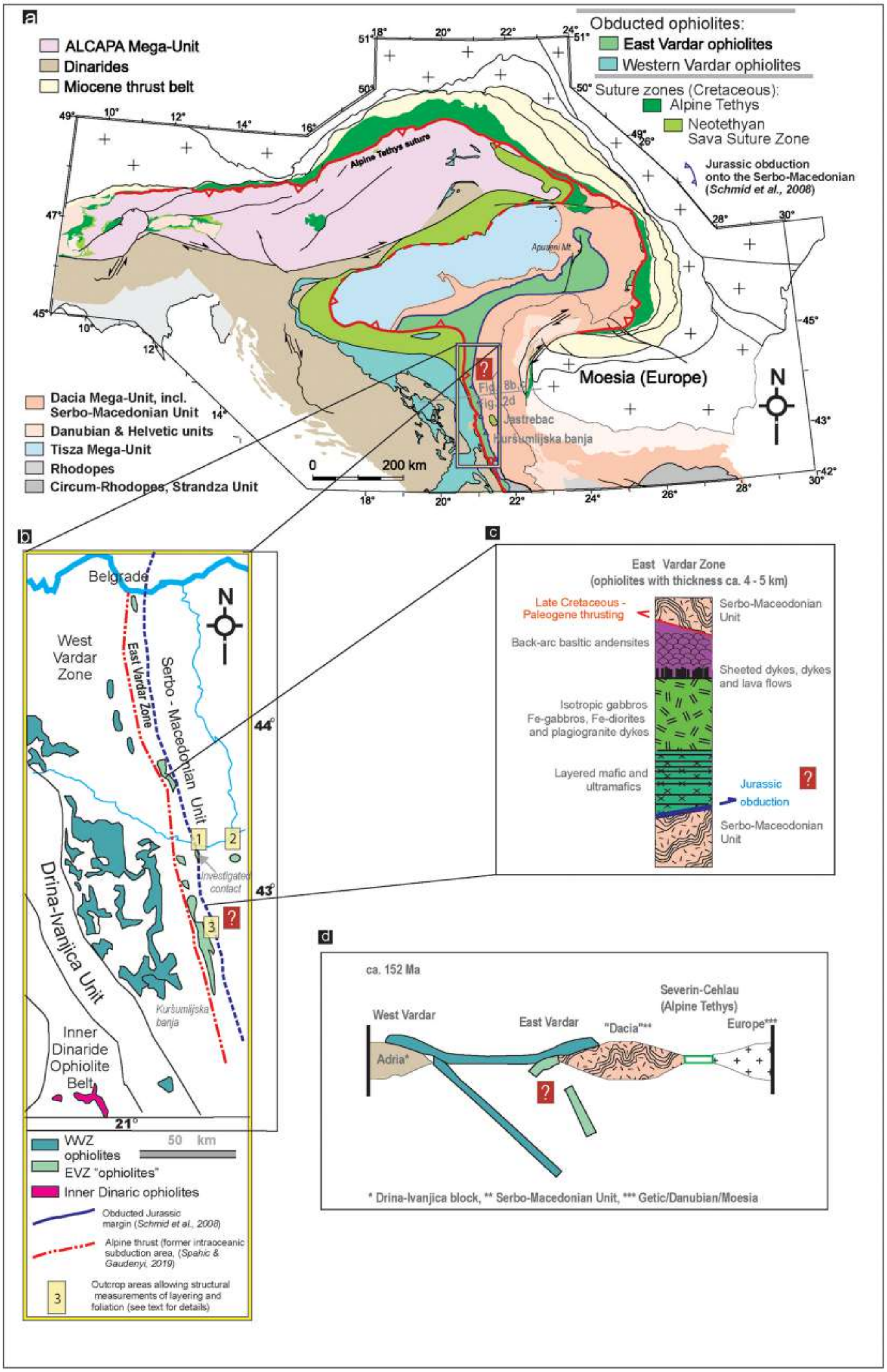
The central EVZ crops out near the city of Belgrade (e.g., Toljić et al. 2018; Sokol et al. 2019; Marinović and Rundić 2020) and is further prominent in central Serbia (Resimić-Šarić et al. 2005; Šarić et al. 2009; Maffione and van Hinsbergen 2018; Maleš et al. 2023; Figs. 1, 2a–c). In central Serbia and North Macedonia, the EVZ, as a former oceanic plate, is cut off to the east by the western Serbo-Macedonian margin, which, generally, is juxtaposed with Tithonian limestones (e.g., Rakić et al. 1969, 1976; Spahić and Gaudenyi 2019; Maleš et al. 2023). The Jurassic ophiolites in central Serbia exhibit no metamorphic sole (Schmid et al. 2008; Maffione and van Hinsbergen 2018), though a recent study indicates the presence of a lower-grade greenschist facies overprint (Maleš et al. 2023).

The Jurassic back-arc ophiolites of the EVZ differ in size: the exhumed limited-size ophiolites are spread across central Serbia, and the larger ones are in its southern limb in North Macedonia and Greece (e.g., Šarić et al. 2009; Michail et al. 2016; Božović et al. 2013; Kukoč et al. 2015). The size of the EVZ ophiolites was probably controlled by the limiting Pelagonian/Korabi - Pelagonian Massif in front of its southern limb (e.g., Robertson et al. 2013). In central Serbia, the metamorphosed deep trench NeoTethyan Vardar crustal equivalents are exposed in the Veliki Jastrebac Mt. tectonic window (Marović et al. 2007a; Erak et al. 2017; Spahić and Gaudenyi 2019; Fig. 3). In eastern Bulgaria, within the NeoTethyan Vardar Jurassic framework, there is a Triassic to Early Cretaceous low-grade metamorphic Circum-Rhodope sequence (Bonev et al. 2023). These pre-Jurassic sequences are lacking in the EVZ in central Serbia. The EVZ segment in central Serbia consists of the following composite units: (i) Middle-Late Jurassic (pre-Kimmeridgean) ultramafic and mafic gabbro-basalts-serpentinites with the MORB-type oceanic lithosphere (Schmid et al. 2008). This igneous assembly includes (ii) the ophiolite mélange (also widespread across the Dinaride-Hellenide belt; e.g., Dimitrijević and Dimitrijević 1973, 1975; Gawlick and Missoni 2019; Fig. 2c); (iii) The topseal belongs to the Tithonian(-Berriasian) limestone sequence (Petrović and Jankićević 1990; Dimitrijević and Dimitrijević 2009; Šarić et al. 2009). The Jurassic EVZ assemblage in Serbia is interrupted by a lowermost Cretaceous unconformity (Maleš et al. 2023; Spahić et al. 2023a), which is further attested by the Tithonian limestone occasionally exposing evidence of paleokarstification (Dimitrijević and Dimitrijević 2009; Spahić et al. 2023a). Indeed, previous and some recent authors have pointed to the involvement of the latest Jurassic–lowermost Cretaceous contraction and nappe-stacking event (e.g., Sandulescu 1984; Bonev and Stampfli 2011; Maleš et al. 2023).

The investigated EVZ Jurassic ophiolite- and limestone-bearing paleotectonic amalgamation was discordantly succeeded by the depositional onset and formation of a 250 km-long N–S striking Lower Cretaceous "paraflysch" (Dimitrijević and Dimitrijević 2009). Regionally, the Lower Cretaceous "paraflysch" carbonate and clastic foreland sequences (Dimitrijević and Dimitrijević 2009) have significant similarities with a shallow marine system in western Bulgaria (Getic unit; Kräutner and Krstić 2006; Ivanova and Chatalov 2022). Nevertheless, this Cretaceous system differs from the Lower Cretaceous overstep sequences that overlies Jurassic ophiolites across the Dinarides (Nirta et al. 2020). The foreland-type "paraflysch" sequences in central Serbia are overlain by the unconformable Upper Cretaceous deep-water sediments and Maastrichtian to lowermost Paleogene pre-collisional turbidites (e.g., Toljić et al. 2018, 2020; Spahić et al. 2023a; Fig. 4a).

Dobroljupci, Jastrebac Mt., and Kuršumlijska banja area, field relationships

Dobroljupci and its surroundings (Levač, Maleš et al. 2023; Fig. 1) represent a rare spot in central Serbia where the investigated tectonic contact between the two main geotectonic units is exposed (Figs. 3, 4, 5, 6). The Dobroljupci area exposes the tectonic contact connecting the composite Jurassic rock assemblage (greenschists, mélange, and Tithonian


a
ALCAPA Mega-Unit
Dinarides
Miocene thrust belt
Obducted ophiolites:
East Vardar ophiolites
Western Vardar ophiolites
Suture zones (Cretaceous):
Alpine Tethys
Neotethyan
Sava Suture Zone
Jurassic obduction
onto the Serbo-Macedonian
(Schmid et al., 2008)
Alpine Tethys suture
Apuseni Mt.
Moesia (Europe)
N
Fig. 8b,c
Fig. 2d
Jastrebac
Kuršumlijska banja
0
200 km
Dacia Mega-Unit, incl.
Serbo-Macedonian Unit
Danubian & Helvetic units
Tisza Mega-Unit
Rhodopes
Circum-Rhodopes, Strandza Unit
b
Belgrade
West
Vardar
Zone
East Vardar Zone
Serbo - Macedonian Unit
Drina-Ivanjica Unit
Inner
Dinaride
Ophiolite
Belt
Investigated
contact
Kuršumlijska
banja
44°
43°
21°
50 km
WVZ
ophiolites
EVZ "ophiolites"
Inner Dinaric ophiolites
Obducted Jurassic
margin (Schmid et al., 2008)
Alpine thrust (former intraoceanic
subduction area, (Spahic &
Gaudenyi, 2019)
Outcrop areas allowing structural
measurements of layering and
foliation (see text for details)
c
East Vardar Zone
(ophiolites with thickness ca. 4 - 5 km)
Late Cretaceous -
Paleogene thrusting
Serbo-Maceodonian
Unit
Back-arc basltic andensites
Sheeted dykes, dykes
and lava flows
Isotropic gabbros
Fe-gabbros, Fe-diorites
and plagiogranite dykes
Layered mafic and
ultramafics
Jurassic
obduction
Serbo-Maceodonian
Unit
d
ca. 152 Ma
West Vardar
East Vardar
"Dacia"**
Severin-Cehlau
(Alpine Tethys)
Europe***
Adria*
* Drina-Ivanjica block, ** Serbo-Macedonian Unit, *** Getic/Danubian/Moesia

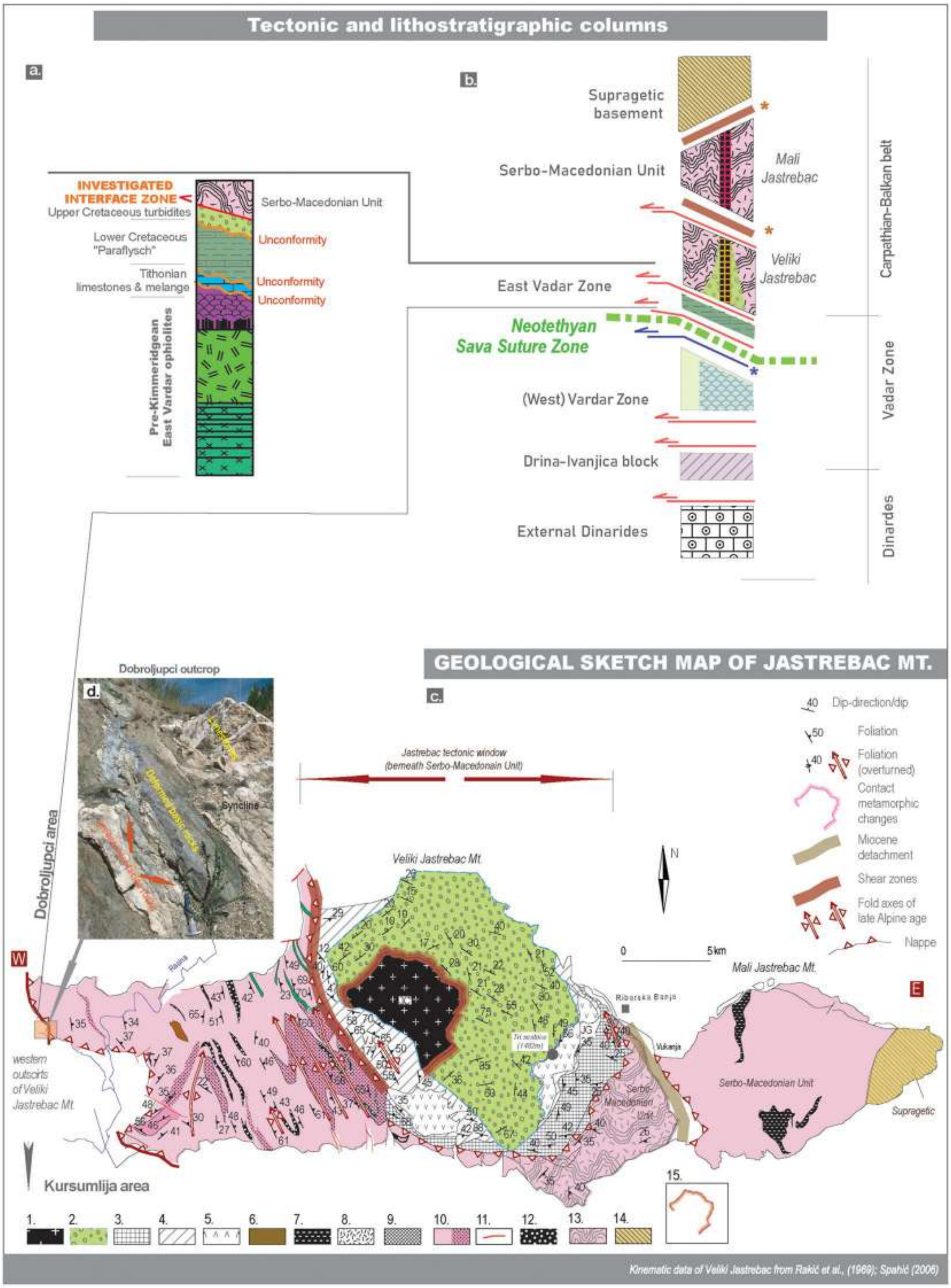
◂**Fig. 2** **a** Modified regional tectonic sketch map (Schmid et al. 2008, inset from Gallhofer et al. 2017). **b** Tectonic units and ophiolites belts according to the concept of Karamata (2006; inset from Bazylev et al. 2009). The geotectonic subdivision of central Serbia, including the study area of the East Vardar Zone. **c** Synthesized East Vardar ophiolites column with their respective cumulative thicknesses (after Maffione and van Hinsbergen 2018). **d** According to the mainstream tectonic model, both ophiolite-bearing belts originate from the same Jurassic Ocean. In contrast, the Jurassic obduction is replaced by the Serbo-Macedonian passive margin (inset from Gallhofer et al. 2015, slightly modified). A red rectangle with a question mark emphasizes the problem of the slab configuration and associated processes

limestones; Fig. 3a, b), overlain by older rocks belonging to the (Neoproterozoic) Cambrian Serbo-Macedonian Unit. The latter top-sealing gneiss is in the Veliki Jastrebac Mt. area pierced by the intrusion of the Paleogene-Neogene core complex (Fig. 3c, 4a–d). From the east of the Dobroljupci outcrop, a small part of the syncline exposes the steeply plunging greenschist-facies rocks of likely Middle Jurassic age (Dolić et al. 1978), i.e. meta-basic rocks, which are overlain by the marker Tithonian limestones (Fig. 3d, see position on Fig. 4b). The ca. 200–300 m long E-W striking section of the Dobroljupci outcrop further exposes the inverted tectonic configuration of the two crustal domains, wherein the older metamorphic rocks (Serbo-Macedonian gneisses) are structurally overlying these younger sediments (Jurassic composite unit with Tithonian limestones on top; Fig. 4b). The central section of the outcrop exposes some strongly foliated footwall sediments (not metamorphites) with the almost vertically orientated foliation and schistosity, thus additionally marking an intensive tectonic interference along this segment of the paleosuture (Fig. 4c, d). Nevertheless, immediately to the south of the outcrop (Fig. 2b), the well-preserved set of basaltic rocks is exposed (Fig. 7). In addition, the Dobroljupci outcrop has no record of the Upper Cretaceous paleosuture turbidites.

These latest Cretaceous–Paleogene collisional (meta) turbidites are, in turn, widespread across the Jastrebac Mt. abutting its eroded granodiorite core (Fig. 3c). Structurally below the Upper Cretaceous–Palaeogene turbidites are the Boljevac-Vukanja greenschists, which contain (meta)gabbro, calcschists and marbles (Fig. 3c, #3,4,5). According to the structural superimposition, the Boljevac-Vukanja assembly could represent an exhumed remnant of the subducted Neo-Tethyan oceanic crust (Spahić 2006; Marović et al. 2007a, b) or could be interpreted as the metamorphosed pre-obduction assembly (Maleš et al. 2023). Interestingly, the tectonic window of the Jastrebac Mt. shows the same inverted position, which is identical to the configuration exposed at the Dobroljupci outcrop: gneiss of the Serbo-Macedonian positioned on top of the Boljevac-Vukanja greenschists, including gabbro, calcareous schists, and marbles. The latter magmatic and sedimentary sequences are most likely

Table 2 The comparison between several NeoTethyan tectonic-paleogeographic models proposed in the last 20 years.

Study	Geotectonic units of Vardar Zone			Jurassic NeoTethyan Ocean(s)	"Cretaceous Ocean"
	Western Vardar eastern belt	East Vardar-	Western Vardar western belt or Dinaric Tethys		
Schmid et al. (2008)	West Vardar Zone ophiolites	East Vardar Ophiolites	Dinaric and Mirdita-Pindos ophiolites	Single Vardar Ocean	relic "Sava Ocean"
Dimitrijević (1997, 2001)	External Vardar subzone and Central Vardar subzone	Internal Vardar subzone	Ophiolite belt	Vardar Ocean + "Dinaric Tethys"	No oceans
Karamata (2006) and Karamata et al. (2000)	Vardar Zone Western belt	Main Vardar Zone	Inner Dinaric Ophiolite belt	Vardar Ocean as successor of Paleo-Tethys + "Dinaric Tethys"	"Relic Sava ocean" belongs Vardar Zone Western belt
Toljić et al. (2019)	Western Vardar Zone	Eastern Vardar Zone	Dinaride Ophiolite belt	Single Vardar Ocean,	Relic "Sava Ocean"
Pamić (2002)	"Sava–Vardar Zone"		Dinande-Hellenide Ophiolite Zone	Vardar Ocean + "Dinaric Tethys"	Relic "Sava Ocean"
Prelević et al. (2017) and Sokol et al. (2019)	Western Vardar Ophiolitic Unit	East Vardar Ophiolitic Unit	West Vardar Ophiolitic Unit	Single Vardar Ocean/ Cretaceous Basalts are localized in continental crust	
Spahić and Gaudenyi (2022)	Western Vardar Zone	East Vardar Zone	Inner Dinaric Ophiolite belt	Vardar Ocean + "Dinaric Tethys"	No oceans, narrowing pull-apart corridor, no oceanic crust of Upper Cretaceous age



the subducted analogs of the Tithonian limestone sequence (Figs. 3c, 4a; e.g., Rakić et al. 1969, 1976; Spahić 2006; Marović et al. 2007a; Erak et al. 2017). The Jastrebac tectonic window does not contain pure limestones but mainly reveals calc-schists and rare marbles of unknown, but most likely Mesozoic (Tithonian?) age (Spahić 2006; Marović et al. 2007a, b).

Further to the south of the EVZ, the Tithonian limestones observed at the Dobroljupci area crop out in the Kuršumlijska banja area (Petrović and Jankićević 1990; Fig. 2c). Importantly, at the Kuršumlijska banja area, the Tithonian limestones contain the redeposited cm-scale diabase inclusions. These EVZ diabases, in turn, record several inclusions embedded in Tithonian limestone. The contact between diabase and limestone is mylonitized (Petrović

◂**Fig. 3** **a** Geological column of the East Vardar ophiolites (inset from Maffione and van Hinsbergen 2018, significantly modified). **b** Synthetic geological column of the wider study area (inset from Spahić 2022c, modified). **c** Geological sketch map of Mt. Jastrebac (inset from Spahić and Gaudenyi 2019, slightly modified). Numbers: 1. Eocene granodiorite; 2. Veliki Jastrebac metaturbidites (note that for simplicity, we use the same color and hatching for the western Veliki Jastrebac Upper Cretaceous flysch-bearing system); 3. Calcschists and marbles; 4. Greenschists: Actinolite schists, phillites, marbles, calcschists, sericite schists, quartzites; 5. Metagabbro; 6. Amphibolite and amphibolitic schists; 7. Triassic granitoid; 8. Mylonitic rocks; 9. Green schists: chloritic schists; 10. gneiss, mica schists with garnet and migmatite; 11. minor faults; 12. mica-rich quartzite; 13. gneiss with staurolite and mica schists; 14. graphite-bearing gneiss; 15. Contact-type metamorphism, core center of Veliki Jastrebac. Continuing from the Dobroljupci area, the Jurassic subduction assembly is consistent with numbers 3, 4, and 5. **d** Dobroljupci outcrop exposes a large metre-scale syncline, its eastern branch (see position in Fig. 4b). The photo shows a steeply dipping assemblage of greenschist-facies rocks (lower greenschist facies), meta-basic rocks, overlain by the limestones. The greenschist-facies rocks of the Dobroljupci area can be considered Middle Jurassic in age, similar to the nearby northern Levač area (palynomorphic dating; Dolić et al. 1978). These greenschist facies are in contact with Jurassic meta-basic rocks, metamorphosed limestones, identical to the contact in the Levač area (Maleš et al. 2023)

and Jankićević 1990). Furthermore, the primary Tithonian limestone marker occurs as fragmented inclusions with even meter-sized boulders embedded in the overlying Lower Cretaceous paraflysch (Dimitrijević and Dimitrijević 2009). Nearby mylonites, including a non-pervasive subvertical mylonitic zone, ophiolites are exposed for several meters (Petrović and Jankićević 1990; Fig. 8a; Table 3). However, mylonites in the Tethyan realm are frequently associated with the extensional exhumation and uplift of the formerly entrenched Tethyan rocks (e.g., Ricou and Godfriaux 1994; Kydonakis et al. 2014; Groβ et al. 2020). The same is true for the tectonic window of Mt. Jastrebac (Marović et al. 2007a, b; Erak et al. 2017). Alternatively, intrusions of isolated dykes penetrating the EVZ gabbro-diabase ophiolitic sections record a similar mylonitic contact (Šarić et al. 2009).

Structural record

Several transects were studied in the field to understand the superposition relations and associated deformation. The structural study was conducted within the largest outcrop areas, exposing the Tithonian limestone markers and the Jurassic mélanges across the eastern EVZ central Serbia region. The limestones and Jurassic (earliest Cretaceous?) mélange exposed along this particular zone underlie the Serbo-Macedonian medium- to high-grade suite (including the nearby Levač area; Maleš et al. 2023, including the area near Kuršumlijska banja; Fig. 2b). The transect-based structural profiling involved the measurement campaigns within the key outcrops that are striking along the W-E direction. Data were collected from several km of transect or from surface reaching ~ 100 km^2. In this manner, we collected the data perpendicular to the exposed N–S-directing contact between the EVZ and the western Serbo-Macedonian Unit. Most structures received the new measurements of bedding planes in the sediments (Figs. 4, 5a, b, 6). The field measurements include the two newly mapped folds (Fig. 5a, b). The most prominent structure observed is the west-vergent Alpine-age thrust comprised of overriding Serbo-Macedonian gneissic suite (Figs. 4a, 5b). The bedding measurements are collected from Late Jurassic limestones, mudstones, and sandstones of the Tithonian age, including Early Cretaceous sandstone and mudstone sediments of the Valangian/Hauterivian age. The spatial data (dip-direction/dip) from the Jurassic limestone sequence are in line with the observed underlying metamorphic sequence (dip-direction/dip has the same position despite the developed foliation; Fig. 3d). Additionally, the structural analysis included an extensive database which involved the previously measured foliations (dip and dip direction). These are collected from the available geological maps (extracted from Rakić et al. 1969, 1976, and others). The extracted and measured dip data were manually sorted out to get the best fit statistically, whereby folds and their axis were analyzed separately**.** For that purpose, we separated trends of layering data, which follow two shortening directions, the same for Lower Cretaceous rocks and Serbo-Macedonian foliation trends (Figs. 3a, 4a, 6a–d). Conventional open-source structural geology software for statistical analysis, Stereonet (v. 11, 2020), is used for data presentation, whereas the direct inversion methods of Angelier (1984) were also undertaken. Data were stereo-plotted as poles of the measured planes with the resulting statistical π belts (Fig. 6).

Shear-sense criteria, e.g., drag folds (Mukherjee 2014) that occur close to the litho-contacts represent the older shortening episode (as per Dimitrijević and Dimitrijević 2009). This compression happened during the latest Jurassic–lowermost Cretaceous (Dimitrijević and Dimitrijević 2009; Spahić et al. 2023a). This event was has also been interpreted as the E-vergent nappe-stacking event (e.g., Maleš et al. 2023; Mposkos et al. 2024). The relative timing of the initial shortening was additionally derived from the observed folding patterns and unconformities/paleokarstification episodes (Fig. 4a). The two generations of folds are observed. In contrast, the older population is embedded into the younger and larger syncline (Fig. 4a, b).

In addition to the spatial data extraction, the investigated geological and tectonic setting of the latest Jurassic–earliest Cretaceous interface was studied by using the available basic geological maps of the SFRY on a 1:100,000 scale and the accompanying explanatory booklets Sheet Kruševac. Data and results were collected from several publications: Dimitrijević and Dimitrijević (2009), Spahić and Gaudenyi

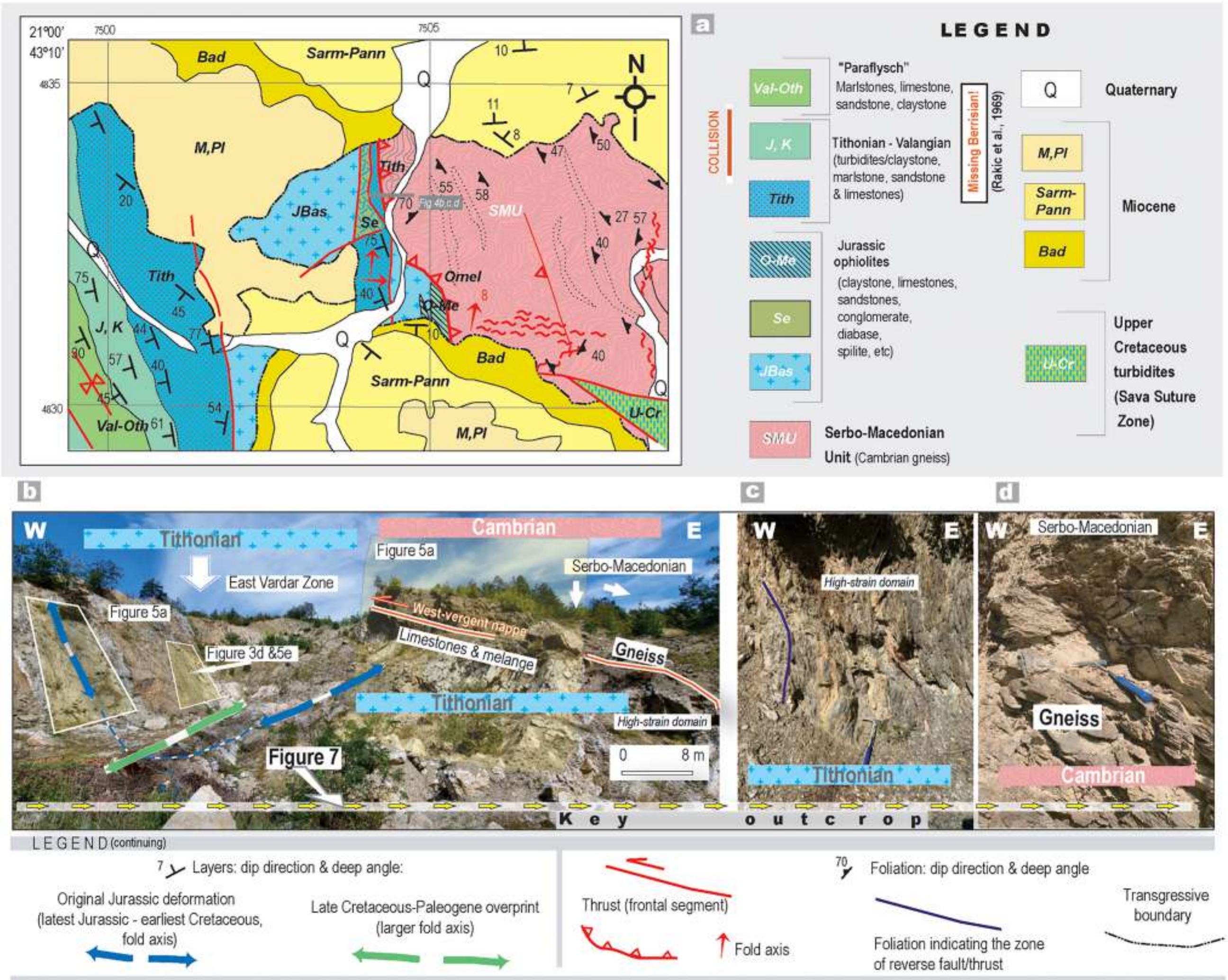


Fig. 4 **a** Geological sketch-map showing gneisses (Serbo-Macedonian Unit) in the overriding position over the East Vardar "ophiolites" (after Rakić et al. 1969, modified). The thick grey line in the middle shows the position of the studied lithospheric-scale contact in the Dobroljupci area, and the photographs taken here are **b–d**. **b** The pictures of the key Dobroljupci area (central Serbia, 43° 25′ 16″ N, 021° 26′ 24″ E) with the outline interpretation of the tectonic contact expose a large EVZ syncline in which the precursor folding is embedded (positions of the folds shown in Figs. 3a, 5b, 7a). The area photo also exposes the fontal thrust level of the Serbo-Macedonian gneiss, which lies above the EVZ limestone, ophiolitic mélange, and low-grade greenschist. **c**, **d** Photos exposing the contact clean the thrust: steep foliation marking high stresses that continue eastwards for the next 50 m in the Serbo-Macedonian gneiss

(2019), Petrović et al. (2015), Maleš et al. (2023), Spahić et al. (2023a), eventually comparing the results of this with the larger-scale studies of Schmid et al. (2008, 2020) and van Hinsbergen et al. (2020). The obduction-related compressive Jurassic deformation is compared with the proposed Apuseni Mt. (Romania; Gallhofer et al. 2017). The composite study also incorporates the subsurface data derived from the reflection seismic/magnetic/gravity 3D model interpretations (Petrović et al. 2015). Field kinematic and superposition criteria (including a borehole in Kuršumlijska banja piercing Tithonian limestone repeated section; Petrović and Jankićević 1990) were used to extrapolate the configuration with a nearby Jastrebac tectonic window (Spahić 2006; Marović et al. 2007a; Erak et al. 2017). The extrapolated data were subsequently incorporated into the resulting crustal profiles.

Statistical analysis

The structural survey of primary importance within the Dobroljupci area included the surface bedding observations in limestone sequence and the exposed foliation elements in gneiss (Figs. 3a, 4a). Two directions of the tectonic contraction have been found: (i) Jurassic compression, having the E-W shortening direction (Fig. 4a, 5a), and (ii) the Cretaceous compression, having the WSW-ENE direction (Fig. 5a, b, 6). As will be shown, these tectonic shortening parameters, including their timing, are consistent with a recent study by Maleš et al. (2023). Mylonites are observed in the nearby Kuršumlijska banja and Jastrebac Mt. area (Petrović and Jankićević 1990; Spahić 2006; Erak et al. 2017; Fig. 3b, c).

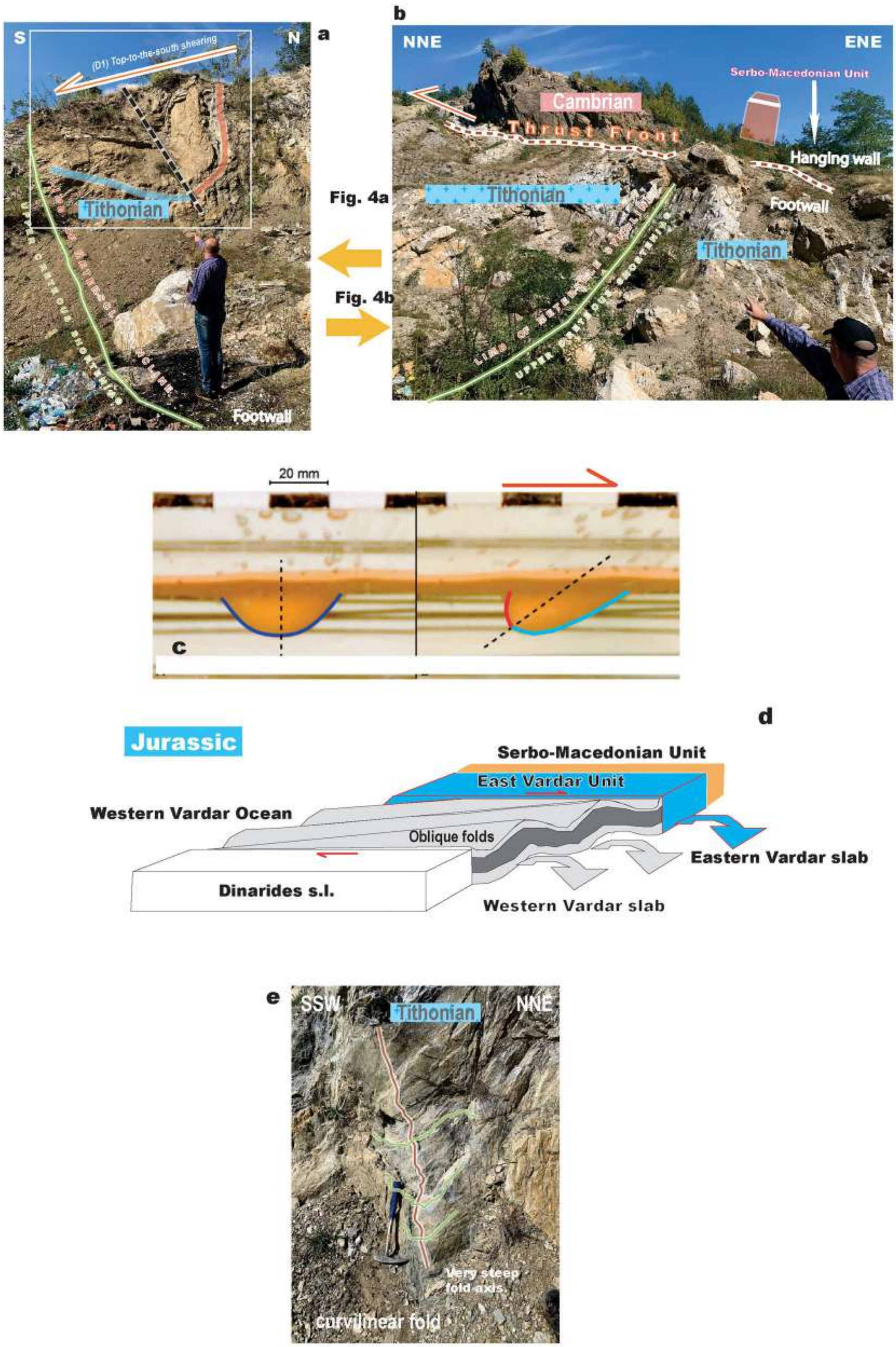
The S_1 and S_2 diagrams represent the statistical bedding configurations (poles) taken from the Jurassic sediments. The diagrams exhibit the two principal trends (Fig. 6a, b). The S_1 diagram has the π belts or statistical maximum with the following elements: dip direction/dip of 077/26 and 270/30. Most of these measurements outline the westward direction of the plunging layers. The S_2 diagram has the π belts with a maximum dip direction/dip 061/32 and 234/53, with most measurements having a SW direction. The two statistical maxima likely exhibit a single shortening event, with the changing principal maximum stress: initially having E–W and then the NE–SW direction (probably due to minor rotation). S_3 and S_4 diagrams contribute to the same interpretation. Diagrams S_3 and S_4 show the same trends but have a slightly more significant dip than S_1 and S_2 (Fig. 6c, d). The S_3 π belts have the maximum dip direction/dip of 082/39 and 266/27, indicating the presence of westward dipping structures. The S_4 has π belts with the maximum dip direction/dip of 052/47 and 234/44. Most of the statistical measurements indicate the SW-ward dip. The hinge line data exhibit the NE–SW trending (Fig. 6e). Statistical analysis of the F_1 and F_2 diagrams uses foliation data from the Serbo-Macedonian Unit (Fig. 6f, g). The F_1 diagram presents the E–W foliation pattern, with the two π belts with a maximum of 267/35 and 088/44. The majority of the measurements are directed to the east. The F_2 diagram represents the statistical foliation pattern with a NE–SW direction, consisting of the π belts with a maximum of 234/39 and 057/32 (mostly NE dip direction).

B_1 diagram represents the hinge line measurements collected exclusively from Jurassic carbonates (not observed in the Dobroljupci Cretaceous surroundings), which have the NE-SW orientation. One π belt with the SW orientation corresponds to S_2 and S_4 (perpendicular to the younger N–S hinges). Such consistency of the trends involving different data types and ages (Jurassic fold hinge fitting with dominant post-Jurassic bedding trend; Figs. 6b, d, e) indicates the presence of a strong overprint affecting the original layering (S_2-S_4). The two similar trends, S_1 and S_2, as well as S_3 and S_4, are in line with the Late Cretaceous northeast-directed subduction of the "remnant Vardar Ocean" (Western Vardar Zone; Table 1), inducing shortening of the Cretaceous Adria-Europe aquatic corridor (Chiari et al. 2011; Bortolotti et al. 2013; Spahić and Gaudenyi 2022). Maleš et al. (2023) are of a similar opinion, highlighting the severity of the postdating overprint. However, there is a noticeable difference in the statistical trends that separate the Jurassic and Cretaceous data.

Interpretation: deformation stages and folding

Older smaller-scale folds in the Jurassic rocks of the EVZ are documented for the first time in this study (Figs. 4a, 5a). The proposed redefinition of the contractional structures of the Alpine age and their kinematics in the Dobroljupci area is explained by introducing the D_1–D_3 deformation phases. Until recently, the well-accepted brittle or ductile Alpine compressional deformation stages are mainly related to the D_2 phase or the latest Cretaceous–Paleogene shortening (e.g., Schmid et al. 2008; Köpping et al. 2019). Unlike the Levač area (Maleš et al. 2023), the observed foliation pattern in the westernmost Serbo-Macedonian Unit is consistent with a younger generation of statistical elements collected within the Tithonian limestones of the EVZ (Fig. 6f, g). A foliation pattern is evident from the dip-direction-dip measurements and the N–S-directed fold hinges (Fig. 3c, red-white arrows, and a segment of the Serbo-Macedonian Unit that lies west of the Veliki Jastrebac Mt., Rakić et al. 1969). As shown in Fig. 6, the main difference between the metamorphic and the exposed sedimentary units is between the F_1 and F_2 foliations dip, which has mostly E-ward trending, whereas the S_1–S_4 have a W-ward dip. All these structural imprints and their trending are related to D_2. This terminal stage is often interpreted as the base for the subsequent late Alpine D_3 extension and related extensional exhumation (e.g., Jastrebac and nearby Toplica area; e.g., Spahić 2006; Marović et al. 2007a, b; Erak et al. 2017; Spahić et al. 2023a).

Even though the oldest D_1 stage was not previously mapped in the Dobroljupci region, the collected composite data show that the latest Jurassic – lowermost Cretaceous contraction may have tentative analogous deformations in the area itself (e.g., Maleš et al. 2023). Interestingly, Marović et al. (2007a) observed intense folding and the formation of the "intrafolial folds" in a subducted segment of the same Tethyan sequence (exposed by the exhumed Jastrebac Mt. domain). However, their study could not connect the folding vergence related to the initial or pre-Late Cretaceous shortening stage. The fold hinges, measured across Dobroljupci area demonstrate a pre-Cretaceous deformation embedded into the eroded limbs of a larger



syncline. Fold hinges are best depicted in the Tithonian limestones (Figs. 4b, 5a). Consequently, the measurements taken across the broader area of Dobroljupci (Figs. 2b, 4a) yielded the two compressional stages that have almost orthogonal orientation: (i) the latest Jurassic D_1 deformation

◂**Fig. 5** Detailed structural interpretations of the Dobroljupci area. **a** Photomicrograph showing evidence of the latest Jurassic–earliest Cretaceous folding (top-south shear sense): the red line shows a shorter limb of the small syncline (sheath fold), while the blue line represents the geometry of the extended syncline limb. The latter is oriented toward the present-day south. The white-green under the fold highlights the geometry of the large syncline in which the ancestral fold is embedded. **b** The larger syncline is obviously under the Serbo-Macedonian thrust. **c** Analog model of different strain regimes during developing the sheath fold (slightly modified after Dell'Ertole and Schellart 2013). Left: In the initial stage, the dashed line indicates the axial line of the fold, and the dark blue outline marks the undeformed posterior and anterior limbs (symmetrical configuration); right: the axial line shows an apparent rotation from the initial vertical position, while the posterior limb (in red) shortens and the anterior limb (in light blue) elongates. Half arrow indicates shear direction from top to right. **d** Schematic drawing of the oblique collision zone with the position of central tectonic units (Fossen 2010, modified). **e** Meter-scale folds with the sub-vertical fold axis embedded in the large syncline

with E–W fold hinges and (ii) D_2 deformation with a NNW-SSE strike of the axial surface (Figs. 4b, 6).

Folding patterns

The younger D_2 folding is a typical Alpine compressional large syncline with an axis that is parallel to the Serbo-Macedonian N-S-directed frontal thrust (Figs. 4b, 5b; Dimitrijević and Dimitrijević 2009). This footwall rotation and buckling (D_2) is related to a progressive and diachronous emplacement of the Serbo-Macedonian front towards the west (over EVZ). The two lithospheric-scale intra-Mesozoic compressional episodes affecting the EVZ have just recently been introduced (Dimitrijević and Dimitrijević 2009; for the nearby Levač area, see Maleš et al. 2023; and for the wider Belgrade area, see Spahić et al. 2023a).

The older or latest Jurassic-earliest Cretaceous D_1 compression produced a non-planar cylindrical polyclinal folding pattern in the Tithonian limestones (Haify 2019; Nabavi and Fossen 2021). The geometry resembles a sheath fold (Fig. 5a, c). Notably, the sheath folds resemble the successively developed folds (Srivastava 2011). The observed older folds have an arcuate axial trace exposed in a steep fold axis (Fig. 5e). Sheath folds may originate from simple shear and develop in the elevated strain regimes (Dell'Ertole and Schellart 2013; review in Mukherjee et al. 2015; Fig. 5c of this paper). The folds observed in the Dobroljupci area exhibit no tight isoclinal precursory folding (Figs. 5a, 7a). The non-planar cylindrical folds are comparable with earlier stage, slightly leaning towards the subsequent curvilinear folding episode introduced by Alsop and Carrerad (2007). Alternatively, the initial folding was formed in a strike-slip oblique convergence zone that forms an acute angle within the large shear zone, which in this case could be interpreted as underplating structure (Fig. 5d). Strike-slip motions have recently been reintroduced to explain the mid-Mesozoic and late Alpine kinematics of this part of the NeoTethyan Ocean (e.g., Ratschbacher et al. 1993; Grubić 2002; Köpping et al. 2019; Sokol et al. 2019; Spahić and Gaudenyi 2022).

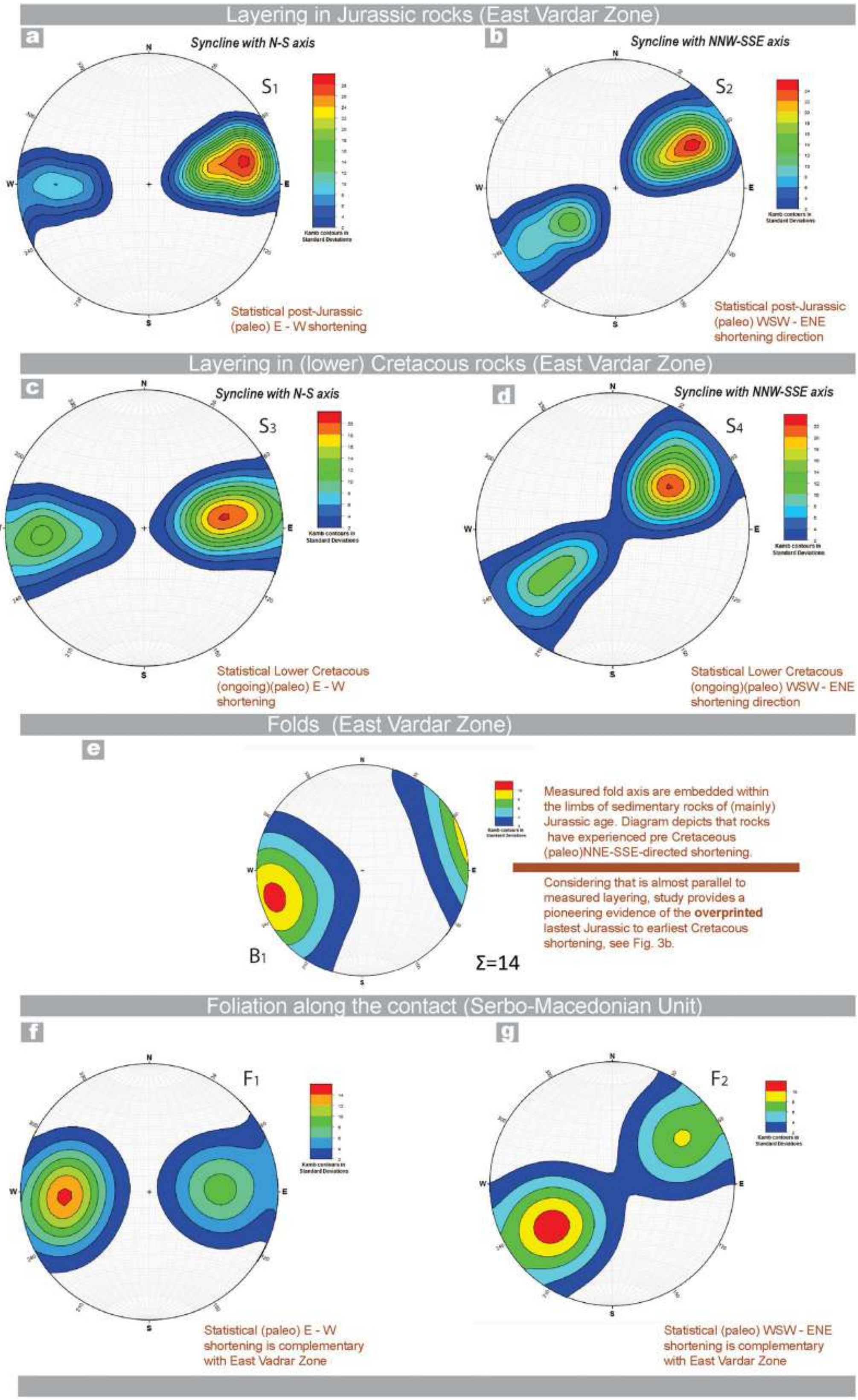
In addition, we observed the irregular fold hinges associated with the refolded steeply-plunging (> 70°) D_1 folds (Fig. 5a, e). Such structures are not typical for the fold-and-thrust belts (e.g., Steiner and Hickey 2022; Fig. 5e). This information is consistent with the proposed compressional event occurred during Jurassic (with no significant crustal thickening): (i) limited-extent nappe stacking episode or (ii) regional obduction-related shortening event (Sandulescu 1984; Maleš et al. 2023). A similar event with a pronounced unconformity is observed in the same Late Jurassic interval of Alpine Tethys (Steiner et al. 2021). At a basic geometric level, there are three ways to create steeply plunging folds in thrust belts (Steiner and Hickey 2022): (i) curved hinges with local steep plunges generated through heterogeneous strain along the hinge (Fig. 5e), (ii) through the rotation or re-folding of pre-existing folds to a steep geometry, and alternatively, (iii) layering previously steepened by tilting/folding can be folded by layer-parallel shortening or non-coaxial shear. The Dobroljupci fold connotes top-to-south shear (Fig. 5a).

Discussions and interpretations

Deformational history: implications for latest Jurassic–earliest Cretaceous lithospheric-scale processes

The deformation history of the Mesozoic NeoTethyan EVZ sequences is obtained from (i) field structural geological studies (Tables 1, 2), (ii) existing geological maps (e.g., Rakić et al. 1969) involving depositional history of the Jurassic sedimentary formations (paleokarstification episode; Spahić et al. 2023a). Study also introduces constraints on the age of the low-grade metamorphic imprint (greenschist-facies; Dolić et al. 1978; Marović et al. 2007a, b). Apart from the two types of greenschist-facies rocks (Dobljupci and Jastrebac; Fig. 3a–d), the fieldwork yielded two generations of the locally exposed Mesozoic folds and their rotated hinges embedded in the deformed Tithonian limestone (Figs. 4b, 5a, b). Such multidirectional contractional structures are often interpreted as the result of temporally distinct shortening episodes (e.g., Toljić et al. 2018; review in Héja et al. 2022).

The observed top-to-south shear, indicated by the outcrop-scale folds, provides essential evidence for the early interaction between the EVZ narrow oceanic system and the western Serbo-Macedonian margin (Fig. 5a, e; see also in Dimitrijević and Dimitrijević 2009; Spahić et al. 2023a). These folds contain a minimal exposure of the



Layering in Jurassic rocks (East Vardar Zone)
a
Syncline with N-S axis
S1
Statistical post-Jurassic (paleo) E - W shortening
b
Syncline with NNW-SSE axis
S2
Statistical post-Jurassic (paleo) WSW - ENE shortening direction
Layering in (lower) Cretacous rocks (East Vardar Zone)
c
Syncline with N-S axis
S3
Statistical Lower Cretacous (ongoing)(paleo) E - W shortening
d
Syncline with NNW-SSE axis
S4
Statistical Lower Cretacous (ongoing)(paleo) WSW - ENE shortening direction
Folds (East Vardar Zone)
e
Measured fold axis are embedded within the limbs of sedimentary rocks of (mainly) Jurassic age. Diagram depicts that rocks have experienced pre Cretaceous (paleo)NNE-SSE-directed shortening.
Considering that is almost parallel to measured layering, study provides a pioneering evidence of the overprinted lastest Jurassic to earliest Cretacous shortening, see Fig. 3b.
B1
Σ=14
Foliation along the contact (Serbo-Macedonian Unit)
f
F1
Statistical (paleo) E - W shortening is complementary with East Vadrar Zone
g
F2
Statistical (paleo) WSW - ENE shortening is complementary with East Vardar Zone

◂**Fig. 6** Statistical data were extracted from the wider lithospheric contact area. Data were extracted from the field log and geological maps of the SFRY. **a**, **b** The statistical polar trends measured/extracted from the Jurassic rocks. **c**, **d** The statistical polar trends measured/extracted from the Jurassic rocks. **e** Axial plane of more minor folds of the older generation. **f**, **g** Statistical trends in foliation. See the main text for interpretation

greenschist-facies rocks (Fig. 3d); thus, we interpreted that the very limited obduction might have occurred. This event took part slightly before or simultaneously with the "docking" and the formation of these meter-scale folds (Table 3). The original location of these folds was along the Serbo-Macedonian margin. In contrast, the presumed underlying slab in the late Jurassic configuration is consistent with top-to-foreland shear (or, in this case, top-to-(paleo)south, comparable to the nearby Alpine Tethys and its subduction zone, e.g., Groβ et al. 2020; Fig. 5a).

Late Cretaceous–Paleogene configuration

The observed and extracted statistical orientation of the prominent late Cretaceous–Paleogene spatial elements allowed the identification of the more prominent W–E-directed folds (D_2) (Fig. 4b). The eastern section of the Dobroljupci exposes a localized high-angle foliation pattern intervening between the Mesozoic structural elements and beneath the Serbo-Macedonian upper plate (Fig. 4b–d). This ~ 50 m long section represents a former rooting or the higher-angle segment of the thrust fault itself. Chronologically, the Serbo-Macedonian west-vergent nappe (Fig. 4b) correlates with the widely accepted latest Cretaceous–early Paleogene D_2 deformation (e.g., Toljić et al. 2018; Maleš et al. 2023). This ongoing latest Cretaceous–early Paleogene regional E-W-directed shortening (Figs. 4, 5a–e, 6a–d) perturbed and overprinted the older latest Jurassic–earliest Cretaceous generation of the m-scale non-planar cylindrical folds (Figs. 4b, 5a, b). Consequently, the preserved rare outcropping meter-scale folds result from the precursory latest Jurassic–earliest Cretaceous contraction (Figs. 5a, b, 6e). The resulting finite configuration places the Serbo-Macedonian hanging wall overlying the EVZ limestones, basalts, mélanges, and greenschists (Figs. 3d, 4b, 7a–c).

Restoring the Late Jurassic–earliest Cretaceous near-margin configuration: subduction, carbonate production, and convergence

The study also identified the two structural levels of Neo-Tethys-related deformations using the data on the recognized metamorphic grades. The east-vergent unmetamorphosed slab segments initially interacted within Western and East Vardar Jurassic geodynamic framework (Table 3; Fig. 8b, c). This brittle rather shallow deformation level of the proposed Jurassic NeoTethyan Vardar paleosuture is identified by the observed diabase and limestone fragments/inclusions exposed in the Kuršumlija area (Fig. 8a; Table 3). Diabase and limestone inclusions indicate a syndepositional and relatively shallow interaction between the EVZ oceanic lithosphere (diabase) and the top-sealing oceanic bottom Tithonian limestone sediments. Deformations in diabase and limestone were probably produced by the compressional interference between these Tithonian limestones and the EVZ oceanic crust (Fig. 8a, b). In addition, a single borehole "BKB-2" (Petrović and Jankićević 1990) that penetrates the Kuršumlija diabase reveals a repeated section configuration (for definition of repeated sections see e.g., Williams et al. 1989). The vertical borehole profile exposes the underlying but younger Tithonian limestones positioned beneath the diabase. The absence of Cretaceous sedimentary record further correlates with the late Jurassic compression and earliest Cretaceous nappe stacking. This early or pre- Late Createaceous nappe-stacking configuration indicates the timing of initial deformation which is the latest Tithonian to earliest Cretaceous age.

The spatially aligned with the Dobroljupci along N-S direction is nearby Ždraljica ophiolite of central Serbia (Fig. 1). The Ždraljica EVZ oceanic crustal remnants contain a bimodal fingerprint involving the Jurassic peraluminous granite characterized by post-collisional volcanic arc signatures (168.4 ± 6.7 Ma on quartz-diorite; Resimić-Šarić et al. 2005; Šarić et al. 2009). The geochemical fingerprint (including adakite-like features) shows that some of the Jurassic central Serbian EVZ granites were formed by melting immature volcanoclastic sediments (Šarić et al. 2009). These melts represent a mafic/intermediate volcanoclastic debris originating in an island-arc setting that is restrained to the east (or towards Serbo-Macedonian) by the Tithonian limestones (Resimić-Šarić et al. 2005). Such a setting fits well with the proposed Jurassic supra-subduction-related configuration or oceanic over oceanic slab situation (two Jurassic slabs) topped by the Tithonian carbonate sequence. Similar rocks exposed in the southern Dobroljupci area represent the analog Jurassic assembly (Fig. 3d, see #1 in Fig. 8c). However, if we presume the presence of Jurassic obduction, it appears that both Dobroljupci or Levač greenschist-facies rocks have the same low-grade imprints equal to the slab segment beneath the internal Serbo-Macedonian margin (Boljevac–Vukanja system of the Jastrebac Mt.; Marović et al. 2007a; Erak et al. 2017).

Underneath the internal Serbo-Macedonian margin (Jastrebac Mt. Figure 3c), there is a deeper Neotethan crustal section uncovering formerly subducted Jurassic oceanic WVZ assembly (opposite structural level to the highest or obducted section;Marović et al. 2007a; Spahić et al. 2023b; Fig. 8c). The Jastrebac Mt. tectonic assembly in its lower sections experienced greenschist-type metamorphic overprint (including calc-schist or rocks with limestone protolith), which is most pronounced at the Boljevac–Vukanja subsystem (Marović

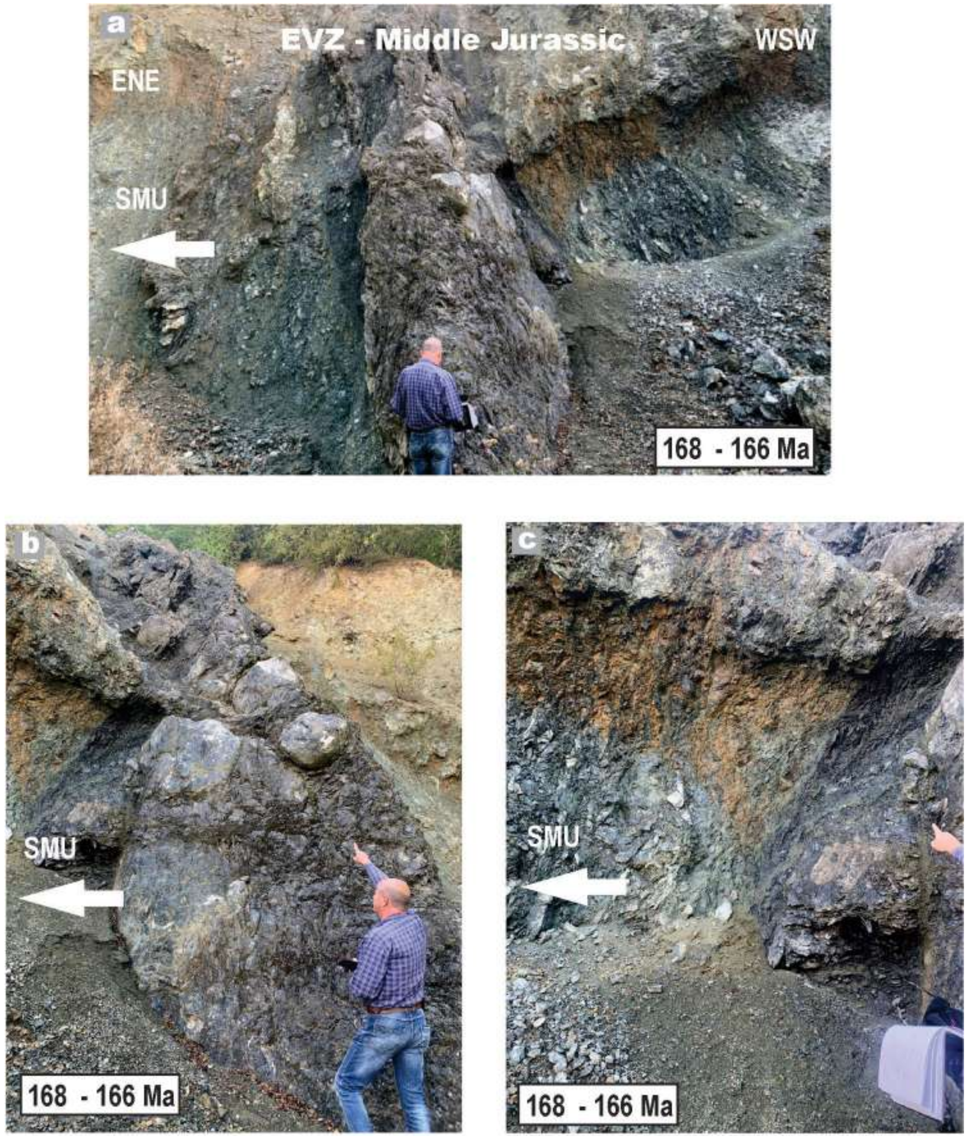


Fig. 7 **a**–**c** Configuration of basaltic rocks and mélange exposed near the large syncline in the Dobroljupci area. The ages are taken from Resimić Šarić et al. (2009) and Maffione and van Hinsbergen (2018). The VZ black basalts spatially occupy a very high angle relative to the adjacent nappe front. White arrows indicate the position of the nearby nappe (SMU—Serbo-Macedonian Unit)

et al. 2007a). In turn to Dobroljupci EVZ exposure, the Boljevac–Vukanja greenschists can be interpreted either as both: (i) a segment of the Western Vardar plate and the "Sava Zone" by Schmid et al. (2008), Marović et al. (2007a), or (ii) as the segment of the EVZ by Petrović et al. (2015).

As there is no visible evidence of the significant latest Jurassic–earliest Cretaceous crustal thickening in the Dobroljupci area, we believe that the obduction path of the EVZ ophiolites (if any) may have solemnly affected the underlying greenschist-facies rocks that have limited exposure (similar to Maleš et al. 2023). Progressive subduction and shortening produced non-planar cylindrical meter-size top-to-the-south folds (latest Jurassic–earliest Cretaceous deformation at the Dobroljupci area or D_1). Once such folds propagate and amplify, fold axes may behave passively and rotate toward the shear direction (Fig. 5a–e). This allows the fold hinges to rotate progressively toward the transport direction, resulting in highly curvilinear folds (Alsop and Carrerad 2007). The shape of these non-planar cylindrical folds in this context can indicate the proximity of the latest Jurassic tensor. The shape of the exposed folds may pinpoint the presence of previously reported transpression-type underplating (Grubić 2002; Spahić and Gaudenyi 2022; Fig. 5d). Such a regional shear direction is marked by a syncline-related limb elongation (Fig. 5a, blue line). Consequently, the latest Jurassic–earliest Cretaceous deformation front comprised the Serbo-Macedonian plate (Fig. 5a; Boev et al. 2018). The folds are positioned below an unconformity in the Tithonian limestones (Fig. 5a).

The extracted latest Jurassic–earliest Cretaceous compressional markers

The proposed new kinematic interpretation yields several processes: the Western Vardar underplating under the EVZ, limited obduction of the EVZ ophiolite, "docking," and collision (uplift, tectonic exhumation, and erosion/paleokarstification). The underplating of the active Western Vardar slab temporarily ceased in the latest Jurassic–earliest Cretaceous (contractional stage). In contrast, the production of EVZ oceanic crust ceased in the uppermost Kimmeridgian (Boev et al. 2018), while the uplifting type of tectonism terminated the Tithonian (Berriasian) carbonate production. By the earliest Cretaceous, the proposed intra-Mesozoic contraction, limited ophiolite obduction, and regional uplift (Berriasian) are moreover depicted by several additional suture-related imprints:

(i) There is a subaerial paleokarstification episode in the latest Jurassic eroding the Tithonian limestones (see point vii). Notably, the latest Jurassic - earliest Cretaceous paleokarstification episode is consistent with the mid-Mesozoic compressional event observed in the region (e.g., Bulgaria/Rhodopean Massif, Bonev and Stampfli 2011; Greece/Inner Hellenides, Mposkos et al. 2024) and in the nearby Alpine Tethys (Steiner et al. 2021);

(ii) The presence of the tectonically exhumed metamorphic rocks with the Jurassic protoliths, absence of sediments of Cretaceous age (e.g., Karamata et al. 1994; Marović et al. 2007a, b; Bonev et al. 2023; Maleš et al. 2023). The metamorphic greenschist-facies rocks near the Serbo-Macedonian margin (Levač and Dobroljupci) margin may indicate a limited initial obduction during the latest Jurassic shortening. Further testing of the Levač and Dobroljupci protoliths and the exact age is a must (including Jastrebac Mt. assembly);

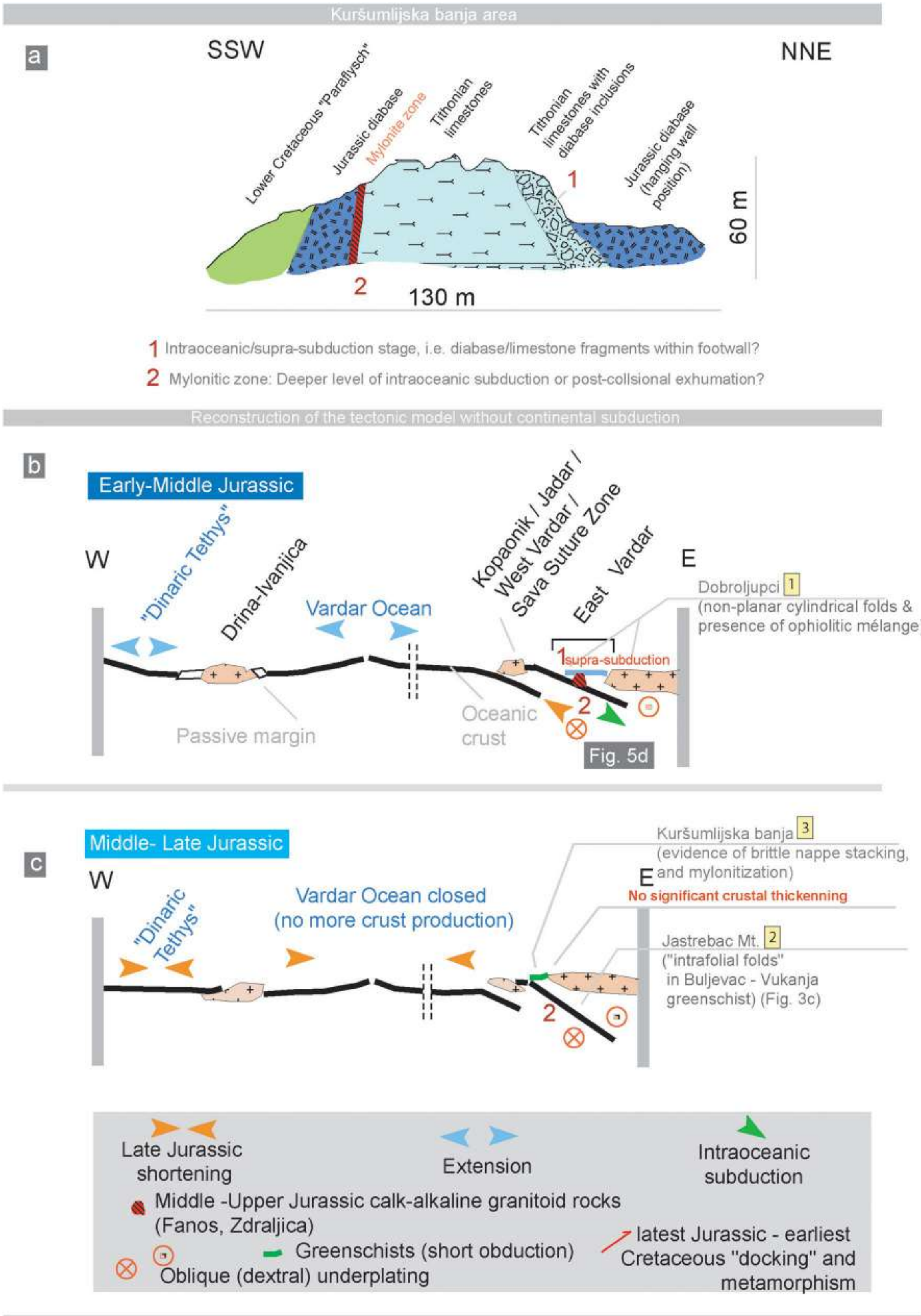
(iii) The newly observed overprinted meter-scale folds (D_1) are the critical marker of the latest Jurassic–earliest Cretaceous shortening and uplift episode;

(iv) The statistical analyses show the eastern vergence of the EVZ and its underlying configuration beneath the west-vergent Serbo-Macedonian thrust;

(v) The subsurface geophysical data additionally support the EVZ downwards configuration beneath the Serbo-Macedonian thrust (Fig. 8b, c). The 3D model is based on the survey lines perpendicular to the investigated tectonic interface (Petrović 2015; Petrović et al. 2015). Such a configuration may suggest that the initial minimal obduction was likely succeeded by the EVZ underplating underneath the Serbo-Macedonian. The geophysical subsurface visualization of the same ophiolites in North Macedonia additionally outlines a similar tectonic interfingering with the Paleozoic basement (including the older gneissic 'Eastern Veles Series'/Serbo-Macedonian Unit; Petrović 2015; Petrović et al. 2015; Spahić et al. 2019);

(vi) The arc-type latest Jurassic–earliest Cretaceous collision has regional analogs within the Circum-Rhodope belt of eastern Bulgaria (vicinity of Rhodope Massif). The magmatism and metamorphism occurred at ~ 168–154 Ma (Resimić-Šarić et al. 2005; Bonev and Stampfl 2011; Bonev et al. 2023 and references cited). The eastern Balkans sector, or the Strandja Massif, subducting entity was exhumed during the late Jurassic-early Cretaceous, inclusive its western part (c. 156–123 Ma; Elmas et al. 2011; Sunal et al. 2011). This event also corresponds to the Middle Jurassic-Early Cretaceous plutons intruding to the western sector of the Rhodope Massif (c. 164–135 Ma; Turpaud and Reischmann 2010);

(vii) The proposed latest Jurassic–earliest Cretaceous contraction, collision, "docking," and a very limited regional obduction are imprinted within the latest Jurassic limestones and the "paraflysch" sequence of the EVZ (Fig. 4a). Namely, the lowermost sequence of "paraflysch" is characterized by the rarely exposed transgressive breccia. The 'Basal series' composed of breccia carrying the evidence of paleokarstification (Dimitrijević and Dimitrijević 2009). The lowermost 'Basal series' of the Lower Cretaceous "paraflysch" comprise eroded calcareous



Kuršumlijska banja area
a
SSW
NNE
Lower Cretaceous "Paraflysch"
Jurassic diabase
Mylonite zone
Tithonian limestones
Tithonian limestones with diabase inclusions
Jurassic diabase (hanging wall position)
1
2
130 m
60 m
1 Intraoceanic/supra-subduction stage, i.e. diabase/limestone fragments within footwall?
2 Mylonitic zone: Deeper level of intraoceanic subduction or post-collsional exhumation?
Reconstruction of the tectonic model without continental subduction
b
Early-Middle Jurassic
W
"Dinaric Tethys"
Drina-Ivanjica
Vardar Ocean
Kopaonik / Jadar / West Vardar / Sava Suture Zone
East Vardar
E
Dobroljupci 1
(non-planar cylindrical folds & presence of ophiolitic mélange)
1 supra-subduction
2
Passive margin
Oceanic crust
Fig. 5d
c
Middle- Late Jurassic
W
"Dinaric Tethys"
Vardar Ocean closed
(no more crust production)
Kuršumlijska banja 3
(evidence of brittle nappe stacking,
E and mylonitization)
No significant crustal thickenning
Jastrebac Mt. 2
("intrafolial folds"
in Buljevac - Vukanja
greenschist) (Fig. 3c)
2
Late Jurassic shortening
Extension
Intraoceanic subduction
Middle -Upper Jurassic calk-alkaline granitoid rocks (Fanos, Zdraljica)
Greenschists (short obduction)
Oblique (dextral) underplating
latest Jurassic - earliest Cretaceous "docking" and metamorphism

◀**Fig. 8** Tectonic reconstructions outlining paleo-subduction zones (inset after Robertson et al. 2008, significantly modified). Please use Table 3 for interpretation. **a** The Kuršumlijska banja outcrop, Fig. 2b#3 (Petrović and Jankićević 1990, modified). The outcrop reveals two important tectonic boundaries: 1. Limestones with diabase inclusions and vice versa, including the repeated section represented by a vertical section of borehole "BKB-2", and 2. The mylonite zone which is on the opposite side of the inclusions, indicating a post-Jurassic exhumation. **b** Early-Middle Jurassic tectonic reconstruction, with the two east-vergent paleosubduction slabs and the observed non-planar folds in Dobroljupci (Fig. 2b, #1). The numbers in the yellow rectangle indicate the position of the outcrops in Fig. 2b. Once the Western Vardar slab stopped its downgoing subduction (orange arrow), the EVZ slab was able to start its downgoing movements (green arrow; slab dynamics modified according to Boev et al. 2018). **c** The Middle-Late Jurassic configuration of the EVZ, exposing the latest Jurassic-Early Cretaceous Neotethyan closure, early collision, and metamorphism (Jastrebac area, Fig. 2b, #2) with regional nappe stacking (repeated section in the Kuršumlija area, Fig. 2b, #3)

crystallized breccia, microconglomerate, including abundant large fragments of the Tithonian limestone (Petrović and Jankićević 1990; Kurešević et al., 2022; Spahić et al. 2023a). This stratigraphical lowermost sequence of the latest Jurassic–earliest Cretaceous age exposes somewhat chaotic olistolith-like feature discovered in the vicinity of Belgrade (Dimitrijević and Dimitrijević 2009; Kurešević et al. 2022; Fig. 4a). The recent survey of the "Ropočevo breccia" indicated, however, the presence of the latest Jurassic–lowermost Cretaceous Berriasian unconformity (breccia is covered by the Late Cretaceous turbidites belonging the EVZ; Spahić et al. 2023a; Fig. 3a). The paleokartstification observed within the "Ropočevo breccia" is outlining the tectonic uplift, which is defined as the D_{1-2} stage (Table 3; similar to a segment of Alpine Tethys; Steiner et al. 2021). The latest Jurassic–earliest Cretaceous collision or "docking" and subsequent erosion were succeeded by a prompt extension and subsidence, which lasted up to the Cenomanian (Table 3) (similar to the North Macedonian segment; Robertson et al. 2013).

On the other hand, the absence of any ophiolite fragments in the 'Basal Series' of the"paraflysch" and the "Ropočevo breccia" itself (Dimitrijević and Dimitrijević 2009; Spahić et al. 2023a) is questioning the obduction. Moreover, the 'Basal Series' lies directly on the top of the crystalline Serbo-Macedonian basement (Dimitrijević and Dimitrijević 2009). The absence of ophiolite and its fragments (which should be on top of Serbo-Macedonian crystalline schists), with the presence of greenschist-facies rocks beneath the latter, requires a new attempt to provide more solid evidence of obduction. The observed absence of thickened Jurassic crust indicates that the latest Jurassic–earliest Cretaceous obduction was limited in length. The results from central Serbia show that the model of the two slabs obducted on top of the Jurassic continental margin can be excluded (no similarities with the Apuseni Mts. (Gallhofer et al. 2017).

The renewed post-Jurassic subduction of the shortly stagnating trench (same Jurassic oceanic crust) restarted during Lower Cretaceous (Berriasian). The renewed movements of the Jurassic oceanic crust generated by a slab pull is responsible for the ultimate latest Cretaceous–Paleogene suturing of the remnant aquatic corridor (Table 2) and the final orogenic wedging. The collision allocated the western Serbo-Macedonian Unit in the highest structural position (collision is related to the second contractional deformation D_2 event).

Conclusions

New structural data collected within the EVZ and the Serbo-Macedonian rocks from Dobroljupci, Kuršumlijska banja (and Kopaonik Mt.) and Jastrebac Mt. areas, including a limited number of published data for central Serbia, permitted constituting a cross-lithospheric the mid-Mesozoic regional-structural-tectonic relationship. We trace and reconstruct the NeoTethyan Jurassic oceanic crustal segments and follow their interaction with the Serbo-Macedonian margin, emphasizing the mode of the latest Jurassic-Early Cretaceous tectonics and paleogeography. The widespread topping Tithonian limestone sequence is of particular importance ("tubiditic limestone" per Dimitrijević and Dimitrijević 1975), as it shows both the unconformity-related paleokartstification, and the exposed nappe-staked mid-Mesozoic configuration traceable along the entire EVZ.

The NeoTethyan Western Vardar Zone and the EVZ collided in the latest Jurassic, terminating the carbonate-producing paleoenvironment, further resulting in the tectonic exhumation of the continental margin. The collision did not result in significant crustal thickening, though there could be some evidence of the precursory very limited obduction in the form of Jurassic greenschists (Maleš et al. 2023). The successor, or

Table 3 Deformation stages for the investigated segment of the East Vardar Zone

Deformation stage[a] (for details see Fig. 8b, c)	Type of deformation	Dobroljupci (Jurassic foreland)	Jastrebac Mt. (deeper trench)	Kuršumlijska banja/Kopaonik Mt. (proximity of intraoceanic domain)	Regional stress field
D_0 (Middle-Late Jurassic)	Supra-subduction related fragmenting of diabase and limestone	presence of ophiolitic mélange	Deeper crustal metamorphism	Limestone inclusions in diabase	Extension to compression
D_1 (latest Jurassic or late Tithonian to earliest Cretaceous or Berriasian)	Obduction-related greenschist-facies rocks[b], non-planar cylindrical folds	Shallow lower greenschist-facies rocks are folded having top-to-the-south shearing	"intrafolial folds" (likely sheath folds in Buljevac – Vukanja greenschist)	Diabase inclusions in Jurassic limestone	ca. N–S compression in Jurassic reference
D_{1-1} (latest Jurassic–earliest Cretaceous)	Tectonic uplift formation of the hiatus, nappe-stacking[c]	Uplift and erosion			ca. N–S compression in latest Jurassic–earliest Cretaceous reference
D_{1-2} (early Cretaceous to late Lower Cretaceous)	Rapid subsidence onset and chaotic deposition of the 'Basal series' of "Paraflysch"	Presence of "Paraflysch"	–	Limestone inclusions in "Paraflysch"	Regional subsidence
D_2 (latest Cretaceous – Paleogene)	Nappe-stacking	Large syncline with NNW-SSE striking hinge line		Rock inclusions	ca. E-W Compression
D_3 (Neogene)	Widespread extension, including extensional exhumation (mylonites)	–	Exhumed core-complex via Vukanja shear zone?	–	Extension

[a]Early Middle Jurassic extensional oceanic initiation and the formation of the first supra-subduction crustal configuration is excluded

[b]Greenschist-facies rocks of Middle Jurassic are presumed to be the result of the ophiolite obduction (Maleš et al. 2023)

[c]Also proved by an unconformable character of the 'Basal series' of "paraflysch"

slightly postdating compressional episode (D_1, D_{1-1}), induced the regional uplift (unconformity; Maleš et al. 2023; Spahić et al. 2023a). After a short uplift episode, the entire area subsided during the Lower Cretaceous, producing the mixed clastic-carbonate “paraflysch” (D_{1-2}).

Contrary to several obducted ophiolite belts distributed across the Mediterranean area (e.g., Schmid et al. 2008; Jolivet et al. 2016), the study results show that the latest Jurassic obduction on top of the Serbo-Macedonian continental margin in central Serbia has a limited amount of evidence. The exposed greenschist-facies rocks (Levač and Dobroljupci areas) lie beneath this Central Serbo-Macedonian Unit as a suspected obduction-related footwall assembly. The latter hangingwall unit was tectonically placed (west-vergent nappe) above the bulk mid-Mesozoic - Late Cretaceous- Paleogene EVZ-related subduction-accretion complex of central Serbia (D_2 stage, Late Cretaceous–Paleogene). The distinctive Jastrebac Mt. greenschist is likely a volcanic arc assembly that descended into the Jurassic-Cretaceous trench, being lifted and exhumed much later during the Neogene. The Kuršumlijska banja area exposes a mid-Mesozoic nappe-stacked configuration with tectonically deformed and crushed diabase rocks embedded into the Tithonian limestone and vice versa. Such a configuration confirms that the EVZ crustal segments were in the supra-subduction setting with the WVZ (D_{1-1} and D_{1-2});

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Author contributions D.S. Field work, English writing of original ms, interpretation of data, literature analysis; M.B. Field work, statistical diagrams; S.M. Review of the work, manuscript improvements; Z.B.: Fileld work, project management.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest This research did not receive a specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors declare they have no financial interests.

References

Alsop GI, Carreras J (2007) The structural evolution of sheath folds: a case study from Cap de Creus. J Struct Geol 29(12):1915–1930. https://doi.org/10.1016/j.jsg.2007.09.010

Angelier J (1984) Tectonic analysis of fault slip data sets. J Geophys Res: Solid Earth 89(B7):5835–5848

Anđelković MŽ (1973) Geology of the Mesozoic in the vicinity of Belgrade. Geološki Anali Balkanskoga Polustrva 38:1–142

Anders B, Reischmann T, Poller U, Kostopoulos D (2005) Age and origin of granitic rocks of the eastern Vardar Zone, Greece: new constraints on the evolution ofthe Internal Hellenides. J Geol Soc 162(5):857–870

Antić MD, 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). Int J Earth Sci 106(5):1665–1692. https://doi.org/10.1007/s00531-016-1380-6

Bazylev BA, Popević A, Karamata S, Kononkova NN, Simakin SG, Olujić J, Memović E (2009) Mantle peridotites from the Dinaridic ophiolite belt and the Vardar zone western belt, central Balkan: a petrological comparison. Lithos 108:37–71. https://doi.org/10.1016/j.lithos.2008.09.011

Boev B, Cvetkovic V, Prelevic D, Šaric K, Boev I (2018) East Vardar ophiolites revisited: a brief synthesis of geology and geochemical data. Contributions, section of natural, mathematical and biotechnical sciences. MASA 39(1):51–68

Bonev N, Stampfli G (2008) Petrology, geochemistry, and geodynamic implications of Jurassic island arc magmatism as revealed by mafic volcanic rocks in the Mesozoic low-grade sequence, eastern Rhodope, Bulgaria. Lithos 100(1–4):210–233. https://doi.org/10.1016/j.lithos.2007.06.019

Bonev N, Stampfli G (2011) Alpine tectonic evolution of a Jurassic subduction-accretionary complex: deformation, kinematics and $^{40}Ar/^{39}Ar$ age constraints on the Mesozoic low-grade schists of the Circum-Rhodope Belt in the eastern Rhodope-Thrace region, Bulgaria-Greece. J Geodyn 52(2):143–167. https://doi.org/10.1016/j.jog.2010.12.006

Bonev NG, Dotseva Z, Chiaradia M (2022) Comparative Nd-Sr-Pb isotopes geochemistry of the eastern Circum-Rhodope belt ophiolitic mafic suites, Greece-Bulgaria. Rev Bulg Geol Socy 83(3):69–72. https://doi.org/10.52215/rev.bgs.2022.83.3.69

Bonev N, Dotseva Z, Filipov P (2023) Geochemistry and tectonic significance of metamorphosed mafic ophiolitic rocks in the upper high-grade basement unit of the eastern Rhodope Massif (Bulgaria–Greece). Geol Carpathica 74(1):23–39. https://doi.org/10.31577/GeolCarp.2023.05

Bortolotti V, Chiari M, Marroni M, Pandolfi L, Principi G, Saccani E (2013) Geodynamic evolution of ophiolites from Albania and Greece (Dinaric-Hellenic belt): one, two, or more oceanic basins? Int J Earth Sci 102(3):783–811. https://doi.org/10.1007/s00531-012-0835-7

Božović M, Prelević D, Romer RL, Barth M, Van Den Bogaard P, Boev B (2013) The Demir Kapija Ophiolite, Macedonia (FYROM): a snapshot of subduction initiation within a back-arc. J Petrol 54(7):1427–1453. https://doi.org/10.1093/petrology/egt017

Chiari M, Djerić N, Garfagnoli F, Hrvatović H, Krstić M, Levi N, Malasoma A, Marroni M, Menna F, Nirta G, Pandolfi L, Principi G, Saccani E, Stojadinović U, Trivić B (2011) The Geology of the Zlatibor-Maljen Area (Western Serbia): a Geotraverse across the Ophiolites of the Dinaric-Hellenic Collisional Belt. Ofioliti 36(2):139–166

Csontos L, Vörös A (2004) Mesozoic plate tectonic reconstruction of the Carpathian region. Palaeogeogr Palaeoclimatol Palaeoecol 210(1):1–56. https://doi.org/10.1016/j.palaeo.2004.02.033

Dell'Ertole D, Schellart WP (2013) The development of sheath folds in viscously stratified materials in simple shear conditions: an analogue approach. J Struct Geol 56:129–141. https://doi.org/10.1016/j.jsg.2013.09.002

Dilek Y, Furnes H (2019) Tethyan ophiolites and Tethyan seaways. J Geol Soc 176(5):899–912. https://doi.org/10.1144/jgs2019-129

Dilek Y, Furnes H, Shallo M (2007) Suprasubduction zone ophiolite formation along the periphery of Mesozoic Gondwana. Gondwana Res 11(4):453–475. https://doi.org/10.1016/j.gr.2007.01.005

Dimitrijević MD (1997) Geology of Yugoslavia. Geoinstitute, Belgrade

Dimitrijević MD (2001) Dinarides and the Vardar Zone: a short review of the geology. Acta Vulcanol 13(1–2):1–8

Dimitrijević MD, Dimitrijević MN (1973) Olistostrome mélange in the Yugoslavian Dinarides and late Mesozoic plate tectonics. J Geol 81(3):328–340. https://doi.org/10.1086/627874

Dimitrijević MD, Dimitrijević MN (1975) Ofiolitski melanž Dinarida i Vardarske Zone: Geneza i geotektonsko značenje [Ophiolite mélange of the Dinarides and the Vardar Zone: Genesis and its geotectonic importance]. II godišnji znanstveni skup, Znanstveni savjet za naftu JAZU, Sekcija za primjenu geologije, geofizike I geokemije, ser. A, 5: Zagreb **(in Serbo-Croatian)**

Dimitrijević MN, Dimitrijević MD (2009) The Lower Cretaceous paraflysch of the Vardar Zone: compositionand fabric. Geoloski anali Balkanskoga poluostrva 70:9–21

Dolić D, Kalenić M, Lončarević Č, Hadži-Vuković M (1978) Osnovna geološka karta SFRJ 1:100.000. List Paraćin [Basic geological map of Former Yugoslavia 1:100.000. Sheet Paraćin—in Serbian]. Savezni geološki zavod, Beograd

Elmas A, Yılmaz I, Yiğitbaş E, Ullrich T (2011) A Late Jurassic-Early Cretaceous metamorphic core complex, Strandja Massif, NW Turkey. Int J Earth Sci 100(6):1251–1263. https://doi.org/10.1007/s00531-010-0540-3

Erak D, Matenco L, Toljić M, Stojadinović U, Andriessen PA, Willingshofer E, Ducea MN (2017) From nappe stackingto extensional detachments at the contact between the Carpathians and Dinarides-The Jastrebac Mountains of Central Serbia. Tectonophysics 710:162–183

Faul UH, Garapić G, Lugović B (2014) Subcontinental rift initiation and ocean-continent transitional setting of the Dinarides and Vardar zone: evidence from the Krivaja–Konjuh Massif, Bosnia and Herzegovina. Lithos 202–203:283–299. https://doi.org/10.1016/j.lithos.2014.05.026

Ferriére J, Chanier F, Ditbanjong P (2012) The Hellenic ophiolites: eastward or westward obduction of the Maliac Ocean, a discussion. Int J Earth Sci 101:1559–1580. https://doi.org/10.1007/s00531-012-0797-9

Ferriére J, Baumgartner PO, Chanier F (2016) The Maliac Ocean: the origin of the Tethyan Hellenic ophiolites. Int J Earth Sci. https://doi.org/10.1007/s00531-016-1303-6

Festa A, Pini GA, Ogata K, Dilek Y (2019) Diagnostic features and field criteria in recognition of tectonic, sedimentary and diapiric mélanges in orogenic belts and exhumed subduction-accretion complexes. Gondwana Res 74:7–30. https://doi.org/10.1016/j.gr.2019.01.003

Fossen H (2010) Structural geology. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511777806

Gallhofer D, Quadt AV, Peytcheva I, Schmid SM, Heinrich CA (2015) Tectonic, magmatic, and metallogenic evolution of the Late Cretaceous arc in the Carpathian-Balkan orogen. Tectonics 34(9):1813–1836. https://doi.org/10.1002/2015TC003834

Gallhofer D, von Quadt A, Schmid SM, Guillong M, Peytcheva I, Seghedi I (2017) Magmatic and tectonic history of Jurassic ophiolites and associated granitoids from the South Apuseni Mountains (Romania). Swiss J Geosci 110(2):699–719. https://doi.org/10.1007/s00015-016-0231-6

Gawlick HJ, Missoni S (2019) Middle-Late Jurassic sedimentary mélange formation related to ophiolite obduction in the Alpine-Carpathian-Dinaridic Mountain Range. Gondwana Res 74:144–172. https://doi.org/10.1016/j.gr.2019.03.003

Gawlick HJ, Missoni S, Suzuki H, Sudar M, Lein R, Jovanović D (2016) Triassic radiolarite and carbonate components from a Jurassic ophiolitic mélange (Dinaridic Ophiolite Belt). Swiss J Geosci 109(3):473–494. https://doi.org/10.1007/s00015-016-0232-5

Groß P, Handy MR, John T, Pestal G, Pleuger J (2020) Crustal-scale sheath folding at HP conditions in an exhumed alpine subduction zone (Tauern Window, Eastern Alps). Tectonics 39(2):e2019TC005942. https://doi.org/10.1029/2019TC005942

Grubić A (2002) Transpressive periadriatic suture in Serbia and SE Europe. Geol Carpathica 53:141–142

Grubić A, Radoičić R, Knežević M, Cvijić R (2009) Occurrence of Upper Cretaceous pelagic carbonates within ophiolite-related pillow basalts in the Mt. Kozara area of the Vardar zone western belt, northern Bosnia. Lithos 108:126–130. https://doi.org/10.1016/j.lithos.2008.10.020

Grubić A, Ercegovac M, Cvijić R, Milošević A (2010) The age of the ophiolite mélange and turbidites in the North-Bosnian zone. Bulletin, CXL. Academie Serbe Des Sciences Et Des Arts, Classe Des Sciences Mathematiques Et Naturelles, Sciences Naturelles 46:41–56

Haify NN (2019) Developing the geometrical classification of non-cylindrical folds. IOP Conf Ser Mater Sci Eng 518(2):022006. https://doi.org/10.1088/1757-899X/518/2/022006

Héja G, Ortner H, Fodor L, Németh A, Kövér S (2022) Modes of oblique inversion: a case study from the Cretaceous fold and thrust belt of the western Transdanubian Range (TR), West Hungary. Tectonics 41(3):e2021TC006728

Hrvatović H, Pamić J (2005) Principal thrust-nappe structures of the Dinarides. Acta Geol Hung 48(2):133–151. https://doi.org/10.1556/ageol.48.2005.2.4

Ilić A, Neubauer F (2005) Tertiary to recent oblique convergence and wrenching of the Central Dinarides: constraints from a palaeostress study. Tectonophysics 410(1–4):465–484. https://doi.org/10.1016/j.tecto.2005.02.019

Ivanova D, Chatalov I (2022) New stratigraphical and sedimentological data on the Lower Cretaceous rocks in section Kalotina, western Bulgaria. Comptes rendus de l'Acad´emie bulgare des Sciences 75(12): 1785–1795. https://doi.org/10.7546/CRABS.2022.12.10

Jolivet L (2023) Tethys and Apulia (Adria), 100 years of reconstructions. Comptes Rendus Géosci 355(S2):1–20. https://doi.org/10.5802/crgeos.198

Jolivet L, Faccenna C, Agard P, Frizon de Lamotte D, Menant A, Sternai P, Guillocheau F (2016) Neo-Tethys geodynamics and mantle convection: from extension to compression in Africa and a conceptual model for obduction. Can J Earth Sci 53(11):1190–1204. https://doi.org/10.1139/cjes-2015-0118

Karamata S (2006) The geological development of the Balkan Peninsula is related to the approach, collision, and compression of Gondwanan and Eurasian units. In: Robertson AHF, Mountrakis D (eds) Tectonic development of the Eastern Mediterranean Region, vol 260. Geological Society of London, Special Publication, pp 155–178. https://doi.org/10.1144/GSL.SP.2006.260.01.07

Karamata S, Knezevic V, Memovic E, Popevic AA (1994) The evolution of the Northern part of the Vardar zone in Mesozoic = H εξέλιξη του βόρειου τμήματος της ζώνης Αξιού (Vardar) κατά το Μεσοζωϊκό. Δελτίον της Ελληνικής Γεωλογικής Εταιρίας 30(2):479–486

Karamata S, Olujić J, Protić L, Milovanović D, Vujnović L, Popević A, Memović E, Radovanović Z, Resimić-Sarić K (2000) The western belt of the Vardar Zone—the remnant of a marginal sea. In: Karamata S, Jankovic S (eds) International Symposium Geology and metallogeny of the Dinarides and the Vardar zone. Academy of Sciences and Arts of Republika Srpska, Banja Luka, pp 131–135

Köpping J, Peternell J, Peternell J, Prelević D, Rutte D (2019) Cretaceous tectonic evolution of the Sava-Klepa Massif, Republic of North Macedonia e Results from calcite twin based automated

paleostress analysis. Tectonophysics 758:44–54. https://doi.org/10.1016/j.tecto.2019.03.010
Kräutner HG, 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. http://www.geologicacarpathica.com/data/files/files/special%20issue/K/Krautner_Krstic.pdf
Kräutner HG, Krstić B (2006) Geological map of the Carpatho-Balkanides between Mehadia, Oravita, Niš and Sofia. In: Proceedings of XVIII Congress of the Carpathian-Balkan Geological Association, Belgrade, September 3–6, 2006, CD-r (without pagination).
Kukoč D, Goričan Š, Košir A, Belak M, Halamić J, Hrvatović H (2015) Middle Jurassic age of basalts and the post-obduction sedimentary sequence in the Guevgueli Ophiolite Complex (Republic of Macedonia). Int J Earth Sci 104(2):435–447. https://doi.org/10.1007/s00531-014-1086-6
Kukoč D, Slovenec D, Šegvić B, Vukovski M, Belak M, Grgasović T, Smirčić D (2024) The early history of the Neotethys archived in the ophiolitic mélange of northwestern Croatia. J Geol Soc 181(1):jgs2023-143
Kurešević L, Septfontaine M, Vušović O, Delić-Nikolić I (2022) Contribution to geology and genetic pathway of the Ropočevo breccia—an "orphan" olistolithic body within the Upper Cretaceous flysch near Sopot (central Serbia). Geol Maced 36(1):5–18. https://doi.org/10.46763/GEOL22361005k
Kydonakis K, Kostopoulos D, Poujol M, Brun JP, Papanikolaou D, Paquette JL (2014) The dispersal of the Gondwana Super-fan System in the eastern Mediterranean: new insights from detrital zircon geochronology. Gondwana Res 25(3):1230–1241
Kydonakis K, Moulas E, Chatzitheodoridis E, Brun JP, Kostopoulos D (2015) First-report on Mesozoic eclogite-facies metamorphism preceding Barrovian overprint from the western Rhodope (Chalkidiki, northern Greece). Lithos 220:147–163. https://doi.org/10.1016/j.lithos.2015.02.007
Maffione M, van Hinsbergen DJJ (2018) Reconstructing plate boundaries in the Jurassic Neo-Tethys from the East and West Vardar Ophiolites (Greece and Serbia). Tectonics. https://doi.org/10.1002/2017TC004790
Maleš M, Ranđelović N, Krstekanić N, Kostić B, Ćirić N, Stojadinović U (2023) New insights into tectonic relations between the Eastern Vardar Ophiolitic and Serbo-Macedonian units: inferences from a microtectonic study in central Serbia. Geoloski Anali Balkanskoga Poluostrva 84(1):2–2. https://doi.org/10.2298/GABP230130002M
Marinović Đ, Rundić L (2020) Depth geological relations of the wider area of Belgrade-based on the wells and geophysical data. Geoloski Anali Balkanskoga Poluostrva 81(2):1–32. https://doi.org/10.2298/GABP201030009M
Marović M, Đoković I, Toljić M, Spahić D, Milivojević J (2007a) Extensional Unroofing of the Veliki Jastrebac Dome (Serbia). Geološki Anali Balkanskoga Poluostrva 68:21–27. https://doi.org/10.2298/GABP0701021M
Marović M, Toljić M, Lj R, Milivojević J (2007b) Neoalpine tectonics of Serbia. Serbian Geological Society
Marroni M, Frassi C, Göncüoğlu MC, Di Vincenzo G, Pandolfi L, Rebay G, Ellero A, Ottria G (2014) Late Jurassic amphibolite facies metamorphism in the Intra-Pontide Suture Zone(Turkey): an eastward extension of the Vardar Ocean from the Balkans into Anatolia? J Geol Soc 171:605–608. https://doi.org/10.1144/jgs2013-104
Meinhold G, Kostopoulos D, Reischmann T, Frei D, BouDagher-Fadel MK (2009) Geochemistry, provenance and stratigraphic age of metasedimentary rocks from the eastern Vardar suture zone, northern Greece. Palaeogeogr Palaeoclimatol Palaeoecol 277(3–4):199–225. https://doi.org/10.1016/j.palaeo.2009.04.005
Menant A, Jolivet L, Vrielynck B (2016) Kinematic reconstructions and magmatic evolution illuminating crustal and mantle dynamics of the eastern Mediterranean region since the late Cretaceous. Tectonophysics 675:103–140. https://doi.org/10.1016/j.tecto.2016.03.007
Michail M, Pipera K, Koroneos A, Kilias A, Ntaflos T (2016) New perspectives on the origin and emplacement of the Late Jurassic Fanos granite, associated with an intra-oceanic subduction within the Neotethyan Axios-Vardar Ocean. Int J Earth Sci 105(7):1965–1983. https://doi.org/10.1007/s00531-016-1321-4
Mikes T, Christ D, Petri R, Dunkl I, Frei D, Báldi-Beke M, Reitner J, Wemmer K, Hrvatović H, von Eynatten H (2008) Provenance of the Bosnian Flysch. Swiss J Geosci 101(1):31–54. https://doi.org/10.1007/s00015-008-1291-z
Mposkos E, Krohe A, Walton C, Baziotis I (2024) Jurassic to early Cretaceous geodynamic evolution of the easternHellenides. Int J Earth Sci 113(1):1–22
Mukherjee S (2014) Review of flanking structures in meso- and microscales. Geol Mag 151:957–974. https://doi.org/10.1017/S0016756813001088
Mukherjee S, Punekar J, Mahadani T, Mukherjee R (2015) A review on intrafolial folds and their morphologies from the detachments of the western Indian Higher Himalaya. In: Mukherjee S, Mulchrone KF (eds) Ductile shear zones: from micro- to macroscales. Wiley Blackwell, pp 182–205. ISBN: 978-1-118-84496-0
Nabavi ST, Fossen H (2021) Fold geometry and folding–a review. Earth-Sci Rev 222:103812
Nirta G, Aberhan M, Bortolotti V, Carras N, Menna F, Fazzuoli M (2020) Deciphering the geodynamic evolution of the Dinaric orogen through the study of the 'overstepping' Cretaceous successions. Geol Mag 157(8):1238–1264. https://doi.org/10.1017/S001675682000045X
Okay AI, Altıner D, Danelian T, Topuz G, Özcan E, Kylander-Clark AR (2022) Subduction-accretion complex with boninitic ophiolite slices and Triassic limestone seamounts: Ankara Mélange, central Anatolia. Geol Mag. https://doi.org/10.1017/S0016756822000504
Pamić J (2002) The Sava-Vardar Zone of the Dinarides and Hellenides versus the Vardar Ocean. Eclogae Geol Helv 95(1):99–113
Pamić J, Tomljenović B, Balen D (2002a) Geodynamic and petrogenetic evolution of Alpine ophiolites from the central and NW Dinarides: an overview. Lithos 65:113–142. https://doi.org/10.1016/S0024-4937(02)00162-7
Pamić J, Balen D, Herak M (2002b) Origin and geodynamic evolution of Late Paleogene magmatic associations along the Periadriatic-Sava-Vardar magmatic belt. Geodynamica Acta 15:209–231. https://doi.org/10.1080/09853111.2002.10510755
Petrović D (2015) The spatial position of the East Vardar Zone ophiolite: geophysical–geological model and implications of its geodynamic evolution. University of Belgrade—Faculty of Mining and Geology. Unpublished Ph.D. dissertation, Belgrade **(in Serbian)**
Petrović M, Jankičević J (1990) Tithonian limestones of the Kuršumlijska Banja area. Geološki Anali Balkanskoga Poluostrva 54:49–52
Petrović D, Cvetkov V, Vasiljević I, Cvetković V (2015) A new geophysical model of the Serbian part of the East Vardar ophiolite: implications for its geodynamic evolution. J Geodyn 90:1–13. https://doi.org/10.1016/j.jog.2015.07.003
Prelević D, Wehrheim S, Reutter M, Romer RL, Boev B, Božović M, Schmid SM (2017) The Late Cretaceous Klepa basalts in Macedonia (FYROM)—Constraints on the final stage of Tethys closure in the Balkans. Terra Nova 29(3):145–153. https://doi.org/10.1111/ter.12264

Putiš M, Soták J, Li QL, Ondrejka M, Li XH, Hu Z, Ružička P (2019) Origin and age determination of the Neo-Tethys Meliata Basin ophiolite fragments in the Late Jurassic-Early Cretaceous accretionary wedge mélange (Inner Western Carpathians, Slovakia). Minerals 9(11):652. https://doi.org/10.3390/min9110652

Rakić M, Hadži-Ruković R, Kalenić M, Marković V, Milovanović LJ (1969) Osnovna geološka karta SFrJ 1:100 000—list Kruševac [Basic Geologic Map of former Yugoslavia1:100 000, Sheet Kruševac—in Serbian]. Savezni Geološki Zavod, Beograd

Rakić M, Hadži-Ruković R, Dimitrijević R, Kalenić R, Marković V (1976) Osnovna geološka karta SFRJ 1: 100 000. Tumač za list Kruševac K34-19 [Basic Geologic Map of former Yugoslavia 1:100 000. Explanatory booklet for the sheet Kruševac—in Serbian, English, and Russian Summaries]. Savezni Geološki Zavod, Beograd

Ratschbacher L, Linzer HG, Moser F, Strusievicz RO, Bedelean H, Har N, Mogoş PA (1993) Cretaceous to Miocene thrusting and wrenching along the central South Carpathians due to a corner effect during collision and orocline formation. Tectonics 12(4):855–873

Resimić-Šarić K, Cvetković V, Balogh K (2005) Radiometric K/Ar data as evidence of the geodynamic evolution of the Ždraljica ophiolitic Complex (central Serbia). Geološki Anali Balkanskoga Poluostrva 66:73–79. https://doi.org/10.2298/GABP0566073R

Richards JP (2015) Tectonic, magmatic, and metallogenic evolution of the Tethyan orogen: from subduction to collision. Ore Geol Rev 70:323–345. https://doi.org/10.1016/j.oregeorev.2014.11.009

Ricou L-E, Godfriaux I (1994) The Thessaloniki klippe: a nappe of Vertiskos origin emplaced upon the Mesozoic flysches of the Vardar basin. Bull Geol Soc Greece 33(2):69–78

Ricou LE, Burg JP, Godfriaux I, Ivanov Z (1998) Rhodope and Vardar: the metamorphic and the olistostromic paired belts related to the Cretaceous subduction under Europe. Geodin Acta 11(6):285–309. https://doi.org/10.1080/09853111.1998.11105326

Robertson AH (2012) Late Palaeozoic-Cenozoic tectonic development of Greece and Albania in the context of alternative reconstructions of Tethys in the Eastern Mediterranean region. Int Geol Rev 54(4):373–454. https://doi.org/10.1080/00206814.2010.543791

Robertson AHF, Trivić B, Đerić N, Bucur II (2013) Tectonic development of the Vardar Ocean and its margins: evidence from the Republic of Macedonia and Greek Macedonia. Tectonophysics 595–596:25–54. https://doi.org/10.1016/j.tecto.2012.07.022

Saccani E, Bortolotti V, Marroni M, Pandolfi L, Photiades A, Principi G (2008a) The Jurassic association of backarc basin ophiolites and calc-alkaline volcanics in the Guevgueli Complex (Northern Greece): implication for the evolution of the Vardar Zone. Ofioliti 33(2):209–227

Saccani E, Photiades A, Santato A, Zeda O (2008b) New evidence for supra-subduction zone ophiolites in the Vardar zone of Northern Greece: implications for the tectono-magmatic evolution of the Vardar oceanic basin. Ofioliti 33(1):65–85. https://doi.org/10.4454/ofioliti.v33i1.360

Sandulescu M (1984) Geotectonica Romaniei. Editura Technica, Bucharest (**in Romanian**)

Šarić K, Cvetković V, Romer RL, Christofides G, Koroneos A (2009) Granitoids associated with East Vardar ophiolites (Serbia, FYR of Macedonia and northern Greece): origin, evolution, and geodynamic significance inferred from major and trace element data and Sr–Nd–Pb isotopes. Lithos 108(1–4):131–150. https://doi.org/10.1016/j.lithos.2008.06.001

Schefer S, Egli D, Missoni S, Bernoulli D, Fügenschuh B, Gawlick HJ, Sudar M (2010) Triassic metasediments in the internal Dinarides (Kopaonik area, southern Serbia): stratigraphy, paleogeographic and tectonic significance. Geol Carpathica 61(2):89–109. https://doi.org/10.2478/v10096-010-0003-6

Scherreiks R, Boudagher-Fadel M (2021) The closure of the Vardar ocean (the western domain of the northern Neo-Tethys) from early Middle Jurassic to Paleocene time, based on surface geology of eastern Pelagonia and the Vardar zone, biostratigraphy, and seismic-tomographic images of the mantle below the Central Hellenides. UCL Open: Environment Preprint

Schmid MS, Bernoulli D, Fügenschuh B, Matenco L, Schefer S, Schuster R, Tischler M, Ustaszewski K (2008) The Alps-Carpathians-Dinarides connection: correlation of tectonic units. Swiss J Geosci 101(1):139–183. https://doi.org/10.1007/s00015-008-1247-3

Schmid MS, Fügenschuh B, Kounov A, Matenco L, Nievergelte P, Oberhansli R, Pleugerg J, Schefer S, Schuster R, Tomljenović B, Ustaszewski K, van Hinsbergend DJJ (2020) Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. Gondwana Res 78:308–374. https://doi.org/10.1016/j.gr.2019.07.005

Şen (2024) Defining the Cimmerian orogeny in the West Pontides: Geochronological and geochemical data from the Permo-Triassic dykes in the İstanbul-Zonguldak Tectonic Unit. Int Geol Rev. https://doi.org/10.1080/00206814.2024.2361466

Shabanian N, Neubauer F (2024) From Early Jurassic intracontinental subduction to Early-Middle Jurassic slab break-off magmatism during the Cimmerian orogeny in the Sanandaj-Sirjan Zone, Iran. J Asian Earth Sci. https://doi.org/10.1016/j.jseaes.2024.106153

Sokol K, Prelević D, Romer RL, Bozović M, van den Bogaard P, Stefanova E, Kostić B, Cokulov N (2019) Cretaceous ultrapotassic magmatism from the Sava-Vardar Zone of the Balkans. Lithos 354–355:105268. https://doi.org/10.1016/j.lithos.2019.105268

Spahić D (2006) Geological setting of the Veliki Jastrebac Mt. (central Serbia) (Magister thesis). Retrieved from: https://www.researchgate.net/publication/366372503_Geological_setting_of_the_Veliki_Jastrebac_Mt_central_Serbia. https://doi.org/10.13140/RG.2.2.30882.50884

Spahić D (2022a) Missing link on the western Paleotethys configuration: stratigraphic constraints on the truncated Triassic "Gornjak" sequence (eastern Serbia, Balkan/Carpathian hinterland). Ital J Geosci 141(2):278–292. https://doi.org/10.3301/IJG.2022.14

Spahić D (2022b) The birth of the Sava Suture Zone: the early geological observations and the context of bimodal magmatism (southern Belgrade outskirts; Anđelković, 1973). Geoloski Anali Balkanskoga Poluostrva 83(1):23–37. https://doi.org/10.2298/GABP220404004S

Spahić D (2022c) Towards the Triassic configuration of western Paleotethys. J Earth Sci 33:1494–1512. https://doi.org/10.1007/s12583-021-1578-9

Spahić D, Gaudenyi T (2018) Primordial geodynamics of Southern Carpathian-Balkan basements (Serbo-Macedonian Mass): Avalonian vs. Cadomian arc segments. Proc Geol Assoc 130(2):142–156. https://doi.org/10.1016/j.pgeola.2018.10.006

Spahić D, Gaudenyi T (2019) Intraoceanic subduction of the northwestern Neo-Tethys and geodynamic interaction with Serbo-Macedonian foreland: descending vs. overriding near-trench dynamic constraints (East Vardar Zone, Jastrebac Mts., Serbia). Geoloski Anali Balkanskoga Poluostrva 80:65–85. https://doi.org/10.2298/GABP1902065S

Spahić D, Gaudenyi T (2020a) Reconsidering paleozoic differences between the Jadar block and the Drina-Ivanjica unit. Geološki Anali Balkanskoga Poluostrva 81(1):1–9

Spahić D, Gaudenyi T (2020b) The role of the 'Zvornik suture' for assessing the number of Neotethyan oceans: surface–subsurface constraints on the fossil plate margin (Vardar Zone vs. Inner Dinarides). Geološki Anali Balkanskoga Poluostrva 81(2):63–86. https://doi.org/10.2298/GABP200918008S

Spahić D, Gaudenyi T (2021) The role of the pre-Alpine polycrystalline basement in the paleogeographic configuration of multiple

Neotethyan oceanic basins. Geologija 64(2):143–158. https://doi.org/10.5474/geologija.2021.008
Spahić D, Gaudenyi T (2022) On the Sava suture zone: post-Neotethyan oblique subduction and the origin of the Late Cretaceous mini-magma pools. Cretac Res 131:105062. https://doi.org/10.1016/j.cretres.2021.105062
Spahić D, Gaudenyi T, Glavas-Trbić B (2019) A hidden suture of the western Palaeotethys: regional geological constraints on the late Paleozoic 'Veles Series' (Vardar Zone, North Macedonia). Proc Geol Assoc 130(6):130–136. https://doi.org/10.1016/j.pgeola.2019.10.008
Spahić D, Bojić Z, Popović D, Gaudenyi T (2020a) Vestiges of Cambro-Ordovician continental accretion in the Carpathian-Balkan orogen: first evidence of the 'Cenerian event' in the central Serbo-Macedonian Unit. Acta Geol Pol 71:219–247. https://doi.org/10.2442/agp.2020.134558
Spahić D, Glavaš-Trbić B, Gaudenyi T (2020b) The inception of the Maliac Ocean: regional geological constraints on the western Circum-Rhodope belt (northern Greece). Mar Pet Geol 113:104133. https://doi.org/10.1016/j.marpetgeo.2019.104133
Spahić D, Kurešević L, Cvetković Ž (2023a) The paleokarst origin of the carbonate "Ropočevo breccia" and a closing Neotethys: regional geological constraints on the Vardar zone s.s. (Belgrade area, Central Serbia). Carbonates Evaporites. https://doi.org/10.1007/s13146-023-00863-z
Spahić D, Šajnović A, Burazer N, Radisavljević M, Jovančićević B (2023b) Neogene subsidence rates of the southern PeriPannonian Realm s.l. (1D basin modeling): constraints on the extensional geodynamic drivers of the asymmetric Toplica Basin (central-southern Serbia). J Pet Sci Eng. https://doi.org/10.1016/j.geoen.2023.211714
Srećković-Batoćanin D, Vasković N, Matović V, Gajić V (2012) Correlation of metabasic rocks from metamorphic soles of the Dinaridic and the Western Vardar zone ophiolites (Serbia): three contrasting pressure-temperature-time paths. Geološki Anali Balkanskoga Poluostrva 73:61–85. https://doi.org/10.2298/GABP1273061S
Srivastava DC (2011) Geometrical similarity in successively developed folds and sheath folds in the basement rocks of the northwestern Indian Shield. Geol Mag 148(1):171–182. https://doi.org/10.1017/S0016756810000610
Stampfli GM, Kozur HW (2006) Europe from the Variscan to the Alpine cycles. In: Geetha DG, Stephenson RA (eds) 2006. European lithosphere dynamics, vol 32. Geological Society, London, Memoirs, pp 57–82
Steiner AP, Hickey KA (2022) The formation of steeply-plunging folds in fold-and-thrust belts. J Struct Geol 164:104728. https://doi.org/10.1016/j.jsg.2022.104728
Steiner TMC, Gawlick HJ, Melcher F, Schlagintweit F (2021) Ophiolite derived material as parent rocks for Late Jurassic bauxite: evidence for Tithonian unroofing in the Northern Calcareous Alps (Eastern Alps, Austria). Int J Earth Sci 110(5):1847–1862. https://doi.org/10.1007/s00531-021-02044-6
Sunal G, Satir M, Natal'in BA, Topuz G, Vonderschmidt O (2011) Metamorphism and diachronous cooling in a contractional orogen: the Strandja Massif, NW Turkey. Geol Mag 148(4):580–596
Toljić M, Matenco L, Stojadinović U, Willingshofer E, Ljubović-Obradović D (2018) Understanding fossil fore-arc basins: inferences from the Cretaceous Adria-Europe convergence in the NE Dinarides. Glob Planet Change 171:167–184. https://doi.org/10.1016/j.gloplacha.2018.01.018
Toljić M, Stojadinović U, Krstekanić N (2019) Vardar Zone: new insights into the tectonodepositional subdivision. Kongres Geologa Bosne i Hercegovine Sa Međunarodnim Učešćem II:60–73
Toljić M, Glavaš-Trbić B, Stojadinović U, Krstekanić N, Srećković-Batoćanin D (2020) Geodynamic interpretation of the Late Cretaceous syn-depositional magmatism in central Serbia: inferences from biostratigraphic and petrographical investigations. Geol Carpathica 71(6):526–538. https://doi.org/10.31577/GeolCarp.71.6.4
Turpaud P, Reischmann T (2010) Characterisation of igneous terranes by zircon dating: implications for UHP occurrences and suture identification in the Central Rhodope, northern Greece. Int J Earth Sci 99(3):567–591
Ustaszewski K, Schmid SM, Lugović B, Schuster R, Schaltegger U, Bernoulli D, Hottinger L, Kounov A, Fügenschuh B, Schefer S (2009) Late Cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): implications for the collision of the Adriatic and European plates. Lithos 108:106–125. https://doi.org/10.1016/j.lithos.2008.09.010
Ustaszewski K, Kounov A, Schmid SM, Lugović B, Schaltegger U, Krenn E, Frank W, Fügenschuh B (2010) Evolution of the Adria-Europe plate boundary in the northern Dinarides: from continent-continent collision to back-arc extension. Tectonics 29:TC6017. https://doi.org/10.1029/2010TC002668
Van Hinsbergen DJ, Peters K, Maffione M, Spakman W, Guilmette C, Thieulot C, Kaymakcı N (2015) Dynamics of intraoceanic subduction initiation: 2. Suprasubduction zone ophiolite formation and metamorphic sole exhumation in context of absolute plate motions. Geochem Geophys Geosyst 16:1771–1785. https://doi.org/10.1002/2015GC005745
van Hinsbergen DJ, Torsvik TH, Schmid SM, Maţenco LC, Maffione M, Vissers RL et al (2020) The orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. Gondwana Res 81:79–229. https://doi.org/10.1016/j.gr.2019.07.009
Vavvasis I, de Bono A, Stampfli GM, Giorgis D, Valloton A, Amelin Y (2000) U-Pb and Ar-Ar geochronological data from the Pelagonian basement in Evia (Greece): geodynamic implications for the evolution of Paleotethys. Schweiz Miner Petrogr Mitt 80:21–43
Williams GD, Powell CM, Cooper MA (1989) Geometry and kinematics of inversion tectonics. Geol Soc Lond Spec Publ 44(1):3–15. https://doi.org/10.1144/GSL.SP.1989.044.01.02
Yu W, Oggiano G, Mongelli G, Zhou J, Buccione R, Xu L et al (2022) U-Pb detrital zircon ages and Hf isotope from Sardinia and Adria Cretaceous bauxite (Italy): constraints on the Alpine Tethys paleogeography and tectonic evolution. Ore Geol Rev. https://doi.org/10.1016/j.oregeorev.2022.105272
Zachariadis P, Kostopoulos D, Reischmann T, Himmerkus F, Matukov D, Sergeev S (2006) U–Pb ion-microprobe zircon dating of the subduction-related magmatism from northern Greece: the age of the Guevgueli, Thessaloniki and Chalkidiki igneous complexes. Geophysical Research Abstracts 8. SRef-ID: 1607-7962/gra/EGU06-A-0556
Zulauf G, Dörr W, Fisher-Spurlock SC, 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 Res 28:642–667. https://doi.org/10.1016/j.gr.2014.06.011