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Review paper
Прегледни рад

Transition from Paleotethys to Neotethys as a forgotten input for Vardar paleo-oceanic studies: Differences between the early Alpine, Early Cimmerian (Middle–Late Triassic) and "Neocimmerian" (latest Jurassic) deformation stages („weak accretion")

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Abstract. An analysis of the extensive geoscientific legacy of the late Professors Milorad Dimitrijević ("Kvaks") and Stevan Karamata, a century after their birth, shows that both authors published numerous studies on the Neo-Tethys, primarily focused on the Mesozoic Vardar Ocean. The term "Vardar Ocean", in its modern sense, was introduced by Prof. Dimitrijević, whose work also addressed the geology of western Serbia and the Inner Dinaride Ophiolite Belt. Similarly, Prof. Stevan Karamata concentrated on the westernmost and central parts of the Vardar Zone (East Vardar Zone). Despite their detailed investigations of the exposed ophiolite belts across the western Balkan Peninsula, both authors made only a few, though highly significant, observations regarding the largely overlooked western Paleotethys Ocean, interpreted as a precursor oceanic domain. Despite these contributions, the role of the Paleotethys Ocean in the evolution of the Neotethys Vardar Ocean remains poorly understood. Terms such as "Early Cimmerian" (a post-Variscan suturing event related to Paleotethys closure) and "Neocimmerian" (a suturing event related to the Neotethys and Innerdinaric oceans) have been omitted from many published studies. Importantly, both the Early Cimmerian and Neocimmerian events are characterized by weak accretion or "docking". By examining the role of the Paleotethys Ocean, and whether its subduction and closure influenced the opening and development of the Neotethys Vardar Ocean, this study provides an initial insight into the overlapping early Alpine and Eocimmerian tectonic stages.

Key words
Neotethys, Paleotethys, 'Veles Series', Early Cimmerian, Neocimmerian.

Апстракт. Анализа научног наслеђа и геолошке заоставштине покојних проф. др Милорада Димитријевића („Квакс“) и проф. др Стевана Карамате, сто година након њиховог рођења, показује да су оба аутора објавила бројне студије о Неотетису, са посебним фокусом на мезозојски Вардарски океан. Термин „Вардарски океан“ у савременом смислу увео је проф. Димитријевић, који је током свог изузетно активног научног рада превасходно проучавао терене западне Србије, са нагласком на офио-

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литски појас Унутрашњих Динарида. Слично њему, проф. Стеван Карамата се углавном бавио централним деловима Вардарске зоне, данас познате као Источна вардарска зона. Упркос њиховом детаљном раду на тектонски ексхумираним и доминантним офиолитским појасевима широм западног дела Балканског полуострва, оба аутора су оставила релативно мало, али научно веома значајних запажања која се односе на занемарени (западни) Палеотетис. Палеотетис, као прекурсорски палеоокеански ентитет, представља кључну компоненту чија улога у развоју неотетиског Вардарског океана и даље није у потпуности разјашњена. Уз неколико изузетака, тектонски термини као што су „ранокимеријски" (пост-варисцијски сутурни догађај повезан са „доковањем" преосталог Палеотетиса) и „младокимеријски" (јурски сутурни догађај повезан са „доковањем" Унутрашње динаридског океана у оквиру Неотетиса) данас се ретко користе у литератури. У оба случаја карактеристично је „доковање", односно колизија слабог интензитета. Ова студија се посебно бави улогом Палеотетиса, односно питањем да ли су субдукција и затварање Палеотетиса утицали на отварање и развој неотетиског Вардарског океана. На тај начин рад даје први увид у преклапање ране алпске и еокимеријске тектонске фазе.

Кључне речи:
Неотетис, Палеотетис, „велешка серија", ранокимријски, неокимријски.

Introduction

Despite more than 50 years of research, the role of Paleotethys in the opening and spreading of the well-studied Vardar Ocean remains poorly understood. The following review and synthesis of the scientific legacy of the late Prof. Dr Milorad Dimitrijević and Prof. Dr Stevan Karamata demonstrate that both scholars recognized Paleotethyan interactions with the Vardar Ocean and its branches within the Dinaride and Carpathian–Balkan regions. Their contributions to the regional geology of the Carpathian–Balkanides and Dinarides (including the Vardar Zone) are best illustrated by the geotectonic sketch maps they produced (Dimitrijević, 1995, 1997; Karamata & Krstić, 1996; Karamata, 2006; Supplementary Figure 1a,b). Although both authors successfully outlined the principal Neotethyan-type suture zones and several tectonically exhumed Jurassic oceanic features (ophiolites), they only rarely discussed the sutures of older paleo-oceanic domains and their closure processes. Nevertheless, their work provides valuable insights into the location and development of the Paleotethyan Ocean within the Western Balkans. Subsequent reports dealing with configuration of Paleotethys have remained scarce, and Paleotethys itself is still commonly neglected as an important precursor framework in Neotethyan studies.

Neotethyan Vardar legacy

Although the role of Paleotethys in the Alpine configuration of the Dinarides–Carpathians–Balkans was discussed by Prof. Dr Milorad Dimitrijević and Prof. Dr Stevan Karamata, as well as in several recent Paleotethyan reconstructions (Csontos & Vörös, 2004; Schmid et al., 2008, 2022; Robertson et al., 2009; van Hinsbergen et al., 2022), its influence on the opening of the Neotethys remains largely speculative. The main reason is not only the lack of regional geological constraints on the Permian to intra-Triassic evolution and closure of Paleotethys, but also the prevailing interpretation of the latest Jurassic "obduction stage" (e.g., Schmid et al., 2008; Chiari et al., 2011; Gallhofer et al., 2017; Maffione & van Hinsbergen, 2018).

Regarding the evolution of the successor Neotethyan Ocean, Karamata et al. (2005) and Karamata (2006) introduced the concept of the "Vardar relic Sava Ocean". This interpretation was widely accepted by mainstream researchers (e.g., Schmid et al., 2008, 2020; Ustaszewski et al., 2009, 2010; Bortolotti et al., 2013; Maffione & van Hinsbergen, 2018; Toljić et al., 2018, among many others). However, this single-ocean model has recently been increasingly questioned and is often regarded as outdated, primarily because no evidence of Cretaceous oceanic crust has yet been identified (e.g., Cvetković et al., 2014; Spahić & Gaudenyi, 2022).

In response to the increasingly obsolete "Sava Ocean" concept, the "multiple Neotethyan ocean model" proposed by Dimitrijević (2001) has recently attracted renewed attention. This multiple-ocean model was also initially rejected, although several recent studies additionally emphasize the oblique nature of the interactions between the developing oceanic domains and their continental margins. (e.g., Grubić, 2002; Dilek et al., 2007; Bazylev et al., 2009; Bonev & Stampfli, 2011; Dilek & Furnes, 2014; Köpping et al., 2017; Prelević et al., 2017; Argnani et al., 2018; Sokol et al., 2020; Spahić & Gaudenyi, 2022; Vergely & Mercier, 2024; Spahić et al., 2025a).

Paleotethyan legacy. One of the key insights into the evolution of the Paleotethyan Ocean (Fig. 1a,b), provided by Karamata et al. (1994), is the initial interpretation of the limestone-bearing "Veles Series", formed within the southern part of the Vardar Zone (Fig. 2a,b). This basement unit is exposed only locally as a fragment of the southern Vardar Zone in North Macedonia (Karamata et al., 1994; Grubić & Ercegovac, 2002; Karamata, 2006). While Stojanović (1980) and Grubić & Ercegovac (2002) initially dated the "Veles Series" to the Late Devonian–Carboniferous interval (Fig. 2b), Karamata (2006) later proposed that Paleotethys developed alongside the Neotethyan Ocean ("Main Vardar Ocean") during its final Jurassic stage (also discussed by Sudar & Kovacs, 2006). This concept of a remnant Paleotethyan Ocean (Fig. 1b, pinkish dashed lines) has recently been supported by Neubauer et al. (2019) and further indicated by evidence of Triassic Anisian biotic changes and the oxygenation of formerly restricted, rift-related oceanic segments extending into the External Carpathians (Hips, 2022). In addition, marine sediments associated with Triassic magmatic rocks, ranging in age from the Permian to the Jurassic, have been documented within the Jadar Block of the Vardar Zone (Pešić et al., 1988; Filipović et al., 2003). With respect to the more southern, or main, Paleotethys branch within the Dinarides–Hellenides (Fig. 1b), Prof. Dimitrijević earlier proposed that the main Paleotethyan suture was related to the External Dinarides and represented by the unresolved "Anisian flysch" (for details on the "Anisian flysch", see Dimitrijević, 1995, 1997; Smirčić et al., 2020).

The following synthesis examines the multistage evolution of the western Paleotethys and provides a brief overview of (i) late Paleozoic partial closure of the Paleotethyan oceanic domain, (ii) the "Early Cimmerian" events, and (iii) the Jurassic Neotethyan closure. This closure is expressed through a weak collision and obduction episode corresponding to the "Neocimmerian" event, commonly associated with bauxite-bearing unconformities. Special attention is given to the Triassic evolution of the Paleo-tethys and to the late-stage closure of the Neotethyan Vardar and Inner Dinaride oceanic domains.

Paleotethyan paleogeography, Variscan and Early Cimmerian events

Regarding terminology, the "western Paleotethys" refers to a paleogeographic region representing the oceanic fragment that likely surrounded its westernmost pivot area, connecting the Alps, Carpathian–Balkanides, Rhodope, and Dinaride–Hellenides/Paleo-Adria systems (Dornsiepen et al., 2001; Robertson, 2012, 2021; Spahić, 2022a,b, 2024; Fig. 1a,b). This also includes the concept of a "remnant Paleotethys", interpreted as an oceanic domain that persisted after the Variscan collision at the end of the early Carboniferous (c. 320 Ma) and continued into the Triassic (Stampfli & Borel, 2002; Robertson, 2021; Spahić, 2022a,b, 2024; Fig. 1a,b). The post-Variscan relic Paleotethyan Ocean is inferred through extrapolation of biostratigraphic, paleogeographic, and, most importantly, tectonic data (including missing stratigraphic intervals and related nappes, reverse faults, and other discontinuities). In contrast, the eastern Paleotethyan realm–characterized by much better exposed oceanic and tectonic records—extends from eastern Moesia to East Asia (see also Şengör et al., 1985; Tari et al., 1996, 2010; Okay et al., 2001, 2006; Nikishin et al., 2006; Natal'in et al., 2012; Bonev et al., 2019, 2022; Cao et al., 2025; Ratschbacher et al., 2026; Fig. 1a).

Accounting for a west-to-east diachronous closure of Paleotethys, the overall structure of the rapidly diminishing post-Variscan "western Paleo-tethyan"

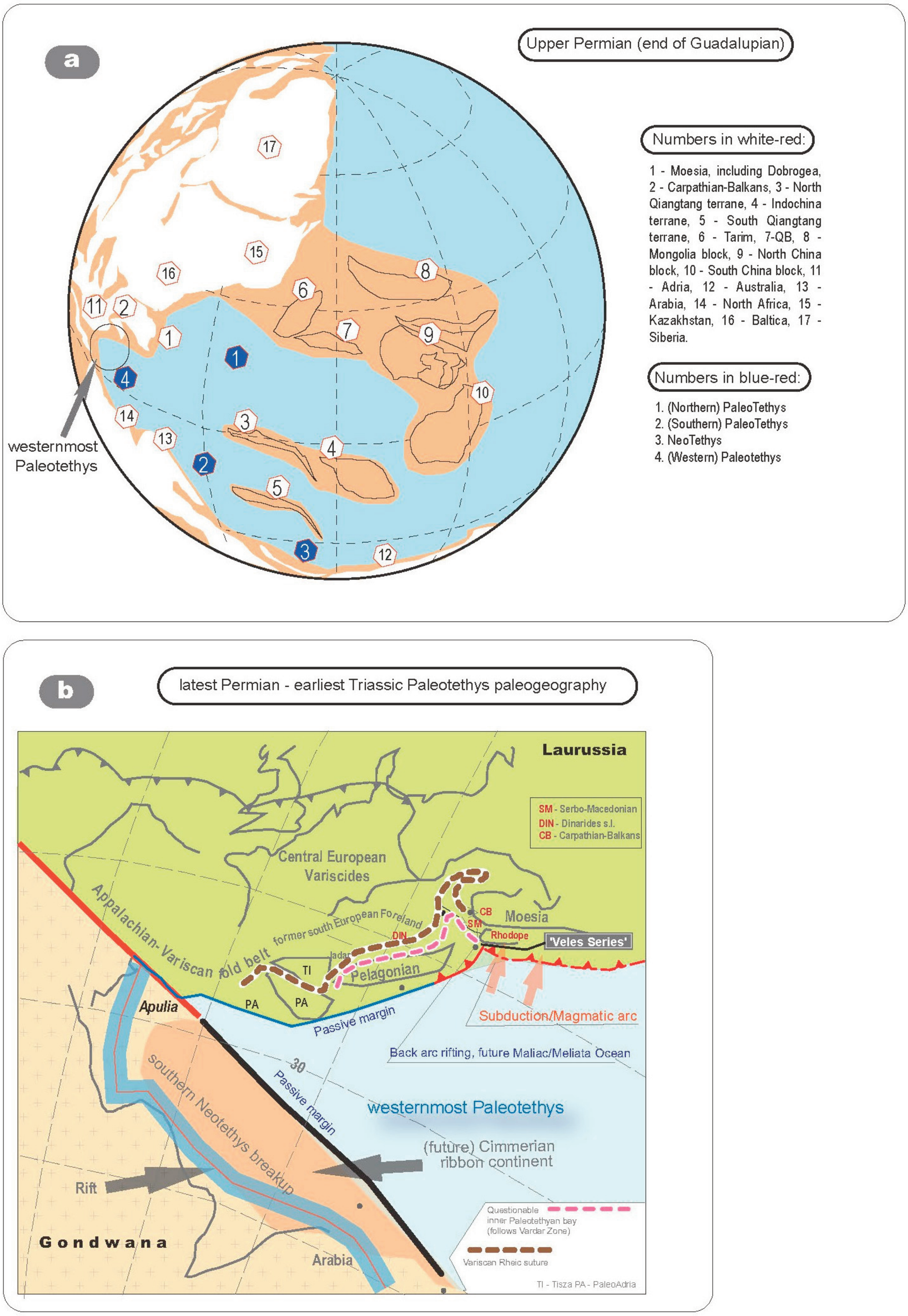

Fig. 1. a. *Paleogeographic reconstruction of the Paleotethys at 260 Ma (Upper Permian; modified after* CAO *et al., 2025). The reconstruction highlights the principal structural elements of the Paleotethyan Ocean, including the Cimmerian ribbon continent and features related to the western and eastern segments of Paleotethys.* ***b.*** *The latest Permian–earliest Triassic reconstruction of the westernmost segment of Paleotethys suggests that a small gulf or bay remained active until the final Permian closure (modified after* SPAHIĆ *et al., 2025a).*

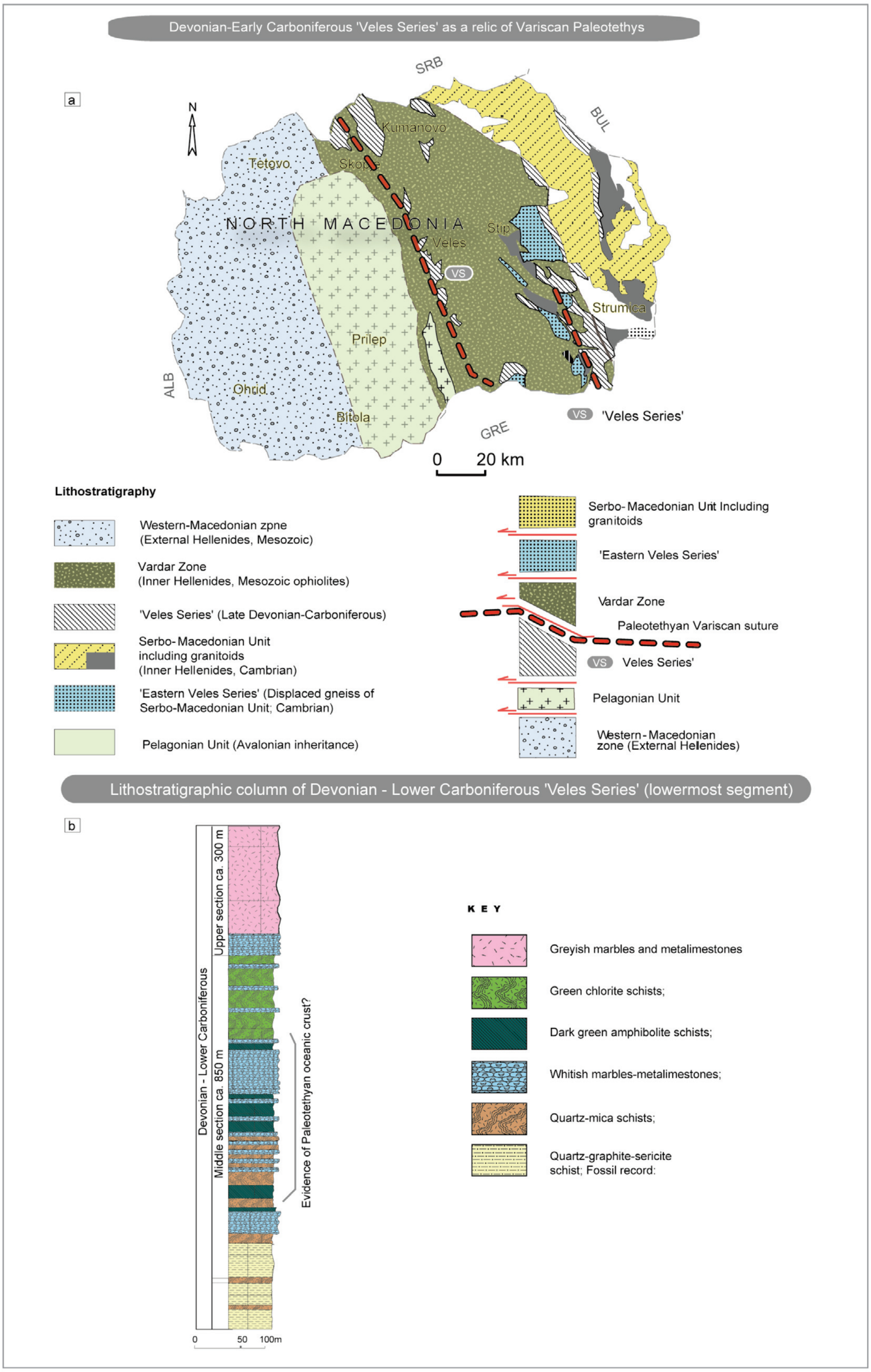

Fig. 2. a. *Geological position of the 'Veles Series' within North Macedonia (inset modified after* Spahić *et al., 2019). The 'Veles Series' represents a marker of the partial Variscan closure of Paleotethys. Variscan amalgamation with the Serbo–Macedonian gneiss is confirmed by the occurence of Variscan granitic magmatism in the adjoining Pelagonian massif, as documented by* Vavvasis *et al. (2000).* ***b.*** *Detailed local lithostratigraphic column of the Lower and Middle sections of the 'Veles Series' (slightly modified after* Stojanovic*, 1978).*

Ocean (Fig. 1a) remains uncertain. Some researchers emphasize the lack of evidence for a continuous Cimmerian ribbon continent (e.g., Topuz et al., 2013; Fig. 1b), whereas others propose alternative interpretations, particularly based on evidence for more internal Paleotethyan remnants (e.g., in the Alps; Neubauer et al., 2019, 2022; Fig. 1b). To further complicate the Carpathian–Balkan framework, the presence of Paleotethyan domains in the Rhodope–Hellenides—especially within the Hellenides—is relatively well documented (e.g., Meinhold et al., 2010; Vangelov et al., 2013; Zulauf et al., 2015, 2018; Petrik et al., 2016). Consequently, there is an increasing need for a revised model to address the remaining uncertainties in the paleogeographic and geodynamic evolution of the Carpathian–Balkan segment.

Paleozoic opening and closure events related to Paleotethys: from Gondwana to the Early Cimmerian episode

Key controversies concerning the western Paleotethys begin with the formation of this paleo-ocean, likely initiated during Early Paleozoic N–S-directed rifting and oceanic development (Fig. 3a), and its subsequent evolution through spreading and suturing stages associated with Late Paleozoic Variscan events (Vavvasis et al., 2000; Pamić & Jurković, 2002; Zulauf et al., 2015; Spahić et al., 2025a,b; Fig. 3b). Remaining uncertainties include the distribution and continuity of post-Variscan Paleotethyan remnants across the Balkan–Hellenide region, which may have persisted into the intra-Triassic (Zulauf et al., 2018; Spahić, 2022a,b; Fig. 3b,c). These issues have so far been addressed in only a limited number of studies.

Several paleogeographic and paleotectonic models have been proposed to explain the mechanisms responsible for the opening of Paleotethys and the development of Paleozoic oceanic domains (e.g., Kroner & Romer, 2013; Stampfli et al., 2013; Neubauer et al., 2022). The “rift–drift” model of Stampfli et al. (2013) places the onset of oceanic opening in the Silurian–Devonian (Antić et al., 2016; Spahić et al., 2019; Neubauer et al., 2022). This timing suggests that the Paleotethys Ocean likely formed during the final stages of long-lasting rift–drift processes along the northern margin of Gondwana, corresponding to present-day North Africa (Pamić & Jurković, 2002; Ebner et al., 2010; Robertson, 2021; Fig. 3a).

Slab-pull processes associated with pre- and post-Variscan subduction beneath the northern margin of Eurasia (Vizan et al., 2017) are inferred to have driven the northward motion of Paleotethyan oceanic and continental crust. Detachment of continental fragments was, in turn, facilitated by back-arc rifting related to subduction zones beneath the northern Gondwanan margin, although the polarity and geometry of these systems remain debated. Along northern Africa, rifting and the formation of the Cimmerian ribbon continent contributed to its northward drift (Stampfli, 1996; Fig. 1b). As the Neotethyan Ocean expanded, promoting separation of the Cimmerian ribbon continent from Gondwana, continued northward subduction pulled continental fragments away from the northern Gondwanan margin (Fig. 1b). This sequence of processes ultimately led to the collision (“docking”) of the Cimmerian ribbon continent with Eurasia and the terminal closure of Paleotethys (Şengör et al., 1985). Processes such as Cimmerian docking, weak accretion, and the closure of Paleotethys left a substantial geological imprint in eastern Eurasia, with evidence linking Moesian Paleotethyan influences (Tari et al., 1996, 2010) to regions as far as East Asia (e.g., Metcalfe, 2000; Sashida et al., 2022; Fu et al., 2022; Ershadinia et al., 2023; Cao et al., 2025; Fig. 1a,b). However, this is not the case for the investigated, yet strongly overprinted, western part of the paleo-ocean, where direct evidence of oceanic crust and associated tectonic structures remains largely obscured (Robertson, 2021; Spahić, 2022a,b).

Variscan closure

Despite the complex pre-Variscan configuration (Figs. 1b, 3b), evidence for partial closure of Paleotethys across the Carpathian–Balkan and Dinaride regions during the Variscan event is substantial. Northward-directed subduction of Paleotethyan

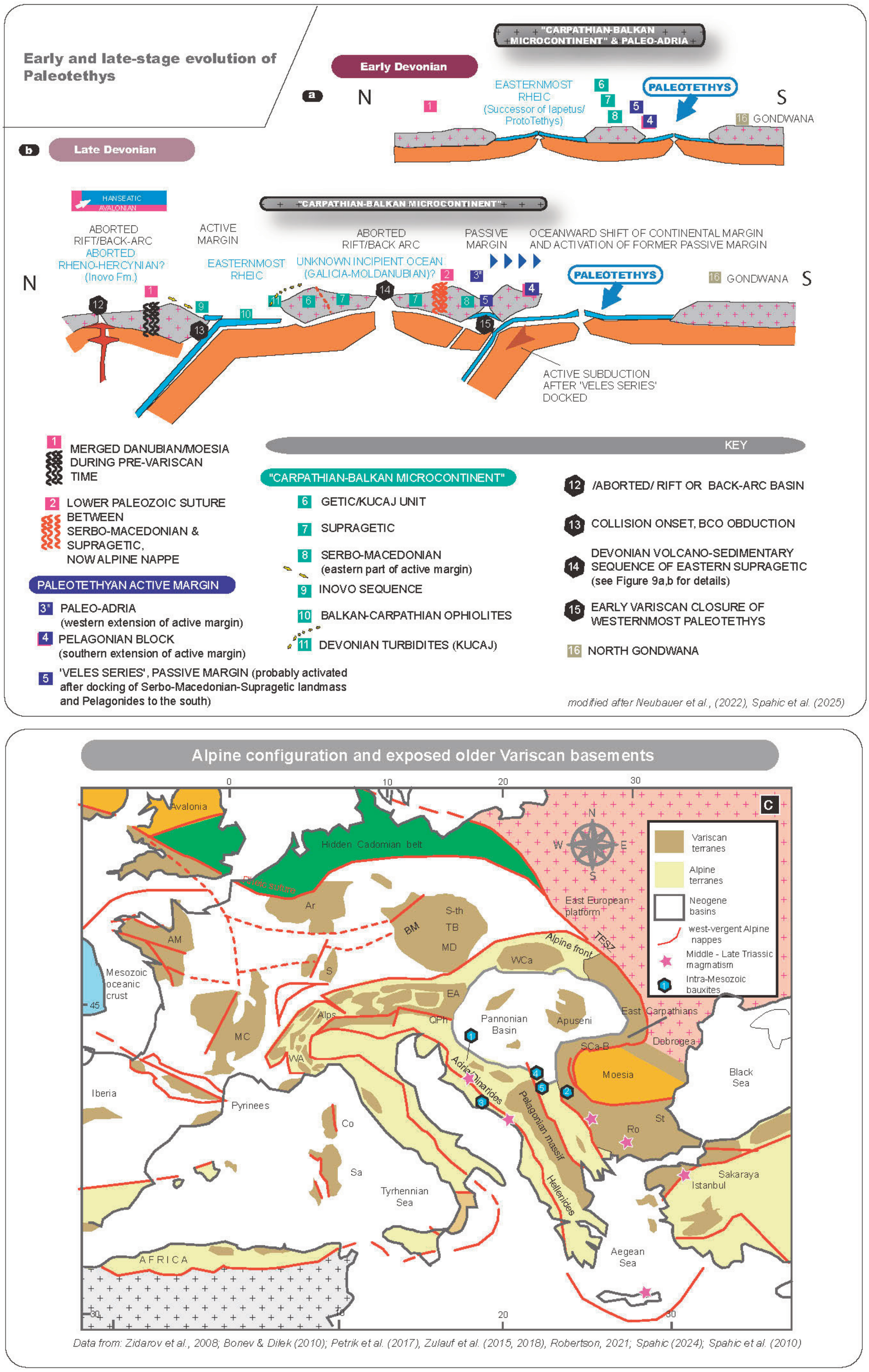

Fig. 3. a. *Early Devonian opening of Paleotethys (modified after* N*EUBAUER et al., 2022; and* S*PAHIĆ et al., 2025b).* ***b.*** *Terminal pre-Variscan configuration during the Late Devonian (after* S*PAHIĆ et al., 2025b).* ***c.*** *Alpine configuration and exposed Variscan basement units (inset modified after* F*AURE &* F*ERRIÉRE, 2022), showing evidence of Triassic magmatism. Key: Ar: Ardenne, BM: Bohemia, S – Th: Saxo–Thuringian, TB: Tepla–Barandian, MD: Moldanubian, Co: Corsica, AM: Armorican Massif, EA: Eastern Alps, MC: Massif Central, Q – Ph: "Quartz–Phyllites", Ro: Rhodope, S: Schwarzwald, Sa: Sardinia, St: Strandja, TESZ: Trans–European Suture Zone, WA: Western Alps, WCa: Western Carpathians, SCa – B: South Carpathians–Balkans. Stars indicate the locations of scarce magmatism related to Paleotethys. Data sources are indicated in the figure.*

oceanic crust is recorded through Devonian, Carboniferous, and Permian activity beneath Eurasia (Robertson & Ustaomer, 2009; Vizan et al., 2017). Until recently, this process was commonly expressed mainly through granitic magmatism, as documented across the Balkans, Rhodope, and Hellenides (e.g., Vavvasis et al., 2000; Turpaud & Reischmann, 2010; Zulauf et al., 2015; Robertson, 2021).

Partial closure of the (western segment of the) Paleozoic Paleotethys began during the highly complex, two-stage Variscan event (Vavvasis et al., 2000; Pamić & Jurković, 2002; Zulauf et al., 2015; Spahić et al., 2019; Šoster et al., 2020; Criniti et al., 2023; Arenas et al., 2024; Spahić, 2024; Fig. 3b). The first stage of Variscan evolution involved closure of Paleotethys and affected both the Dinarides and the Carpathian–Balkan–Hellenide domains. Variscan Paleotethyan interaction and associated two-stage unconformities are particularly well expressed in the External Dinarides (Pamić & Jurković, 2002; Aljinović & Kozur, 2003; Robertson, 2021; Spahić, 2024). Within the Dinarides, two groups of Variscan magmatic imprints can be distinguished: a "late Variscan" phase (ca. 290–325 Ma) and an "early Variscan" phase (ca. 353–390 Ma) (see Spahić, 2024, and references therein). In addition to magmatism and tectonic exhumation, most Dinaride basement units lack Permian marine sediments (e.g., the Drina–Ivanjica Block and the Mid-Bosnian schistose basement unit). The Drina–Ivanjica Block contains Carboniferous metasediments with no Permian record (Đoković, 1985), whereas other basement units—representing the northern Gondwanan passive margin, the Paleotethyan oceanic domain, and the consuming Eurasian margin—exhibit distinct Late Variscan to Permian evolutionary histories (Pamić & Jurković, 2002). Importantly, the Variscan unconformity is recorded across Paleotethyan domains. In contrast to the External Dinarides, the presence of Paleotethys has been confirmed closer to the Inner Dinarides, within the Vardar Zone and its Jadar Block (Supplementary Figure 1a).

The second stage, representing the post-Variscan relic western Paleotethys, is evidenced by mapped Permian–Triassic marine successions within the Jadar Block (Pešić et al., 1988; Spahić & Gaudenyi, 2020; Kolar-Jurkovšek et al., 2021). These successions display a clearly marine character with a continuous transition into the Triassic (Filipović et al., 2003) and are marked by the absence of a post-Carboniferous unconformity. The western Serbian segment of the Jadar Block contains seven biostratigraphic levels within Upper Permian limestone successions, including the *Edmondia permiana* beds, "Productiis" limestones, richthofenian bioherms, calcisponge beds, the *Waagenophyllum indicum* horizon, and *Notothyris* beds, which collectively indicate a carbonate platform environment within western Paleotethys (Pešić et al., 1988).

This second branch of the Variscan Paleotethys likely extends from Mt. Kopaonik (Sudar & Kovacs, 2006) to the southernmost Vardar Zone in North Macedonia (Fig. 2a). The southern Vardar Zone contains the Late Devonian–Early Carboniferous "Veles Series" (Karamata et al., 1994; Karamata, 2006; Sudar & Kovacs, 2006; Ebner et al., 2010; Figs. 2a,b, 3b,c). Only recently has the Late Paleozoic "Veles Series", including remnants of possible Paleotethyan oceanic crust, been interpreted within a Variscan Paleotethyan framework (Sudar & Kovacs, 2006; Spahić et al., 2019, 2020; Šoster et al., 2020; see lithostratigraphic column in Fig. 2b, for magmatic remnants). Pre-Alpine magmato-tectonic overprinting is supported by the Late Devonian–Early Carboniferous age of the "Veles Series", which is difficult to reconcile with a purely rift-related origin, as no rifting event of this age is documented in the studied region. The presence of greenschist-facies rocks, (ortho)-amphibolites, marbles, and serpentinite relics interpreted as fragments of oceanic crust further supports former subduction-related underplating. In addition, Paleozoic oceanic closure, as indicated by Variscan post-collisional magmatism, is recorded in the Štip magmatic complex (biotite-rich granites dated by LA-ICP-MS U–Pb at 304 ± 3 Ma; Serbo–Macedo-nian Unit / "Eastern Veles Series"; Antić et al., 2016), as well as in the more southern Vertiskos Unit (Spa-hić et al., 2020; Mposkos et al., 2021).

Further east, beneath southern Moesia, some authors propose dual subduction of Paleotethys from the Early Carboniferous to the Late Permian (e.g., Robertson & Ustaomer, 2009; Candan et al., 2016). In this framework, the southern Paleotethyan branch, related to subduction beneath Gondwana, influenced Neotethyan rifting and the separation of the Cimmerian ribbon continent at ca. 285 Ma (e.g., WEI et al., 2023, 2025).

Early Cimmerian closure of relic Paleotethys ("docking" episode)

The Early Cimmerian orogeny refers to an event that occurred approximately 210–200 Ma (VANGELOV et al., 2013). On a regional scale, "Early Cimmerian" tectonic interference is best documented in the North Dobrogea region, i.e., the northern domain of Moesia (HIPPOLYTE, 2002). In addition, within the subsurface of Moesia—represented by a thick (>10 km) sedimentary succession—Early and Neocimmerian structures are identified in seismic data (TARI et al., 1997, 2010; Fig. 4). At the broader Balkan scale, "Early Cimmerian" compressional deformation is represented by only a few well-documented examples:

(i) Rarely documented intra-Triassic ultrahigh-pressure (UHP) metamorphism at ca. 200 Ma in the central Rhodopes (U–Pb–Th dating of monazite in diamond-bearing gneisses; PETRIK et al., 2016);

(ii) Absence of Upper Triassic sedimentation (e.g., eastern Serbia; Fig. 5), expressed by the recently defined "Cimmerian unconformity" (observed mainly in Moesia, but rarely mapped at the surface; SPAHIĆ, 2022b, 2024; Fig. 6a,b). As noted above, at the regional scale this unconformity is most clearly expressed in the North Dobrogea orogen (HIPPOLYTE, 2002).

(iii) Broad north-vergent folding, mainly observed within the Moesian sedimentary succession (TARI et al., 1996, 2010), with fold structures interpreted as Late Triassic (Norian?–Rhaetian) in age (Fig. 4).

Deformation affecting transitional Permian–Triassic successions and attributed to the "Early Cimmerian" phase is rarely reported. In the External Dinarides, evidence of intra-Triassic truncation is well documented; however, its tectonic origin is often not

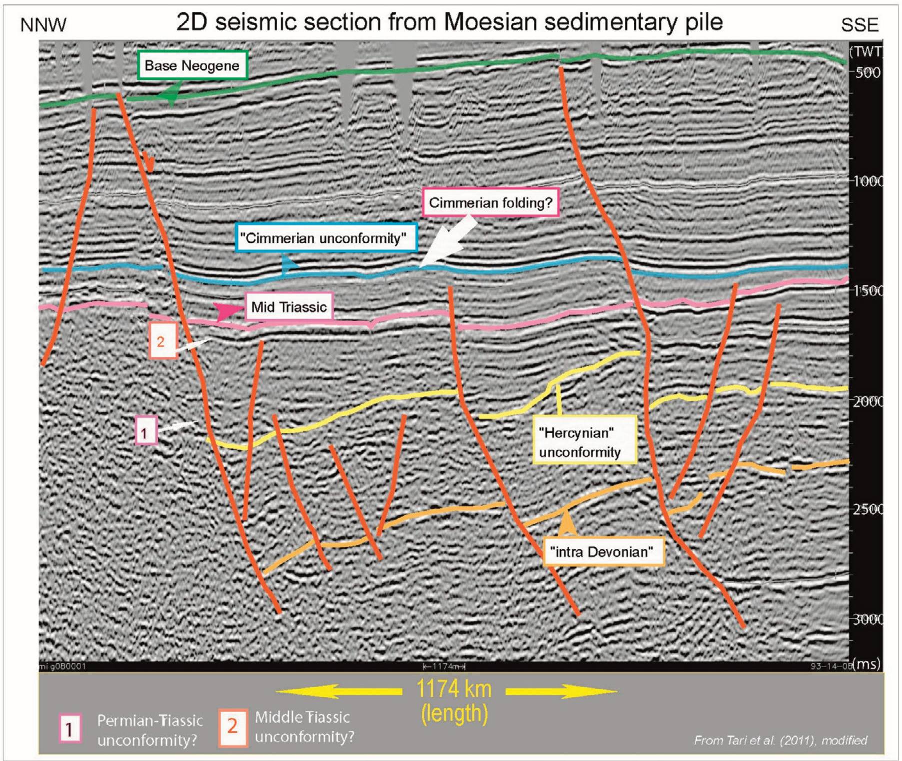

Fig. 4. 2D seismic line showing the intra-Triassic and Jurassic truncations in the Romanian sector of the Moesian platform (inset modified after TARI et al., 2010). Number 1 (white rectangle with a pinkish frame) marks the absence of a Permian-Triassic unconformity within the Moesian sedimentary succession. The reflector anomaly located beneath the top of the "Middle Triassic" formation is interpreted as the position of the Middle–Upper Triassic truncation (Number 2, white rectangle with a reddish frame; see explanation in SPAHIĆ, 2022b). The Early Cimmerian unconformity truncates the Upper Triassic strata. In addition, gentle folding of the sequence is visible, with fold axes trending N–S, as also suggested by TSCHOUMATCHENKO et al., 2006).

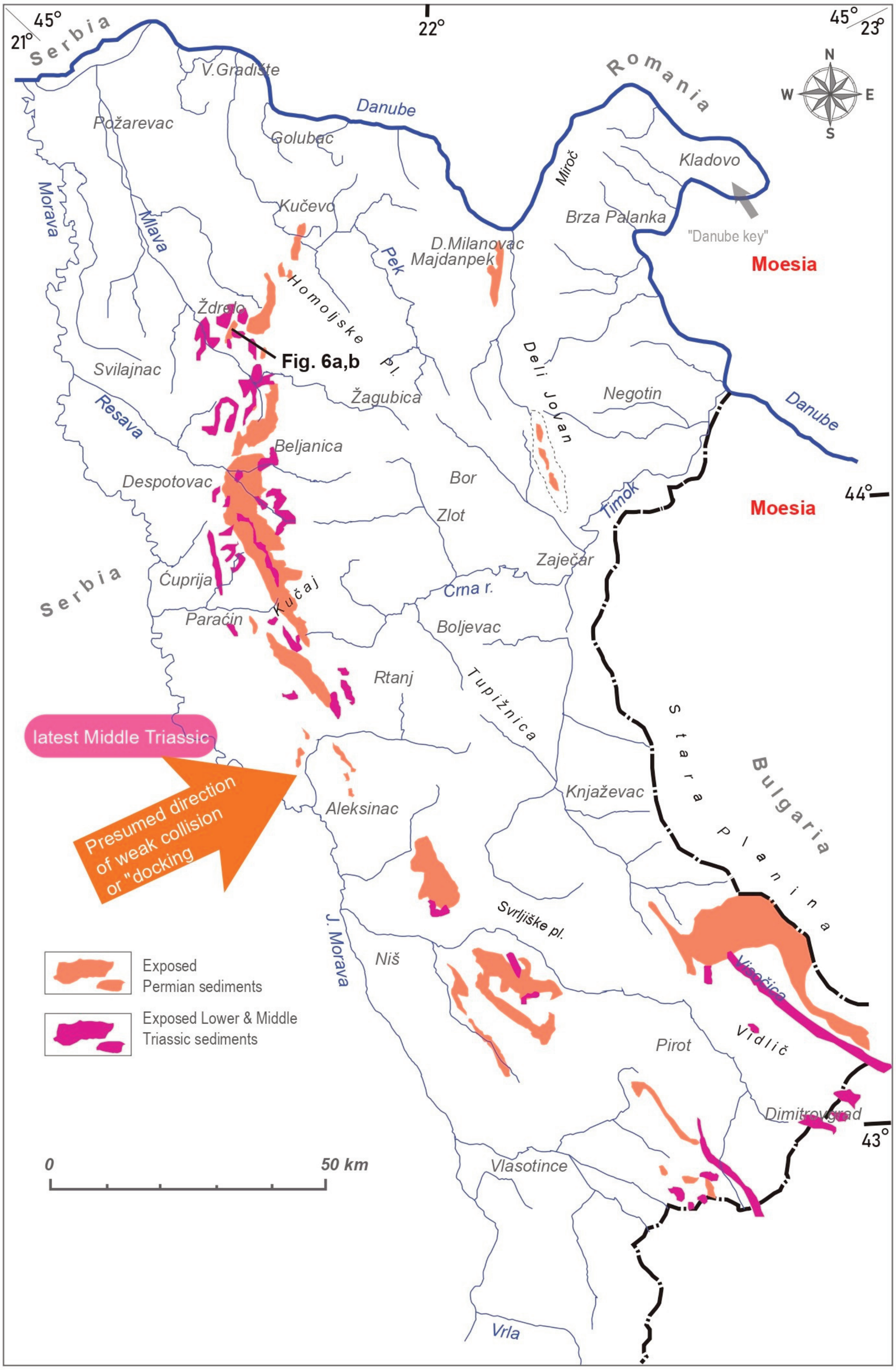

Fig. 5. Distribution of outcrops exposing the truncated Lower–Middle Triassic sequence. The sequence lacks Upper Triassic–Lower Jurassic deposits (inset modified after Anđelković & Urošević*, 1975, and* Spahić*, 2022b)*

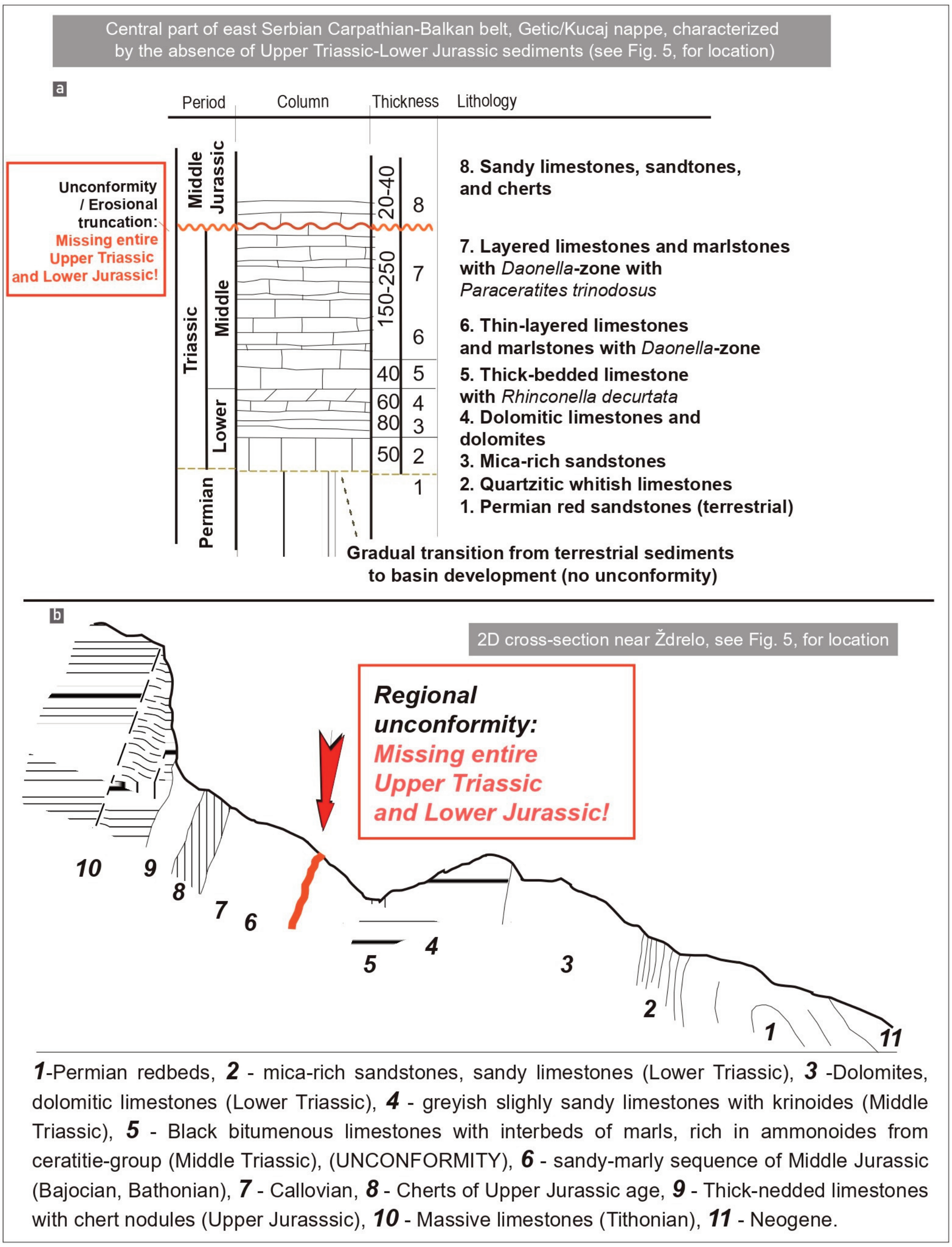

***Fig. 6. a.** Regional synthetic stratigraphic column of the Gornjak area (modified after Anđelković & Urošević, 1975). The Lower–Middle Triassic "Gornjak" sequence is approximately 400 m thick and is truncated by a hiatus extending into the Middle Jurassic. The transition from the Permian to the Triassic is gradual, without the unconformity observed elsewhere on the Moesian platform. The column clearly demonstrates a major regional-scale erosional truncation. **b.** Local cross section near Ždrelo showing the Upper Triassic unconformity (after Antonijević, 1954, in Anđelković & Urošević, 1975, modified). The inclination and spatial arrangement of the bedding below and above the unconformity suggest a compressional event that caused erosional truncation at the end of the Middle Triassic. This event did not significantly affect the overall structural arrangement, which explains why the Middle Jurassic sequence displays a similar dip and dip direction.*

fully discussed (e.g., Čadjenović et al., 2008; Sudar et al., 2013, 2014; Goričan et al., 2022; Gawlick et al., 2023). With a few exceptions providing regional-scale syntheses (Stampfli, 1996; Krystyn et al., 2019; Robertson, 2021; Spahić, 2024), these numerous intra-Triassic unconformities across the Dinarides have not been systematically interpreted in terms of Early Cimmerian collisional tectonic interference. The tectonic origin of some of these Dinaride intra-Triassic hiatuses, often expressed as missing stratigraphic sections, therefore requires further investigation (see Spahić, 2024, and references cited therein).

In the Carpathian–Balkan region, rare reports indicate the presence of post-Middle Triassic hiatuses or erosional unconformities, marked by the absence of Upper Triassic and Lower Jurassic successions. In the eastern Serbian inner belt of the Kučaj Nappe (Spahić, 2022a,b) and the Louda Kamchia area of the eastern Stara Planina Mountains in western Bulgaria (Tschoumatchenko et al., 2004), subsurface folding has been documented on the Moesian Platform (Fig. 4).

In contrast, in the neighboring Hellenides, recent studies confirm the presence of all three Paleotethyan signatures: a Variscan stage, continuous Variscan to Triassic sedimentation, and a still-debated presence of Cimmerian continental fragments (e.g., Crete; Zulauf et al., 2015, 2018). Variscan interference with Paleotethyan evolution is documented in the Pelagonian Massif (U–Pb zircon ages of 308 and 319 Ma, and 40Ar/39Ar mica ages of 288–297 Ma; Vavvasis et al., 2000), while similar Variscan ages are also reported from Crete (321 Ma, 310 ± 3 Ma, and 300 Ma; Zulauf et al., 2015). The Tyros Unit of Crete further records post-Variscan Paleotethyan–Cimmerian separation of a future ribbon continent, indicated by Early Triassic felsic volcanic activity and detrital zircon ages around 240 Ma (Zulauf et al., 2015). At the same time, the Variscan orogenic belt was exhumed and eroded, as reflected by detrital input into Lower to Middle Triassic sediments. Notably, Tyros beds are almost devoid of Variscan-age detritus (Zulauf et al., 2015), supporting the existence of a Cimmerian continental domain in the Hellenides. The terminal closure of the post-Variscan remnant western Paleotethys in this broader region is therefore consistent with a Ladinian age (Zulauf et al., 2015), which correlates with the truncation events observed in the Carpathian–Balkan region, particularly eastern Serbia (Spahić, 2022b).

Other studies focusing on the Carpathian–Balkan–Rhodope region have mainly relied on interpretations of (Late) Carboniferous–Permian and Triassic magmatic events (Bonev & Dilek, 2009; Meinhold et al., 2010; Zlatkina et al., 2014; Zulauf et al., 2014, 2018; Neubauer et al., 2019; Petrik et al., 2022; Robertson, 2022; Spahić, 2022a,b, 2024). Geochemical data from metamafic rocks or “proto-ophiolites” in the Serbo–Macedonian and western Rhodope massifs indicate an ocean-floor affinity for high-Ti groups, consistent with mid-ocean ridge and within-plate settings (based on immobile trace elements and rare earth elements), whereas low-Ti rocks suggest arc-related tectonic environments (Bonev & Dilek, 2010). Similarly, the Skrut granitoid in the western Belasitsa Mountain (Serbo–Macedonian Unit) yields a U–Pb age of 248 Ma (Triassic), while Rb–Sr whole-rock isochron data indicate a later overprint age of 167.3 ± 8.1 Ma (Zidarov et al., 2007). In addition, within the intervening Rhodope Massif (Muttoni et al., 2000), evidence for intra-Triassic metamorphism at ca. 200 Ma has been reported from the central Rhodope Massif (U–Pb–Th dating of monazite in diamond-bearing gneisses; Petrik et al., 2024). The recently compiled datasets suggest a more complex paleogeographic configuration than previously assumed (e.g., Neubauer et al., 2019; Spahić, 2024), which cannot be restricted solely to the Crete–External Hellenides suture zone (Zulauf et al., 2018, 2024). Consequently, the available evidence points to the need for a revised Paleotethyan model that accounts for the interaction between westernmost Cimmerian ribbon-shaped continental fragments and Triassic deformation events (e.g., Stampfli, 1996; Neubauer et al., 2019; Spahić, 2024; Fig. 7).

”Neocimmerian” configuration of the western Neotethys and its seaways

The latest Jurassic “obduction stage” corresponds to an intra-Mesozoic collisional phase commonly referred to as the Neocimmerian stage. This latest Jurassic–earliest Cretaceous interval is generally interpreted as a closure-related phase characterized by weak accretion during the final evolution of Jurassic oceanic domains. In this context, the Neotethyan Ocean and its associated seaways, such as the Intradinaride Ocean (Dimitrijević, 2001), underwent deformation during the so-called “Neo-

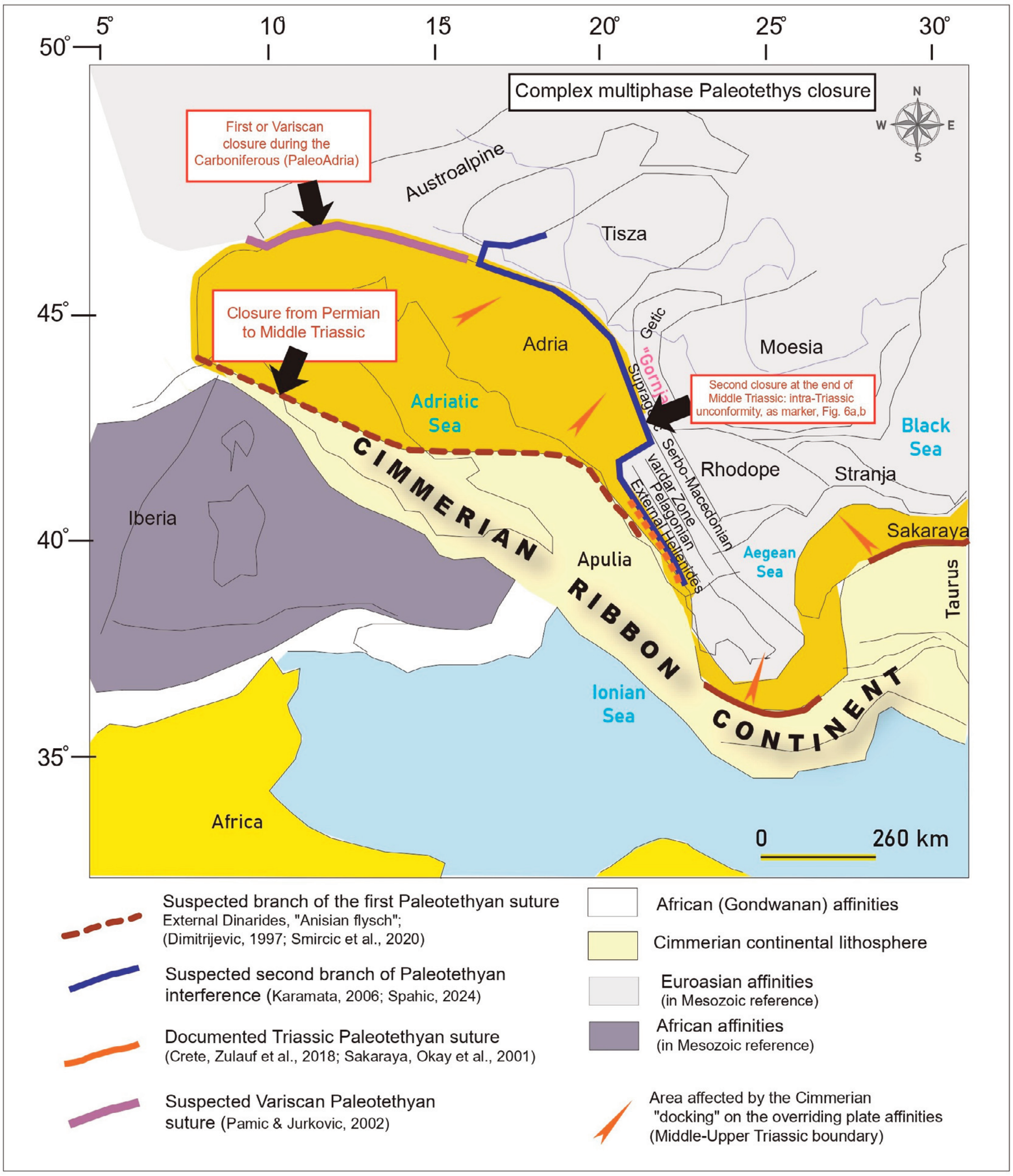

Fig. 7. *Sketch map illustrating the position of the westernmost segment of the Cimmerian ribbon continent within the Dinaride–Hellenic sector (inset modified after* Spahić*, 2022b). The tectonic model highlights the role of the Apulian Plate during the Eocimmerian "docking" event ("Eocimmerian welding of Apulia and Adria"; see also Figure 8 and the model of* Robertson *et al., 2009). The second bay was partially closed either during the Variscan event/Permian or during a later tectonic event (red arrows) (see* Spahić*, 2024, for discussion).*

cimmerian stage" (e.g., Bonev & Stampfli, 2011; Spahić et al., 2023, 2024, 2025a; Mposkos et al., 2024).

Latest Jurassic Paleogeography and the Neocimmerian unconformity

The latest Jurassic "obduction stage" corresponds to an intra-Mesozoic collisional phase commonly referred to as the Neocimmerian stage. This latest Jurassic–earliest Cretaceous interval is generally interpreted as a closure-related phase characterized by weak accretion during the final evolution of Jurassic oceanic domains. In this context, the Neotethyan Ocean and its associated seaways, such as the Intradinaride Ocean (Dimitrijević, 2001), underwent deformation during the so-called "Neocimmerian stage" (e.g., Bonev & Stampfli, 2011; Spahić et al., 2023, 2024, 2025a; Mposkos et al., 2024).

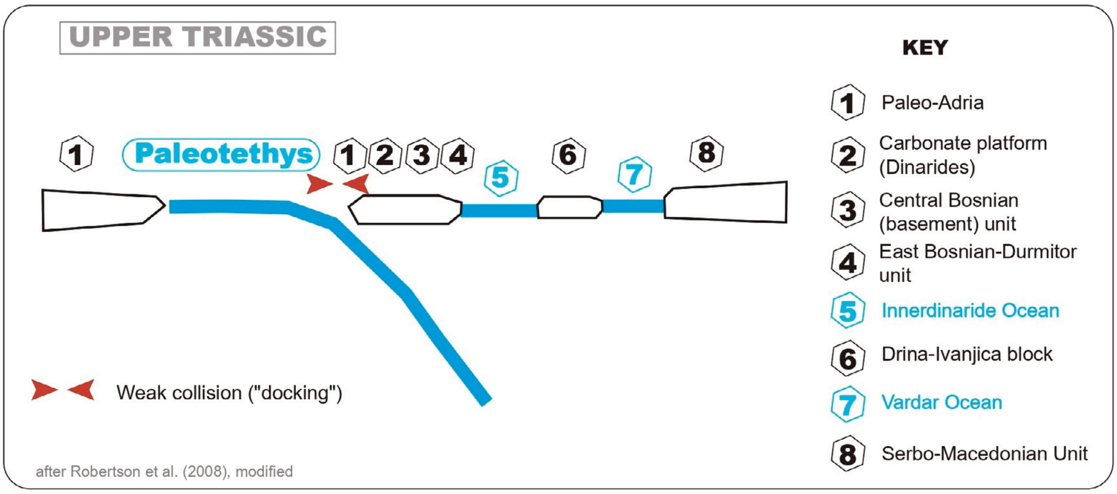

Fig. 8. Paleotectonic model of northward subduction and back-arc rifting (modified after Robertson et al., 2009, and references therein). The model proposes the existence of a still-open Late Paleozoic Ocean (Paleotethys) beyond the northern margin of Adria (see Fig. 1a). During the Triassic, this ocean subducted northwards, leading to the opening of a back-arc basin along the northern continental margin of Eurasia/Serbo–Macedonian Unit. The back-arc extension influenced the inicial development of the Intradinaric and Vardar oceans.

In paleogeographic and paleotectonic terms, as suggested by both Dimitrijević (1995, 1997) and Karamata (2006), the Neotethyan Vardar Ocean consists of Jurassic oceanic fragments located east of the Drina–Ivanjica Block (Fig. 8; Supplementary Figure 1a,b). The Inner Dinaride Ocean, as proposed by Dimitrijević (2001), comprises oceanic fragments situated west of the Drina–Ivanjica Block (Supplementary Figures 1a,b). The Late (Neo-)Cimmerian stage is associated with an intra-Jurassic deformation event dated at ~165–145 Ma in the Carpathian–Balkan region (Vangelov et al., 2013). Other authors propose a broader temporal range extending from the Late Triassic to the Early Cretaceous (ca. 208–100 Ma), lasting approximately 100 Myr (Catto et al., 2017). Within the Carpathian–Balkan region, Neocimmerian deformation is only locally documented, mainly as north-vergent, pre-Late Cretaceous (and most likely pre-Callovian) W–E–trending folds (Tschoumatchenko et al., 2004; Spahić, 2022b, 2024). This interpretation is further complicated by its overlap with the Triassic–Jurassic evolution of the Circum-Rhodope Belt and associated ophiolites, which are predominantly Triassic in age (e.g., Ferriere et al., 2012, 2016; Bonev et al., 2019; Spahić et al., 2020).

If the inferred Jurassic oceans (Vardar and Inner Dinaride/Dinaric oceans) formed between 174–160 Ma (Maffione & van Hinsbergen, 2018; Vergély & Mercier, 2024; Spahić et al., 2025a) and had already closed by the latest Jurassic, then collisional deformation features such as folding and unconformities would be expected. Indeed, earlier and more recent studies have reported indications of Neocimmerian deformation, including Late Jurassic nappe emplacement (e.g., Grubić, 1980; Robertson et al., 2009; Bonev & Stampfli, 2011; Lužar-Oberiter et al., 2012; Robertson, 2012; Spahić et al., 2025a). The "Neocimmerian stage", in addition to ophiolite obduction, also includes less-studied compressional deformation and metamorphism, such as Jurassic subduction–accretion complex nappes preserved beneath the Serbo–Macedonian margin (Bonev & Stampfli, 2011). Available age constraints from the Vardar Zone are largely based on metamorphic soles interpreted as markers of ophiolite obduction, with ages clustering around ca. 160 Ma, while the Inner Dinaride Ophiolite Belt yields Jurassic ages ranging from 176 to 157 Ma (K–Ar on hornblende; Pamić et al., 2002). Schefer (2012) summarized metamorphic sole ages at the base of obducted ophiolites, showing slightly older values (174–157 Ma; Aalenian–Oxfordian) compared to the ophiolitic ultramafic and mafic plutonic rocks of both belts, which are mainly Middle to early Late Jurassic in age (163–148 Ma; Callovian–early Tithonian). However, comprehensive structural studies remain scarce, with most evidence limited to unconformities widely

Table 1. *A number of selected bauxite locations within the main tectonic entities of the Dinarides and the Carpathian–Balkan belt sensu lato (or the Serbo–Macedonian, Getic/Supragetic/Danubian; see the caption of Fig. 1 for explanations and the main text for further details). Abbreviations: OR–ore region; OD–ore deposit; MAJ–major minerals; MIN–minor and/or accessory minerals; References: [1)]Borojević Šoštarić et al. (2022); [2)]Cvetković & Tančić (2019); [3)]Dangić (1985); [4)]Dangić (1988); [5)]Maksimović & Panto (1991); [6)]Maksimović & Radoičić (1996); [7)]Radusinović et al. (2017); [8)]Timotijević (1995); [9)]Timotijević (2001); and [10)]Bilić et al. (2023).*

Bauxite / Laterite	External Dinarides	Inner (Internal) Dinarides	Carpathian–Balkan belt *sensu lato*
Upper Cretaceous		1. **Grebnik OR** (Metohija, Serbia; Turonian[6)]). MAJ: diaspore, boehmite, hematite (Al-type [2)]). MIN: kaolinite, quartz, goethite, rutile, hydrohematite, pyrite, chromite, anatase, brookite, ilmenite, garnet.[2), 5), 9)] 2. **Central Bosnia (Jajce) OR** (Bešpelj, Crvene stijene, Poljana, Skakavac OD; B&H). MAJ: boehmite, hematite, diaspore. MIN: kaolinite, goethite, calcite, anatase, rutile, zircon. [1), 10)]	
Lower Cretaceous		3. **Vlasenica OR** (Palež, Podbraćan, Šumarnica, Štedra, Crvene stijene, Kosturi, Gerovi, Dragošnica, Žedanjsko, Pribojevići, Kutuzero OD; B&H). MAJ: boehmite, diaspore, hematite. MIN: kaolinite, anatase, rutile, brookite.[1), 3), 4), 5)] 4. **Poćuta OR** (Petrovići, Bakića Brdo and Jasike OD), 5. **Tara OR** (Aluge OD) and 6. **Mačkat OR** (Trafostanica, Bjelaci and Vezirov Potok OD) (Western Serbia). MAJ: boehmite, hematite, kaolinite. MIN: limonite, goethite, magnetite, pyrite, chlorite, quartz, calcite, illite, anatase, sphene, opal, spinel.[8), 9)]	7. **Babušnica OR** (Eastern Serbia). MAJ: boehmite, hematite, kaolinite. MIN: limonite, goethite, calcite, quartz, illite, rutile.[9)]
Upper Jurassic	8. **Vojnik–Maganik OR** (Zagrad OD; Nikšić, Montenegro). MAJ: boehmite, hematite. MIN: kaolinite, anatase, rutile, quartz.[7)] Štitovo OD. MAJ: boehmite, hematite. MIN: kaolinite.[5)]		

observed across the region (e.g., Chiari et al., 2011; Nirta et al., 2020; Spahić et al., 2023, 2025a). The most prominent indicator of Neocimmerian deformation in the Dinarides is the widespread occurrence of bauxites, whereas other structures such as brittle reverse faults are difficult to document due to strong late Alpine overprinting (Spahić et al., 2025a).

Mesozoic bauxites as markers of unconformities

A growing number of studies on intra-Mesozoic (bauxite-bearing) unconformities indicate that, regardless of the extent of latest Jurassic obduction, there is strong evidence for weak collision between oceanic domains and their continental margins, particularly well documented in the East Vardar Zone and its contact with the Serbo–Macedonian Unit (Bonev & Stampfli, 2011; Spahić et al., 2024, 2025a; Mposkos et al., 2024). This evidence is mainly expressed by tectonically controlled intra-Mesozoic unconformities, which are frequently associated with bauxite deposits (see Spahić et al., 2025a, and references therein).

Using additional data on intra-Mesozoic bauxites, we further provide evidence supporting a latest Jurassic–earliest Cretaceous Neocimmerian tectonic overprint and subaerial exposure of Mesozoic ophiolites (which represent primary source areas for bauxite formation; Fig. 9a,b; Table 1). Analysis of the binary Th/Sc versus Cr/Th diagram (Fig. 9a; Table 2) and the ternary V–Ni–Th×10 plot (Fig. 9b; Table 2) indicates that the studied bauxites were derived from different weathering sources, distinct from their parental rocks, which are predominantly of Upper Jurassic to Upper Cretaceous age. Specifically, Babušnica in the Carpathian–Balkan region (Lower Cretaceous; Fig. 3b, blue hexagon #1), Jajce (Upper Cretaceous; Fig. 3b, blue hexagon #2), and Nikšić (Upper Jurassic; Fig. 3b, blue hexagon #3) from the External Dinarides show the strongest contribution from felsic source rocks, approaching upper continental crust (UCC) composition. In contrast, bauxites from the Inner Dinarides, such as Mačkat (Lower Cretaceous; Fig. 3b, blue hexagon #4) and Grebnik (Upper Cretaceous; Fig. 3b, blue hexagon #5), reflect a stronger influence of ultramafic source rocks. These results confirm the presence of a dominant Upper Jurassic (to Upper Cretaceous) unconformity surface, indicating Neocimmerian tectonic overprinting, consistent with the interpretations of Spahić et al. (2025a).

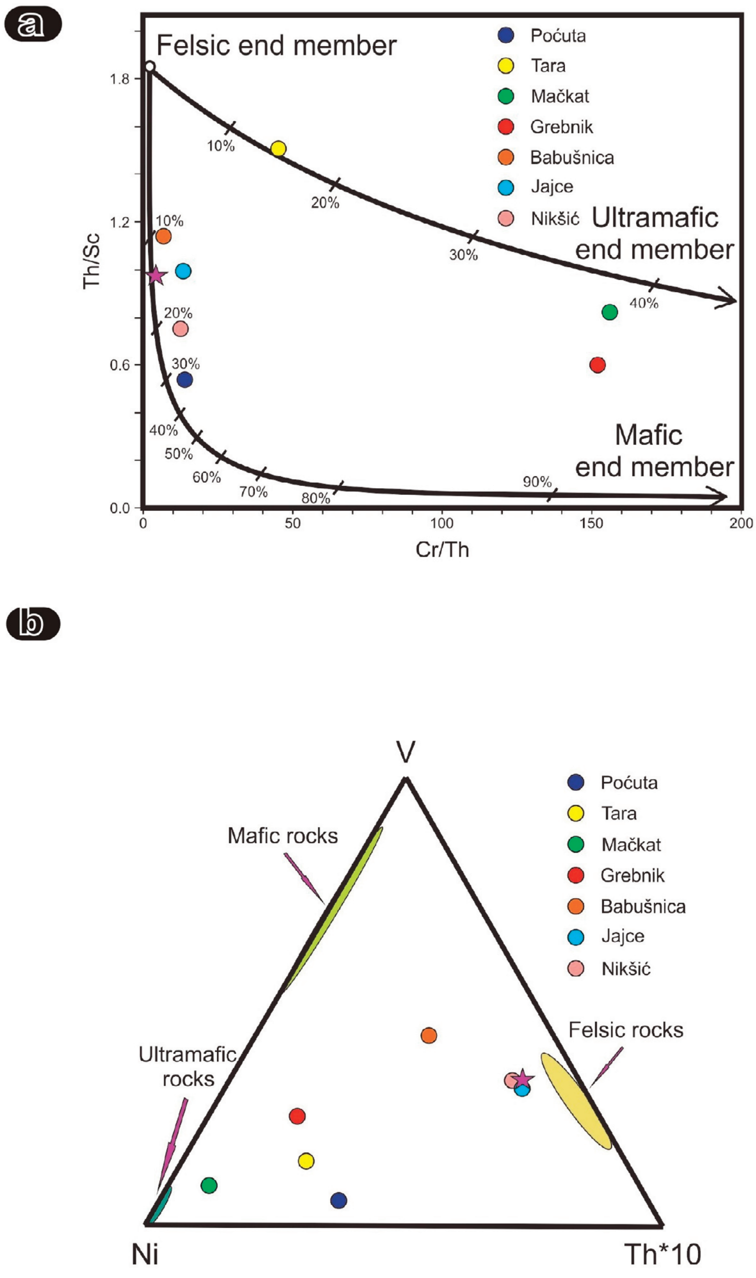

Fig. 9. The studied Poćuta, Tara, Mačkat, Grebnik, Babušnica, Jajce, and Nikšić bauxites (represented by blue, yellow, green, red, orange, cyan, and pink circles, respectively) plotted on: ***a.*** *the binary Th/Sc vs. Cr/Th diagram (modified after Bracciali et al., 2007 and references therein); and* ***b.*** *the ternary V–Ni–Th×10 diagram (after Bracciali et al., 2007). The purple star in both figures represents the UCC (upper crust composition; after Plank & Langmuir, 1998).*

Table 2. *Selected trace-elements contents (ppm) of the studied bauxites (Spahić et al, 2025a; and references therein). Legend: n.d. – not determined; n.c. – not calculated; * – calculated in this paper.*

Element	Poćuta	Tara	Mačkat	Grebnik	Babušnica	Vlasenica	Jajce	Nikšić
Cr	368	1195	3200	5387	257	425	800	600
La	29	75	79	65	92	47	112.1	153.1
Ni	477	691	2140	1211	279	540	128	115
Sc	52	18	25	59	34	18	63	64
Th	27.67	26.81	20.42	35.56	38.70	n.d.	61.3	48.3
V	43	159	225	501	487	225	324	284
Th/Sc*	0.53	1.49	0.82	0.60	1.14	n.c.	0.97	0.75
Cr/Th*	13.30	44.57	156.71	151.49	6.64	n.c.	13.05	12.42
V*	5.40%	14.22%	8.76%	24.23%	42.24%	n.c.	30.42%	32.20%
Ni*	59.87%	61.80%	83.29%	58.57%	24.20%	n.c.	12.02%	13.04%
Th×10*	34.73%	23.98%	7.95%	17.20%	33.56%	n.c.	57.56%	54.76%
La*	26.69%	62.60%	63.49%	40.74%	55.86%	n.c.	47.42%	57.69%
Sc*	47.85%	15.02%	20.09%	36.98%	20.64%	n.c.	26.65%	24.11%
Th*	25.46%	22.38%	16.41%	22.29%	23.50%	n.c.	25.93%	18.20%

From the ternary La–Th–Sc diagram used for tectonic discrimination (Fig. 10; Table 2), it is evident that all studied bauxites plot within the continental island arc field, except for Poćuta (Lower Cretaceous), which plots closer to the oceanic island arc field. Because both oceanic and continental island arc settings represent convergent plate margins (Bhatia & Crook, 1986), the inferred exposure of oceanic crust is consistent with a compressional Neocimmerian tectonic regime and with the observations of Spahić et al. (2025a; their Fig. 17a).

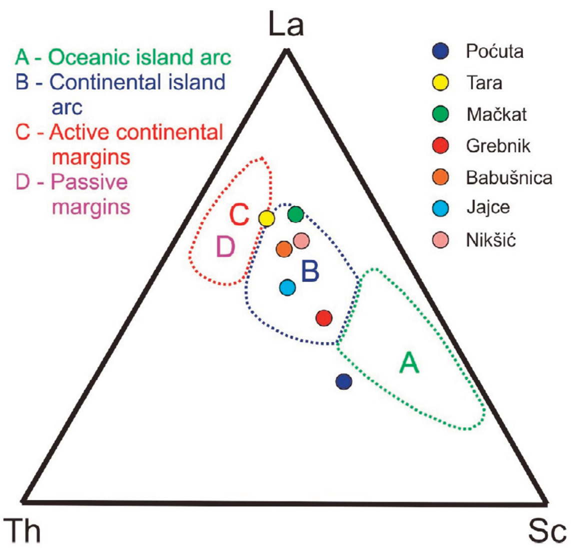

Fig. 10. *The studied Poćuta, Tara, Mačkat, Grebnik, Babušnica, Jajce, and Nikšić bauxites (represented by blue, yellow, green, red, orange, cyan, and pink circles, respectively) plotted on the ternary La–Th–Sc diagram for tectonic-setting discrimination (after Bhatia & Crook, 1986).*

Conclusions

This study shows that several paleogeographic and paleotectonic events are recorded within the post-Variscan to late Alpine Carpathian–Balkan–Dinaride framework. Most of these events remain insufficiently investigated, despite earlier contributions by authors such as Dimitrijević (1995, 1997) and Karamata et al. (1994), who provided important foundations for further research. Although the Early Cimmerian stage was defined long ago (e.g., Grubić, 1980), the Carpathian–Balkan region remains largely understudied in this context;

A similar situation applies to the latest Jurassic Neocimmerian stage. Despite evidence for metamorphism and deformation, this stage is commonly interpreted in recent literature solely as an "obduction stage";

The results of this study clearly highlight the need for a new transnational research initiative focused on these two intra-Mesozoic deformation stages.

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Резиме

Прелаз Палеотетиса на Неотетис: разлике између раноалпског, ранокимеријског (средњи–горњи тријас) и неокимеријског (најмлађа јура) деформационог стадијума („слаба акреција”)

Упркос детаљним студијама изложених офиолитских појасева широм западног Балканског полуострва, оба наведена аутора (проф. Димитријевић и проф. Карамата) изнела су само неколико, али научно веома значајних запажања о занемареном (западном) Палеотетису, као претходном океанском ентитету. И поред њихових доприноса, улога Палеотетиса у развоју неотетиског Вардара и даље остаје недовољно разјашњена. У терминолошком смислу, „западни Палеотетис” се односи на палеогеографску област која представља океански фрагмент који је вероватно окруживао своју најзападнију зону повезивања, спајајући Алпе, Карпатско–балкански венац, Родопе и Динариде–Хелениде/Палео-Адрију (Dornsiepen et al., 2001; Robertson, 2012, 2021; Spahić, 2022a,b, 2024). Овај појам обухвата и „реликтни Палеотетис” као палеоокеански ентитет који је опстао након варисцијске колизије крајем доњег карбона (око 320 Ma) и наставио свој развој у тријасу и јури (Stampfli & Borel, 2002; Robertson, 2021; Spahić, 2022a,b, 2024).

У погледу еволуције Неотетиса, Karamata et al. (2005), Karamata (2006) су предложили концепт „вардарског реликтног Сава океана”, који је касније био широко прихваћен у литератури (Schmid et al., 2008, 2020; Ustaszewski et al., 2009, 2010; Bortolotti et al., 2013; Maffione & van Hinsbergen, 2018; Toljić et al., 2018, и други). Међутим, овај једноокеански модел у последње време све више се доводи у питање и често се сматра превазиђеним.

Као одговор на овај концепт, „модел више неотетиских океана”, који су предложили Dimitrijević (2001) и Karamata & Krstić (1996), а који је у почетку био одбачен, поново добија на значају. Савремени истраживачи све више разматрају моделе који укључују постојање више тетијских океанских домена.

Ранокимеријска орогена фаза односи се на догађај који се одиграо приближно пре 210–200 милиона година (Vangelov et al., 2013). Компресиони догађај се може уочити преко следећих слабо изражених и слабо истражених деформација:

(i) ретко документован интра-тријаски метаморфизам (Petrik et al., 2016);

(ii) одсуство горњотријаских седимената (нпр. источна Србија), што је интерпретирано као „ранокимеријска дискорданција”, углавном препозната у подини Мезије, али ретко директно у теренским условима (Spahić, 2022b, 2024).

Што се тиче неокимеријске орогене фазе, она се у већини радова интерпретира као фаза обдукције, али се у овом контексту разматра као пост-палеотетијска колизиона епизода, односно друга интра-мезозојска фаза слабе акреције („docking”). Неокимеријски тектонски интервал, који обухвата касну јуру до најранију креду, тумачи се као завршна фаза конвергенције, током које долази до слабог затварања јурских океанских домена. У регионално-геолошком смислу, Неотетиски океан и његови океански пролази, као што је Интрадинаридски океан (Dimitrijević, 2001), прошли су кроз такозвану „неокимеријску фазу” конвергенције (нпр. Bonev & Stampfli, 2011; Spahić et al., 2023, 2024, 2025a; Mposkos et al., 2024).

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