Field Trip Guide
17th EGU Émile Argand Conference on Alpine Geological Studies
Fruška Gora, Serbia

GEOLOŠKI ANALI BALKANSKOGA POLUOSTRVA
Volume 87 (1), July 2026, 189–204
https://doi.org/10.2298/GABP260608011M
Review paper
Прегледни рад

Transect through the Vardar Mega Suture Zone

ANA MLADENOVIĆ[1] & DEJAN PRELEVIĆ[1,2]

Abstract. In this contribution, we present the field guide that accompanies the post-meeting excursion FT4 of the 17th EGU Émile Argand Conference on Alpine Geological Studies. Tectonic maps of Serbia are dominated by broad, chiefly NNW–SSE belts of ophiolitic and ophiolite-related units - East Vardar, West Vardar, and Dinaric ophiolites - representing dismembered fragments of Mesozoic oceanic lithosphere. These assemblages include serpentinized peridotites, gabbros, and basalts, associated with a deep-marine sediments and exotic blocks (olistoliths and olistoplaques) set within a silty-sandy matrix. Although strongly deformed following obduction, the ophiolite complexes constitute the key archive for reconstructing Phanerozoic interactions between the southern Eurasian margin and terranes derived from northern Gondwana across the Mesozoic Tethys. The excursion stops span this spectrum – from kilometer-scale obducted peridotite massifs and their metamorphic soles, through gabbro–diabase complexes and granitoid intrusions, to small basaltic and radiolarian chert olistoliths in mélange, offering direct field evidence of the Tethyan lithosphere and its tectonic evolution.

Key words:
Vardar Zone, ophiolites, Europe, Dinarides.

Апстракт. У овом прилогу представљамо теренски водич који прати постконференцијску екскурзију FT4 у оквиру 17. EGU Конференције о алпским геолошким студијама (17th Alpine Workshop). Тектонским картама Србије доминирају широки појасеви офиолитских јединица претежно оријентисаних правцем ССЗ–ЈЈИ: Источновардарски, Западновардарски и Динарски офиолити, који представљају остатке мезозојске океанске литосфере. Ови склопови обухватају серпентинисане перидотите, габро и базалте, заједно са дубокоморским седиментима и егзотичним блоковима (олистолити и олистоплаке) у глиновито-песковитом матриксу. Иако снажно деформисани након обдукције, офиолитски комплекси представљају кључни архивски запис за реконструкцију фанерозојских интеракција између јужне маргине Евроазије и терана који потичу са северне Гондване. Тачке на екскурзији обухватају цео овај спектар – од обдукованих перидотита километарских размера и њихових метаморфних ђонова, преко габро–дијабазних комплекса и гранитоидних интрузија, до малих базалтних и радиоларитних олистолита у меланжу, пружајући непосредне теренске доказе о литосфери Тетиса и њеној тектонској еволуцији.

Кључне речи:
Вардарска зона, офиолити, Европа, Динариди.

[1] University of Belgrade - Faculty of Mining and Geology, Belgrade, Serbia
[2] Serbian Academy of Sciences and Arts, Belgrade, Serbia

Geological summary of Serbia

Serbia occupies the central part of the Balkan Peninsula and sits at the junction of two major Alpine-derived orogenic systems (Schmid et al., 2008). To the west and centre, the Dinaric belt trends broadly NNW–SSE (turning N–S after a northwest Serbian inflection) (Dimitrijević, 2001), whereas the Carpatho–Balkan system extends from the northeast and curves around the Pannonian Basin to enter Serbia near the Danube Gorge (Schmid et al., 2020). Although their origins differ, both belts are ultimately products of Alpine orogenesis and meet across Serbian territory.

A practical geotectonic subdivision of Serbia reflects this junction of oppositely verging orogenic branches. From east to west the principal domains comprise: (1) the East Serbian Carpatho–Balkanides, including the Serbo–Macedonian Unit; (2) the complex ophiolitic suture zone, incorporating the Vardar-zone mélanges and related basement fragments (Jadar–Kopaonik, Drina–Ivanjica) and Dinaride mélanges; and (3) the Internal and External Dinarides. Field traverses described in this guide cross all these domains, except most of the External Dinarides, whose main exposures lie west of the Serbia–Bosnia border (Fig. 1).

The most striking feature on tectonic maps of Serbia is a wide, predominantly NNW–SSE-oriented belt(s) of ophiolitic and ophiolite-related units, including East Vardar-, West Vardar- and Dinaric-ophiolites. These bodies comprise fragmented remnants of former Mesozoic oceanic lithosphere, including serpentinized peridotites, gabbros and basalts (Robertson & Karamata, 1994). They occur alongside deep-marine sediments and exotic blocks such as olistoliths and olistoplaques, within silty-sandy matrices (Dimitrijević & Dimitrijević, 1976; Dimitrijević, 1997; Karamata et al., 1999; Djerić et al., 2024). Despite intense post-obduction deformation, these ophiolitic complexes provide the primary archive for reconstructing Phanerozoic interactions

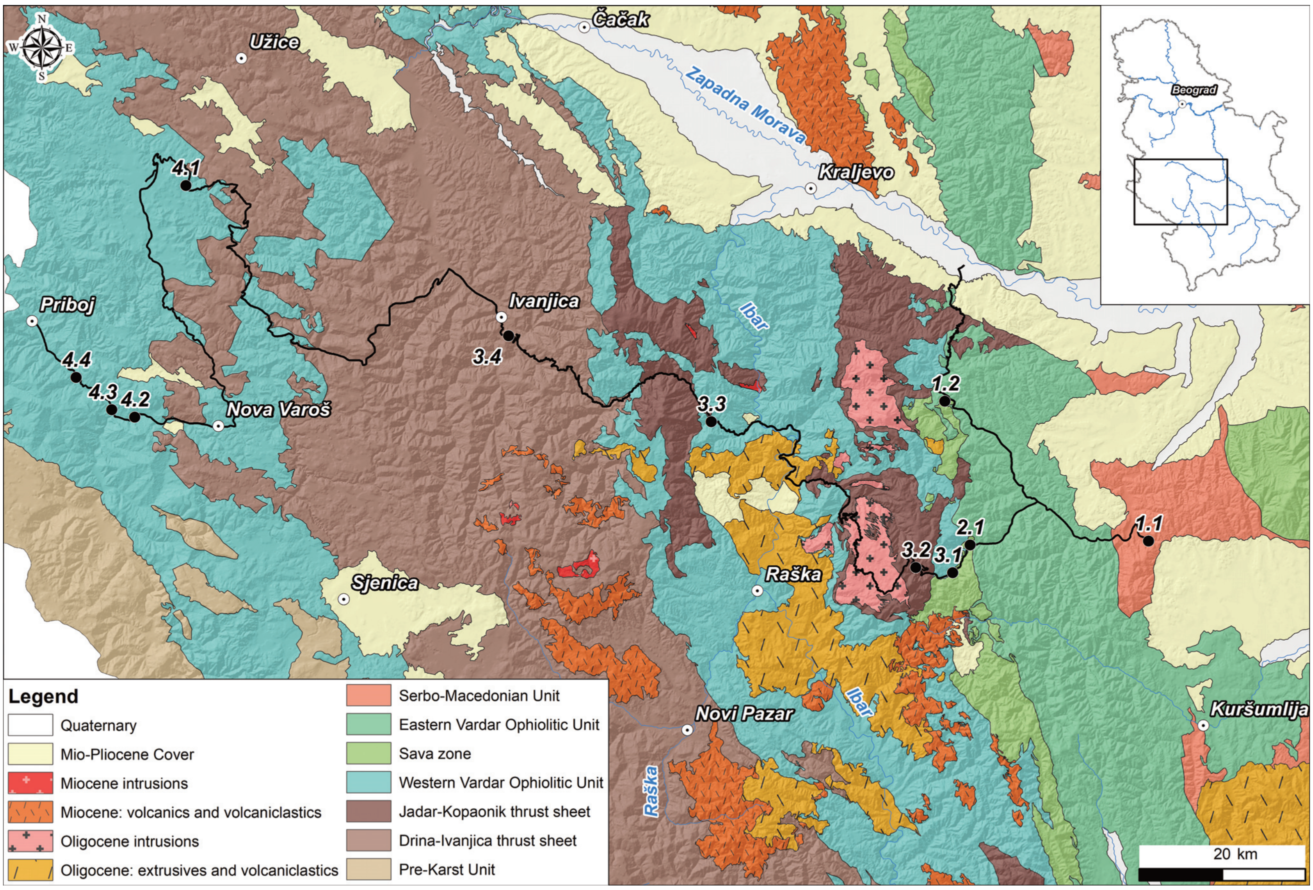

Fig. 1. *Tectonic map of the central Serbia (after Schmid et al., 2020) and position of the field points to be visited during the excursion.*

between the southern Eurasian margin and terranes derived from northern Gondwana across the Mesozoic Tethys (Karamata, 2006). A working regional tectonic model therefore treats Central Balkans as two amalgamated continental domains – the former southern/southwestern Eurasian margin and the northern/northeastern Adria (Gondwanan) margin – separated and locally sutured by dismembered ophiolitic belts (Schmid et al., 2020). Closure of the intervening Tethyan oceanic domains, largely completed by the latest Mesozoic, produced the accretionary and collisional architecture observed today; subsequent Cenozoic shortening and later extensional phases further modified this tectonic collage (Ustaszewski et al., 2010).

Active debate continues over the number, nature and closing times of these intervening oceanic domains and the provenance of basement fragments preserved within mélange. Single-ocean reconstructions argue for one continuous Tethys between Eurasia and Gondwana, interpreting many basement exposures as tectonic windows within a single suture and noting compositional similarities between Vardar and Dinaridic ophiolites (Schmid et al., 2008). Multi-ocean models propose several discrete oceanic basins and multiple sutures, treating some basement blocks within mélanges as displaced microcontinents (terranes) (Csontos & Vörös, 2004; Karamata, 2006; Bortolotti et al., 2013). Both hypotheses remain active research topics.

Additionally, the timing of the final oceanic closure remains controversial. Traditional models argue that main oceanic domains completely closed during the Late Jurassic via massive ophiolite obduction (Robertson & Karamata, 1994; Csontos & Vörös, 2004). Modern hypotheses suggest that a remnant branch, the Sava Ocean, persisted much longer (Pamić, 2002; Schmid et al., 2008, 2020; Gallhofer et al., 2015) and did not close until the latest Cretaceous to early Paleogene.

Current research programs address these questions from complementary angles: mantle and peridotite geochemistry, igneous-petrological studies of ophiolitic lithologies, biostratigraphy and provenance of associated sediments, and structural-tectonic investigations of mélanges, metamorphic soles and nappe geometries. The field stops (Fig. 1) included in this excursion illustrate the full range of these elements: from km-scale obducted peridotite bodies and their metamorphic soles through gabbro–diabase complexes and granitoid intrusions to small basaltic and chert olistoliths in mélange and provide direct observation of the Tethyan lithosphere and its tectonic history.

This summary is intentionally concise: it highlights the principal geological elements and interpretative frameworks useful for a professional visitor approaching Serbia for the first time, while omitting detailed local descriptions and unresolved controversies that are better addressed in specialized studies.

1. East Vardar and Serbo–Macedonian Unit: accretionary architecture of the European margin

Researchers generally agree that the narrow ophiolitic strip along the western margin of the Serbo–Macedonian Unit, commonly called the East Vardar Zone, differs from other Balkan ophiolites. These ophiolites exhibit the strongest supra-subduction geochemical signatures and are thought to have formed in a short-lived intra-oceanic back-arc basin associated with subduction initiation. Recent geotectonic models treat the East Vardar ophiolites and the Serbo–Macedonian Unit as components of the Carpatho–Balkan orogenic system.

1.1 Metamorphic rocks of the Serbo–Macedonian Unit

Coordinates: 21°10’ E, 43°21’ N

(Razbojna village exposure)

On the left side of the road Brus–Kuršumlija, metamorphic lithologies of the Serbo–Macedonian Unit are exposed. This multiply deformed, metamorphosed unit forms part of the east-verging Carpatho–Balkan orogen, representing the deformed European margin, and generally lies structurally below the Eastern Vardar Ophiolitic Unit. The outcrop exposes a highly deformed crystalline section of the Northern Serbo–Macedonian Sub-unit

(NSMU), representing the westernmost continental segment of the Europe-derived Dacia Mega-Unit.

The outcrop comprises amphibolite-facies rocks locally overprinted by greenschist-facies retrogression. Lithologies include mica schists and, less commonly, gneisses of variable composition, together with minor migmatites and intercalated quartzites, amphibolites and marbles. Metamorphic ages in the immediate area remain poorly constrained. Structural evidence in the wider region indicates at least three principal deformational phases related to Late Cretaceous–Paleogene orogenesis.

Crucial insights into the pre-Alpine baseline of NSMU are provided by recent U–Pb zircon geochronology and Lu–Hf isotope geochemistry from the Juhor Mountains, situated further northward (Maleš et al., 2026; submitted for publication). Both the basement micaschists (metagreywacke protoliths) and the crosscutting syn-kinematic, S-type Kolare leucogranite yield overlapping Middle Ordovician (~460 Ma) zircon core crystallization ages. Coupled with mildly subchondritic to juvenile εHf values, these data show that the pre-metamorphic protoliths formed within a peri-Gondwanan ensialic volcano-sedimentary arc during the early Paleozoic Cenerian orogeny (~460–440 Ma). Zircon rims from these units record successive early Paleozoic thermal pulses culminating in a late Early Carboniferous (~330 Ma) event. This final pre-Alpine signature marks the Variscan orogeny, which accreted this Gondwana-derived margin to the Moesian Platform and drove regional high-grade metamorphic differentiation. Remarkably, high-temperature U–Pb zircon analysis detects no post-Carboniferous or Alpine thermal resetting in the crystalline core. This proves that while Alpine tectonics strongly overprinted regional deformational patterns, its high-temperature thermal influence remained highly localized.

1.2 Ophiolites of the Eastern Vardar Ophiolitic Unit

Coordinates: 20°57' E, 43°28' N
(Grčak village exposure)

The serpentinized peridotites exposed at this station belong to the east-vergent Eastern Vardar Ophiolitic Unit, tectonically emplaced above the deformed European margin (i.e., the Carpatho–Balkan orogen). This ultramafic body lacks an associated metamorphic sole, suggesting that the present contacts with neighbouring units were shaped by later tectonic processes.

The serpentinites are intensely brecciated. Primary mineralogy included olivine (≈22–55 vol%), enstatite (≈10–20 vol%), with subordinate diopsidic clinopyroxene and chromite; these phases are largely altered to serpentine. The consensus interpretation is that these rocks represent serpentinized tectonitic harzburgites.

Associated basaltic rocks occur as relics of shallow intrusions and dykes. Individual dykes range from 40 to 100 cm in width and display prominent one-way vitrophyric chilled margins. Low-grade ocean-floor metamorphism has replaced the glass and groundmass with clay minerals, chlorite, and epidote, while transforming primary clinopyroxene into tremolite. Whole-rock geochemistry classifies these intrusive relics as high-Mg basalts and basaltic andesites (Marroni et al., 2004; Božović, 2013). They show diagnostic boninitic signatures including high Mg# (up to 86.9) and elevated MgO contents, extreme depletion in high field strength elements coupled with classic U-shaped REE patterns.

These geochemical trends indicate that the boninites were generated by ~10% partial melting of a highly refractory, multi-stage depleted mantle harzburgite residue (Marroni et al., 2004; Božović, 2013). The source was subsequently fluxed and enriched in incompatible elements by subduction-derived hydrous fluids. Because boninites require rapid extension and shallow volatile-fluxed melting during subduction initiation or slab rollback, this unique occurrence provides definitive evidence that parts of the Eastern Vardar Zone ophiolites evolved within an intraoceanic supra-subduction zone (SSZ) forearc basin rather than a purely mid-ocean ridge environment.

The isotopic analyses of the Grčak boninites (Božović, 2013) reveal unradiogenic Nd compositions, with a leached $^{143}Nd/^{144}Nd$ ratio of 0.51259 and a negative epsilon value εNd = –0.8. This contrasts sharply with the strongly radiogenic, depleted mantle signatures typical of the surrounding Dinaric mid-ocean ridge ophiolites. This negative εNd coupled with enriched initial $^{87}Sr/^{86}Sr$ ratios 0.7064 confirms that the refractory mantle wedge beneath the Eastern Vardar fore-arc was significantly fluxed and geochemically overprinted by subduction-related fluids or subducted continental sediments during intra-oceanic subduction initiation (Božović, 2013).

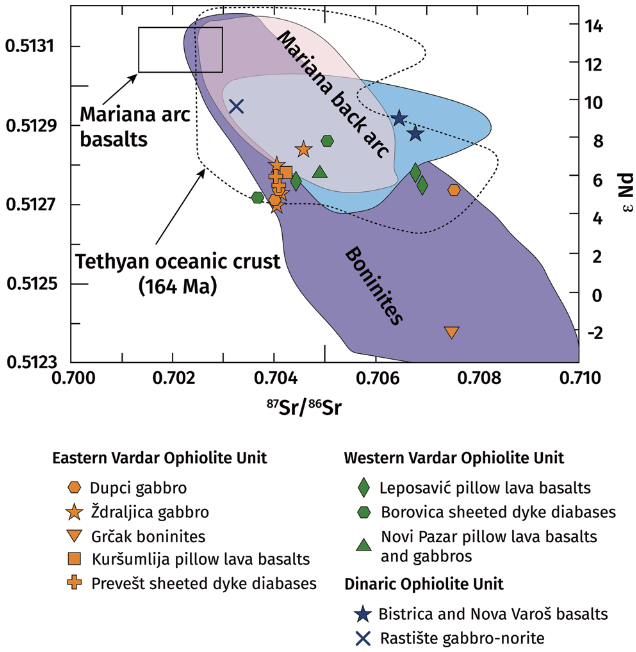

***Fig. 2**. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ isotopic composition plot for the Dinaric, Western and Eastern Vardar Ophiolite Units rocks (Božović, 2013). Tethyan oceanic crust (164 Ma) MORB data are taken from (Zhang et al., 2005). Data for Mariana arc basalts, Mariana back arc basalts, boninites and mantle array are taken from http://georoc.mpch-mainz.gwdg.de/georoc/*

2. Sava-Zone: the final suture in the Balkans?

The Sava (or Sava–Vardar) Zone (Pamić, 2002) is a narrow belt extending from south of Zagreb in a WNW–ESE trend toward Belgrade, before bending southward into North Macedonia. It is younger and locally more metamorphosed than other Cretaceous flysch units that overlie Jurassic mélanges. Because it contains Upper Cretaceous basaltic rocks, some researchers interpret the Sava Zone as the youngest suture recording a Tethyan oceanic domain during the Late Cretaceous (Karamata, 2006; Robertson et al., 2009; Schmid et al., 2020). Many authors (e.g., Gallhofer et al., 2015) link Late Cretaceous subduction of Sava Zone oceanic lithosphere to development of the Banat–Timok–Srednogorie magmatic–metallogenic belt. The view that the Sava Zone hosts the youngest ophiolites here has, however, been questioned recently by Prelević et al. (2017) and many others.

2.1 Upper Cretaceous sediments of the Sava Zone

Coordinates: 20°55′ E, 43°20′ N

Proceeding along the road to Brzeće, one encounters turbiditic outcrops; this field stop represents the first exposure of an Upper Cretaceous succession, which unconformably overlies the Kopaonik Metamorphic Series and the Western Vardar Ophiolitic Unit.

These deposits include large olistoliths dominated by ophiolitic and metamorphic blocks. The succession rests on a calcitic sedimentary breccia containing ophiolitic detritus and fragments derived from metamorphosed rocks. The package is largely composed of red pelagic limestones, with incorporated olistoliths of calcarenites, conglomerates and metamorphosed grainstones.

As with other units on the eastern Kopaonik Mt. flanks, these rocks display a penetrative ESE-dipping foliation and abundant kinematic indicators recording top-WNW shear. This Upper Cretaceous succession is interpreted as the southern extension of the Sava Zone, considered the principal suture between Adria and Europe. Parts of the turbidite sequence likely formed during Late Cretaceous–Early Paleogene closure of the Vardar branch of the Neotethys.

Detrital zircon U–Pb age distribution profiles analyzed along the broader Sava Zone axis (Fig. 3), including the Kopaonik–Brzeće sector of the Sava Zone (sample 22KOP-006) visited at this field stop, provide empirical insight into the provenance of detrital material of these Upper Cretaceous basins. The KDE curves exhibit variable but constant influx of Triassic and Permo–Triassic age components typical for Dinaric sources in all sediments (Prelević et al., in preparation), together with Europe-derived components of the spectre, including Paleozoic Cenerian (~460–440 Ma) and Neoproterozoic Cado-

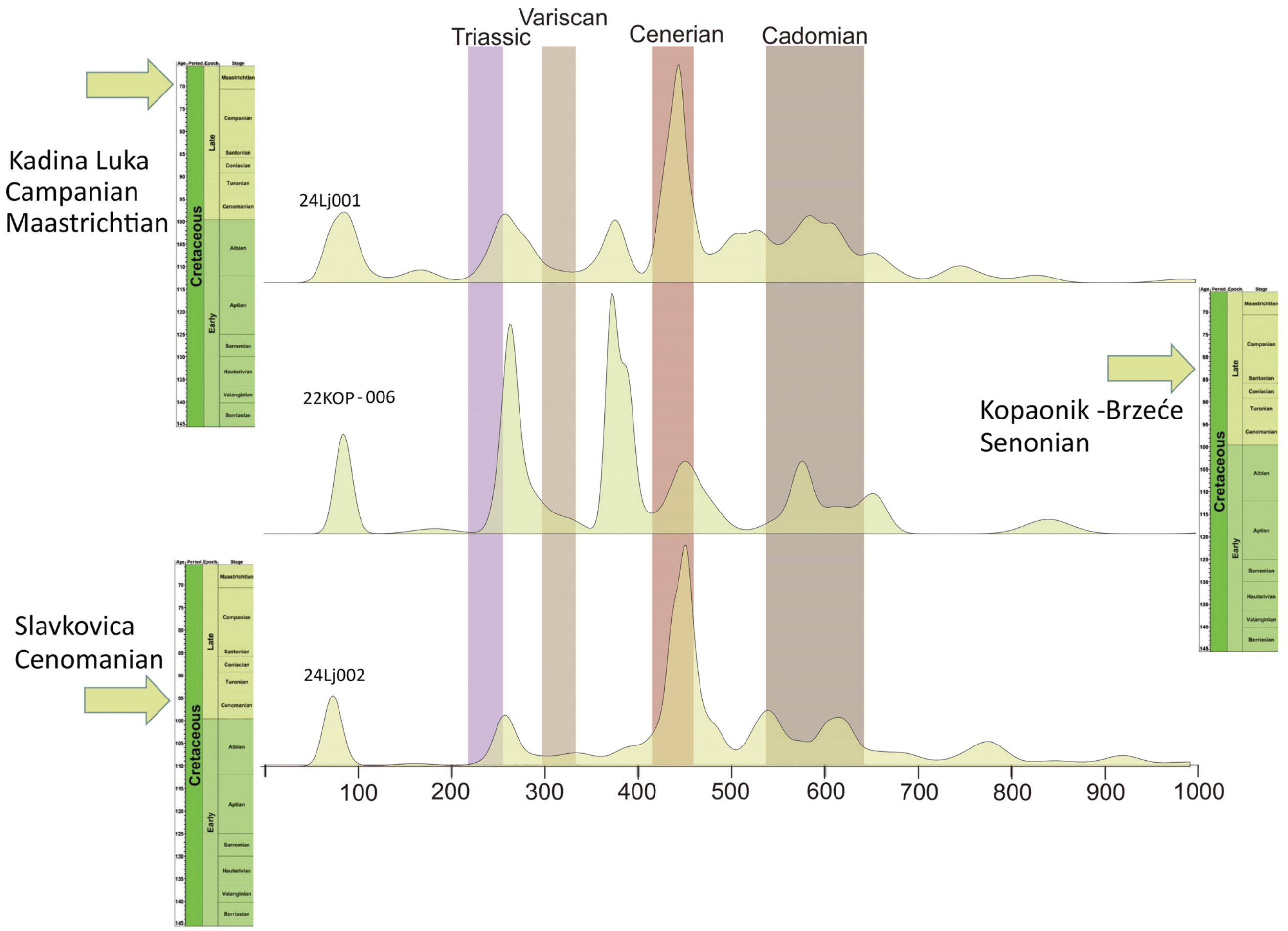

Fig. 3. Detrital zircon U - Pb age Kernel Density Estimation (KDE) diagrams from Upper Cretaceous siliciclastic successions associated with the Sava Zone in Serbia, sequentially ordered by stratigraphic/depositional age from bottom to top (Prelević et al., in preparation). Green horizontal arrows align the samples with their chronostratigraphic positions on the simplified Cretaceous stages. The shaded vertical bands mark the core regional tectonic baselines: Triassic and Permo–Triassic magmatic rifting (purple), Variscan basement accretion (brown), Cenerian arc building (red), and Neoproterozoic Cadomian positioning (gray). Note the constant influx of Triassic age components in all sediment (of different intensity), together with European-derived components of the spectre (Cenerian), documenting a mixed-margin sediment sourcing during active Adria–Europe convergence.

mian (~650–550 Ma) age peaks. These Cenerian and Cadomian European peaks reflect primary sediment derivation from the crystalline core of the adjacent European margin (Dacia Mega-Unit/Serbo–Macedonian Unit). This documents a mixed-margin sediment sourcing during active Adria–Europe convergence. In other words, the basin was actively trapping sediment shed simultaneously from the upper plate (Europe) and the rising, lower-plate margins of the Adriatic/Dinaric domain. This complex provenance supports models where these turbidites formed within a highly unstable, syn-orogenic basin or a deep transtensional pull-apart trough (Prelević et al., 2017).

3. Western Vardar Ophiolitic Unit and its basement

Balkan ophiolite complexes include not only oceanic basement lithologies (basalts, gabbros, peridotites) but also a chaotic suite of lithologies delivered to the trench through time. The matrix consists of silty-sandy deep-marine sediment, locally flysch-like, and the association contains syn-sedimentary slump structure (olistostromes) as well as exotic gravitationally introduced olistoliths (chert, limestone, diabase-basalt, etc). This syn-sedimentary mélange was subsequently tectonically reworked during subduction (accretionary wedge processes, obduction of large ophiolitic nappes) and post-collision (shortening, nappe stacking, shearing, boudinage).

Resistant diabase and chert blocks commonly protrude above the eroded silty matrix, which led to the historical name Diabase–Chert (Hornstein) Formation, a label retained despite earlier misinterpretations of its Triassic age due to incorrect application of stratigraphic superposition.

3.1 Metamorphosed ophiolitic mélange

Coordinates: 20°54' E, 43°18' N

Along the Brus–Brzeće road an exposure of the Western Vardar Ophiolitic Unit's ophiolitic mélange is visible. The mélange is dominated by centimetre- to decimetre-sized serpentinite blocks, with subordinate fragments of basalt, turbiditic sandstone, and carbonate, all set within a silty, brown-to-reddish muddy matrix. This thick ophiolitic mélange tectonically overlies the Kopaonik Metamorphic Series on the eastern Kopaonik flanks.

The outcrop displays a pronounced foliation interpreted as Paleogene deformation related to the Kopaonik region.

3.2 Kopaonik Metamorphic Series

Coordinates: 20°51' E, 43°18' N (Metođe section); 20°49' E, 43°18' N (Jaram section)

A several-kilometre-long exposure along the road from Brzeće toward the Kopaonik tourist center exposes low-grade metamorphic rocks of the Kopaonik Metamorphic Series. This series forms part of the Jadar–Kopaonik thrust sheet, representing the most distal segment of the Adriatic margin, which is locally capped by an obducted Late Jurassic ophiolite nappe. Both the thrust sheet and its ophiolitic cover were involved in Late Cretaceous out-of-sequence top-W thrusting.

The series consists of a Paleozoic metasedimentary basement overlain by metamorphosed Triassic to Middle/Upper(?) Jurassic sediments. These Mesozoic metasediments record a polyphase penetrative tectonic overprint from the three main phases of Cretaceous–Paleogene compression, followed by Miocene extension that exhumed the Kopaonik core complex. Cretaceous–Paleogene compression produced polyphase greenschist-facies metamorphism, locally progressing to lower-amphibolite facies. Today, the oldest deformational phase is preserved only in form of refolded foliation, that can be seen only in thin sections. The D2 structures are represented by rootless isoclinal folds, that are refolded by the D3 structures (Fig. 4a). The D4 deformational phase is represented by extensional structures in the form of open folds with subhorizontal axial planes (Fig. 4b).

Kopaonik Oligocene granite intrusion and core complex formation can be best traced in the Jaram section. In this field stop, contactly metamorphosed calcschists, forming scarn can be observed. These rocks expose both older deformations related to the Cretaceous–Paleogene tectonic processes, as well as younger extension, related to the Oligocene–Miocene formation of the Kopaonik Mt. granite and core complex that exhumed both the granite body and the surrounding metamorphic complex.

3.3 Studenica Series

Coordinates: 20°32' E, 43°28' N (Studenica Monastery section); 20°24' E, 43°29' N (Mlanča village section)

The Studenica Metamorphic Series occupies the Studenica River valley and is exposed as a window beneath the Western Ophiolitic Unit. Lithologies span from lower-greenschist-facies calcschists in the southern sector to biotite-garnet schists and amphibolites of amphibolite facies within the main Studenica River valley (Schefer et al., 2010). Except for the southernmost exposure adjacent to Gradac section, metamorphic intensities in the Studenica Series are generally higher than those recorded in the eastward Kopaonik Metamorphic Series. Structural indicators such as sigma clasts and shear bands record a sinistral sense of shear consistent with top-N transport.

The visited outcrop comprises the lower segment of the Studenica series. It is characterized by a thick, multiply deformed volcano-sedimentary succession (Dimitrijević, 1997). In the field and in

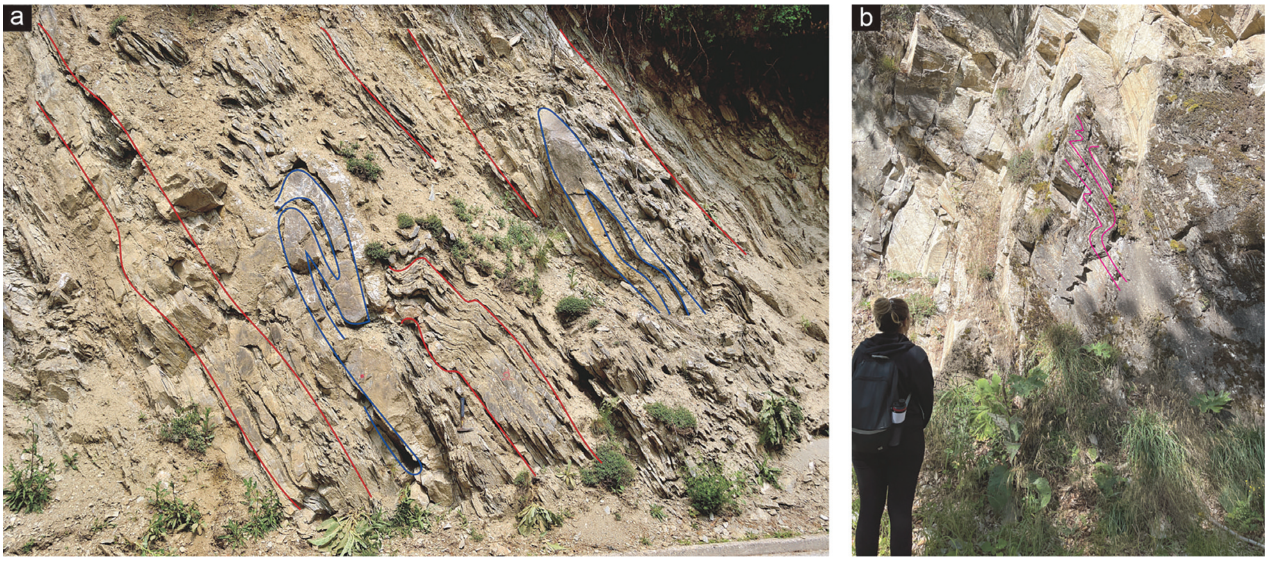

Fig. 4. ***a)*** *Kopaonik Metamorphic Series, exposes folds of D2 (isoclinal folds, blue lines) and D3 deformational phases (red lines), related to the Late Cretaceous–Paleogene tectonic phases. Hammer for scale;* ***b)*** *Kopaonik Metamorphic Series, exposes folds of D4 deformational phase in the form of open folds with subhorizontal axial planes. This deformational phase is related to Miocene extension, that exhumed Kopaonik Mts. granite and surrounding metamorphic rocks.*

thin section, these lithologies comprise high-grade quartz–albite-biotite schists and associated volcano–sedimentary greenschists. The thin section displays a highly penetrative, planar regional schistosity and strong mineral lineation. This micro-structural fabric is defined by the strict parallel alignment of fine-grained phyllosilicates (predominantly biotite, muscovite, and chlorite) alternating with dynamically recrystallized, elongated quartz and albite aggregates.

Figure 5 (top) integrates U–Pb detrital zircon age profiling with corresponding εHf isotope values. The Kernel Density Estimation (KDE) plot is dominated by a massive Devonian peak ranging between 370–400 Ma, tracking Eo–Variscan magmatism. Crucially, the εHf isotope values for this population exhibit an extraordinary vertical spread, spanning from strongly positive, juvenile mantle signatures (+5 to +12) down to deeply unradiogenic, ancient crustal values (–5 to under –15). Additionally, the spectrum preserves a classic, continuous peri-Gondwanan signature with a prominent Neoproterozoic to Ediacaran (Cadomian axis, ~550–650 Ma) baseline, anchored by ancient Proterozoic and Archean inherited cores.

The absence of younger Mesozoic (Alpine) zircons within the lower Studenica series confirms that the primary volcano-sedimentary architecture of the Studenica basin is fundamentally Paleozoic. Geodynamically, this distinct Devonian magmatic and sedimentary signature records the massive rifting of the northern Gondwanan margin during the birth and evolution of the Paleo-Tethys Ocean. This is mainly supported by the extreme vertical bimodal split in the Devonian εHf data, coupled with the heavy influx of ancient Cadomian basement zircons, which track the progressive maturity and propagation of a continental rift: early-stage stretching accommodated swift conduit ascent of primitive, mantle-derived melts (yielding positive εHf values). However, as rifting propagated and intensified, massive basaltic underplating introduced a considerable thermal anomaly into the deep lower crust, driving widespread anatexis and remelting of the old Gondwanan foundation (generating deeply negative εHf signatures).

3.4 Drina–Ivanjica Element

Coordinates: 20°15’ E, 43°33’ N (Ivanjica section)

The Drina–Ivanjica thrust sheet constitutes the second tectonic unit that carries obducted ophiolites and their subjacent mélanges. Unlike other Di-

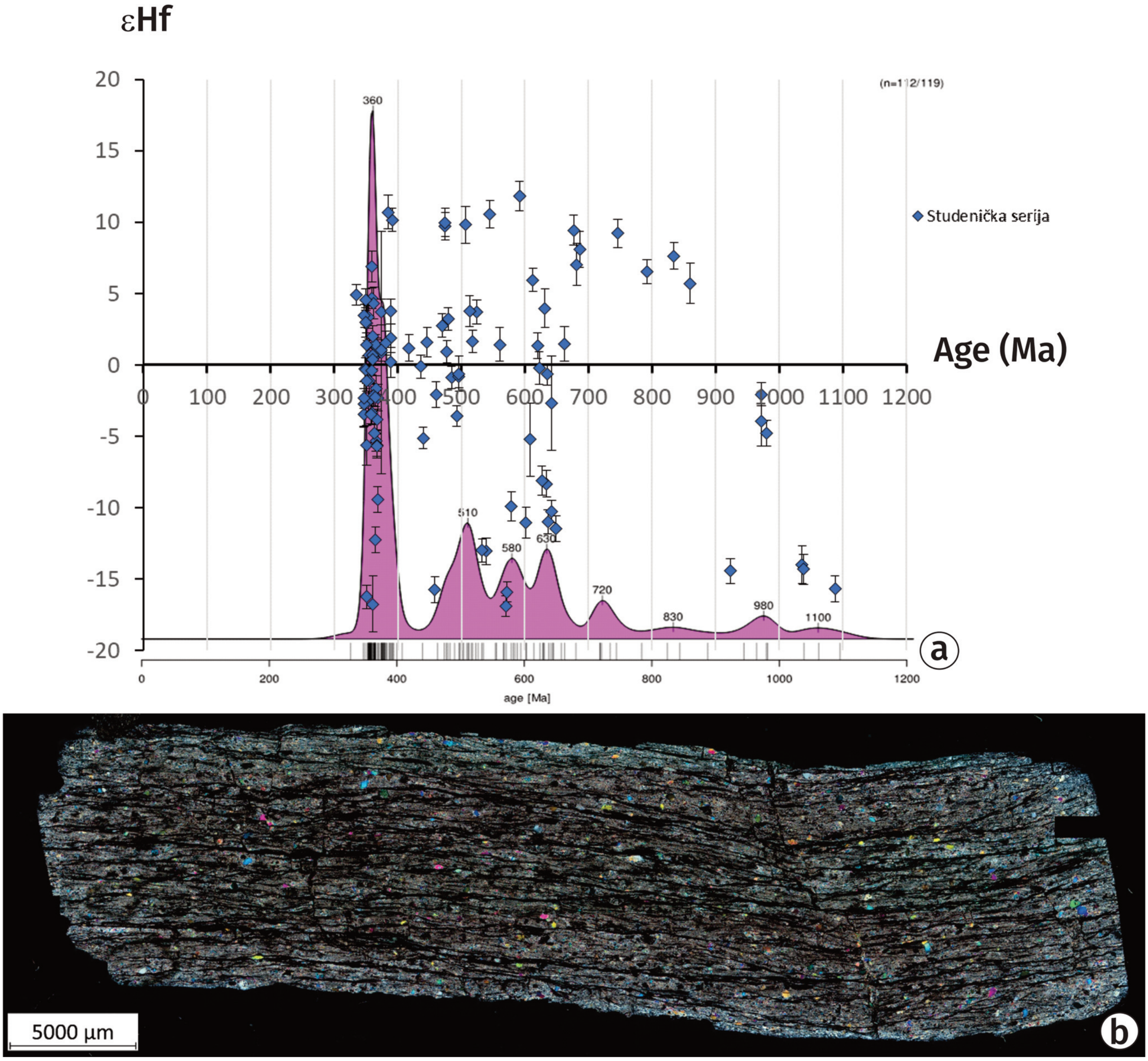

Fig. 5. *Isotopic datasets and petrology of the Lower Studenica Series (Studenička Serija), Central Serbia (Prelević et al., in preparation).* ***a)*** *Integrated detrital zircon U–Pb age Kernel Density Estimation (KDE) diagram paired with a corresponding εHf isotope scatter diagram. The high-amplitude Devonian Eo-Variscan (~370–400 Ma) peak features an extreme vertical spread of εHf values (from +12 down to -15). This bimodal split, records simultaneous asthenospheric mantle upwelling and deep crustal anatexis driven by the thermal propagation of an intracontinental rift most probably linked to the opening of the Paleo-Tethys.* ***b)*** *High-resolution optical scans (cross-polarized light) of a quartz-albite-biotite schist thin section from the sampled outcrop (5000 µm scale bars). The microstructures reveal total metamorphic recrystallization under quartz-albite-biotite greenschist-facies conditions (note, due to higher thin-section thickness, Q grains are with the higher interference).*

naric tectonic units, this thrust sheet was already emplaced in the Early Cretaceous, as indicated by the absence of post-Jurassic strata in the footwall of its basal thrust (Schmid et al., 2020). In the Zlatibor region, the frontal basal thrust locally ramps into previously obducted ophiolites of the underlying East Bosnia–Durmitor nappe, producing a duplication of ophiolitic units (Schmid et al., 2020). A detailed structural and geochronological transect across the Drina–Ivanjica sheet (Porkolab et al., 2019) identifies an early deformational phase characterized by WNW-facing isoclinal folds formed under anchizonal metamorphic conditions, dated to ~150–135 Ma (Tithonian–Valanginian). Since this event is synchronous and kinematically consistent with W-directed obduction of the Western Vardar ophiolites, it records syn-obduction thrusting that likely accompanied emplacement of the entire Drina–Ivanjica sheet over the East Bosnian–Durmitor thrust sheet.

The pre-Mesozoic basement of the Drina–Ivanjica thrust sheet comprises Gondwana-derived Neoproterozoic–Cambrian crystalline rocks overlain by a Carboniferous clastic succession (Spahić et al., 2018).

4. Dinaric ophiolitic belt and its metamorphic soles

The Dinaric ophiolitic belt represents the westernmost stretch of the Balkan ophiolite belt. Related massifs further west in Bosnia (e.g., Krivaja–Konjuh) occupy the same structural domain. Locally the Dinaric ophiolites reach ~3 km of thickness but more commonly occurs as a much thinner ophiolitic slice (Pamić, 2002). Lherzolite dominates, with subordinate harzburgite; dunite and pyroxenite are rare. Serpentinization is generally weak but intensifies toward margins, and listwaenite also occurs at some sites. Typical lherzolites contain olivine, orthopyroxene, clinopyroxene and brown to brown-yellow, Al-rich spinel. Secondary phases are mainly serpentine, with rare talc and chlorite. Locally, peridotites rest on metamorphic sole rocks, commonly amphibolites.

During the late Early Cretaceous into the earliest Late Cretaceous, the ultramafics underwent intense weathering (lateritization), producing weathering profiles above many exposures. These profiles show limonite near the surface grading downward into smectitic horizons, then serpentinite and unaltered lherzolite with magnesite. Locally economically significant Fe-rich bauxite deposits formed atop these peridotites.

Following early observations of key locations in the Balkans (e.g. Brezovica Mt.), studies of metamorphic soles beneath Dinaric ophiolites provide key tools for constraining ophiolite emplacement and reconstructing Tethyan paleogeography. Historical work in the region documented inverted metamorphic aureoles beneath peridotite bodies (Lanphere et al., 1975; Karamata & Lovrić, 1978). This is also a situation that can be observed across Western Serbia. High-temperature, high-pressure fabrics record the exact moment when hot, young oceanic slabs obducted onto the adjacent oceanic crust.

4.1 Amphibolites of the metamorphic sole beneath the Zlatibor massif

Coordinates: 19°45’ E, 43°43’ N

Beneath the Zlatibor ultramafic body, a metamorphic sole sequence is preserved, ranging from amphibolite- to greenschist-facies, locally grading into weakly sheared, unmetamorphosed protoliths derived from underlying olistostrome mélange. Amphibolites are best exposed in this area; parts of the full succession are detached or concealed. Regional kinematic indicators consistently record top-WSW transport.

The amphibolites consist of green hornblende, plagioclase (up to ~50% An), epidote and minor clinopyroxene (3–7% jadeitic component). P–T estimates indicate peak conditions of ≈620–650°C and ~3–4 kbar. Geochemical data indicate a MORB-type basalt protolith, and K-Ar dating of metamorphic hornblende yields 160 ± 8 Ma, implying obduction of the hot ultramafic slab onto the olistostrome mélange in the late Middle Jurassic (Srećković-Batoćanin et al., 2012).

4.2 Olistoliths within the Bistrica ophiolitic mélange

Coordinates: 19°36’ E, 43°30’ N

Toward Bistrica two olistoliths, one basaltic and one limestone, sit within a silty-clayey matrix. The matrix contains centimetre- to metre-scale elongated or rounded sandstone fragments, characteristic of the Diabase–Chert Formation in Serbia.

The basaltic olistolith consists of unsorted subangular to subrounded basalt fragments (cm to ~1 m) in a fine hyaloclastic matrix, yielding an open-framework fabric. The matrix is heavily altered (chlorite, calcite), although relicts of glass shards from chilled margins are preserved. Geochemically, the basalt differs from typical Dinaridic pillow basalts, showing a more OIB-like signature.

A ~30 m long, ~10 m high and 3–4 m thick olistolith of Triassic Bódvalenke-type red bedded cherty limestone crops out nearby. This unit, known from Darno and Szarvaskó ophiolite complexes in Hungary and widespread in Othrys and North Pindos ophiolites in Greece, represents another feature linking Vardar-zone mélanges with broader Mediterranean ophiolitic suites.

4.3 Ultramafic and metamorphic series of Bistrica

Coordinates: 19°38’ E, 43°29’ N

Long alternations of ultramafic and metamorphic rock exposures (hundreds of meters to kilometers) occur along the road to Bistrica, where tectonic contacts and kinematic indicators consistently record top-WNW transport.

Peridotites are tectonized lherzolites with occasional dunite lenses from meters to ~100 m thickness; rare centimetre- to decimetre-scale garnet–pyroxenite veins are present. Peridotite foliation, defined by elongated orthopyroxene and olivine porphyroclasts, trends NNW–SSE and dips towards SE.

Corundum- and pargasite-bearing amphibolites occur as blocks tectonically juxtaposed against ultramafics, and alternate with garnet amphibolites. Textures are dominantly nematoblastic with local granoblastic and rare porphyroblastic domains.

The metamorphic rocks of the Bistrica location outcrop repeatedly along the road Priboj–Bistrica. Their origin is uncertain but together with large serpentinite and pillow-lava blocks, they likely represent kilometre-sized metamorphosed olistoliths, whose relationships with the surrounding matrix are often obscured. These rocks completely lack magmatic relics due to total metamorphic recrystallization, but preserve retrograde greenschist-facies overprints (chlorite, prehnite) from exhumation.

Eclogites (Eclogite-like / Garnet–Clinopyroxenites) are medium- to coarse-crystalline, composed primarily of fractured garnet porphyroblasts with brown kelyphyric rims and grayish–greenish xenoblastic clinopyroxene. They feature no preferred orientation or foliation.

Garnet-Amphibolites are medium to coarse-crystalline. Mineral assembly includes large, fractured garnet porphyroblasts (up to 7 mm), clinopyroxene, dark green/brown amphibole, and weathered plagioclase. Unlike eclogites, they display a distinct lineation and preferred mineral orientation.

Amphibolites consist of well-preserved subidioblastic amphibole with characteristic cleavages, small plagioclase grains with multiple twinning, and slightly weathered clinopyroxene. They exhibit clear structural lineation.

Trace element discrimination plots (Floyd & Winchester, 1975) classify the igneous protoliths of all three rock types as subalkaline basic basalts, originally derived from cumulate gabbros and diabase dolerites. However, they represent two distinct geodynamic environments, potentially due to different protolith ages (Prelević et al., in preparation) (Table 1).

Table 1. *Geochemical characteristics of metamorphic rocks from the Bistrica area.*

Rock Type	Geochemical Affinity	Key Chemical Signatures	Protolith Age
Eclogites	N-MORB (Subduction-unrelated)	Depleted LREE over HREE; negative Eu anomaly (plagioclase fractionation); negative Zr anomaly.	Middle/Late Triassic to Early Jurassic ?
Amphibolites & Garnet-Amphibolites	Island Arc / SSZ (Subduction-related)	Enriched in LILE (Cs, Rb, Ba, K, Sr, Pb); positive Eu anomaly (plagioclase accumulation); strongly depleted in HFSE (Nb, Zr).	Early Jurassic ?

Synkinematic and postkinematic pargasite growth can be distinguished *microscopically*, while corundum occurs as fine pink–violet aggregates.

Thermodynamic calculations define following metamorphic conditions (Srećković-Batoćanin et al., 2012): Eclogite Facies (Eclogites) P: 8–9 kBar, T: 750°C, Depth: ~33 km; Granulite Facies (Garnet–Amphibolites) P: 8–9 kBar, T: 600–670°C, Depth: ~33 km; Amphibolite Facies (Amphibolites), T: 500–600°C.

Geochronological Constraints on Ophiolite Emplacement: U–Pb Zircon and Apatite Data

High-precision U–Pb geochronology has been applied to both highly refractory minerals (zircon) and lower-closure-temperature systems (apatite) collected from the metamorphic soles of the Bistrica and Zlatibor regions (Fig. 6) (Prelević et al., in preparation). The combination of these two distinct geochronometers offers a powerful, high-resolution record of the rate of intra-oceanic subduction, metamorphic sole formation, and subsequent rapid tectonic cooling during obduction. Zircon exhibits an exceptionally high closure temperature (>900 °C) for U–Pb diffusion. When isolated from metamorphosed mafic rocks within the metamorphic sole, these zircon grains directly date either the age of magmatic production of the oceanic crust, or peak metamorphic crystallization.

P–T estimates for the Zlatibor amphibolites indicate relatively low-temperature peak metamorphic conditions and pressures. Because these metamorphic temperatures never reached the threshold required for zircon resetting or new metamorphic growth, the robust Middle Jurassic concordia age of 165 Ma (Callovian) records the magmatic crystallization age of the oceanic crust. Combined with a diagnostic MORB-type basalt geochemical signature, this age directly dates the active spreading phase of this branch of the Neotethys ocean shortly before its destruction.

In contrast to zircon, apatite has a significantly lower U – Pb closure temperature, typically ranging between 350 and 550°C, depending on grain size and local cooling rates (Cherniak et al., 1991). Furthermore, apatite incorporates substantial common lead during growth, creating the diagnostic linear mixing trend observed on the Tera–Wasserburg diagram, where the regression line projects from the common-Pb composition on the y-axis down to the lower intercept on the concordia curve (Fig. 6). Nevertheless, rather than dating peak metamorphism, this apatite lower intercept records the tim-

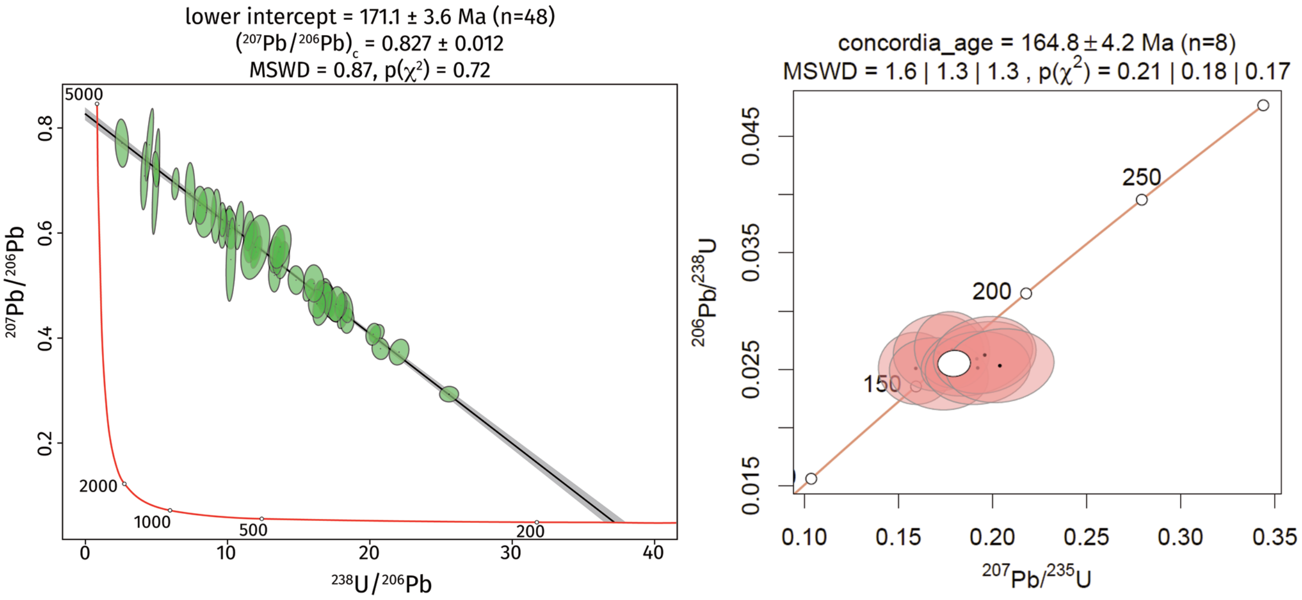

Fig. 6*. U–Pb radioisotopic dating plots from the metamorphic soles of Western Serbia (Prelević et al., in preparation). Left (Bistrica): Tera–Wasserburg concordia diagram $^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$ displaying apatite U–Pb measurements. The steep linear array reflects a strong mixture with common Pb, anchoring a well-defined lower-intercept age. Right (Zlatibor): Wetherill concordia diagram $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ displaying laser ablation ICP–MS zircon data yielding a robust Middle Jurassic concordia age of 164.8 Ma (Prelević et al., in preparation).*

ing of cooling below the closure temperature during the tectonic exhumation of the sole.

Assuming the metamorphic soles from both localities as coeval products of a single-stage tectonic emplacement places important constraints on their evolution. The close overlap between the apatite cooling age and the ~165 Ma zircon peak metamorphic age reveals extremely rapid, single-stage cooling. This brief duration proves that the metamorphic sole escaped prolonged storage at deep structural levels within the subduction channel. Rather, immediately following intra-oceanic crust-producing event (zircon U–Pb crystallization age in Zlatibor), the entire ophiolitic slice was rapidly transported upward and thrust onto the cooler Adriatic oceanic crust, as being recorded by apatite from Bistrica amphibolite.

Acknowledgement

This study is financed by the Science Fund of the Republic of Serbia, through project RECON TETHYS (7744807) and by the Ministry of Science, Technological Development and Innovations of the Republic of Serbia through a contract 451-03-33/2026-03/200126. Constructive and helpful comments of Duje Smirčić, and editorial handling of Nevenka Đerić improved this manuscript.

References

Bortolotti, V., Chairi, 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? *International Journal of Earth Sciences*, 102: 711–738.

Božović, M. 2013. *Petrology and Geochemistry of the Balkan ophiolites*. Johannes Gutenberg University Mainz, PhD Thesis, 254 pp.

Cherniak, D. J., Lanford, W. A. & Ryerson, F. J. 1991. Lead diffusion in apatite and zircon using ion implantation and Rutherford Backscattering techniques. *Geochimica et Cosmochimica Acta*, 55: 1663–1673.

Csontos, L. & Vörös, A. 2004. Mesozoic plate tectonic reconstruction of the Carpathian region. Palaeogeography, Palaeoclimatology, Palaeoecology 210: 1–56.

Dimitrijević, M.D. 1997. *Geology of Yugoslavia*. Belgrade: Barex.

Dimitrijević, M.D. 2001. Dinarides and the Vardar Zone: a short review of the geology. *Acta Vulcanologica*, 13: 1–8.

Dimitrijević, M.D. & Dimitrijević, M.N. 1976. The polyphase melange of the Vardar Zone. *Bulletin de la Societe Geologique de France*, S7-XVIII: 205–208.

Djerić, N., Gawlick, H.-J. & Sudar, M. 2024. The Jurassic ophiolitic mélanges in Serbia – a review and new insights. In: Festa, A., Dilek, Y. & Barbero, E. (Eds.). *Significance of ophiolites, mélanges and blueschist assemblages in probing the crustal anatomy and geodynamic evolution of orogenic belts*. Geological Society, London, Special Publications, 181 (2).

Floyd, P.A. & Winchester, J.A. 1975. Magma Type and Tectonic Setting Discrimination Using Immobile Elements. *Earth and Planetary Science Letters*, 27: 211–218.

Gallhofer, D., Quadt, A. v., Peytcheva, I., Schmid, S.M. & Heinrich, C.A. 2015. Tectonic, magmatic, and metallogenic evolution of the Late Cretaceous arc in the Carpathian–Balkan orogen. *Tectonics*, 34: 1813–1836.

Karamata, S. 2006. The geological development of the Balkan Peninsula related to the approach, collision and compression of Gondwanan and Eurasian units. In: Robertson, A.H.F. & Mountrakis, D. (Eds.). *Tectonic Development of the Eastern Mediterranean Region*. London: Geological Society, London, 155–178.

Karamata, S., Dimitrijević, N.M. & Dimitrijević, D.M. 1999. Oceanic realms in the central part of the Balkan Peninsula during the Mesozoic. *Slovak Geological Magazine*, 5: 173–177.

Karamata, S. & Lovrić, A. 1978. The age of metamorphic rocks of Brezovica and its importance for the explanation of ophiolite emplacement. *Bull. Acad. Serbe Sci. Arts, Classes Sci. Math. Nat., Sci. Nat.*, 17: 1–9.

Lanphere, M.A., Coleman, R.G., Karamata, S. & Pamić, J. 1975. Age of amphibolites associated with alpine peridotites in the Dinaride ophiolite zone, Yugoslavia. *Earth and Planetary Science Letters*, 26: 271–276.

Maleš, M., Stojadinović, U., Randjelović, N., Sokol, K., Xie, J-C. & Prelević, D. 2026. Pre-Alpine thermal evolution of the Juhor Mts., central Serbia (Northern Serbo-Macedonian Sub-unit): Constraints from zircon U-Pb geochronology and Hf isotope geochemistry, submitted for publication.

Marroni, M., Pandolfi, L., Saccani, E. & Zelić, M. 2004. Boninites from the Kopaonik area (Southern Serbia): New evidences for suprasubduction ophiolites in the Vardar zone. *Ofioliti*, 29: 251–254.

Pamić, J. 2002. The Sava–Vardar zone of the Dinarides and Hellenides versus the Vardar Ocean. *Eclogae Geologicae Helvetiae*, 95: 99–114.

Prelević, D., Wehrheim, S., Reutter, S., Romer, R.L., Boev, B., Božović, M., van den Bogaard, P., Cvetković, V. & Schmid, S.M. 2017. The Late Cretaceous Klepa basalts in Macedonia (FYROM): Constraints on the final stage of Tethys closure in the Balkans. *Terra Nova*, 29: 145–153.

Prelević, D., Mladenović, A., Gajić, V., Sokol, K., Cvetković, V., Radisavljević, M. & Lowe, G. A first attempt at zircon provenance study of the Central Balkan terrains: Implications for the pre-Alpine evolution of the critical suture zone, in preparation.

Robertson, A.H.F. & Karamata, S. 1994. The role of subduction-accretion processes in the tectonic evolution of the Mesozoic Tethys in Serbia. *Tectonophysics*, 234: 73–94.

Schefer, S., Egli, D., Missoni, S., Bernoulli, D., Fügenschuh, B., Gawlick, H.-J., Jovanović, D., Krystyn, L., Lein, R., Schmid, S. & Sudar, M. 2010. Triassic metasediments in the internal Dinarides (Kopaonik area, southern Serbia): Stratigraphy, paleogeographic and tectonic significance. *Geologica Carpathica*, 61: 89–109.

Schmid, S., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K. 2008. The Alpine–Carpathian–Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, 101: 139–183.

Schmid, S.M., Fügenschuh, B., Kounov, A., Maţenco, L., Nievergelt, P., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenović, B., Ustaszewski, K. & van Hinsbergen, D.J.J. 2020. Tectonic units of the alpine collision zone between eastern Alps and western Turkey. *Gondwana Research*, 78: 308–374.

Spahić, D., Glavaš-Trbić, B., Đajić, S. & Gaudenyi, T. 2018. Neoproterozoic–Paleozoic evolution of the Drina Formation (Drina–Ivanjica Entity). *Geološki anali Balkanskoga Poluostrva*, 79 (2): 57–68.

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.

Ustaszewski, K., Kounov, A., Schmid, S.M., 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.

Zhang, S.Q., Mahoney, J.J., Mo, X.X., Ghazi, A.M., Milani, L., Crawford, A.J., Guo, T.Y. & Zhao, Z.D. 2005. Evidence for a Widespread Tethyan Upper Mantle with Indian-Ocean- Type Isotopic Characteristics. Journal of Petrology, 46: 829–858.

Manuscript received June 08, 2026
Revised manuscript accepted June 24, 2026