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^{40}Ar/^{39}Ar ages of glaucophane and phengitic muscovite from the Mt. Medvednica blueschists (NW Croatia): Evidence for Middle–Late Jurassic subduction in the northwestern Neotethys

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Abstract: In the northwesternmost part of the Dinarides, which is a part of the southwestern segment of the Zagorje–Mid-Transdanubian Zone within the Mt. Medvednica area, localized occurrences of blueschists with an OIB-type protolith affinity preserve evidence of vestiges of high-pressure, low-temperature metamorphism. New ^{40}Ar/^{39}Ar ages from glaucophane (160.0±1.5 to 164.9±1.0 Ma) and phengitic muscovite (154.4±1.0 Ma), obtained from phengite–ferroglaucophane and glaucophane–Mg-riebeckite schists, constrain the metamorphism to the Middle to Late Jurassic (Callovian to Kimmeridgian). This indicates the formation of the analysed rocks within an accretionary prism above an intra-oceanic subduction zone in the northwestern Neotethys. In a regional context, these data are consistent with a diachronous, northeast-dipping subduction system operating across parts of the western Neotethys. Metamorphic soles in the Dinaridic Ophiolite Belt, dated at 174 to 157 Ma, mark the onset of early hot subduction, whereas Jurassic to Early Cretaceous HP/LT assemblages in Pelagonia and Mt. Fruška Gora record continued convergence and progressive cooling at comparable depths. Coeval HP/LT rocks in the Western Carpathians broadly document comparable subduction depths and thermal gradients farther northeast. Mt. Medvednica occupies a temporally and structurally-intermediate position within this regional framework and preserves the northwesternmost record of Middle to Late Jurassic HP/LT metamorphism in the Dinarides. Together, these observations suggest regionally distributed and diachronous subduction-related processes, with ridge-proximal subduction initiating in the Bajocian, maturing during the Callovian to Kimmeridgian, and progressively shifting southeastward in response to trench retreat across the Dinaridic–Vardar realm.

Keywords: ^{40}Ar/^{39}Ar dating, glaucophane, phengitic muscovite, blueschists, Middle–Late Jurassic subduction, northwestern Neotethys, Mt. Medvednica

Introduction

Metamorphic rocks of the blueschist facies, which are characterized by index minerals, such as glaucophane, lawsonite, jadeite, and aragonite, are exclusively associated with convergent plate boundaries and represent a diagnostic petrological signature of subduction zone environments (Bowes 1989; Bucher & Grapes 2011; Li 2020). The research of metamorphic events recorded in blueschist rocks can thus provide valuable insights into the nature of subduction, as well as the characteristics of collisional and exhumation regimes (Smith et al. 1999; Gao & Klemd 2003; Agard et al. 2009). Moreover, these high-pressure and low-temperature (HP/LT) metamorphic rocks record temporal variations in pressure and temperature and may reflect exhumation processes associated with subduction. The average P–T values for the blueschist facies series of mafic protolith at well-studied subduction localities, such as the Sanbagawa area in Japan and the Franciscan complex in California, vary in the range of HP (~ 0.6–1.4 GPa) and LT (~ 300–500 °C) conditions (e.g., Wakabayashi 1990, 1999; Wakabayashi & Unruh 1995; Li 2020; Pepesch et al. 2025; Tomioka et al. 2025). Therefore, the identification of blueschists can help to draw inferences on the nature and timing of convergence zones, that is, provide evidence for the onset and evolution of subduction-driven plate tectonics (Draper & Lewis 1991; Gao et al. 1995; Palin & White 2016). Pressure increases progressively with depth, whereas a rise in temperature is delayed due to the low thermal conductivity of deep crustal and mantle rocks. The subduction of cold lithosphere thus generates a low geothermal gradient along the plate interface, thereby creating conditions conducive to blueschist formation (Li 2020). Blueschist facies rocks are stable within subduction zones at depths of about 30 to 60 km, and their preservation requires rapid exhumation rates (Li 2020), eventually leading to the development of an orogenic belt (Matsuda & Ueda 1971; Kawai et al. 2007; Agard et al. 2009).

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Therefore, metamorphic units of blueschists, accompanied by ophiolitic mélange, play a crucial role in constraining the evolution of subduction–accretion zones and the collision of orogenic systems.

Within the Alpine–Carpathian–Dinaridic (ACD) orogenic system, blueschist-facies rocks are widely regarded as key markers of Neotethyan subduction processes and record the diachronous closure of multiple oceanic domains along the southern Eurasian margin (Stampfli & Borel 2002; Schmid et al. 2008, 2020; Robertson et al. 2009; Stampfli et al. 2013). In this framework, the Dinaridic and Vardar domains represent segments of a complex Neotethyan realm that formed as a variably segmented oceanic domain. This system is locally expressed as oceanic embayments and marginal basins within the Meliata–Maliac–Vardar system and is characterized by intra-oceanic subduction, ophiolite obduction, and subsequent continental collision, with spatial and temporal variations in metamorphic conditions reflecting evolving subduction dynamics across the region. High-pressure/low-temperature assemblages related to these processes are documented across several segments of the ACD system, including the Meliatic units of the Western Carpathians in Slovakia (e.g., Faryad 1995; Nemec et al. 2020), the Dinaridic domain at Mt. Medvednica and Mt. Fruška Gora (e.g., Milovanović et al. 1995; Belak & Tibljaš 1998), and the Vardar zone in North Macedonia and Northern Greece (e.g., Kostopoulos et al. 2000; Altherr et al. 2023) (Fig. 1). Although these occurrences reflect variable protolith affinities, pressure–temperature conditions, and geodynamic settings, their broadly overlapping Jurassic to Early Cretaceous ages point to spatially distributed and diachronous subduction-related processes in the Neotethyan realm. Blueschist occurrences documented and studied in the Mt. Medvednica area are part of the mountain system of northwestern Croatia situated at the junction of three major geotectonic units: the Southern Alps, the Tisza Continental Block, and the Dinarides (Pamić & Tomljenović 1998; Fig. 1). The geology of Mt. Medvednica is characterized by the juxtaposition of Paleozoic and Mesozoic Alpine–Dinaridic lithologies. According to the tectonic framework proposed by Schmid et al. (2008, 2020), its northwestern part belongs to the Western Vardar Ophiolitic Unit, represented by an ophiolitic mélange, whereas the southeastern slopes form part of the Bükk–Jadar–Kopaonik Unit (Fig. 1). The latter consists of a Paleozoic to Triassic metamorphic complex (Belak et al. 1995; Belak 2005; Fig. 2A, B) whose potential protolith successions may have been represented by ophiolitic mélange rocks (Belak et al. 2022). These pre-Neogene tectonostratigraphic and tectonometamorphic units record a complex geodynamic evolution of the northwestern Dinaridic branch of the Neotethys, involving extension and the formation of oceanic lithosphere during the Middle Triassic to Middle Jurassic, followed by intra-oceanic subduction in the late Middle to Late Jurassic (Slovenec & Šegvić 2024).

Although Belak & Tibljaš (1998) proposed that the high-pressure glaucophane-bearing schists in the northeastern part of Mt. Medvednica formed during Middle Jurassic oceanic subduction, their exact age has not been determined. The aim of this study is, therefore, to constrain the timing of metamorphism of the Mt. Medvednica blueschists using new $^{40}Ar/^{39}Ar$ data, as well as evaluate their geodynamic significance in the northwestern segment of the Neotethyan realm. In this sense, the newly obtained age constraints provide a basis for discussing the temporal framework of subduction-related processes in the Dinaridic domain rather than establish a comprehensive petrogenetic or tectonic reconstruction.

Geological outline

According to Pamić & Tomljenović (1998), Mt. Medvednica represents the integral southwestern segment of the paleogeographic unit known as the Zagorje–Mid-Transdanubian Zone (ZMTDZ; Fig. 1). In the regional geology context, the ZMTDZ may correspond to the Gemer–Bükk subunit, which is located in the southern part of the Alpine–Carpathian–Pannonian (ALCAPA; Fig. 1) block of the Intra-Carpathian Area (ICA) (Harangi et al. 1996). This suture zone is defined by two regional fault zones: the Zagreb–Zemplin fault in the south and the Periadriatic–Balaton fault in the north. This particular zone has a width of approximately 100 km and a length of 400 km, extending toward the northeast (Fig. 1). It is chararacterized by pre-Neogene heterogenous, superimposed Dinaric and Alpine tectonostratigraphic and tectonometamorphic units of still debated origin (e.g., Tari & Pamić 1998; Haas et al. 2000; Pamić 2002).

Mt. Medvednica is composed of tectonically disturbed rocks of both continental and oceanic provenance, which are subdivided into several tectonostratigraphic units (Fig. 2A–C): (1) The low-grade Paleozoic–Triassic metamorphic complex, which underwent its final metamorphic overprint in the Early Cretaceous (Belak et al. 1995, 2022; Belak 2005; Lugović et al. 2006; Borojević-Šoštarić 2012; Mišur et al. 2023); (2) The Middle–Upper Jurassic(?) Drenova Unit (Belak & Tibljaš 1998; Belak 2005); (3) The Triassic clastic and carbonate sedimentary rocks (Šikić et al. 1978, 1979); (4) Triassic carbonate of the Sava nappe; (5) The Jurassic ophiolite mélange, also known as the Repno Complex (Babić et al. 2002; Slovenec & Pamić 2002); (6) Uppermost Jurassic–Lower Cretaceous flysch-type deposits (Oštrc Formation; Zupanič et al. 1981); (7) Albian–Cenomanian clastic and carbonate sedimentary rocks (Šikić et al. 1978; Crnjaković 1979); (8) Upper Cretaceous–Paleocene clastics and Scaglia type limestone (Šikić et al. 1978, 1979; Crnjaković 1979; Pavelić et al. 1995) and (9) Miocene–Quaternary sediments (Pavelić et al. 2024). The most widespread low-pressure Paleozoic–Triassic metamorphic complex, which outcrops in the central and southwestern parts of Mt. Medvednica, is thrust over the Jurassic ophiolitic mélange (Fig. 2A). However, in the northeastern part of Mt. Medvednica (Zelinska gora), rocks of the Drenova Unit are found in the broader Žitomir–Plešivica area (Belak 2005; Fig. 2A–C). The rocks of this unit are in tectonic thrust contact with Triassic strata on both

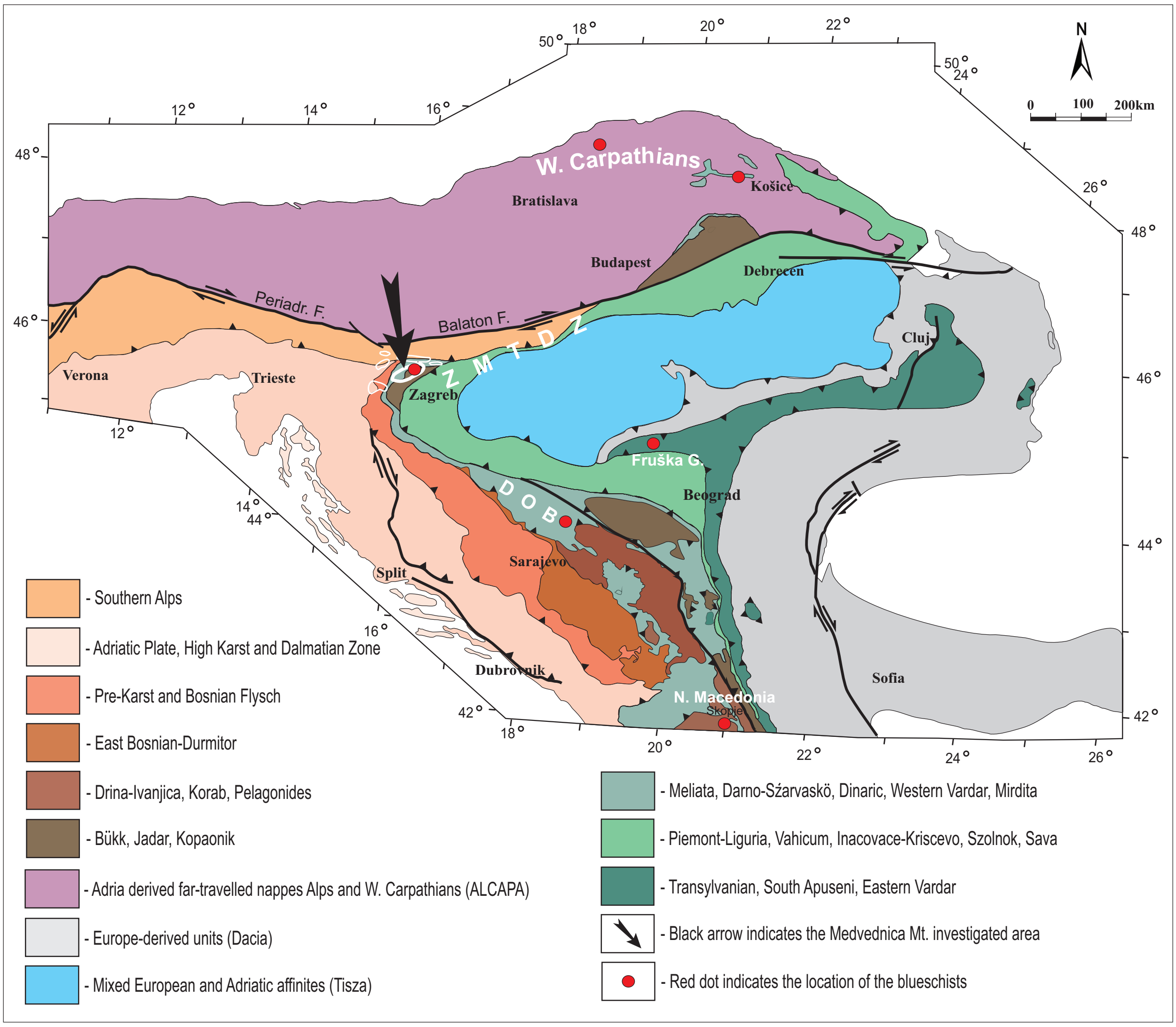

Fig. 1. Geotectonic sketch map of the major tectonic units (simplified after Schmid et al. 2008, 2020). Legend: DOZ = Dinaridic Ophiolite Belt; ZMTDZ = Zagorje–Mid-Transdanubian-Zone

the northwestern and southeastern sides, while in the eastern parts, they are unconformably overlain by Upper Cretaceous and Tertiary deposits. Lithologically, the rocks of this unit differ clearly from the other low-grade metamorphic lithostratigraphic units of Mt. Medvednica. The Drenova Unit is predominantly composed of light-gray, massive to thick-bedded marble and various types of carbonate schist that differ in the modal proportions of chlorite, micas, and other silicates. Subordinate occurrences include serpentinized peridotite and amphibolite, as well as sericite–glaucophane schist (blueschist) and dark metapsammitic to metapelitic rocks (phengite–chloritoid schist) (Belak & Tibljaš 1998; Belak 2005). The blueschists that were investigated in this study occur in several facies types (Belak 2005; Fig. 2C): phengite–paragonite–jadeite–aegirine–ferroglaucophane schist, phengite–paragonite–jadeite–ferroglaucophane–glaucophane schist, glaucophane–Mg-ribeckite (“glaucophanite”) and garnet (spessartine)–Mg-ribeckite (crossite) schist. Detrital grains of glaucophane have also been identified in Miocene sedimentary rocks from the broader Mt. Medvednica area (Mutić & Dmitrović 1991), which unconformably overlie the rocks of the Drenova Unit (Fig. 2A, B), as well as in Upper Cretaceous sediments transgressive to the Drenova unit (Fig. 2B, C) (Belak 2005). Blueschists are quite rare in Croatia, yet similar lithologies have been reported from the Dinarides (Eastern Bosnia and Herzegovina), the Western Carpathians (Slovakia), and the Fruška Gora area in Northern Serbia (Fig. 1).

Materials and analytical techniques

Description of analysed samples

The analysed representative samples of blueschist rocks were collected during the geological mapping of the Republic of Croatia at a scale of 1:50,000 as well as in the course of

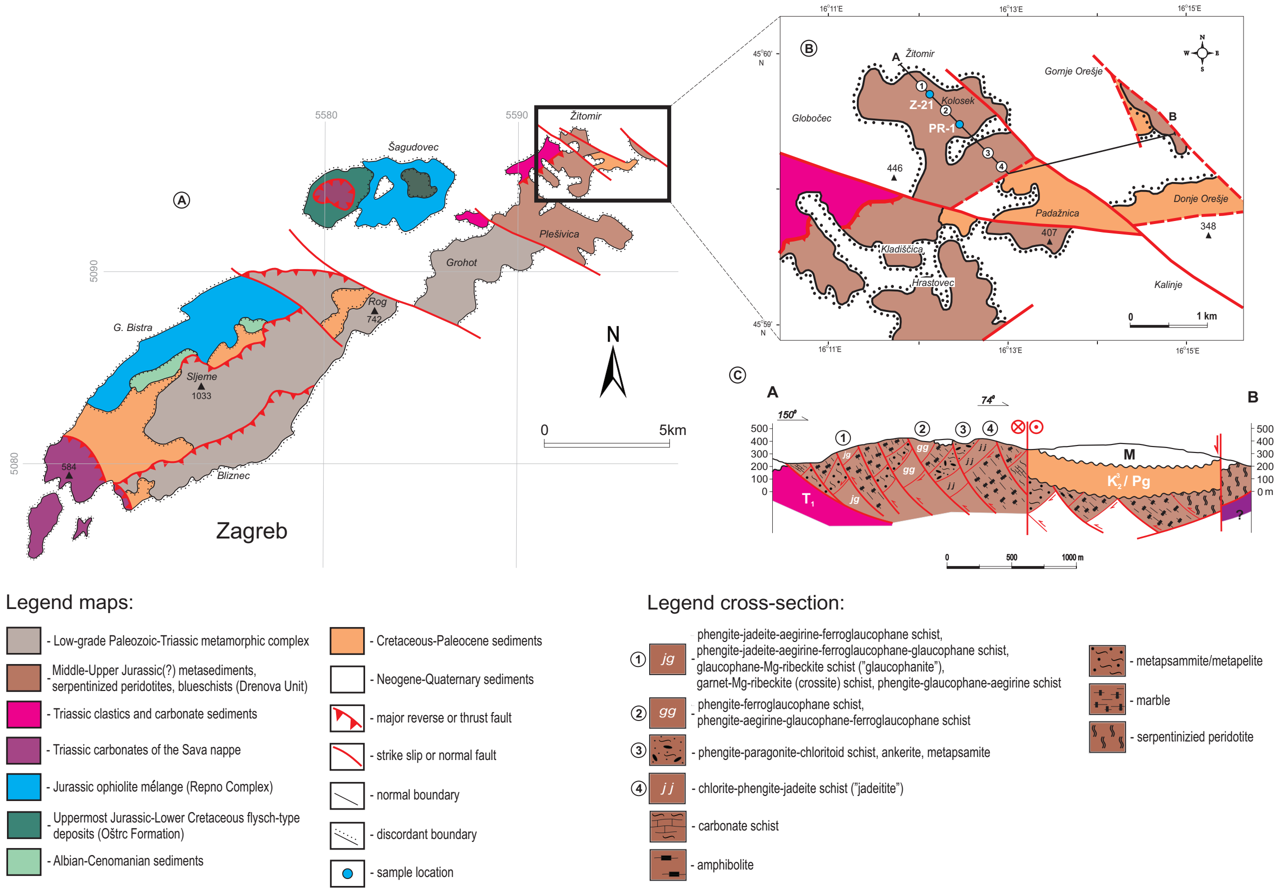

Fig. 2. (A) Simpflied geological sketch map of the Mt. Medvednica (modified after Šikić et al. 1978; Basch 1981; Belak 2005). **(B)** Detail of simplified geological map and **(C)** cross-section of the eastern part of Mt. Medvednica (after Belak 2005).

the first author's doctoral research. Petrographic examinations of minerals and rocks from the blueschist assemblage were carried out on more than 50 samples, of which 13 were selected for further mineralogical and chemical analyses (Belak 2005). From this set, two representative samples (PR-1 and Z-21; Fig. 2B) were selected for ^{40}Ar/^{39}Ar isotopic dating.

Sample PR-1 is a phengite–ferroglaucophane schist of lepidonematoblastic texture and a weak schistose structure (Fig. 3A). In addition to the major mineral phases (phengitic muscovite and ferroglaucophane), the rock contains a range of accessory minerals, including Ti-ferroglaucophane, Ti-riebeckite, riebeckite, albite, quartz, chlorite, pumpellyite, tourmaline, titanite, hematite, magnetite, ilmenite, and calcite. Amphiboles of prismatic habit, 0.2–0.3 mm in size (rarely up to 0.8 mm), contain a riebeckitic component and preserve both prograde metamorphic sequences. The cores are generally richer in the riebeckitic component, whereas the rims are dominated by the ferroglaucophane component (Belak 2005). In the rock matrix, as well as along the cleavage planes, flakes of phengitic muscovite occur, whereas tourmaline forms small porphyroblasts. Pumpellyite fills leucocratic veinlets and forms irregular nests associated mainly with albite and quartz.

Sample Z-21 is a glaucophane–Mg-riebeckite schist (glaucophanite) of non-blastic structure and schistose texture (Fig. 3B). Microstructural analysis revealed two deformation phases: (i) a continuous S_1 cleavage (slaty cleavage), where amphiboles are oriented subparallel to the stretching lineation, and (ii) a crenulation cleavage S_2, an overprint on the continuous (slaty) cleavage that represents the metamorphic peak. At the tips of crenulation microlithons ("boudins"), amphiboles grow perpendicular to S_1, i.e., perpendicular to the reoriented stress field. Amphiboles of prismatic habit, up to 0.5 mm in size, are the only significant rock-forming constituents (modal composition up to 95 vol.%). Their cores are of Mg-riebeckite composition, whereas the rims are glaucophane (Fig. 3 C, D), thereby indicating a prograde metamorphic trend (Belak 2005). Accessory minerals include pyroxenes (aegirine ±aegirine–augite), quartz, and calcite.

Analytical procedure

^{40}Ar/^{39}Ar analysis was performed at the Institute of Geosciences of the University of Heidelberg, Germany. The amphibole (glaucophane) and white mica (phengitic muscovite),

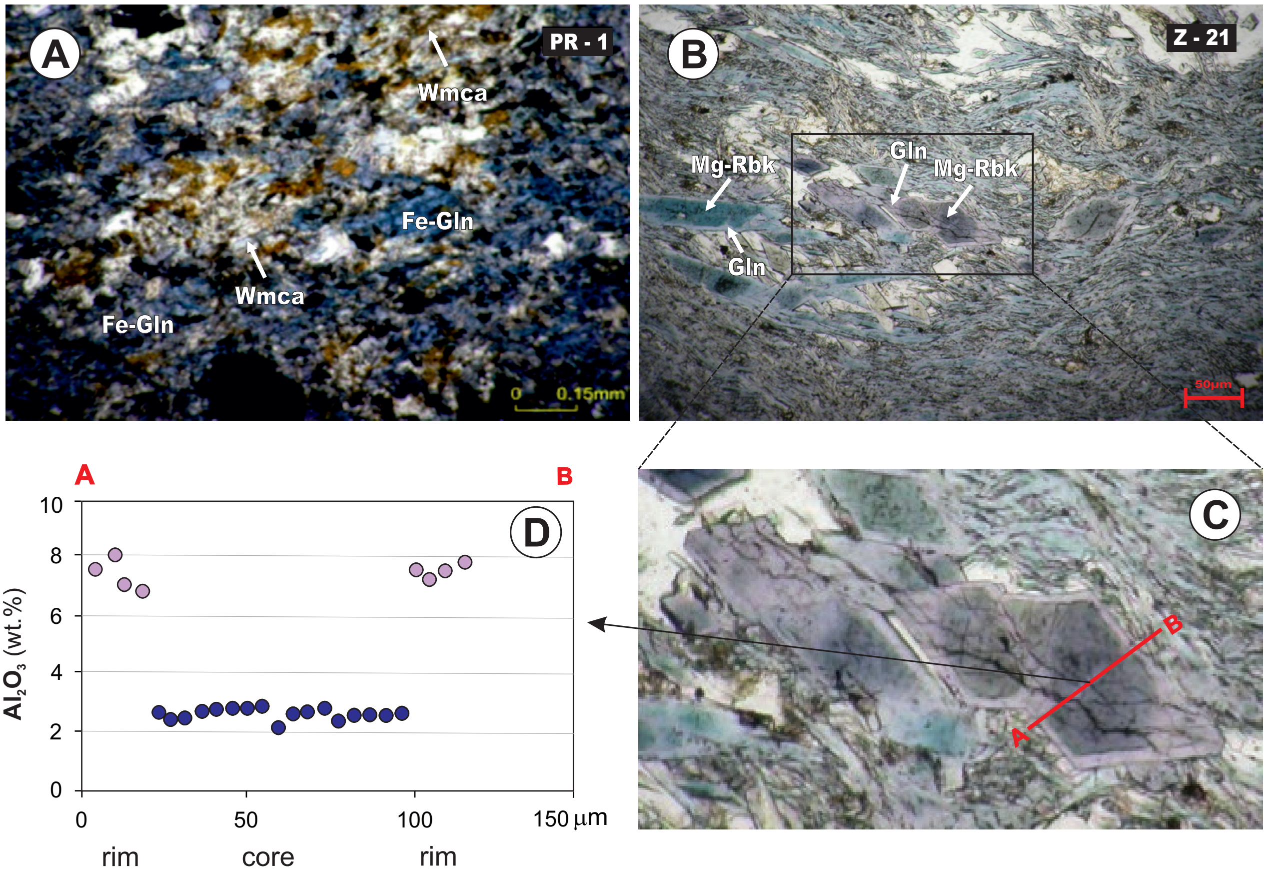

Fig. 3. (A, B) Microphotographs of thin sections of blueschist - metabasalt (N+), **(C)** microphotographs of zonal amphibole (sample Z-21) from the Mt. Medvednica metamorphic complex. Mineral abbreviations after Kretz (1983): Gln=glaucophane, Fe-Gln=Fe-glaucophane, Mg-Rbk=Mg-riebeckite, Wmca=white mica. **(D)** Chemical profile of a progradational zonal amphibole (sample Z-21). The grain core is Mg-ribekite, and the rims are glaucophane.

separated from two blueschist samples (PR-1 and Z-21), were prepared by conventional mineral separation techniques (cracking, sieving, magnetic and heavy liquid separation) and hand picked under a stereomicroscope.

All samples were irradiated at the Portugese Research Reactor (RPI) in Bobadela, Portugal. The samples were shielded from thermal neutrons by Cd-foil to avoid irradiation interferences by slow neutrons and rotated during irradiation in order to mitigate the effects of lateral flux gradients. The vertical flux gradient was monitored by BMus/2 fluence monitors (t=328.5±1.1 Ma (1σ) Schwarz & Trieloff 2007). A CaF_2 standard and a degassed sanidine glass were co-irradiated to determine Ar from isotopic interference reactions on Ca and K, yielding $(^{36}Ar/^{37}Ar)_{Ca}=(3.0\pm1.6)\cdot10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca}=(7.9\pm0.1)\cdot10^{-4}$, $(^{38}Ar/^{39}Ar)_K=(1.2\pm0.1)\cdot10^{-2}$, $(^{40}Ar/^{39}Ar)_K=(1.23\pm0.24)\cdot10^{-2}$, $(^{40}Ar/^{37}Ar)_{Ca}=(3\pm3)\cdot10^{-3}$; the latter value was taken as measured by Turner (1971), assuming the interferences are of the same order of magnitude in different nuclear reactors.

The samples Z-21 glaucophane (grain size: 180–320 µm, weight: 485 mg), PR-1 glaucophane (100–180 µm, 444 mg), as well as PR-1 phengitic muscovite (~50 µm, 23.8 mg) were degassed in variable heating steps between 400 °C and 1400 °C. The gas was purified with Ti- and SAES bulk getters. Furnace blank measurements were carried out in the same manner after each sample with typical ^{40}Ar amounts of 1×10^{-9} cm^3 STP at 1400 °C 5×10^{-10} cm^3 STP at 1200 °C and 1×10^{-10} cm^3 STP at 800 °C. The temperature dependence of the blank was measured after each sample. Gas analyses were performed with a modified CH-5 sector field mass spectrometer routinely used for ^{40}Ar–^{39}Ar dating at the University of Heidelberg. A mass discrimination (usually <0.5 %/amu) and sensitivity were determined with a pipetted Ar-volume at least twice per day. The precision for absolute gas amounts and derived K and Ca concentrations is ~5 %.

All ages (Tables 1–2) were calculated after correcting for mass discrimination, isotopic interferences, blanks, backgrounds, and neutron flux gradient (J-value) using the Steiger & Jäger (1977) conventions. The ^{40}Ar–^{39}Ar ages increase by ca. 0.9 n% (on a time scale of up to 500 Ma) when using the most recently suggested decay constants for ^{40}K (Renne et al. 2010, 2011; Schwarz et al. 2011), which is required when comparing the ^{40}Ar–^{39}Ar data with U–Pb ages. Uncertainties are at 1σ level (unless noted differently) and include the uncertainty of the fluence monitor age (the uncertainty in Tables 1–2 are analytical uncertainties only).

Table 1A: $^{40}Ar/^{39}Ar$ data of amphibole (sample PR-1) from the blueschists of the Mt. Medvednica metamorphic complex.

Step	Temp.	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	Apparent age
				[ccm/g]			±1σ s.d.
	[°C]	[10^{-13}]	[10^{-10}]	[10^{-12}]	[10^{-12}]	[10^{-10}]	[Ma]
1	500	152±8	3±3	4±1	21±1	50±1	48±20
2	550	236±10	4±3	6±1	66±2	86±1	48.0±7.6
3	600	478±16	10±4	13±1	113±3	171±1	51.2±7.9
4	650	303±13	4±3	7±1	69±1	116±1	74±10
5	700	3618±22	14±3	82±2	1497±6	1886±4	104.0±0.9
6	750	1817±15	5±3	40±1	830±4	1099±3	128.0±1.0
7	770	2716±17	9±3	54±1	758±6	1350±3	136.3±1.5
8	790	668±15	16±3	19±1	780±7	853±7	**157.8±1.2**
9	810	629±26	16±3	18±2	1041±6	1082±2	**161.4±1.6**
10	830	334±8	7±3	10±2	1207±8	1113±2	**159.0±1.0**
11	850	485±27	22±4	15±2	1133±10	1094±7	**157.4±1.5**
12	870	1110±32	49±4	30±2	1856±12	1897±9	**158.6±1.1**
13	890	1098±41	58±4	34±3	2455±15	2416±13	**159.8±1.0**
14	910	668±14	16±4	23±4	3376±12	3067±8	**159.41±0.43**
15	930	1245±14	40±4	58±8	7329±18	6624±5	**160.07±0.40**
16	950	1453±83	37±5	53±6	5316±16	4972±5	160.3±0.9
17	970	1723±24	36±4	85±6	5223±26	4958±14	**159.75±0.66**
18	990	987±21	30±6	35±3	1978±12	1958±8	**158.1±0.9**
19	1010	597±32	37±5	19±2	1096±9	1102±7	**158.5±1.8**
20	1050	105±9	4±4	2±1	445±3	411±1	**160.2±1.5**
21	1100	255±17	4±4	7±1	528±7	540±2	164.9±2.5
22	1150	212±15	3±3	7±1	357±3	429±1	190.8±2.5
23	1200	339±22	5±5	15±2	916±8	1078±3	198.1±2.1
24	1300	423±22	8±8	15±2	464±5	764±1	251.9±3.5
Total		21650±130	436±20	653±14	38848±50	39118±28	158.034±0.24

Mass discrimination (measured $^{40}Ar/^{36}Ar=279.9\pm0.2$), argon isotopic abundances corrected for line and furnace blank and nucleogenic interferences $^{40}Ar/^{39}Ar_K=0.015\pm0.004$; $^{38}Ar/^{39}Ar_K=0.018\pm0.002$; $^{36}Ar/^{37}Ar_{Ca}=0.00043\pm0.00002$; $^{39}Ar/^{37}Ar_{Ca}=0.00098\pm0.00003$). J-factor=0.006321±0.000061 (±0.000065) (BMus/2: t=328.5±1.1 Ma, Schwarz & Trieloff 2007).

Results

$^{40}Ar/^{39}Ar$ dating

The two amphibole and the phengitic muscovite samples were degassed with more than 20 steps each (Fig. 4, Tables 1–2). The temperature range at which degassing largely took place for amphibole and phengitic muscovite was around 1000 °C and 800 °C, respectively (Tables 1–2). Step heating diagrams show the step degassing age spectrum marked as "A", and the K/Ca ratio calculated from the $^{37}Ar/^{39}Ar$ ratio for each degassing step for the two amphibole sample is marked as "B" (Fig. 4).

Amphibole extracted from sample PR-1 shows a largely flat spectrum (steps 8–20, 86 % of the ^{39}Ar released) with a total age of 158.0±1.6 Ma and a plateau age of 160.0±1.5 Ma. The first steps could indicate an Ar loss having occurred following the formation of amphibole. On the other hand, the last steps showing higher ages are attributed to another source of Ar present in the sample, which is most likely related to an incomplete degassing during metamorphism (e.g., inherited radiogenic Ar accumulated prior to metamorphism). The K/Ca spectrum is not completely flat, thereby indicating some inhomogeneities of the K and Ca distribution in amphibole or minor inclusions; however, they do not affect the age of the sample.

Amphibole sample Z-21 has a saddle age spectrum with higher ages at the beginning and the end of the degassing, with a total age of 182.3 ±1.7 Ma. The seven steps that form a partial plateau show the same age at 164.9±1.0 Ma (Fig. 4). The spectrum saddle shape likely reflects extraneous Ar, which was possibly inherited or trapped during the formation or metamorphism. The age of the mentioned plateau-shaped seven steps that represent 50 % of the ^{39}Ar released can be regarded as a maximum age of the sample, or at least as the geologically significant age linked to the time of post-metamorphic cooling. The latter is also supported by the K/Ca spectrum, which indicates the presence of impurity at high temperature steps. This in turn affects the age of these steps, i.e. the K/Ca ratio decreases while the age increases.

The spectrum of phengitic muscovite of sample PR-1 shows a hump-like form resulting in a total age of 154.4±1.0 Ma (Fig. 4). This shape may have been caused by Ar redistribution during irradiation attributed to the presence of minor alteration phases in phengitic muscovite that disturbed the expected spectrum shape of mica. The total apparent age of phengitic muscovite of sample PR-1 can therefore be considered as a minimum age of the sample. This is because the loss of Ar, similarly to the onset of the age spectrum of sample PR-1 amphibole, cannot be excluded.

Discussion

Geodynamic significance

The protoliths of the investigated blueschists from the Drenova Unit were most likely Middle Triassic OIB-type basalts metamorphosed under high-pressure (0.9–1.2 GPa) and low-temperature (350–450 °C) conditions corresponding to the Sanbagawa metamorphic type (Belak 2005). Accordingly, the obtained $^{40}Ar/^{39}Ar$ (partial) plateau ages of glaucophane (160.0±1.5–164.9±1.0 Ma) and the hump-shaped minimum age of the phengitic muscovite (154.4±1.0 Ma) from the Mt. Medvednica blueschists clearly indicate their Middle–Upper Jurassic (Callovian–Kimmeridgian) metamorphic age.

From a geodynamic perspective, the origin of these blueschists can be traced to intra-oceanic subduction processes within the accretionary prism of the northwestern segment of the Neotethys during the Middle to Late Jurassic (Fig. 5A).

Table 1B: $^{40}Ar/^{39}Ar$ data of amphibole (sample Z-21) from the blueschists of the Mt. Medvednica metamorphic complex.

Step	Temp.	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	Apparent age
				[ccm/g]			±1σ s.d.
	[°C]	$[10^{-13}]$	$[10^{-11}]$	$[10^{-13}]$	$[10^{-12}]$	$[10^{-10}]$	[Ma]
1	400	30±5	21±16	10±4	4±1	9±1	5.6±84.5
2	500	69±4	3±3	20±3	9±1	22±1	45±26
3	550	36±4	5±5	7±4	6±1	14±1	104±36
4	600	338±10	13±11	102±5	38±11	136±1	181±14
5	650	334±9	31±14	92±6	38±1	136±1	189±14
6	700	758±12	75±15	202±6	131±2	400±1	250.9±5.6
7	750	624±16	29±16	173±6	294±4	543±5	229.8±3.3
8	790	2321±27	43±14	555±11	615±5	1320±6	195.8±2.4
9	810	238±8	39±14	87±7	510±4	508±3	**164.3±1.2**
10	830	147±7	22±19	52±7	423±4	409±2	**165.7±1.3**
11	850	147±6	19±14	55±6	439±3	423±2	**165.8±1.0**
12	870	158±8	24±19	52±8	526±6	497±5	**164.0±1.3**
13	890	115±10	36±15	37±5	358±5	341±4	**164.3±1.8**
14	910	350±13	38±17	146±22	1974±16	1799±14	**164.55±0.55**
15	930	176±5	13±13	92±13	1161±10	1057±8	**165.77±0.60**
16	950	294±11	61±18	45±13	1064±9	1047±8	172.45±0.85
17	970	518±21	169±27	327±17	1073±11	1205±11	186.6±1.3
18	990	551±26	101±27	226±8	645±6	834±7	197.5±2.3
19	1010	356±21	73±18	159±6	339±4	514±5	227.1±3.4
20	1030	229±15	42±32	100±6	204±3	316±3	229.0±4.7
21	1100	201±5	8±8	86±6	342±2	432±1	206.3±1.5
22	1200	109±6	4±4	48±5	249±2	302±1	205.3±1.7
23	1400	210±10	8±8	93±8	349±3	508±1	241.043±2.4
Total		8300±62	878±80	2866±44	10792±28	12776±26	182.32±0.38

Mass discrimination (measured $^{40}Ar/^{36}Ar=279.9\pm0.2$), argon isotopic abundances corrected for line and furnace blank and nuclogenic interferences $^{40}Ar/^{39}Ar_K=0.015\pm0.004$; $^{38}Ar/^{39}Ar_K=0.018\pm0.002$; $^{36}Ar/^{37}Ar_{Ca}=0.00043\pm0.00002$; $^{39}Ar/^{37}Ar_{Ca}=0.00098\pm0.00003$). J-factor=0.006321±0.000061 (±0.000065) (BMus/2: t=328.5±1.1 Ma, Schwarz & Trieloff 2007).

In this part of the Neotethyan realm, a long-lasting phase of continuous extension and oceanic lithosphere formation, accompanied by the development of a typical ophiolitic sequence and deep-marine sedimentary rocks (Middle Triassic to early Middle Jurassic), was followed in the Middle Jurassic (Bathonian) by a change in tectonic regime that initiated intra-oceanic convergence (Slovenec & Šegvić 2024; Fig. 5A). This led to the eastward intraoceanic subduction of an active oceanic ridge and the formation of an accretionary mantle wedge. During these processes, which continued throughout the Late Jurassic, large portions of the upper oceanic plate were subducted and metasomatized, whereas individual oceanic crustal slivers that descended to greater depths underwent metamorphism to varying degrees. This is clearly reflected in the studied Mt. Medvednica blueschists, which record high-pressure and low-temperature metamorphic conditions characteristic of the blueschist facies. Because amphibole grains and phengitic muscovite flakes in these rocks display a relatively weakly developed retrograde metamorphic overprint a rapid exhumation has been inferred (Belak 2005). This process is likely related to the collision between the Adriatic plate and the Eurasian continent during the Late Jurassic to Early Cretaceous (Belak 2005; Fig. 5B). The occurrence of blueschists at Mt. Medvednica therefore provides unequivocal evidence for the existence of an active subduction zone in the northwestern segment of the Neotethyan Ocean during the Middle–Late Jurassic (Callovian–Kimmeridgian). Structural and paleomagnetic data indicate that the pre-Neogene Mt. Medvednica basement experienced large regional-scale tectonic transport from the NW, as well as cca. 130° CW rotation during the Oligocene–earliest Miocene (Tomljenović et al. 2008), which resulted in its recent alignment almost perpendicular to the overall NW–SE Dinaridic structural trend (Fig. 1).

Regional considerations

The investigated Middle–Upper Jurassic blueschists of Mt. Medvednica provide a new temporal constraint for discussing the geodynamic evolution of the western Neotethys. When compared with high-pressure–low-temperature (HP/LT) metamorphic units of the wider regional area (Fig. 1), namely from Fruška Gora (Serbia) (Milovanović et al. 1995; Korikovsky & Karamata 2011), the Internal and External Western Carpathians (Slovakia) (Nemec et al. 2020; Putiš et al. 2023), and the Pelagonian Zone (North Macedonia) (Altherr et al. 2023), as well as with intra-oceanic subduction-related metamorphic sole complexes preserved within the Dinaridic Ophiolite Belt (DOB; Bosnia-Herzegovina, Serbia) (Operta et al. 2003; Chiari et al. 2011; Srećković-Batoćanin et al. 2012; Borojević Šoštarić et al. 2014; Šegvić et al. 2014, 2019, 2020; Balen & Massonne 2021), these data can be placed within a broader Neotethyan context characterized by diachronous and spatially variable subduction processes.

The blueschists of the Meliatic–Fatric system in the Western Carpathians (Fig. 1) record Late Jurassic (ca. 154–152 Ma) subduction of the Meliata Basin, attaining peak conditions of 490–520 °C and 1.55–1.72 GPa (Putiš et al. 2023). These P–T parameters and the mineral assemblages glaucophane + phengitic muscovite + epidote ± garnet ± chlorite show broad similarities to those of the Mt. Medvednica blueschists (350–450 °C; 0.9–1.2 GPa; Belak 2005), although the Carpathian occurrences record higher pressures and reflect a distinct tectonic setting. The nearly identical metamorphic ages of both regions, Middle to Late Jurassic, indicate broadly coeval high-pressure events within different segments of the Neotethyan system rather than a single, laterally continuous subduction zone. Given the differences in protolith affinity and tectonic position, any direct correlation should therefore be considered tentative.

The Fruška Gora Massif (Fig. 1) occupies the northern segment of the Vardar Zone and exposes a sequence of

Table 2: ^{40}Ar/^{39}Ar data of phengite (sample PR-1) from the blueschists of the Mt. Medvednica metamorphic complex.

Step	Temp.	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	Apparent age
				[ccm/g]			±1σ s.d.
	[°C]	[10^{-12}]	[10^{-13}]	[10^{-12}]	[10^{-11}]	[10^{-9}]	[Ma]
1	400	207±8	24±24	43±3	36±1	69±1	43±13
2	500	307±8	19±19	47±7	79±2	103±1	29.2±5.6
3	550	796±13	7±7	156±7	250±3	314±1	60.4±2.9
4	600	1548±20	103±49	330±10	547±3	758±2	103.7±2.0
5	650	2287±25	75±43	471±19	1320±7	1641±3	136.9±1.2
6	700	1315±13	29±29	274±18	1452±8	1632±3	159.29±0.89
7	740	1077±16	114±35	233±24	1992±7	2084±4	164.61±0.65
8	760	2803±22	98±48	554±32	2986±15	3584±14	171.06±0.57
9	780	423±10	85±41	88±20	1832±10	1840±7	173.38±0.71
10	800	233±9	109±51	50±17	1417±10	1373±6	170.68±0.94
11	820	305±8	110±40	55±21	1940±11	1826±8	166.05±0.63
12	840	288±7	78±37	52±17	1573±8	1449±6	161.06±0.49
13	860	307±9	58±53	78±18	1653±8	1492±3	157.72±0.70
14	880	127±9	35±35	21±10	799±5	701±1	154.7±1.1
15	900	227±7	44±44	51±14	1216±7	1059±2	152.02±0.82
16	920	212±9	58±41	59±12	938±4	794±1	145.45±0.72
17	940	172±9	25±25	39±7	387±3	317±3	129.0±1.5
18	960	277±7	22±22	64±7	262±2	205±1	89.1±1.7
19	1000	278±8	6±6	75±7	206±2	119±1	34.4±2.1
20	1050	159±8	15±15	53±10	130±2	57±1	15.3±3.3
21	1150	146±9	28±28	37±6	73±1	50±1	18.4±7.0
Total		13493±56	1140±160	2829±71	21088±31	21468±21	154.352±0.22

Mass discrimination (measured ^{40}Ar/^{36}Ar=279.9±0.2), argon isotopic abundances corrected for line and furnace blank and nucleogenic interferences ^{40}Ar/^{39}Ar$_K$=0.015±0.004; ^{38}Ar/^{39}Ar$_K$=0.018±0.002; ^{36}Ar/^{37}Ar$_{Ca}$=0.00043±0.00002; ^{39}Ar/^{37}Ar$_{Ca}$=0.00098±0.00003). J-factor=0.006321±0.000061 (±0.000065) (BMus/2: t=328.5±1.1 Ma, Schwarz & Trieloff 2007).

glaucophane-bearing metabasites and crossite schists enclosed within an olistostrome mélange that also contains fragments of serpentinite, metasedimentary rocks, and radiolarian chert (Milovanović et al. 1995; Korikovsky & Karamata 2011; Stojadinović et al. 2022). The mineral assemblages – crossite + epidote ± phengite ± chlorite ± albite – reflect epidote-blueschist to transitional facies conditions attained at 0.7–0.9 GPa and 380–420 °C. These pressures and temperatures overlap those of the Mt. Medvednica blueschists (0.9–1.2 GPa; 350–450 °C; Belak 2005); however, the available geochronological data (Early Cretaceous K–Ar ages; Milovanović et al. 1995) indicate a younger metamorphic imprint. This diachroneity suggests that the Fruška Gora assemblages record a distinct stage of subduction-related evolution within the Vardar domain, which may be consistent with protracted subduction of the northern Vardar lithosphere after HP/LT metamorphism had ceased in the northwestern Dinarides. Amphibole chemistry reveals a compositional range from riebeckite- to glaucophane-rich varieties and comparable to ferro- and Mg-glaucophane in the Drenova Unit (Belak 2005) analysed herein. Such mineralogical similarities likely reflect comparable metamorphic conditions, but do not require a direct tectonic linkage. Accordingly, Fruška Gora is best interpreted as documenting a later phase of HP/LT metamorphism within the evolving Neotethyan system. Alternatively, the Fruška Gora assemblages may reflect a younger and more external expression of subduction-related evolution within the Vardar domain, although a direct tectonic linkage with Mt. Medvednica remains unresolved. This line of reasoning is substantiated by the occurrence of Late Jurassic radiolarian assemblages (Oxfordian–Kimmeridgian) intercalated with the Mt. Fruška Gora mélange. They constrain the timing of oceanic crust generation preceding subduction and suggest that the HP/LT metamorphism there postdates slab formation by at least 20–25 Ma (Stojadinović et al. 2022). As a consequence, the Mt. Fruška Gora blueschists are interpreted as recording a later stage of HP/LT metamorphism within the Vardar domain. Their Early Cretaceous age is consistent with a broader geodynamic transition from intra-oceanic to continental-margin subduction and progressive closure of the Neotethys (Spahić et al. 2024; Sokol et al. 2025).

Farther southeast, within the northern Pelagonian Zone of North Macedonia (Fig 1), epidote-blueschist-facies rocks provide additional evidence for Jurassic intra-oceanic subduction (Altherr et al. 2023). These metabasites, calc-schists, and mica-schists record metamorphism at 0.74–0.85 GPa and 340–370 °C, conditions nearly identical to those inferred at Mt. Medvednica. Thermobarometric modelling and structural relations indicate prograde metamorphism during Toarcian–Bathonian time (~175 Ma) followed by obduction of ophiolitic sheets onto the Pelagonian margin by the Valanginian (~140 Ma). These data indicate that comparable HP/LT conditions were attained in different segments of the Neotethyan realm during the Jurassic, but likely do not require a single, laterally continuous subduction system. Therefore, when taking everything into consideration, one can infer that HP/LT occurrences in the Dinaridic–Vardar–Carpathian region reflect spatially distributed and temporally variable subduction-related processes within the Neotethyan domain. Apparent similarities in P–T conditions and partially overlapping ages likely reflect broadly comparable geodynamic regimes, yet they do not define a coherent metamorphic gradient or a single, laterally continuous subduction front at present. Nevertheless, the possibility that these Neotethyan HP/LT occurrences record a southeastward migration of subduction in response to slab rollback and trench retreat within the Western Neotethys (Robertson et al. 2009; Slovenec & Šegvić 2019, 2024) cannot be excluded and warrants further investigation.

The petrological and structural framework of the neighboring Dinaridic Ophiolite Belt (DOB; Fig. 1) provides direct evidence for an earlier, Middle Jurassic phase of intra-oceanic subduction that preceded HP/LT metamorphism in the Mt. Medvednica area. Within the Krivaja–Konjuh Ophiolite

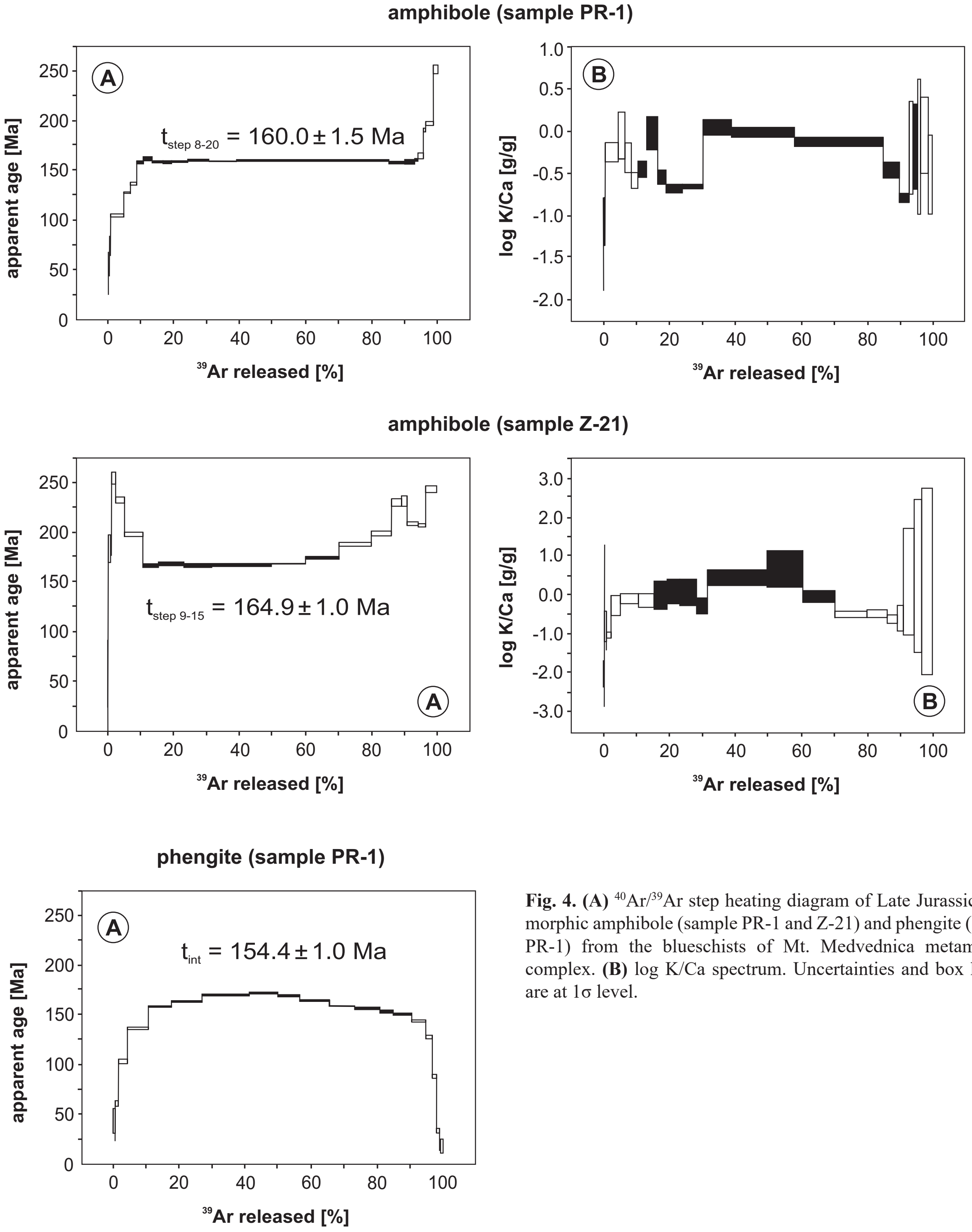

Fig. 4. (A) ^{40}Ar/^{39}Ar step heating diagram of Late Jurassic metamorphic amphibole (sample PR-1 and Z-21) and phengite (sample PR-1) from the blueschists of Mt. Medvednica metamorphic complex. **(B)** log K/Ca spectrum. Uncertainties and box heights are at 1σ level.

Complex (KKOC), amphibolite- and granulite-facies rocks forming the metamorphic sole yield Sm–Nd ages between 174 Ma and 157 Ma, which corresponds to the Bajocian–Bathonian interval (Šegvić et al. 2020). These ages coincide with the onset of intra-oceanic subduction recorded by the appearance of latest Bajocian–early Bathonian radiolarian cherts within the associated mélange (Šegvić et al. 2014). The high-temperature metamorphic soles of the KKOC, equilibrated at ~1 GPa and 800 °C, mark the incipient subduction of a young, still-hot oceanic crust beneath an intra-oceanic arc (Šegvić et al. 2020; Balen & Massonne 2021). Complementary field and radiolarian evidence from the internal Dinarides confirms that the Middle Jurassic was a critical interval of rapid subsidence and onset of deep-marine conditions associated with slab initiation. At Pavlovića Brod on Zlatar Mt. in Serbia, late Aalenian–early Callovian

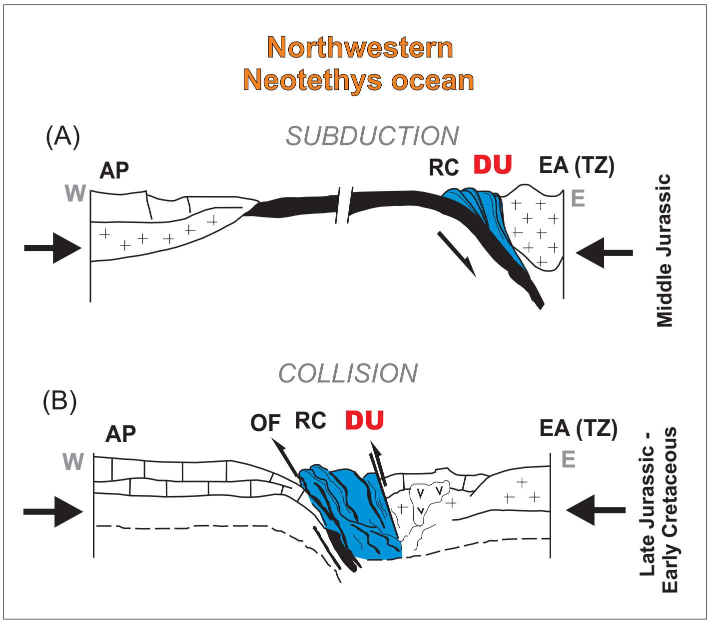

Fig. 5. Schematic geodynamic model of the formation of Mt. Medvednica blueschists and their geotectonic setting (after Belak et al. 2022). **(A)** Ocean subduction – east side of the active continental margin (accretion prism) with the Repno Complex (RC) (Jurassic ophiolite mélange) and Drenova Unit (DU) metamorphic rocks of accretion prism with high-pressure metamorphic rocks, blueschist and jadeite schists (Middle Jurassic); **(B)** Collision of the Adriatic Plate and Eurasia (Tizsa (TZ)), formation of compression foreland basin Oštrc Formation (OF), rocks of Repno Complex (RC) and metamorphic rocks of Mt. Medvednica: Jurassic Drenova Unit (DU), which was exhumed and retrogradely metamorphosed during the Early Cretaceous.

radiolarians (UAZ 2–7) document deposition of deep-marine cherts contemporaneous with the formation of the metamorphic sole (Djerić et al. 2007). Structural and petrological evidence demonstrate that the Dinaridic Ophiolite Belt comprises a series of tectonic slices derived from both the overriding and subducting plates, assembled within a west-verging intra-oceanic thrust system (Lugović et al. 1991; Ustaszewski et al. 2007; Robertson et al. 2009; Schmid et al. 2020; Putiš et al. 2025). This configuration is consistent with a northeast-dipping subduction, with the subducting plate represented by the western Vardar–Dinaridic oceanic lithosphere and the upper plate corresponding to an intra-oceanic arc that subsequently collided with the Adria margin (Fig. 4; Trubelja et al. 1995; Pamić & Tomljenović 1998; Pamić et al. 1998, 2002). The metamorphic soles, dated between 174 and 157 Ma, record the earliest phase of this intra-oceanic convergence, while the overlying radiolarites and lavas of OIB-type affinity indicate contemporaneous spreading and rollback within the forearc. Additional evidence from the Fruška Gora sub-ophiolitic mélange confirms the persistence of oceanic crustal accretion into the Late Jurassic. At that location, the radiolarian cherts intercalated with basaltic and serpentinized blocks yielded Oxfordian–Kimmeridgian assemblages, marking continuous oceanic sedimentation above an active subduction interface (Stojadinović et al. 2022). Presented data from the Dinarides support the existence of intra-oceanic subduction in the Dinaridic–Vardar realm during the Middle to Late Jurassic. The Mt. Medvednica blueschists, which attained their peak metamorphism during the Callovian–Kimmeridgian, may represent a relatively cooler and deeper segment of an evolving subduction system following its initial thermal stabilization, or alternatively, one of several records of HP/LT metamorphism within a broader and diachronous Neotethyan framework.

Conclusions

Integration of the presented datasets provides new geochronological constraints on the timing of HP/LT metamorphism in the northwestern Dinarides and allows its placement within a broader Neotethyan geodynamic framework. The earliest subduction initiation occurred in the Bajocian, as evidenced by the metamorphic-sole ages of 174–157 Ma and coeval deep-sea sedimentation across the Internal Dinarides. During this stage, the subduction interface was hot, producing amphibolite-facies assemblages beneath the hot oceanic crust. With time, continued convergence cooled the thermal structure of the subduction zone, and by the Callovian–Kimmeridgian, HP/LT metamorphism produced the Mt. Medvednica blueschists at depths of 30–40 km.

Regional comparisons indicate that Jurassic to Early Cretaceous HP/LT assemblages in the Pelagonian Zone and Mt. Fruška Gora reflect subsequent and spatially distinct stages of subduction-related evolution within the Neotethyan domain rather than a single, laterally continuous metamorphic system. This diachronous evolution is consistent with a long-lived northeast-dipping subduction system that operated across different segments of the Dinaridic–Vardar realm, although its lateral continuity and kinematic coherence remain to be further constrained.

The Mt. Medvednica blueschists occupy an intermediate structural position within this framework, recording a Middle–Late Jurassic stage of HP/LT metamorphism following the initial, high-temperature phase of intra-oceanic subduction documented by metamorphic soles in the Dinarides. In such a context, Mt. Medvednica blueschists represent the northwesternmost record of Middle–Late Jurassic subduction in the Dinarides and provide a temporal link between Middle Jurassic intra-oceanic convergence and younger HP/LT events farther southeast. Their amphibole- and phengitic muscovite-derived ^{40}Ar/^{39}Ar ages (164–154 Ma) coincide with the transition from ridge subduction to mature intra-oceanic convergence, providing a precise insight into west-Neotethyan subduction processes. Comparable ages and broadly similar P–T conditions are also recorded in the Western Carpathians; however, differences in protolith affinity, peak pressures, and tectonic setting suggest that these occurrences represent distinct segments of the Neotethyan system. As a consequence, any direct correlation should be regarded as tentative. The available data support a model of spatially distributed and diachronous subduction-related processes within the Neotethyan realm, while the hypothesis of a regionally connected and migrating subduction system remains a viable working interpretation that requires further testing.

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