

Age and origin of the Late Oligocene Kosmaj monzogranite (central Serbia): New constraints on post-collisional granitoid magmatism in the Internal Dinarides

NIKOLINA ĆIRIĆ^{1,2}, BOJAN KOSTIĆ², DANICA SREĆKOVIĆ-BATOĆANIN²,
NIKOLA RANDJELOVIĆ², MAJA MALEŠ², MILICA MALETIĆ³ and UROS STOJADINOVIC^{2,✉}

¹University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia

²University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia

³Balkan exploration and mining, Bor, Serbia

(Manuscript received May 18, 2026; accepted in revised form September 21, 2026; Associate Editor: Dražen Balen)

Abstract: In this study, new constraints on post-collisional granitoid magmatism in the Internal Dinarides are provided through petrographic, mineral-chemical, zircon U–Pb geochronological, and zircon Lu–Hf isotopic analyses of the monzogranite intrusion exposed along the southwestern flank of the Kosmaj Mts. in central Serbia. The intrusion consists of a calc-alkaline monzogranite composed mainly of orthoclase, plagioclase, and quartz, with subordinate phlogopite and magnesiohornblende. Amphibole–plagioclase thermobarometry indicates crystallization at 774–831 °C and ~160–260 MPa, consistent with shallow upper-crustal levels prior to or during final emplacement. Zircon U–Pb data yield a concordia age of 24.92 ± 0.31 Myr, constraining magmatism to the Late Oligocene. Zircon Lu–Hf isotopic compositions ($\epsilon_{\text{Hf}}(t) = -1.2$ to $+7.0$) point to a predominantly juvenile magma source with limited crustal involvement. Based on its age, petrographic characteristics, and zircon Lu–Hf isotopic composition, the Kosmaj monzogranite is assigned to the Oligocene–Early Miocene post-collisional I-type granitoid suite of the Internal Dinarides.

Keywords: I-type granitoid, amphibole–plagioclase thermobarometry, zircon U–Pb geochronology, zircon Lu–Hf isotopes, Sava Zone

Introduction

The Internal Dinarides preserve an extensive record of post-collisional granitoid magmatism that accompanied the transition from Adria–Europe continental collision to post-collisional tectonic evolution. Following the latest Cretaceous–Eocene Adria–Europe collision along the Sava Zone (Fig. 1a; Schmid et al. 2008; Ustaszewski et al. 2010), post-collisional granitoid magmatism developed throughout the Oligocene–Miocene, spanning approximately 35–16 Myr and comprising plutonic rocks, as well as their volcanic equivalents distributed along the Adria–Europe collisional belt (Knežević et al. 1991; Kovács et al. 2007; Schefer et al. 2011 and references therein).

The Oligocene–Miocene post-collisional granitoid magmatism developed during a two-stage extensional evolution of the Internal Dinarides. The earlier Oligocene–Early Miocene E–W-directed extension was oriented approximately parallel to the strike of the Dinaridic orogen. It was followed by, and partly overlapped with, Miocene N–S-directed extension, oriented approximately perpendicular to the orogenic strike and associated with the progressive development of the south-eastern Pannonian Basin (Fig. 1b,c; Matenco & Radivojević

2012). This bi-directional extensional regime coincides with two petrographically and geochemically distinct granitoid associations in central Serbia. The older Oligocene–Early Miocene association is dominated by metaluminous I-type granitoids exposed in the Boranja, Cer, Brajkovac, Željin, Kopaonik, and Golija areas, whereas the younger Miocene association comprises predominantly peraluminous S-type granites occurring in the Cer, Polumir, and Bukulja areas (Fig. 1b; Cvetković et al. 2007; Koroneos et al. 2011; Schefer et al. 2011; Stojadinovic et al. 2017; Löwe et al. 2021; Mladenović et al. 2025). Several geodynamic models have been proposed to explain the origin of this magmatism, including post-collisional collapse of an overthickened Dinaridic crust (Cvetković et al. 2004), back-arc magmatism related to retreat of the Carpathian slab (Kovács et al. 2007), and lithospheric delamination associated with slab rollback beneath the Dinarides (Schefer et al. 2011). However, the relationship between these granitoid associations and the two-stage extensional evolution of the Internal Dinarides remains incompletely understood.

The Kosmaj Mts. in central Serbia are situated along the Sava Zone and host a granitoid intrusion emplaced into Upper Cretaceous sedimentary units exposed along their southwestern margin (Fig. 2). Although the petrographic characteristics of the Kosmaj monzogranite were described in previous studies (e.g., Pavlović et al. 1977), robust geochronological

✉ corresponding author: Uros Stojadinovic
uros.stojadinovic@rgf.bg.ac.rs



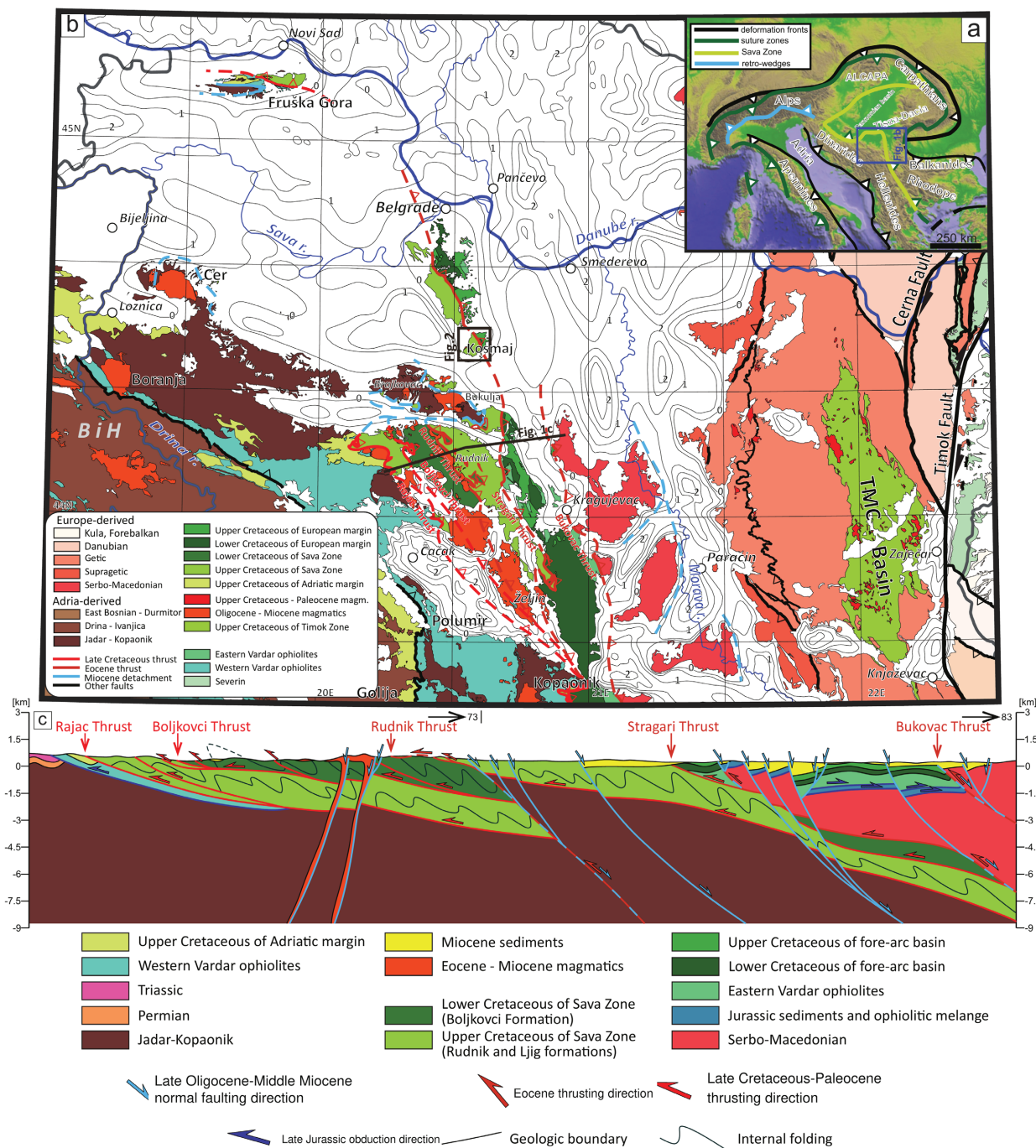


Fig. 1. (a) Topographic map of Central Mediterranean orogens, displaying suture zones, orogenic fronts, and retro-wedges (modified after Krstekanić et al. 2020). The blue rectangle marks the position of Fig. 1b. (b) Geological map of the connection between the Dinarides, Serbian Carpathians, and Pannonian Basin (modified after Stojadinovic et al. 2022). The black rectangle indicates the location of the geological map in Fig. 2a, and the thick black line indicates the location of the cross-section in Fig. 1c. (c) Cross-section across the Sava Zone in central Serbia (modified after Stojadinovic et al. 2022). Named thrusts are shown by red fault traces and labels at their surface intersections; arrows within the cross-section indicate inferred tectonic transport directions.

and isotopic constraints on the intrusion are still lacking. Consequently, the timing of magma emplacement, its petrogenetic affinity, and the regional significance of the Kosmaj intrusion remain poorly constrained, precluding its reliable integration into the post-collisional magmatic evolution of

the Internal Dinarides. In this study, we present new petrographic data, zircon U–Pb age, and zircon Lu–Hf isotopic compositions from the Kosmaj intrusion to (1) constrain the timing of magma emplacement, (2) constrain the magma source and petrogenetic affinity, and (3) establish the position

of the Kosmaj intrusion within the Oligocene–Miocene post-collisional granitoid magmatism of the Internal Dinarides.

Geological background

Regional tectonic framework

The convergence between Adria- and Europe-derived continental units in the Internal Dinarides was associated with the Late Jurassic to Eocene closure of the northern branch of the Neotethys Ocean (Vardar Ocean; [Dimitrijević 1997](#)). During the latest Jurassic to earliest Cretaceous, bi-vergent obduction led to the emplacement of Vardar ophiolites onto both continental margins, forming the Western and Eastern Vardar Ophiolitic Units ([Fig. 1b](#); [Schmid et al. 2008](#); [Porkoláb et al. 2019](#); [Maleš et al. 2023](#)).

During the Cretaceous, the NE-dipping subduction of the remaining Neotethyan lithosphere beneath the European continental margin resulted in the development of the Sava subduction system, comprising trench-related sedimentary successions deposited above the downgoing Adriatic plate and fore-arc to back-arc successions deposited on the upper European plate ([Fig. 1b,c](#); [Toljić et al. 2018](#); [Schmid et al. 2020](#); [Stojadinović et al. 2026](#)). Final continental collision during the latest Cretaceous–Eocene transformed this subduction system into the Sava Zone collisional suture, characterized by a system of in-sequence to out-of-sequence top-to-the-WSW thrusts ([Fig. 1c](#); [Ustaszewski et al. 2010](#); [Stojadinović et al. 2022](#)).

The subsequent Oligocene–Miocene post-collisional evolution was characterized by two-stage extension affecting the Sava Zone and the adjacent Internal Dinarides. The earlier Oligocene–Early Miocene E–W-directed, orogen-parallel extension partly overlapped with the subsequent Miocene N–S-directed, orogen-perpendicular extension associated with the development of the main depocentres of the southeastern Pannonian Basin ([Fig. 1b,c](#); [Matenco & Radivojević 2012](#)). This extensional evolution was accompanied by widespread post-collisional granitoid magmatism affecting the Adria–Europe collisional belt and adjacent Adria-derived units of the Internal Dinarides. Notably, several Oligocene–Miocene magmatic bodies, including those exposed in the Fruška Gora, Cer, Kosmaj, Bukulja, Željin, and Kopaonik areas ([Fig. 1b](#); [Pavlović et al. 1977](#); [Knežević et al. 1991](#); [Schefer et al. 2011](#); [Stojadinović et al. 2017](#); [Löwe et al. 2023](#)), occur within or adjacent to Upper Cretaceous trench-related successions of the Sava Zone rather than within Cretaceous successions of the former European continental margin. This relationship provides an important regional context for the geological setting of the Kosmaj intrusion described below.

Geological setting of the Kosmaj Mts.

The Kosmaj monzogranite crops out along the southwestern flank of the Kosmaj Mts., where it intrudes Upper Cretaceous

trench-related turbidites of the Rudnik Formation west of the Stragari Thrust ([Fig. 2a,b](#)). The Stragari Thrust is a regional Eocene out-of-sequence structure that emplaced the Cretaceous succession of the former European continental margin, together with the underlying Eastern Vardar Ophiolitic Unit, westward over Upper Cretaceous trench-related deposits of the Sava Zone ([Figs. 1c and 2](#); [Ustaszewski et al. 2010](#); [Stojadinović et al. 2022](#)). Consequently, the Kosmaj area preserves two tectono-stratigraphically distinct Cretaceous successions separated by a major tectonic boundary, making it particularly suitable for evaluating the tectonic position of the intrusion within the regional framework of Oligocene–Miocene post-collisional magmatism.

East of the Stragari Thrust, Cretaceous sediments represent the sedimentary record of the active European continental margin that developed during subduction of the Neotethyan lithosphere ([Fig. 2b](#)). The depositional cycle began with a Lower Cretaceous–Cenomanian transgressive succession of shelf-to slope-related deposits (paraflysch units of [Dimitrijević & Dimitrijević 2009](#)), unconformably overlying the Eastern Vardar Ophiolitic Unit. This was followed by Albian–Cenomanian regressive shallow-marine siliciclastic and carbonate deposits, and a renewed Turonian transgression with coarse clastic sediments, platform carbonates, and Campanian–Maastrichtian shallow-marine to distal basin deposits ([Toljić et al. 2018, 2020](#)). West of the Stragari Thrust, Upper Cretaceous sediments belong to the Sava Zone and represent deposits of the former subduction trench. They consist of distal mudstones overlain by clastic–carbonate turbidites of the Rudnik Formation ([Stojadinović & Krstekanić 2023](#)), which constitute the immediate host rocks of the Kosmaj monzogranite ([Fig. 2](#)).

Previous geological investigations recognized several granitoid bodies exposed over an area of approximately 2–3 km² along the western slopes of the Kosmaj Mts. Most outcrops are strongly grusified, although fresh exposures occur locally in the Radovac stream valley. Based on the distribution of contact-metamorphic rocks, [Pavlović et al. \(1977\)](#) suggested that the exposed granitoids probably represent the apical parts of a considerably larger plutonic body concealed at depth. Petrographically, the intrusion was described as a porphyritic to porphyroid magnesiohornblende–phlogopite monzogranite composed predominantly of K-feldspar, plagioclase, quartz, magnesiohornblende, and phlogopite, locally accompanied by aplite and lamprophyre dykes and surrounded by a well-developed contact-metamorphic aureole. The same authors also noted similarities between the Kosmaj intrusion and the granitoids extending south towards Željin and Kopaonik Mts. However, despite these early geological and petrographic observations, neither the emplacement age nor the petrogenetic affinity of the Kosmaj intrusion could be reliably constrained prior to this study because modern geochronological and isotope-geochemical data were unavailable.

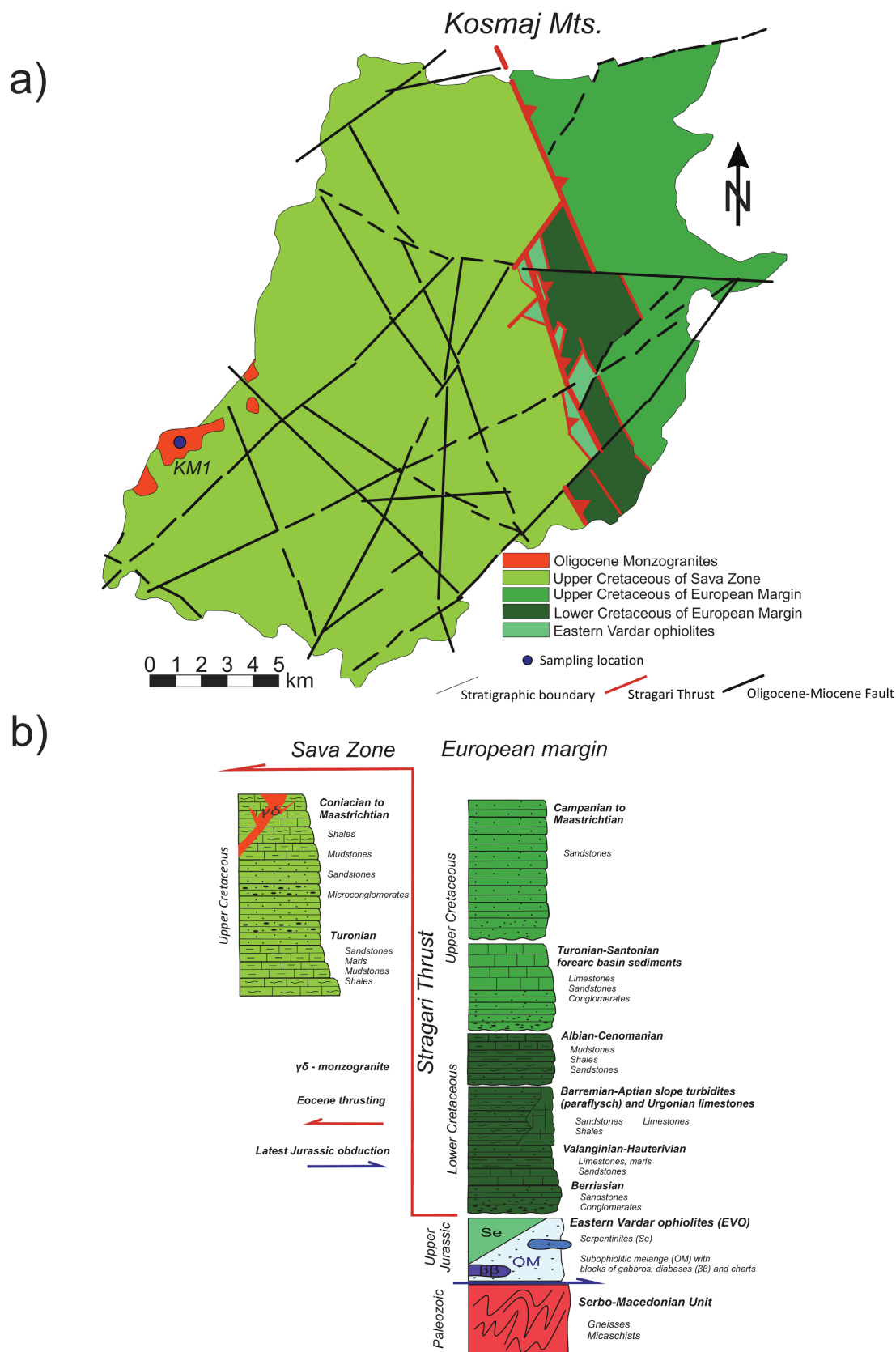


Fig. 2. Geological and tectonostratigraphic setting of the Kosmaj monzogranite. (a) Geological map of the Kosmaj Mts. (modified after the Basic geological map of former Yugoslavia, scale 1:100,000, sheet Smederevo (Pavlović et al. 1977)); (b) Correlation between Cretaceous sedimentary sequences in the Kosmaj Mts. (modified after Stojadinovic & Krstekanić 2023).

Materials and methods

Sampling and petrography

Five granitoid hand specimens (KM1–KM5) were collected from a single outcrop exposed along the southwestern flank of the Kosmaj Mts. The outcrop is located at 44°27'11.2"N 20°33'07.5"E. The representative sample selected for zircon U–Pb and Lu–Hf analyses is KM1, and its location is shown in Fig. 2a. Representative photographs of the sampling locality and sample KM1 are provided in Fig. 3.

Petrographic observations were performed on four polished thin sections using transmitted-light optical microscopy at the Faculty of Mining and Geology, University of Belgrade. Mineral assemblages, relative mineral abundances, grain-size variations, textural relationships, alteration features, and accessory minerals were systematically documented under plane-polarized and cross-polarized light (Fig. 4). Mineral abbreviations used throughout the text and figures follow standard petrographic conventions.

Mineral chemistry and thermobarometry

Mineral chemical compositions of feldspars, magnesiohornblende, and phlogopite were determined using a JEOL JSM-6610LV scanning electron microscope equipped with a wavelength-dispersive spectrometer (SEM–WDS) at the Faculty of Mining and Geology, University of Belgrade. Analyses were performed on fresh mineral domains, avoiding altered or fractured areas whenever possible. Operating conditions included an accelerating voltage of 20 kV, a beam current of 78 nA, and a beam diameter of approximately 2 μ m.

Albite was used as the standard for Si, Al, and Na, orthoclase for K, olivine for Mg, ferric oxide for Fe, and pure metals. Representative mineral compositions and calculated structural formulae are provided in [Supplementary Dataset 1](#).

Equilibrium temperatures were estimated using amphibole–plagioclase thermometry following [Holland & Blundy \(1994\)](#). Temperatures were calculated assuming pressures of 100–300 MPa, consistent with shallow upper-crustal emplacement conditions expected for the Kosmaj intrusion. Pressure estimates were subsequently evaluated using the same amphibole–plagioclase calibration and independently constrained using the total Al content of magnesiohornblende following [Mutch et al. \(2016\)](#). Only texturally equilibrated amphibole–plagioclase pairs were considered. Complete thermobarometric calculations are provided in [Supplementary Dataset 2](#).

Zircon U–Pb dating and Lu–Hf isotopes

Zircon U–Pb analyses were performed on a representative granitoid sample KM1 from the Kosmaj Mts. The sample was crushed to <250 μ m and wet-sieved to remove the <63 μ m fraction. Heavy mineral concentrates were obtained using standard magnetic separation followed by heavy-liquid separation using methylene iodide. Zircon grains were handpicked under a binocular microscope, mounted in epoxy, polished to expose grain interiors, carbon-coated, and imaged using cathodoluminescence (CL) and back-scattered electron (BSE) techniques. Imaging was carried out using the same JEOL JSM-6610LV SEM employed for mineral-chemical analyses, equipped with an EDS system at the Faculty of Mining and Geology, University of Belgrade. Representative CL images showing the internal textures of analysed zircon grains and

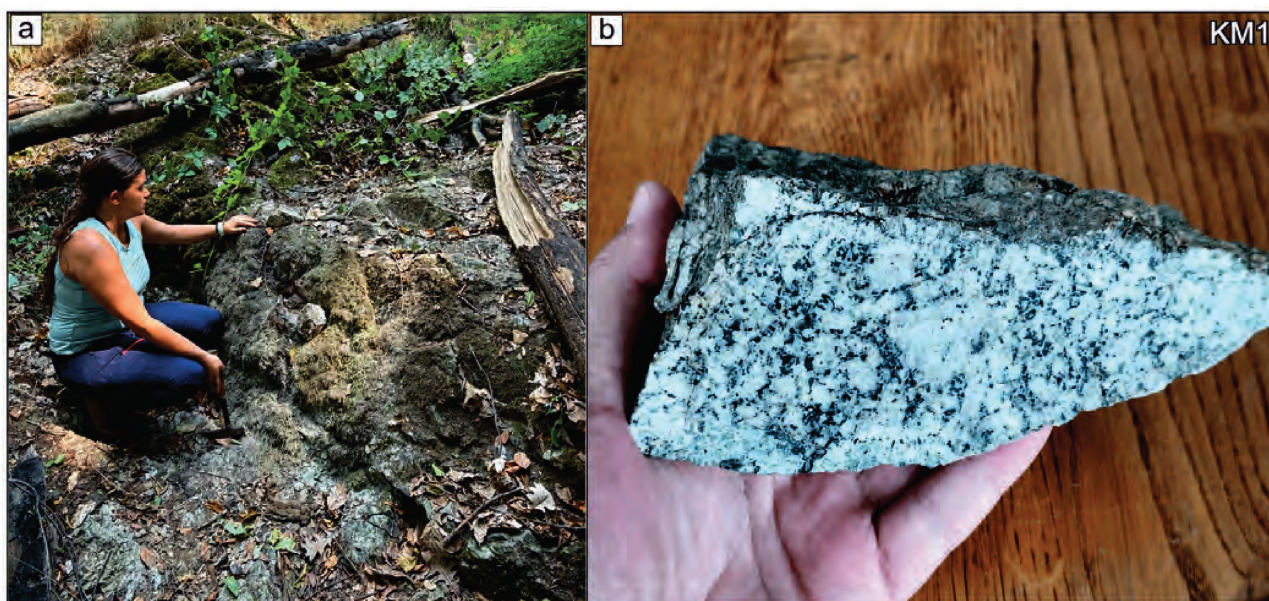


Fig. 3. Field occurrence and hand-specimen appearance of the Kosmaj monzogranite. **(a)** Granitoid outcrop in the Radovac stream valley on the southwestern flank of the Kosmaj Mts.; **(b)** Representative hand specimen of the Kosmaj monzogranite (sample KM1).

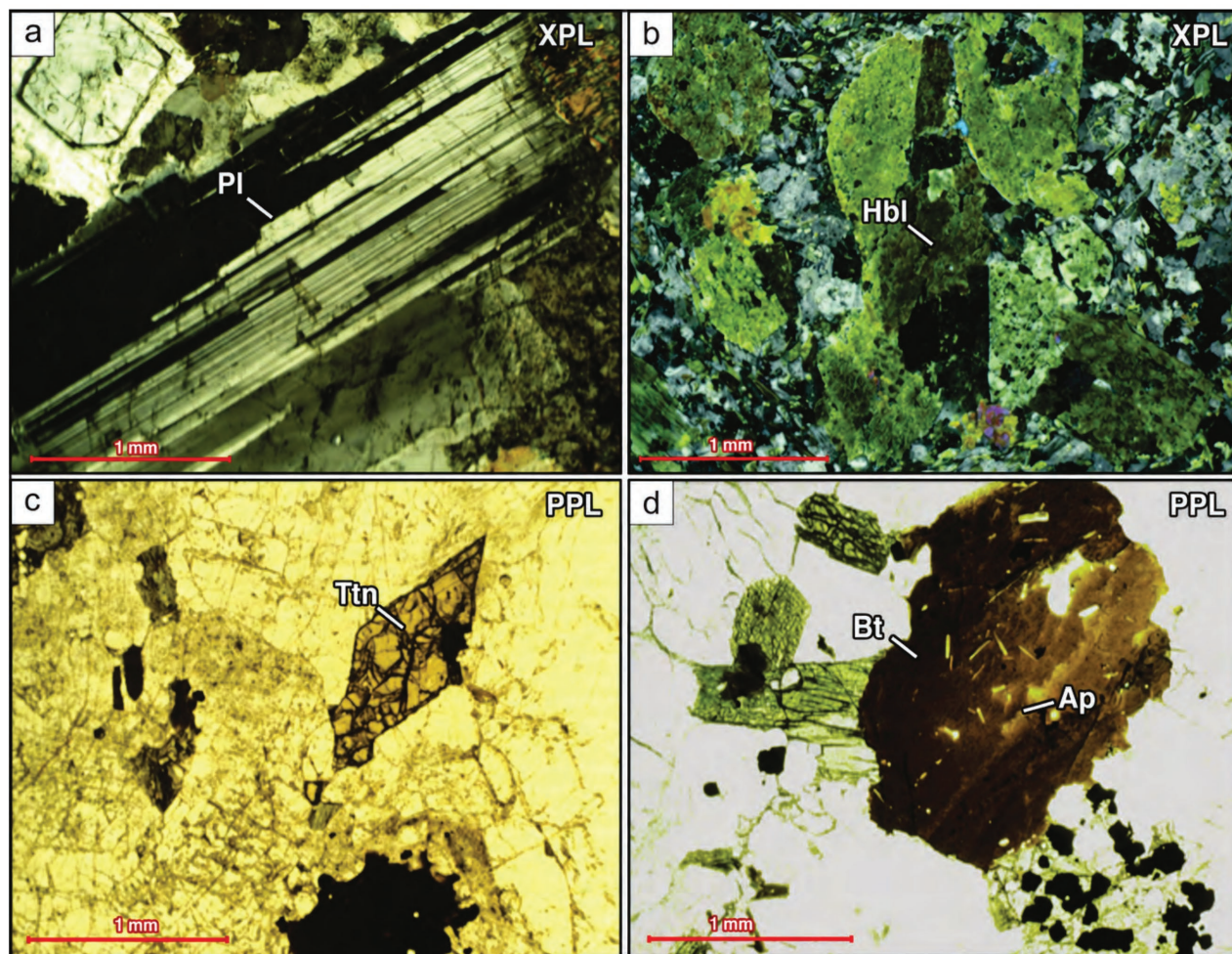


Fig. 4. Representative petrographic features of the Kosmaj monzogranite. (a) Plagioclase (Pl) displaying polysynthetic twinning under cross-polarized light (XPL); (b) Cluster of subhedral hornblende (Hbl) crystals under cross-polarized light (XPL); (c) Euhedral titanite (Ttn) crystal under plane-polarized light (PPL); (d) Biotite (Bt) containing elongated apatite (Ap) inclusions under plane-polarized light (PPL). Scale bars = 1 mm.

the locations of LA-ICP-MS U-Pb analytical spots are presented in Fig. 5a; the corresponding concordia diagram is shown in Fig. 5b.

U-Pb analyses were performed at the Petrochronology Laboratory, University of Bucharest, using a Thermo Fisher Scientific iCAP RQ quadrupole ICP-MS coupled to a Teledyne Photon Machines Iridia 193 nm ArF excimer laser equipped with a two-volume Cobalt sample chamber. Analyses employed a 25 μm spot size, 20 Hz repetition rate, and a fluence of $\sim 3.6 \text{ J/cm}^2$. Each analysis consisted of a 20 s ablation, followed by a 5 s washout and a 15 s background measurement. Measured isotopes included ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , and ^{238}U . Data reduction was carried out using Iolite 4 (Paton et al. 2011) following Paton et al. (2010), including corrections for background, downhole fractionation, and instrumental drift. SLF zircon ($563.5 \pm 3.2 \text{ Myr}$; Gehrels et al. 2008) served as the primary reference material, while FC-1 ($1099.5 \pm 0.5 \text{ Myr}$; Paces & Miller 1993) and Plešovice ($337.13 \pm 0.37 \text{ Myr}$; Sláma et al. 2008) served as secondary standards

to monitor analytical accuracy and precision. A total of 41 U-Pb spot analyses were obtained from 38 zircon grains. All 41 analyses were retained for the concordia-age calculation, and no analyses were excluded. Complete spot-level analytical data are provided in [Supplementary Dataset 3](#).

Twenty in situ zircon Lu-Hf isotopic analyses were carried out at the Arizona LaserChron Center (The University of Arizona) using a ThermoFisher Neptune MC-ICP-MS coupled to a Photon Machines Analyte G2 193 nm ArF excimer laser system, equipped with a two-volume HelEx-2 ablation cell, following Ibáñez-Mejía et al. (2014). Analyses employed a 40 μm spot size, 8 Hz repetition rate, and a fluence of $\sim 7.56 \text{ J/cm}^2$, with analytical spots positioned to overlap previously dated U-Pb domains where possible. Helium was used as the carrier gas for the ablated particles and mixed with 5 SCCM of ultra-high purity N_2 before entering the Ar plasma torch to enhance sensitivity. Measured masses included ^{171}Yb , ^{173}Yb , ^{175}Lu , $^{176}(\text{Yb}+\text{Lu}+\text{Hf})$, ^{177}Hf , ^{178}Hf , ^{179}Hf , ^{180}Hf , and ^{182}W . Analytical sequences were bracketed by repeated

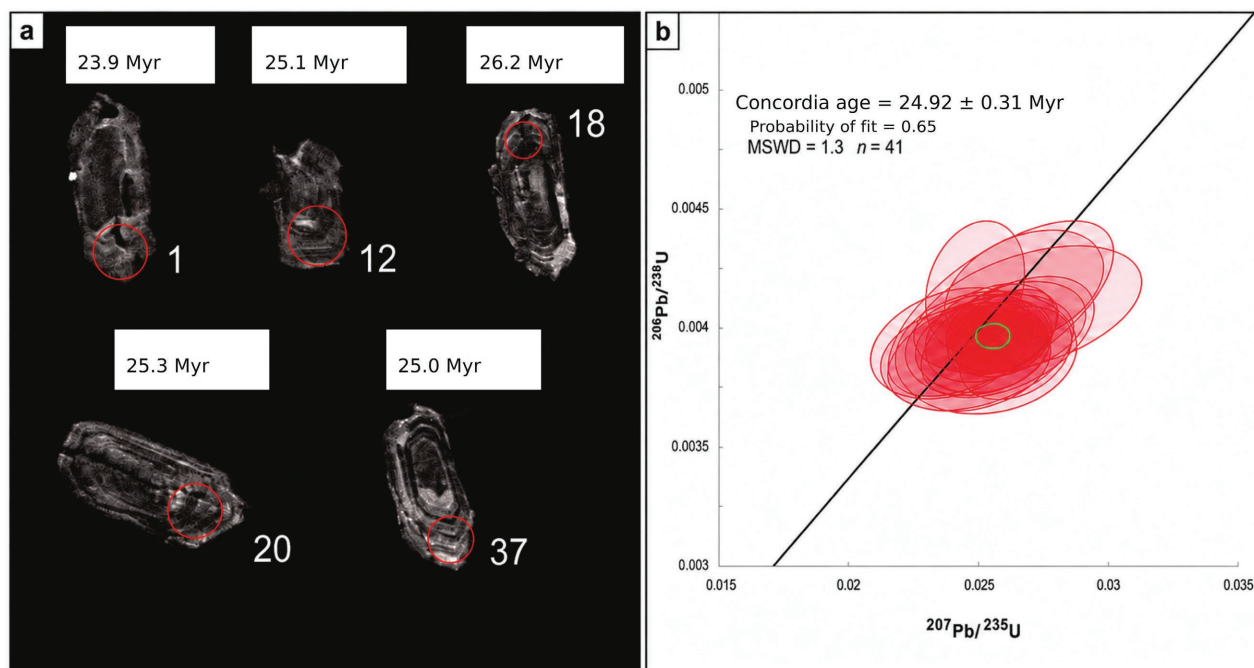


Fig. 5. Zircon U–Pb geochronology of the Kosmaj monzogranite. **(a)** Representative cathodoluminescence (CL) images of analysed zircon grains showing internal textures and the locations of LA–ICP–MS U–Pb analytical spots (red circles). The corresponding $^{206}\text{Pb}/^{238}\text{U}$ ages are indicated for the illustrated spots. **(b)** Concordia diagram for 41 zircon U–Pb analyses, all of which were retained, yielding a concordia age of 24.92 ± 0.31 Myr (MSWD=1.3; probability of fit=0.65; $n=41$). Red ellipses represent individual analyses used in the concordia-age calculation.

measurements of the Mud Tank, Plešovice, R33, FC-1, Temora-2, SL, and 91500 zircon reference materials. Data reduction followed [Gehrels & Pecha \(2014\)](#) and [Ibáñez-Mejía et al. \(2014\)](#), including correction for ^{176}Lu and ^{176}Yb interferences and exponential mass-bias correction ([Fisher et al. 2014](#)). Only non-perturbed spectra were retained. Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\varepsilon\text{Hf}(t)$ values were calculated using the corresponding zircon U–Pb ages, CHUR parameters of [Bouvier et al. \(2008\)](#), and $\lambda^{176}\text{Lu} = 1.867 \times 10^{-11} \text{ yr}^{-1}$ ([Söderlund et al. 2004](#)). Complete analytical data, corresponding $^{206}\text{Pb}/^{238}\text{U}$ ages, calculated initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, and $\varepsilon\text{Hf}(t)$ values are provided in [Supplementary Dataset 4](#).

Results

Petrography

The Kosmaj intrusion consists of light grey to grey, medium- to coarse-grained monzogranite displaying predominantly hypidiomorphic granular textures, locally passing into weakly porphyritic varieties. The rocks are generally massive, although locally developed schlieren structures, defined by the preferred concentration of mafic minerals, are also present. Variable degrees of grusification affect the outcrops but do not significantly obscure the primary magmatic textures. The mineral assemblage is dominated by orthoclase, plagioclase, and quartz, accompanied by subordinate phlogopite

and magnesiohornblende, with accessory titanite, fluorapatite, magnetite, and zircon. The observed mineral assemblage and relative feldspar abundances are consistent with the monzogranitic character previously reported by [Pavlović et al. \(1977\)](#). Accordingly, the term monzogranite is retained here as the established petrographic designation of the Kosmaj intrusion.

Orthoclase occurs predominantly as subhedral to anhedral crystals, locally forming large poikilitic crystals (oikocrysts) up to 10×16 mm in size. Crystals commonly exhibit perthitic intergrowths and are variably affected by sericitization. Plagioclase forms euhedral to subhedral crystals commonly displaying well-developed polysynthetic twinning ([Fig. 4a](#)) and locally preserved compositional zoning. Plagioclase grain boundaries are commonly irregular owing to intergrowth with adjacent quartz and orthoclase, whereas many crystals are fractured and variably sericitized. Quartz occurs predominantly as anhedral interstitial grains showing undulose extinction under cross-polarized light. Magnesiohornblende forms subhedral prismatic crystals, commonly occurring in clusters ([Fig. 4b](#)). Under plane-polarized light, magnesiohornblende displays pronounced pleochroism from greenish-blue to brown. Phlogopite occurs as subhedral flakes closely associated with magnesiohornblende and exhibits strong brown pleochroism. Titanite commonly forms euhedral wedge-shaped crystals ([Fig. 4c](#)), whereas fluorapatite commonly occurs as elongate inclusions in phlogopite ([Fig. 4d](#)). Zircon occurs as a minor accessory phase.

Secondary alteration is unevenly developed throughout the intrusion. Orthoclase is variably replaced by sericite, which locally constitutes approximately 5 vol.% of the whole rock, whereas epidote–zoisite aggregates and chlorite preferentially replace plagioclase and phlogopite. Calcite commonly fills late fractures in the more altered samples, while kaolinite locally develops by alteration of feldspars.

Mineral chemistry and thermobarometry

A total of 37 K-feldspar, 42 plagioclase, 35 magnesiohornblende and 18 phlogopite analyses were obtained. Representative mineral compositions and calculated structural formulae are provided in [Supplementary Dataset 1](#).

K-feldspar compositions range from Or82 to Or87, whereas plagioclase corresponds to oligoclase–andesine compositions, with albite contents ranging from Ab57–72 and anorthite contents from An27–39 ([Supplementary Dataset 1](#)). Magnesiohornblende is classified according to the nomenclature of [Leake et al. \(1997\)](#), with Mg# [=Mg/(Mg+Fe²⁺)] values of 0.75–0.83 ([Supplementary Dataset 1](#)). Phlogopite has Mg# values ranging from 0.59 to 0.62 ([Supplementary Dataset 1](#)). Fluorapatite occurs as an accessory phase.

Amphibole–plagioclase thermometry performed on six texturally equilibrated amphibole–plagioclase pairs yielded equilibrium temperatures of 774–831 °C. Corresponding pressure estimates derived from the amphibole–plagioclase calibration range from 170 to 260 MPa, whereas independent calculations based on the total Al content of magnesiohornblende yield pressures of 160–220 MPa ([Supplementary Dataset 2](#)). The two independent pressure estimates are mutually consistent and indicate comparable crystallization pressures for the analysed samples.

Zircon U–Pb dating and Lu–Hf isotopes

Zircon grains extracted from the analysed monzogranite sample are predominantly euhedral to subhedral and are approximately 150–200 µm long. Cathodoluminescence (CL) images reveal well-developed oscillatory zoning in most crystals, whereas inherited or xenocrystic cores were not observed ([Fig. 5a](#)). Analytical spots were preferentially positioned within oscillatory-zoned magmatic domains, while Lu–Hf analyses were placed to overlap previously dated U–Pb domains wherever possible.

A total of 41 LA–ICP–MS U–Pb spot analyses were obtained from 38 zircon grains. All 41 analyses were retained for the age calculation, and no analyses were excluded ([Supplementary Dataset 3](#)). The analysed zircons define a single statistically coherent population yielding a concordia age of 24.92±0.31 Myr (MSWD=1.3; probability of fit=0.65; n=41), interpreted as the crystallization age of the Kosmaj monzogranite ([Fig. 5](#)). No older inherited age populations were identified.

In situ Lu–Hf isotopic analyses were performed on 20 zircon domains that spatially overlap the dated U–Pb analyses

([Supplementary Dataset 4](#)). Initial ¹⁷⁶Hf/¹⁷⁷Hf ratios range from 0.28273 to 0.28297, corresponding to εHf(t) values between −1.2 and +7.0 ([Fig. 6](#)). The obtained εHf(t) values define a relatively narrow range, with most analyses yielding positive values.

Discussion

The integrated petrographic, mineral-chemical, thermobarometric, geochronological, and zircon Lu–Hf isotope data consistently indicate that the Kosmaj intrusion represents a shallowly emplaced, calc-alkaline I-type monzogranite crystallized during the Late Oligocene. The magnesiohornblende–phlogopite mineral assemblage and the presence of accessory titanite are consistent with a hydrous calc-alkaline granitoid affinity. Amphibole–plagioclase thermobarometry indicates crystallization temperatures of 774–831 °C and pressures of approximately 160–260 MPa, consistent with crystallization at shallow upper-crustal levels prior to or during final emplacement. Zircon crystals display well-developed oscillatory zoning and lack inherited cores, consistent with magmatic crystallization and providing no evidence for the incorporation of older zircon-bearing crustal material. Furthermore, the predominance of positive εHf(t) values, together with only slightly negative values, indicates that the parental magma was derived predominantly from juvenile mantle-derived sources with limited interaction with evolved continental crust. Collectively, these observations identify the Kosmaj intrusion as a mantle-influenced, shallowly emplaced calc-alkaline I-type granitoid and argue against extensive crustal anatexis as the dominant magma-producing process.

Within the regional framework, the Kosmaj monzogranite probably belongs to the Oligocene–Early Miocene I-type granitoid suite of the Internal Dinarides ([Kovács et al. 2007](#); [Schefer et al. 2011](#); [Stojadinovic et al. 2017](#); [Mladenović et al. 2025](#)). Its Late Oligocene age, magnesiohornblende-bearing mineral assemblage, shallow emplacement conditions, and predominantly juvenile zircon Hf isotopic signature closely resemble those reported from other I-type plutons throughout the Internal Dinarides, whereas they clearly differ from the younger Miocene S-type granitoids, which are predominantly

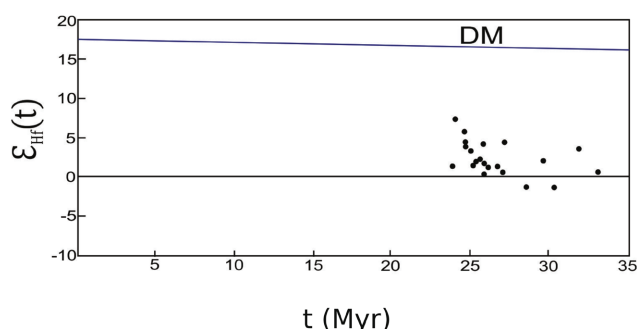


Fig. 6. εHf(t) versus age plots of zircons retrieved from the Kosmaj monzogranite.

peraluminous and characterized by stronger crustal isotopic signatures (Cvetković et al. 2007; Stojadinović et al. 2017; Löwe et al. 2021; Mladenović et al. 2025). An additional observation emerging from the available geochronological dataset is that Oligocene–Early Miocene I-type granitoids are consistently emplaced within, or immediately adjacent to, Upper Cretaceous trench-related successions of the Sava Zone deposited above the downgoing Adriatic plate, whereas comparable intrusions have not been documented from coeval Upper Cretaceous successions of the former European upper plate (see Fig. 1b). Although this spatial relationship alone does not uniquely constrain the underlying geodynamic mechanism, it represents an important first-order characteristic that any regional tectono-magmatic model must explain. In this context, the distribution of the Kosmaj intrusion is consistent with models invoking Neotethyan slab break-off beneath the Internal Dinarides (Schefer et al. 2011 and references therein), whereby slab detachment promoted asthenospheric upwelling, increased mantle heat input, and orogen-parallel E–W-directed extension accompanying gravitational collapse of the Dinaridic collisional belt. Such conditions would favour the generation and emplacement of mantle-influenced I-type granitoids within the former lower plate of the collisional system. In contrast, the younger Miocene S-type granitoids most likely record a subsequent tectono-magmatic stage that partly overlapped with, but became progressively dominated by, orogen-perpendicular N–S-directed extension associated with retreat of the Carpathian slab and development of the Pannonian Basin (Matenco & Radivojević 2012; Mladenović et al. 2025). Within this evolutionary framework, the Kosmaj monzogranite represents one of the youngest preserved granitoid intrusions belonging to the Oligocene–Early Miocene mantle-dominated I-type magmatic episode that preceded the transition towards the younger Miocene S-type magmatic regime.

Conclusions

Integrated petrographic, mineral-chemical, thermobarometric, zircon U–Pb geochronological, and zircon Lu–Hf isotope data demonstrate that the Kosmaj intrusion represents a shallowly emplaced calc-alkaline I-type monzogranite that crystallized during the Late Oligocene (24.92 ± 0.31 Myr). The magnesiohornblende–phlogopite mineral assemblage, low-pressure crystallization conditions (approximately 160–260 MPa), and predominantly positive zircon $\epsilon_{\text{Hf}}(t)$ values consistently indicate crystallization from mantle-influenced juvenile magmas that experienced only limited interaction with continental crust.

At the scale of the Internal Dinarides, the Kosmaj monzogranite is interpreted as part of the Oligocene–Early Miocene I-type granitoid suite, extending its distribution along the Sava Zone. Its emplacement within Upper Cretaceous trench-related deposits, together with the comparable tectonic position of other Oligocene–Early Miocene I-type intrusions,

suggests a systematic spatial relationship between this magmatic episode and the former lower plate of the Adria–Europe collisional system.

Acknowledgments: This research was supported by the Science Fund of the Republic of Serbia, GRANT No TF C1389-YF, GEODYNAMICS OF BASINS ABOVE SUBDUCTED SLABS: an integrated modelling study of tectonics, sedimentation, and magmatism in the Timok Magmatic Complex – TMCmod (PROJECT No 7461). We gratefully acknowledge Vlad-Victor Ene (Faculty of Geology and Geophysics, University of Bucharest) for his assistance in performing zircon U–Pb geochronological analyses. We also sincerely thank Dr. Máté Szemerédi and Prof. Vladica Cvetković for their thorough, constructive, and insightful reviews, which significantly strengthened the scientific content and interpretation of this manuscript.

References

- Bouvier A., Vervoort J.D. & Patchett P.J. 2008: The Lu–Hf and Sm–Nd isotopic composition of CHUR: constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets. *Earth and Planetary Science Letters* 273, 48–57. <https://doi.org/10.1016/j.epsl.2008.06.010>
- Cvetković V., Prelević D., Downes H., Jovanović M., Vaselli O. & Pécskay Z. 2004: Origin and geodynamic significance of Tertiary postcollisional basaltic magmatism in Serbia (central Balkan Peninsula). *Lithos* 73, 161–186. <https://doi.org/10.1016/j.lithos.2003.12.004>
- Cvetković V., Poli G., Christofides G., Koroneos A., Pécskay Z., Resimić-Šarić K. & Erić V. 2007: The Miocene granitoid rocks of Mt. Bukulja (central Serbia): evidence for Pannonian extension-related granitoid magmatism in the northern Dinarides. *European Journal of Mineralogy* 19, 513–532. <https://doi.org/10.1127/0935-1221/2007/0019-1736>
- Dimitrijević M.D. 1997: *Geology of Yugoslavia*. 2nd edition. Geoinstitute, Belgrade, 1–187.
- Dimitrijević M.N. & Dimitrijević M.D. 2009: The lower Cretaceous paraflysch of the Vardar zone: composition and fabric. *Geološki anali Balkanskoga poluostrva* 70, 9–21. <https://doi.org/10.2298/GABP0970009D>
- Fisher C.M., Vervoort J.D. & Hanchar J.M. 2014: Guidelines for reporting zircon Hf isotopic data by LA-MC-ICPMS and potential pitfalls in the interpretation of these data. *Chemical Geology* 363, 125–133. <https://doi.org/10.1016/j.chemgeo.2013.10.019>
- Gehrels G. & Pecha M. 2014: Detrital zircon U–Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America. *Geosphere* 10, 49–65. <https://doi.org/10.1130/GES00889.1>
- Gehrels G.E., Valencia V.A. & Ruiz J. 2008: Enhanced precision, accuracy, efficiency, and spatial resolution of U–Pb ages by laser ablation–multicollector–inductively coupled plasma–mass spectrometry. *Geochemistry, Geophysics, Geosystems* 9, Q03017. <https://doi.org/10.1029/2007GC001805>
- Holland T. & Blundy J. 1994: Non-ideal interactions in calcic amphiboles and their bearing on amphibole–plagioclase thermometry. *Contributions to Mineralogy and Petrology* 116, 433–447. <https://doi.org/10.1007/BF00310910>

- Ibáñez-Mejía M., Gehrels G.E., Ruiz J., Vervoort J.D., Eddy M.E. & Li C. 2014: Small-volume baddeleyite (ZrO₂) U–Pb geochronology and Lu–Hf isotope geochemistry by LA-ICP-MS. Techniques and applications. *Chemical Geology* 384, 149–167. <https://doi.org/10.1016/j.chemgeo.2014.07.011>
- Knežević V., Székyné-Fux V., Steiger R., Pécskay Z. & Karamata S. 1991: Petrology of Fruška Gora latites: volcanic precursors at the Southern Margin of the Pannonian Basin. In: Karamata S. (Ed.): *Geodynamic Evolution of the Pannonian Basin. Proceedings of the International Symposium*. Serbian Academy of Sciences and Arts Beograd, Yugoslavia, 18–20.
- Koroneos A., Poli G., Cvetković V., Christofides G., Krstić D. & Pécskay Z. 2011: Petrogenetic and tectonic inferences from the study of the Mts Cer pluton (West Serbia). *Geological Magazine* 148, 89–111. <https://doi.org/10.1017/S0016756810000476>
- Kovács I., Csontos L., Szabó C., Bali E., Falus G., Benedek K. & Zajacz Z. 2007: Paleogene–early Miocene igneous rocks and geodynamics of the Alpine–Carpathian–Pannonian–Dinaric region: An integrated approach. In: Beccaluva L., Bianchini G. & Wilson M. (eds): *Cenozoic Volcanism in the Mediterranean Area. Geological Society of America Special Paper* 418, 93–112. [https://doi.org/10.1130/2007.2418\(05\)](https://doi.org/10.1130/2007.2418(05))
- Krstekanić N., Matenco L., Toljić M., Mandić O., Stojadinovic U. & Willingshofer E. 2020: Understanding partitioning of deformation in highly arcuate orogenic systems: Inferences from the evolution of the Serbian Carpathians. *Global and Planetary Change* 195, 103325. <https://doi.org/10.1016/j.gloplacha.2020.103325>
- Leake B.E., Woolley A.R., Arps C.E.S., Birch W.D., Gilbert M.C. et al. 1997: Nomenclature of amphiboles: Report of the Subcommittee on Amphiboles of the IMA Commission on New Minerals and Mineral Names. *European Journal of Mineralogy* 9, 623–651. <https://doi.org/10.1127/ejm/9/3/0623>
- Löwe G., Schneider S., Sperner B., Balling P., Pfänder J.A. & Ustaszewski K. 2021: Torn Between Two Plates: Exhumation of the Cer Massif (Internal Dinarides) as a Far-Field Effect of Carpathian Slab Rollback Inferred From ⁴⁰Ar/³⁹Ar Dating and Cross Section Balancing. *Tectonics* 40, e2021TC006699. <https://doi.org/10.1029/2021TC006699>
- Löwe G., Prelević D. & Ustaszewski K. 2023: A first attempt at a provenance study in the Jadar block (Serbia) by means of U–Pb zircon geochronology. *Geološki anali Balkanskoga poluostrva* 84, 17–31. <https://doi.org/10.2298/GABP230303005L>
- Maleš M., Randjelović N., Krstekanić N., Kostić B., Ćirić N. & Stojadinovic U. 2023: New insights into tectonic relations between the Eastern Vardar Ophiolitic and Serbo–Macedonian units: Inferences from a microtectonic study in central Serbia. *Geološki anali Balkanskoga poluostrva* 84, 33–45. <https://doi.org/10.2298/GABP2301033M>
- Matenco L. & Radivojević D. 2012: On the formation and evolution of the Pannonian Basin: Constraints derived from the structure of the junction area between the Carpathians and Dinarides. *Tectonics* 31, TC6007. <https://doi.org/10.1029/2012TC003206>
- Mladenović A., Löwe G., Trivić B., Cvetkov V., Ustaszewski K., Xie J.-C., Sokol K. & Prelević D. 2025: Tectonic control on magmatism at a continental junction: The Bukulja Mountains Pluton, Internal Dinarides, SE Europe. *Tectonophysics* 917, 230945. <https://doi.org/10.1016/j.tecto.2025.230945>
- Mutch E.J.F., Blundy J.D., Tattitch B.C., Cooper F.J. & Brooker R.A. 2016: An experimental study of amphibole stability in low-pressure granitic magmas and a revised Al-in-hornblende geobarometer. *Contributions to Mineralogy and Petrology* 171, 85. <https://doi.org/10.1007/s00410-016-1298-9>
- Paces J.B. & Miller J.D. Jr. 1993: Precise U–Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: Geochronological insights to physical, petrogenetic, paleomagnetic, and tectonomagmatic processes associated with the 1.1 Ga Mid-continent Rift System. *Journal of Geophysical Research: Solid Earth* 98, 13997–14013. <https://doi.org/10.1029/93JB01159>
- Paton C., Woodhead J.D., Hellstrom J.C., Hergt J.M., Greig A. & Maas R. 2010: Improved laser ablation U–Pb zircon geochronology through robust downhole fractionation correction. *Geochemistry, Geophysics, Geosystems* 11. <https://doi.org/10.1029/2009GC002618>
- Paton C., Hellstrom J., Paul B., Woodhead J. & Hergt J. 2011: Iolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry* 26, 2508–2518. <https://doi.org/10.1039/c1ja10172b>
- Pavlović Z., Marković B., Atin B., Dolić D., Gagić N., Marković O., Dimitrijević M. & Vukotić M. 1977: *Osnovna geološka karta SFRJ 1:100.000. List Smederevo* [Basic geological map of Former Yugoslavia 1:100,000. Sheet Smederevo]. Savezni Geološki zavod, Beograd (in Serbian).
- Porkoláb K., Köver S., Benko Z., Heja G.H., Fialowski M., Soos B., Gerzina-Spajić N., Djerić N. & Fodor L. 2019: Structural and geochronological constraints from the Drina-Ivanjica thrust sheet (Western Serbia): implications for the Cretaceous–Paleogene tectonics of the Internal Dinarides. *Swiss Journal of Geosciences* 112, 217–234. <https://doi.org/10.1007/s00015-018-0327-2>
- Schefer S., Cvetković V., Fügenschuh B., Kounov A., Ovtcharova M., Schaltegger U. & Schmid S.M. 2011: Cenozoic granitoids in the Dinarides of southern Serbia: age of intrusion, isotope geochemistry, exhumation history and significance for the geodynamic evolution of the Balkan Peninsula. *International Journal of Earth Sciences* 100, 1181–1206. <https://doi.org/10.1007/s00531-010-0599-x>
- Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K. 2008: The Alpine–Carpathian–Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geosciences* 101, 139–183. <https://doi.org/10.1007/s00015-008-1247-3>
- Schmid S.M., Fügenschuh B., Kounov A., Matenco 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. <https://doi.org/10.1016/j.gr.2019.07.005>
- Sláma J., Košler J., Condon D.J., Crowley J.L., Gerdes A. et al. 2008: Plešovice zircon – A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology* 249, 1–35. <https://doi.org/10.1016/j.chemgeo.2007.11.005>
- Söderlund U., Patchett P.J., Vervoort J.D. & Isachsen C.E. 2004: The ¹⁷⁶Lu decay constant determined by Lu–Hf and U–Pb isotope systematics of Precambrian mafic intrusions. *Earth and Planetary Science Letters* 219, 311–324. [https://doi.org/10.1016/S0012-821X\(04\)00012-3](https://doi.org/10.1016/S0012-821X(04)00012-3)
- Stojadinovic U. & Krstekanić N. 2023: Tectono-sedimentary evolution of the NE Dinarides margin during the Cretaceous Adriatic–Europe convergence. *Geološki anali Balkanskoga poluostrva* 84, 65–74. <https://doi.org/10.2298/GABP2301065S>
- Stojadinovic U., Matenco L., Andriessen P., Toljić M., Rundić L. & Ducea M.N. 2017: Structure and provenance of Late Cretaceous–Miocene sediments located near the NE Dinarides margin: Inferences from kinematics of orogenic building and subsequent extensional collapse. *Tectonophysics* 710–711, 184–204. <https://doi.org/10.1016/j.tecto.2016.08.019>
- Stojadinovic U., Krstekanić N., Matenco L. & Bogdanović T. 2022: Towards resolving Cretaceous to Miocene kinematics of the Adriatic–Europe contact zone in reconstructions: inferences from a structural study in a critical Dinarides area. *Terra Nova* 34, 523–534. <https://doi.org/10.1111/ter.12582>

- Stojadinovic U., Randjelovic N., Kostić B., Maleš M., Grujovski-Stanisavljević M. & Srećković-Batočanin D. 2026: Extension-driven evolution of magmatic systems in slab-top basins: insights from the Timok magmatic complex, Serbian Carpathians. *Frontiers in Earth Science* 14, 1781275. <https://doi.org/10.3389/feart.2026.1781275>
- Toljić M., Matenco L., Stojadinovic U., Willingshofer E. & Ljubović-Obradović D. 2018: Understanding fossil fore-arc basins: Inferences from the Cretaceous Adria-Europe convergence in the NE Dinarides. *Global and Planetary Change* 171, 167–184. <https://doi.org/10.1016/j.gloplacha.2018.09.019>
- Toljić M., Glavaš-Trbić B., Stojadinovic U., Krstekanić N. & Srećković-Batočanin D. 2020: Geodynamic interpretation of the Late Cretaceous syn-depositional magmatism in central Serbia: Inferences from biostratigraphic and petrographical investigations. *Geologica Carpathica* 71, 526–538. <https://doi.org/10.31577/GeolCarp.71.6.4>
- 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, TC6017. <https://doi.org/10.1029/2010TC002668>

Electronic supplementary material is available online:

Supplementary datasets 1–4 at https://geologicacarpathica.com/data/files/supplements/GC-77-6-Ciric_Supplement.xlsx