

Granitic magmatism at the Adria–Europe boundary during the waning of Neotethys: Geochemical and geochronological insights from the Sava Zone, Pannonian Basin (Croatia)

Sanja Šuica^{a,b,*}, Dejan Prelević^c, István Dunkl^d, Jin-Cheng Xie^e, Vesnica Garašić^f, Alan B. Woodland^g, Nina Trinajstić^h, Mihovil Brlek^h

^a Department of Geology, University of Zagreb Faculty of Science, Horvátovac 102a, 10000 Zagreb, Croatia

^b Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Croatia

^c University of Belgrade – Faculty of Mining and Geology, Djušina 7, 11000 Belgrade, Serbia

^d Department of Sedimentology and Environmental Geology, Geoscience Centre, Georg-August-University Göttingen, Goldschmidtstraße 3, 37077 Göttingen, Germany

^e China University of Geosciences, Xueyuan Road 29, 100083 Beijing, China

^f University of Zagreb Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, 10000 Zagreb, Croatia

^g Institut für Geowissenschaften, Goethe Universität Frankfurt, Altenhöferallee 1, 60438 Frankfurt, Germany

^h Department of Geology, Croatian Geological Survey, Sachsova 2, 10000 Zagreb, Croatia

ARTICLE INFO

Keywords:

A-granite
I-granite
Zircon
Late Cretaceous
Dinarides
Tisia

ABSTRACT

In southeastern Europe, the Late Cretaceous Sava Zone igneous rocks consisting of tholeiitic and alkaline basalts, rhyolites and minor A-type granites were interpreted as intraoceanic or fore-arc. This view had strong impact on regional interpretation, proposing that Neotethys ocean did not close during the Mid-Late Jurassic ophiolite obduction but remained open in the Late Cretaceous. The Sava zone is largely covered by deposits of the Pannonian Basin. The Late Cretaceous igneous rocks from the boreholes in eastern Croatia were subjected to geochemical, in situ zircon U–Pb dating and Hf in zircon isotope analysis. Drava Depression is situated in the upper-plate Tisia megaunit, and the orthogneiss with Late Permian A-type protolith (257 ± 2.6 Ma, $\epsilon_{\text{Hf}}(i) = +2.4$ to -3.1) placed the studied part of Slavonia-Srijem Depression within the same unit. Drava hosts calc-alkaline to high-K calc-alkaline I-type granodiorite-monzodiorite (77.3 ± 1.1 Ma, $\epsilon_{\text{Hf}}(i) = +3.3$ to -3.2), with microgranular mafic enclaves, and hybrid quartz-monzodioritic rocks originating from magma-mixing. Slavonia-Srijem hosts A-type alkali-feldspar granites and quartz-alkali-feldspar syenite (83.7 ± 0.6 to 78.8 ± 0.7 Ma; $\epsilon_{\text{Hf}}(i) = +9.7$ to -0.8). Both suites were generated by mixing of mantle and continental crust-derived melts and display geochemical affinity towards Sava Zone, but distinction arise from lower thickness of crust in Slavonia-Srijem. They point to intracontinental origin of Sava Zone magmatism, caused by asthenosphere uprise, proving the absence of ocean in the Late Cretaceous, and indicating complex (post-)collisional processes as a trigger for magmatism.

1. Introduction

The transition from subduction to final ocean closure, with or without ophiolite obduction, represents one of the most complex stages in the Wilson cycle. During this phase, as the system transforms into a collisional orogenic setting, it can be followed by magmatism geochemically resembling intraoceanic one but incorporating substantial components derived from the ensialic continental lithosphere. Understanding the nature of such magmatism is therefore essential for

reconstructing the final stages of ocean closure and the early phases of continental collision.

A comparable transition marked the evolution of the Neotethys Ocean, whose progressive consumption culminated in the formation of the Alpine-Himalayan collisional orogenic belt – a vast and long-lived convergent boundary between Eurasia and Gondwana that has been active since the Permian and early Mesozoic (Schmid et al., 2008). The geological architecture of the southeastern Europe reflects the assembly of several tectonic mega-units (Fig. 1). During the convergence Moesia,

* Corresponding author at: Croatian Natural History Museum, Demetrova 1, 10000 Zagreb, Croatia.

E-mail address: sanja.suica@hpm.hr (S. Šuica).

<https://doi.org/10.1016/j.lithos.2026.108743>

Received 8 February 2026; Received in revised form 21 July 2026; Accepted 18 August 2026

Available online 20 August 2026

0024-4937/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Dacia and Tisia represented parts of the upper, European plate, while ALCAPA (Alps-Carpathians-Pannonia), Southern Alps and Adria-derived nappes of the Dinarides and Hellenides represented the lower, Gondwana-derived Adriatic plate (Schmid et al., 2008, 2020).

The evolution of the ocean involved several stages, from Middle Triassic rifting and divergent spreading during the Late Triassic–Early Jurassic, to Early–Middle Jurassic intraoceanic subduction, and Middle–Late Jurassic ophiolite obduction (Bortolotti et al., 2013; Šuica et al., 2018; Gorican et al., 2022; Slovenec and Segvić, 2023). The onset of obduction and convergence marking the beginning of Neotethys closure is recorded by metamorphic soles formed between 149 and 192 Ma (Lanphere et al., 1975; Karamata and Lovrić, 1978; Segvić et al., 2020). However, the timing and mechanism of final ocean closure remain controversial, representing one of the key unresolved topics in the evolution of the Alpine–Himalayan system (Prelević et al., 2017; Sokol et al., 2020).

Two competing models have been proposed for the final stages of this process, the first with continental collision following soon after ophiolite obduction in the Late Jurassic–Early Cretaceous (Spahić and Gaudenyi, 2022; Stanković et al., 2023), consistent with reconstructions of the Hellenides (Bortolotti et al., 2013), and the second with parts of the Neotethys Ocean persisting until the Late Cretaceous–Paleogene (Schmid et al., 2008, 2020; Ustaszewski et al., 2009, 2010). Support for the latter interpretation comes from Upper Cretaceous calc-alkaline magmatism in the Apuseni-Banat-Timok-Srednogorie (ABTS) belt within the upper (European) plate (Fig. 1), and contemporaneous basalts interlayered with pelagic limestones in the Sava Zone interpreted as oceanic crust (Cvetković et al., 2014; Ustaszewski et al., 2009). Yet, some authors dispute the oceanic origin of the Late Cretaceous basic rocks (Prelević et al., 2017; Sokol et al., 2025; Mladenović et al., 2026) and the active subduction-related genesis of the ABTS magmatism

(Stanković et al., 2026).

Although extensive studies exist on the magmatism of both the ABTS and Sava Zone belts, there are no direct comparisons between them. Consequently, the geodynamic significance of the Sava Zone magmatism, interpreted either as oceanic intraplate (Ustaszewski et al., 2009; Toljić et al., 2018) or intracontinental (Prelević et al., 2017; Sokol et al., 2020, 2025) remains unclear. Like basalts, tectonic setting of rhyolitic and scarce A-type granitic rocks has also been interpreted both as intraoceanic (Cvetković et al., 2014) and intracontinental (Balén et al., 2020; Schneider et al., 2022, 2025). The problem is further compounded by the limited exposure of the Sava Zone, most of which is buried beneath Neogene and Quaternary cover (Pamić et al., 2000; Šuica et al., 2022).

To address the open questions about the Sava Zone, we investigated Late Cretaceous granitic rocks from the basement of the Pannonian Basin in eastern Croatia, namely Drava and Slavonija-Srijem Depression. Petrographic, mineralogical and geochemical analysis, zircon U–Pb dating coupled with zircon Hf isotope data will provide valuable insight into their age, petrogenesis and tectonic setting. Furthermore, it is necessary to define whether studied rocks occur in the upper or lower plate. While this is clear for the Drava Depression overlying Tisia mega-unit, the Slavonija-Srijem overlies a collage of different tectonic units. So, besides granitic rocks, the orthogneiss located 15–20 km east of A-type granites was included in this study to provide insight into a regional affiliation of that part of Slavonija-Srijem Depression. By integrating our data with published information on the ABTS and Sava Zone magmatic belts, we provide a robust and refined framework for delineating the principal Late Cretaceous magmatic provinces of southeastern Europe, thereby improving constraints on the timing, nature, and geodynamic significance of magmatism along the Adria–Europe boundary during the waning stages of the Tethyan cycle.

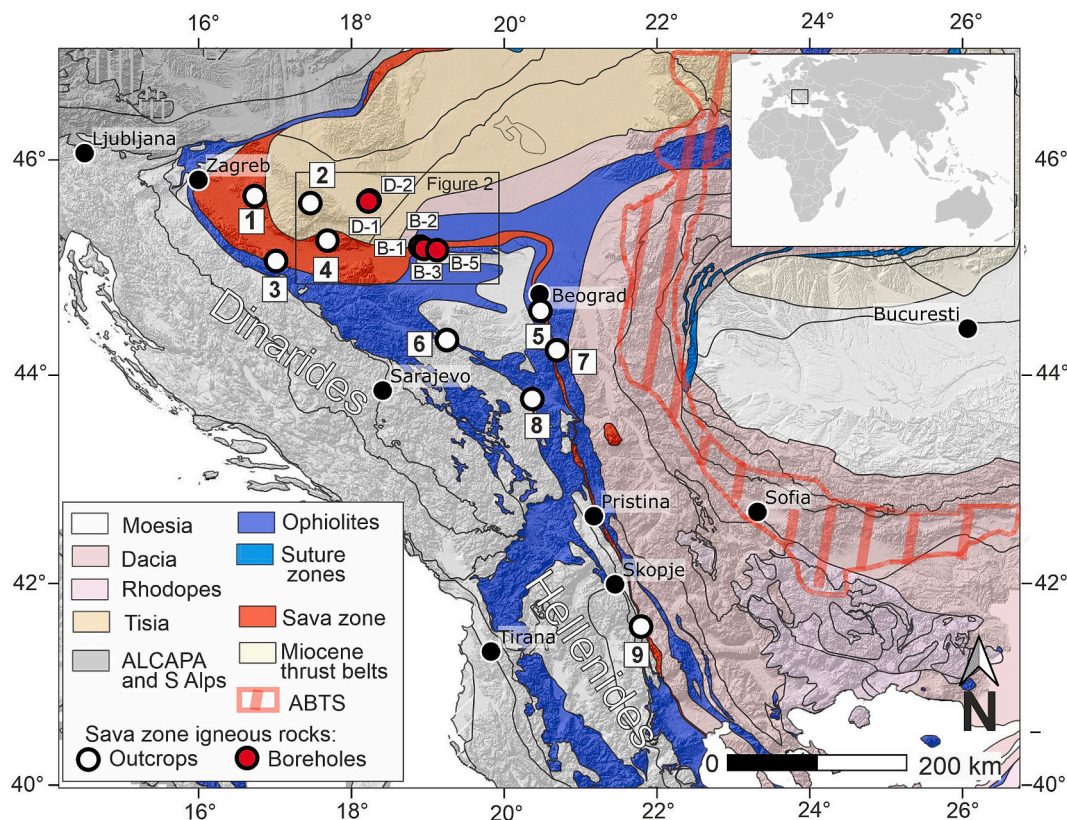


Fig. 1. Map of tectonic units in south-eastern Europe (after Schmid et al., 2020), indicating the position of major Late Cretaceous magmatic belts – ABTS (Apuseni-Banat-Timok-Srednogorie), outcrops of Sava Zone igneous rocks: 1-Moslavačka Gora Mt., 2-Papuk Mt., 3-Kozara Mt. and Prosara Mt., 4-Požeska Gora Mt., 5-Ripanj Mt., 6-Rujevac, 7-Topola, 8-Jelica, 9-Klepa Mt. and boreholes studied in this paper. Digital elevation model (DEM) from © EuroGeographics 2025.

2. Geological setting

During the Late Cretaceous, two different magmatic belts were active in SE Europe: the Apuseni-Banat-Timok-Srednogorie Belt (ABTS) and the Sava Zone (Fig. 1). The ABTS is located on the European plate and represents a calc-alkaline magmatic-metallogenic belt consisting of plutonic, volcanic and volcanoclastic rocks with age range ~ 95 to 67 Ma (Berza et al., 1998; Popov et al., 2002; Gallhofer et al., 2015; Georgiev et al., 2021). Associated with extensional tectonics, the ABTS was originally considered as post-collisional (Berza et al., 1998; Popov et al., 2002), but a subduction-related origin as an Andean-type arc has become a more prevalent scenario (Gallhofer et al., 2015; Georgiev et al., 2021 and references therein). The latter scenario requires a remnant Neotethys Ocean during the Late Cretaceous, and the so-called Sava Ocean is considered the most viable candidate (Ustaszewski et al., 2009, 2010).

The Sava Zone is defined as a belt of igneous and Cretaceous flysch-type sedimentary rocks, interpreted as a suture between the Adriatic and European plates (Schmid et al., 2020). Here, the Late Cretaceous magmatism is mainly manifested by volcanic activity of bimodal character, accompanied by minor shallow plutonism including A-type granites, which crops out in the Kozara and Prosara Mts. in Bosnia and Herzegovina (Ustaszewski et al., 2009, 2010; Cvetković et al., 2014), Zrinska Gora Mt. (Olić Peco et al., 2026) and Požeška Gora Mt. in Croatia (Belak et al., 1998; Pamić et al., 2000; Balen et al., 2020) and Klepa Mountain in North Macedonia (Prelević et al., 2017). Contemporaneous ultrapotassic magmatism in the vicinity of Belgrade and the S-type acidic plutonism of Moslavačka Gora are also attributed to the Sava Zone (Schmid et al., 2008; Sokol et al., 2020). U-Pb zircon ages based on ID-TIMS have been reported for Kozara dolerite (81.4 ± 0.11 Ma), and rhyolite (81.6 ± 0.12 Ma) and Prosara alkali-feldspar granite (82.68 ± 0.13 Ma; Ustaszewski et al., 2009), and in situ LA-ICP-MS for Požeška Gora A-type granite (83.6 ± 1.5 Ma; Balen et al., 2020) and Moslavačka Gora S-type granite (82 ± 2 Ma; Starijaš et al., 2010). Ar-Ar ages from hornblende yielded ~ 80 Ma for Klepa basalt (Prelević et al., 2017) and 86.5 ± 0.5 Ma from phlogopite for Ripanj lamprophyre (Sokol et al.,

2020). Additionally, an in situ LA-ICP-MS U-Pb zircon age of 80.8 ± 1.8 Ma is reported for Papuk Mt. albite rhyolites (80.8 ± 1.8 Ma – 81.1 ± 1.1 Ma) and andesite (81.1 ± 1.1 Ma), located on the upper European plate (Schneider et al., 2022). Localities with Late Cretaceous basalts are also described from both lower and upper-plate localities in Serbia (Jelica, Rujevac and Topola; Sokol et al., 2025), with lower-plate Jelica basalts yielding 87.4 ± 1.8 Ma zircon U-Pb ages obtained by LA-ICP-MS (Mladenović et al., 2026).

While its subduction-unrelated character has never been disputed, different and often conflicting tectonic scenarios have been proposed for the magmatism of the Sava Zone. In line with an intraoceanic interpretation of bimodal magmatism (Ustaszewski et al., 2009; Cvetković et al., 2014), the Sava Zone is understood as a Late Cretaceous basin with oceanic lithosphere subducting beneath the European plate (Schmid et al., 2008, 2020; Ustaszewski et al., 2009, 2010). In contrast, an intracontinental setting has been proposed for bimodal magmatism (Belak et al., 1998; Prelević et al., 2017; Balen et al., 2020; Schneider et al., 2022), and slightly older ultrapotassic rocks (Sokol et al., 2020). This raised the question of the existence of the Late Cretaceous Sava Ocean (Prelević et al., 2017; Sokol et al., 2020; Spahić and Gaudenyi, 2022).

Besides surface outcrops, Late Cretaceous igneous rocks were reported from boreholes in the eastern Drava Depression and the Slavonia-Srijem Depression (Pamić and Pécskay, 1994; Pamić et al., 2000; Šuica et al., 2022). This area is largely concealed beneath Neogene and Quaternary sedimentary cover (Fig. 2). According to Schmid et al. (2020) in the Slavonia-Srijem Depression, key tectonic domains of the Adria–Europe junction are juxtaposed (Fig. 2). The pre-Neogene basement of the eastern part of the Drava Depression belongs to the Tisia mega-unit. Pamić et al. (2000) reported Late Cretaceous volcanic rocks of the Sava Zone affiliation within the Drava Depression.

3. Samples

The studied material comprises core samples from the pre-Neogene basement of four boreholes in the Slavonia-Srijem Depression and two

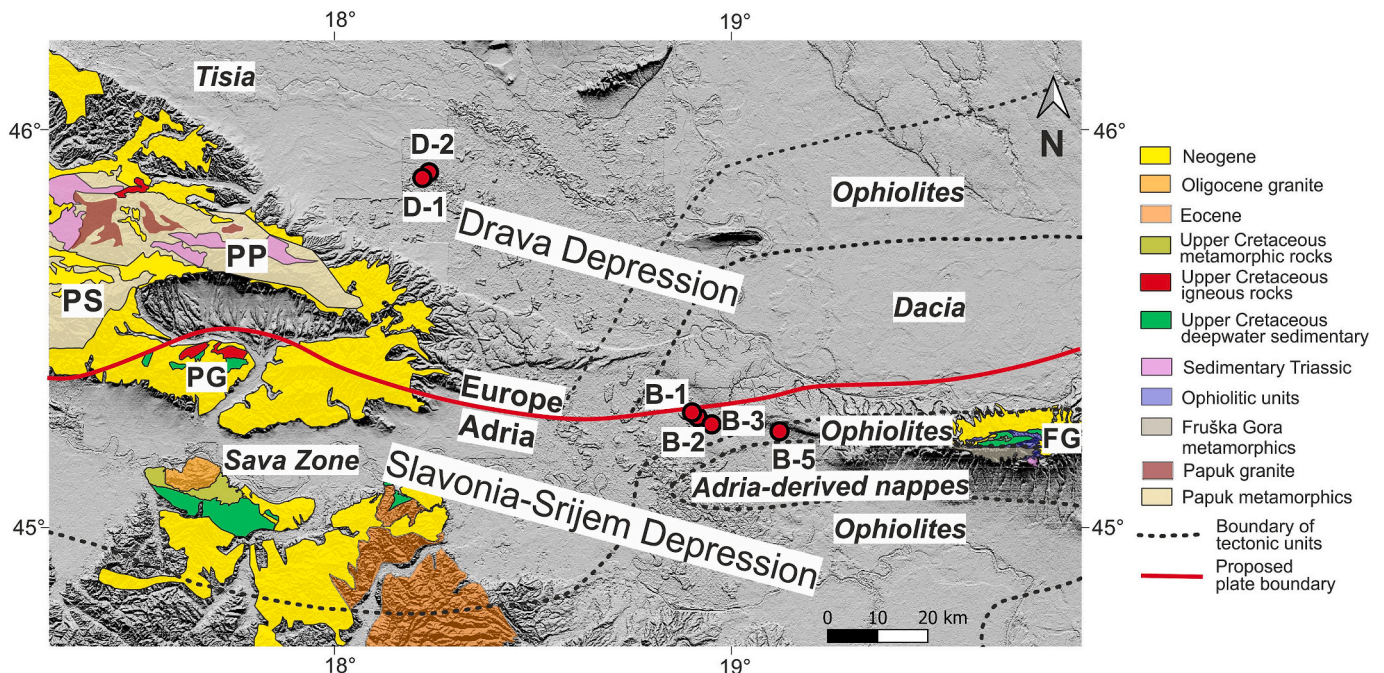


Fig. 2. Geological map of study area with the borehole locations indicated (simplified after Čičulić-Trifunović and Rakić, 1978; Čičulić-Trifunović and Galović, 1984; Croatian Geological Survey, 2009; Šparica et al., 1979; Šparica, 1986;). Digital elevation model (DEM) from © EuroGeographics 2025. PP-Papuk Mt., PS-Psunj Mt., PG-Požeška Gora Mt., FG-Fruška Gora Mt. Grey area with digital elevation model correspond to Pliocene to Holocene sedimentary cover. Boundaries of the tectonic units and proposed plate boundary from Schmid et al. (2020).

boreholes in the Drava Depression (Table 1; Fig. 2). The list of samples and applied methods is presented in Table 1.

Rock classification is shown in the Q–A–P diagram (Fig. 3). Petrography and geochemistry of the SSD samples were previously reported by Šuica et al. (2022) while a concise overview is provided here. Slavonia-Srijem rocks selected for this study are represented by two types of alkali-feldspar granite, one with perthitic (Fig. 4a), and other with antiperthitic feldspar (Fig. 4b), the quartz-alkali-feldspar syenite (Fig. 4c) and the orthogneiss (Fig. 4d).

The Drava igneous rocks in borehole D-1, consist of melanocratic fine-grained equigranular to porphyritic quartz monzodiorite and monzonite to granodiorite, for simplicity regarded as intermediate rocks (IMR) in the further text. The IMR is both in sharp and diffuse contact with monzogranite-granodiorite, hosting numerous microgranular mafic enclaves (MME, Fig. 5a–e). These MME display various shapes, from angular and ellipsoid with sharp contacts and locally leucocratic halos (Fig. 5c) to amoeboid, pillowed (Fig. 5d) and disaggregated (Fig. 5e) with diffuse contacts. Coarser-grained leucocratic veins cut all phases of the pluton. The lowermost material is IMR and gneiss (Fig. 5f), but it is fragmented and no contact is preserved. In borehole D-2, the pre-Neogene basement is quartz-monzodiorite, with subordinate gneiss, while the deepest part is composed of amphibolite and dacite.

4. Methods

Whole-rock chemical analysis was performed by Bureau Veritas Minerals (Vancouver, Canada) using inductively coupled plasma emission spectroscopy (ICP-ES) for major elements and inductively coupled plasma mass spectrometry (ICP-MS) for trace elements. The rocks were analyzed after sample solution by 4-acid digestion of a 0.25 g sample, while the REE was determined after $\text{LiBO}_2/\text{Li}_2\text{B}_4\text{O}_7$ fusion and nitric acid digestion of a 0.1 g sample. Additionally, modified aqua regia digestion (1:1:1 $\text{HNO}_3:\text{HCl}:\text{H}_2\text{O}$) of 0.5 g and 15 g of material (the latter for samples D-1-4-9, D-1-6-9, D-1-7-35, D-1-6-0 D-1-3-2) was used to

Table 1

List of samples and the applied analytical methods.

Sample	Area	Borehole	Cored interval (m)	Lithology	Analysis
B-1-5	SSD	B-1	1140–1141.5	AF granite	*, ZRC
B-2-1	SSD	B-2	1028–1029.5	AF granite	*, ZRC
B-3-5	SSD	B-3	1093–1099	Quartz-AF syenite	*, ZRC
B-5-2	SSD	B-5	1568–1570	Gneiss	*, ZRC
D-1-19-4-9	DD	D-1	2407–2413.49	MME	Pet, WRA
D-1-9D	DD	D-1	2394–2403	MME	Pet, WRA
D-1-19-3-2	DD	D-1	2407–2413.49	IMR	Pet, WRA
D-1B	DD	D-1	2475–2476	IMR	Pet, WRA, EPMA
D-1-19-6-9	DD	D-1	2407–2413.49	IMR	Pet, WRA
D-1-19-6-0	DD	D-1	2407–2413.49	IMR	Pet, WRA
D-1-22	DD	D-1	2570–2571	IMR	Pet, WRA
D-1	DD	D-1	2475–2476	IMR	Pet, WRA
D-2-4	DD	D-2	2349–2352	IMR	Pet, WRA
D-1-9G	DD	D-1	2394–2403	GRD + MME	Pet, WRA
D-1-17-7-35	DD	D-1	2394–2403	GRD	Pet, WRA, ZRC
D-1-8G	DD	D-1	2394–2403	MZG	Pet, WRA
D-1-22G	DD	D-1	2570–2571	Gneiss	Pet, WRA

Abbreviations: DD, Drava Depression, SSD, Slavonia-Srijem Depression; AF, alkali-feldspar; MME, microgranular mafic enclave; IMR, intermediate rocks; GRD, granodiorite; MZG – monzogranite; *, the petrography and geochemistry of these samples were published in Šuica et al. (2022); ZRC, zircon U–Pb age by LA-ICP-MS; Pet, petrography; WRA, whole-rock geochemical analysis; EPMA, electron probe microanalysis.

analyze Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Ag, Au, Hg, Tl, and Se. GeoChemical Data ToolKIT 4.1 software was used for data handling (Janoušek et al., 2006).

Mineral compositions were analyzed using a JEOL JXA 8900 electron microprobe (EPMA) at the Institut für Geowissenschaften, Goethe Universität Frankfurt, operating in wavelength-dispersive mode (WDS) with a 15 kV accelerating voltage, 20 nA (12 nA for feldspars) beam current, and $\sim 3 \mu\text{m}$ beam diameter. Raw data were corrected using CITZAF quantitative matrix correction implemented by JEOL. The mineral formula for feldspar is calculated on the basis of eight oxygen atoms, for amphibole on the basis of 13 cations and 23 oxygen atoms, and for biotite on the basis of 22 O anions and 15 cations, using the spreadsheets retrieved from <https://www.gabbrosoft.org/spreadsheets/>, created by Jeremy Preston. The amphiboles are classified after Leake et al. (1997).

Heavy mineral separation of the 63–125 μm grain-size fraction was performed using sodium polytungstate ($\rho = 2.89 \text{ g cm}^{-3}$). Zircon morphology was determined by scanning electron microscopy (SEM). Grains were mounted on a metal stub, coated with a 15 nm gold layer, and imaged using a JEOL JSM-6510 LV SEM with energy dispersive spectroscopy (EDS, Oxford Instruments, INCA system) at INA-Industrija nafte d.d., Exploration and Production Laboratory, Zagreb.

Zircon crystals selected for U–Pb dating were fixed on a double-sided adhesive attached to a thick glass plate and embedded in a 25 mm diameter epoxy mount. The crystal mount was lapped a 2500 mesh SiC paper and polished using a 9 μm diamond suspension. For all zircon samples and standards used in this study, cathodoluminescence (CL) images were obtained using a JEOL JXA-iHP200F electron microprobe at Geozentrum Göttingen to study their internal structure and to select homogeneous parts for in situ age determinations. The carbon coating used for CL imaging was subsequently removed with a brief hand polish using a 1 μm diamond cloth. In situ U–Pb dating was performed using laser ablation single-collector sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS). The method employed for the analysis was described in detail by Frei and Gerdes (2009). A Thermo Finnigan Element 2 mass spectrometer coupled to a Resonetics Excimer laser ablation system was used. All age data presented here were obtained by single-spot analyses with a laser beam diameter of 33 μm and a crater depth of approximately 10 μm . The laser was fired at a repetition rate of 5 Hz and at nominal laser energy output of 25%. Two laser pulses were used for the pre-ablation. The carrier gases used were He and Ar. Analytes ^{238}U , ^{235}U , ^{232}Th , ^{208}Pb , ^{207}Pb , ^{206}Pb , mass204, and ^{202}Hg were measured by ICP-MS. The data reduction was based on the processing of ca. 46 selected time slices (corresponding to ca. 13 s) starting ca. 3 s. at the start of the signal. If the ablation hits zones or inclusions with highly variable actinide concentrations or isotope ratios, the integration interval was slightly resized, or the analysis was discarded ($\sim 1\%$ of the spots). The individual time slices were tested for possible outliers using an iterative Grubbs test (applied at $P = 5\%$ level). This test filtered out only the extremely biased time slices, and in this way usually less than 2% of the time slices were rejected. Age calculation and quality control are based on drift and fractionation correction by standard sample bracketing using the GJ-1 zircon reference material (Jackson et al., 2004). For further control the Plešovice zircon (Sláma et al., 2008), the 91,500 zircon (Wiedenbeck et al., 1995) and the FC-1 zircon (Paces and Miller, 1993) were analyzed as “secondary standards.” The age results of the standards were consistently within 2σ of the published ID-TIMS values. Drift and fractionation correction and data reduction were performed using in-house software (UranOS; Dunkl et al., 2008). The level of the Hg-corrected ^{204}Pb signal was very low; thus, no common Pb correction was required. If the $^{206}\text{Pb}/^{238}\text{U}$ age was younger than 1.5 Ga then we considered this age, however when the age was older than 1.5 Ga then the $^{207}\text{Pb}/^{206}\text{Pb}$ age was used. This threshold value was determined empirically according to the error trends of the U–Pb and Pb–Pb ages (e.g. Spencer et al., 2016). Zircon grains with age discordance $>10\%$ were not considered for interpretation. The concordia plots and age spectra were constructed using Isoplot/Ex 4.15

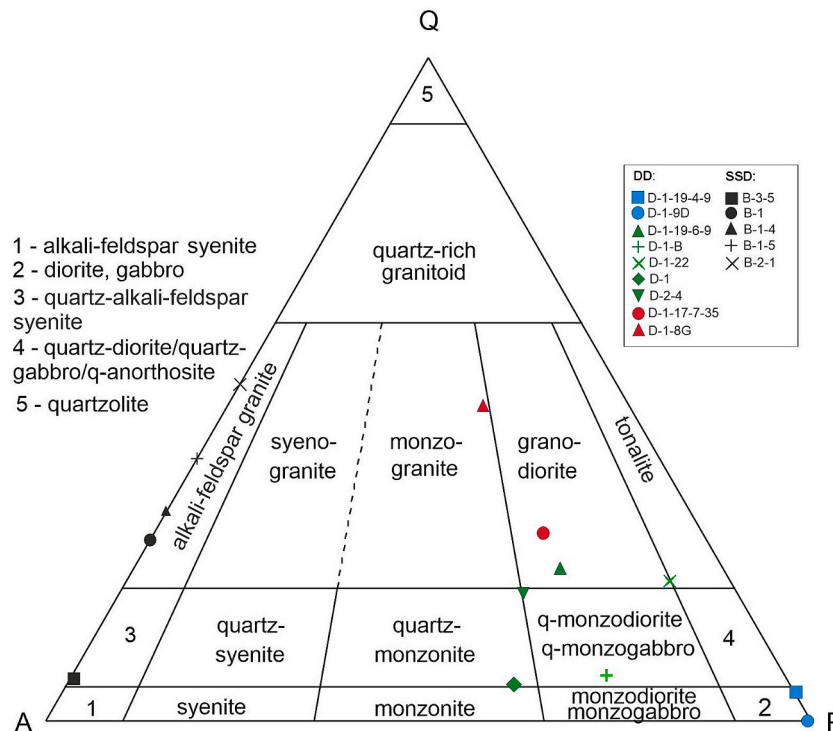


Fig. 3. QAP modal composition diagram after Streckeisen (1974): Q — quartz, A — alkali feldspar, P — plagioclase. DD – Drava Depression, SSD – Slavonia-Srijem Depression.

(Ludwig, 2012) and Isoplot R (Vermeesch, 2018).

In-situ zircon Hf isotopic analyses were conducted using a Neptune Plus MC-ICP-MS (Thermo Fisher Scientific, Germany), coupled to a RESOLUTION S155HR excimer ArF laser-ablation system at the Milma Lab, China University of Geosciences (Beijing) with a beam size of 35 μm , laser pulse frequency of 8 Hz and energy density of 3.0 J cm^{-2} . Makeup gas of argon and carrier gas of helium with the addition of nitrogen mixed in a T-branch pipe prior to introduction into the MC-ICP-MS. In the experiment, L4 to H3 Faraday cups were used to collect ^{171}Yb , ^{173}Yb , ^{175}Lu , ^{176}Lu , ^{176}Hf , ^{177}Hf , ^{178}Hf , ^{179}Hf , and ^{180}Hf , respectively, with the integration time of 0.131 s. The carrier and makeup gas flows were optimized by a line scan (spot size of 35 μm and scan speed of 5 $\mu\text{m}/\text{s}$) ablating NIST SRM610 to obtain maximum signal intensity for ^{232}Th , while minimizing $^{232}\text{Th}/^{16}\text{O}$ ratio. For each analysis, 20 s integration for gas blank and 50 s integration for signal collection were set up with a total of 550 cycles of raw data. Zircon 91500 was used as an external standard for correcting mass discrimination. Zircon standard Plešovice and GJ-1 were analyzed as unknown samples that were inserted between zircon 91500 and the samples. Raw data were converted by Neptune Plus software and then processed using Iolite software.

Single spot measurements with a diameter of 35 μm were situated at the same spots of U – Pb measurement. The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\varepsilon_{\text{Hf}}(t)$ values were calculated with reference to the chondritic reservoir (CHUR) at the time of zircon growth from the magmas. The decay constant for ^{176}Lu of $1.867 \times 10^{-11} \text{ year}^{-1}$ (Söderlund et al., 2004), the chondritic $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282785 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0336 (Bouvier et al., 2008) were adopted. Depleted mantle model ages (TDM) were calculated with reference to the depleted mantle at a present-day $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.28325, and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ (Griffin et al., 2000). The Hf isotope crustal model age (TDMC) was calculated by assuming that its parental magma was derived from an average continental crust, with $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$, that originated from the depleted mantle source (Griffin et al., 2002).

5. Results

5.1. Petrography and mineral chemistry of samples from the Drava area

The monzogranite-granodiorite (Fig. 6 a, b) displays seriate to locally cataclastic textures and consists of plagioclase (31–46 vol%), quartz (26–44 vol%), and orthoclase (18–19 vol%), with biotite (6–9 vol%) and accessory hornblende, ilmenite, apatite, and zircon. Secondary phases include calcite, chlorite, sericite, epidote, and clay minerals. In addition to abundant MMEs, fine-grained enclaves composed of microcline, plagioclase, quartz, and biotite locally occur, showing inequigranular to amoeboid textures indicative of xenolithic origin (Fig. 6b).

The intermediate rocks (IMR, Fig. 6 c-f), exhibit hypidiomorphic granular textures (Fig. 6c), locally porphyritic or poikilitic, and partly cataclastic. They contain plagioclase (36–50 vol%), hornblende (23–33 vol%), orthoclase (7–28 vol%), quartz (4–15 vol%), minor biotite (<5 vol%), and accessory ilmenite, apatite, and zircon. Secondary minerals include chlorite, carbonate, epidote, titanite, pyrite, hematite, sericite, and clay minerals. EPMA analyses (Electronic supplementary materials ESM 1, Table 1) indicate that plagioclase is normally zoned oligoclase with subordinate albite rims (core $X_{\text{An}} = 15.5\text{--}21.1$; rim $X_{\text{An}} = 8.0\text{--}21.0$). Hornblende (0.03–1.2 mm) is calcic, predominantly magnesio-hornblende with subordinate ferro-hornblende and rare ferrotschermakite-ferropargasite (ESM 2 Fig. 1b). Grain cores are characterized by higher Al_{IV} and $\text{Na}_A + \text{K}_A$ and lower Si than rims. Orthoclase is high-temperature K-feldspar with relatively high albite contents ($X_{\text{Ab}} = 6.0\text{--}12.7$; ESM2 Fig. 1a). The biotite compositions include low K_2O contents (5.48–8.78 wt%), elevated FeO, and depressed totals (<93 wt%). It has relatively high TiO_2 content (3.09–5.06 wt%), Fe/(Fe + Mg) ratios of 0.61–0.65, and Al_{IV} values of 2.16–2.47 p.f.u., but these parameters should be interpreted with caution due to the incomplete preservation of primary chemistry.

Microgranular mafic enclaves (MMEs) have intergranular to porphyritic textures (Fig. 6g) and consist of plagioclase (55–61 vol%), hornblende (30–41 vol%), minor biotite (4–6 vol%), and local quartz (<3 vol



Fig. 4. Samples from Slavonija-Srijem Depression: a) alkali-feldspar granite (B-1-5), b) alkali-feldspar granite (B-2-1), c) quartz-alkali-feldspar syenite (B-3-5); d) orthogneiss (B-5-2).

%), plus accessory ilmenite, apatite, and zircon. Alteration is stronger in smaller enclaves and resulting in secondary assemblage as in IMR.

Detailed description of mineral phases from monzogranite-granodiorite, intermediate rocks and MMEs is provided in Table 2.

Leucocratic veins are medium- to coarse-grained, dominated by anhedral to subhedral quartz, orthoclase, and plagioclase, locally with hornblende, biotite, and ilmenite.

The *gneiss* has a porphyroclastic texture (Fig. 6h) and is composed of plagioclase (~34 vol%), quartz (~33 vol%), microcline (~19 vol%), biotite (~14 vol%) and accessory apatite and zircon. The secondary minerals include calcite, chlorite, sericite, and clay minerals.

5.1.1. Petrographic evidence for magma-mixing and hybridization

MMEs in the monzogranite-granodiorite represent mafic magma blobs injected into a felsic magma chamber, as indicated by their finer grain size, pillow-like and amoeboid shapes (Fig. 5d), diffuse contacts (Fig. 5d, e), and disintegrated textures (Fig. 5e e.g., Frost and Mahood, 1987; Vernon, 1984). Poikilitic biotite, quartz pools and quartz-plagioclase globules in the enclaves and local leucocratic halos around them (Fig. 5a) support enclave-host interaction. The IMR represents a hybrid magma rather than a cumulate. It shows sharp contacts with the monzogranite-granodiorite but also has diffuse transition zones with MMEs. Textures vary markedly even within a single thin section.

Disequilibrium features include sieve- and patchy-zoned plagioclase (Fig. 6c-f), resorbed plagioclase margins against quartz and orthoclase, ocelli-like hornblende rims (Fig. 6e), anti-rapakivi alkali-feldspar overgrowths, abundant acicular apatite, and disturbed crystallization sequences where hornblende occurs both as early inclusions (Fig. 6d) and late poikilitic grains (Fig. 6f). These features collectively reflect dynamic interaction between mafic and felsic magmas and hybridization.

5.2. Petrography and mineral chemistry of samples from the Slavonia-Srijem area

The *alkali-feldspar granites* (Fig. 4a, b) are leucocratic, pinkish to grey, and range from coarse-grained equigranular to fine-grained hololeucocratic varieties. Coarser samples from B-1 borehole are locally porphyritic, with K-feldspar phenocrysts (≤ 5 mm) set in a granophyric matrix, whereas finer-ones from the B-2 borehole display prominent graphic quartz-feldspar intergrowths. Mineralogically, the coarser granites consist mainly of perthitic K-feldspar (up to 67%) with low albite contents ($X_{Ab} = 2-6$), quartz (25), and albite (3%), with low anorthite ($X_{An} = 2-6$), accompanied by accessory biotite, hornblende, zircon, apatite, and opaque minerals. Biotite is characterized by a high Fe/(Fe + Mg) ratio (0.66 to 0.71), moderate TiO_2 (1.57–3.77 wt%), and Al_{IV} values of 2.10–2.71 p.f.u. Hornblende is calcic, ferro-edenite, characterized by



Fig. 5. Samples from Drava Depression: a) sharp contact between monzogranite-granodiorite and microgranular mafic enclave (MME), characterized by leucocratic halo; b) contact between monzogranite-granodiorite and intermediate rock (IMR); c) angular MME in monzogranite-granodiorite (D-1-19-4-9); d) larger pillow-like MME (D-1-9G) and numerous smaller MME in monzogranite-granodiorite (D-1-9G); e) disaggregated MME in monzogranite-granodiorite (D-1-17-7-35); the composition of the area where MME is disaggregated fully resembles composition of the IMR; f) gneiss (D-1-22G).

low total Al (1.08–1.34 apfu; ESM 2 Fig. 1). Albite locally forms rounded clusters with hornblende and biotite, possibly representing small microgranular mafic enclaves. MMEs are present in the deepest intervals and may occur together with miarolitic cavities. Secondary minerals include sericite, chlorite, hematite, carbonate, kaolinite, epidote, allanite, titanite, fluorite, pyrite, calcite, and minor stilpnomelane. The fine-grained variety (Fig. 4 b) consists of quartz (46 vol%), antiperthitic albite (40 vol%), perthitic K-feldspar (8 vol%), accessory apatite, zircon, and opaque minerals. Secondary minerals include sericite (6 vol%), chlorite, hematite, carbonate, and kaolinite.

The leucocratic quartz-alkali-feldspar syenite (Fig. 4c) is porphyritic, coarse-grained, and largely subjected to brittle deformation. It is composed of K-feldspar (56 vol%), albite (32 vol%), minor quartz (5 vol%), biotite (4 vol%), and hornblende (2 vol%) with accessory zircon, apatite, and opaque minerals. Secondary minerals are chlorite, epidote, hematite, carbonate, sericite, and kaolinite. The orthogneiss (Fig. 4d)

exhibits a porphyroclastic texture and contains quartz (33–35 vol%), plagioclase (28–34 vol%), microcline (19–25 vol%), biotite (6–14 vol%), muscovite (5 vol%), and garnet (1 vol%), with accessory apatite, zircon, and opaque minerals. Secondary phases include calcite, chlorite, sericite, and clay minerals.

5.3. Whole rock geochemistry

The analyzed Drava igneous rocks (ESM 1, Table 2) span a wide range of SiO₂ contents (48.72–66.36 wt%). The MMEs (samples D-1-19-4-9 and D-1-9D) are characterized by high Al₂O₃, TiO₂, Fe₂O₃, P₂O₅, Na₂O, and K₂O, coupled with low CaO, MgO, Mg# (40–48%), and SiO₂ (<50 wt%). The IMR samples (D-1-19-3-2, D-1-19-6-0, D-1-19-6-9, D-1-22, D-1, and D-2-4) display similar major-element signatures, but show notable enrichment in Na₂O and P₂O₅. Sample D-1B differs from the rest of the IMR group by its elevated CaO and MgO and lower Fe₂O₃, Na₂O,

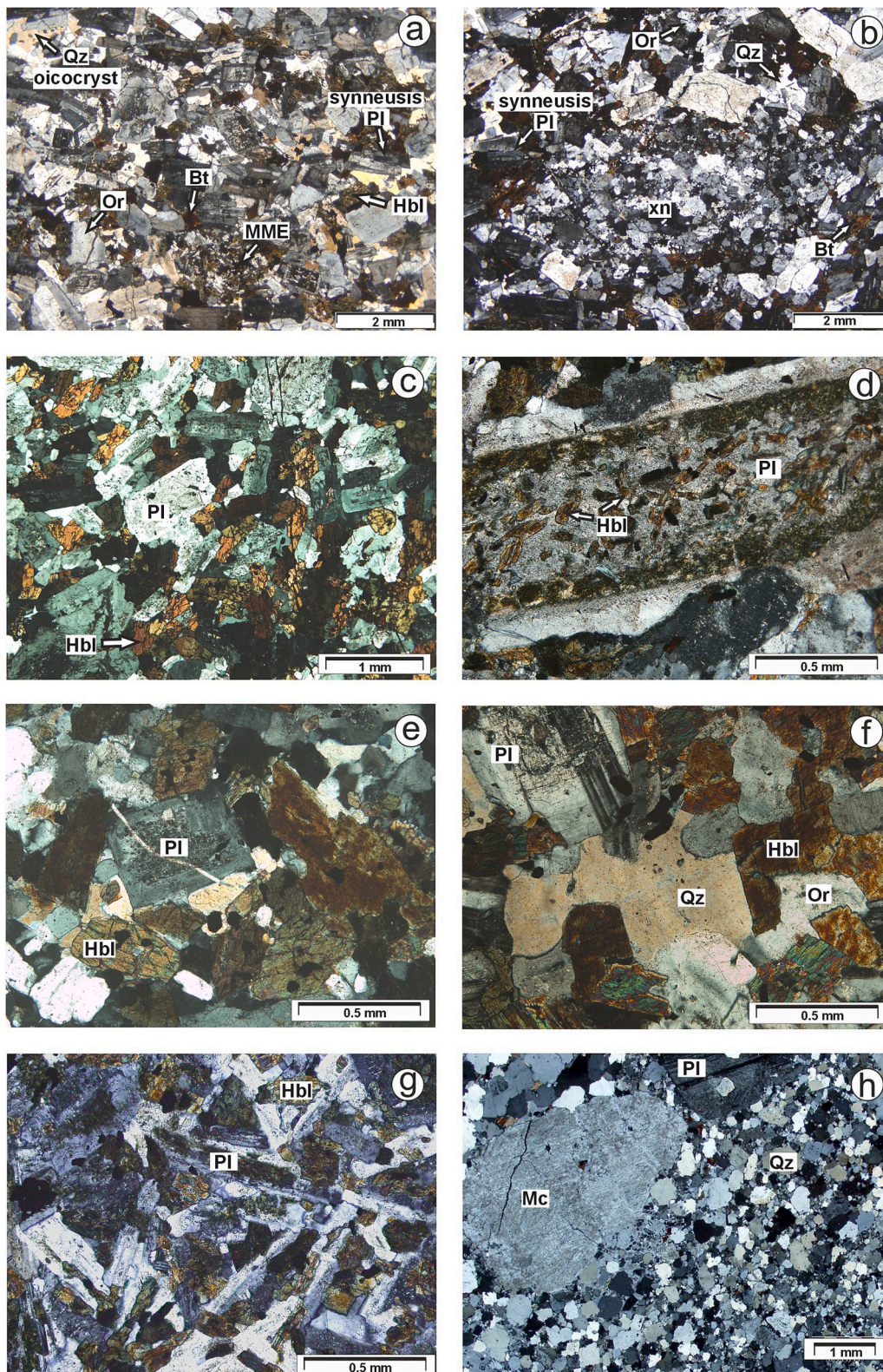


Fig. 6. Microphotographs of samples from Drava Depression in crossed-polarized light: a) monzogranite-granodiorite with synneusis plagioclase, quartz oikocrysts and microgranular mafic enclave (MME) (D-1-9G); b) monzogranite-granodiorite with xenolith composed of microcline, plagioclase, quartz, and biotite (D-1-8G); c) intermediate rock (IMR) with hypidiomorphic granular texture; d) IMR with plagioclase containing chloritized core with numerous inclusions of hornblende (D-1-22); e) IMR with plagioclase and quartz surrounded by hornblende in ocelli-like forms (D-1); f) plagioclase with altered core and fresh rim, intergranular quartz in IMR (D-1B); g) intergranular texture of MME (D-1-9D); h) porphyroblast of microcline in gneiss (D-1-22G). Abbreviations: Pl-plagioclase, Qz-quartz, Hbl-hornblende, Or-orthoclase, Bt-biotite, Mc-microcline, MME-microgranular mafic enclave, xn-xenolith.

Table 2

Detailed petrographic description of main mineral phases in igneous rocks of Drava area.

Lithology	Monzogranite-granodiorite	Intermediate rocks (IMR)	MMEs
Plagioclase	0.1–4.3 mm - subhedral, prismatic - weakly zoned - locally forms synneusis clusters - near MMEs euhedral and aligned parallel to enclave margins, commonly with patchy zoning	0.1–5 mm - mostly subhedral, prismatic - weakly zoned - larger grains with patchy zoning and sieve-textured cores, hornblende or biotite inclusions - resorbed contacts with quartz and orthoclase	0.02–0.8 mm in groundmass ≤3 mm phenocrysts - prismatic phenocrysts (≤3 mm) with patchy zoning and inclusions of hornblende and biotite - quartz-plagioclase globules (<10 mm)
Quartz	0.2–2 mm - anhedral, interstitial - locally oikocrystic	–0.1–2 mm - anhedral, interstitial - locally oikocrystic	- present locally ≤0.2 mm interstitial ≤1.5 mm in pools, near enclave-host contacts - not present
Orthoclase	0.1–2 mm, - anhedral - local micro to cryptoperthitic exsolution	≤1 mm - anhedral, - micro to cryptoperthitic exsolution - interstitial rims or oikocrysts around hornblende and plagioclase, commonly producing anti-rapakivi textures	
Biotite	0.1–1 mm - anhedral to subhedral flakes	0.2–1 mm - anhedral flakes	0.1–0.5 mm - anhedral, locally poikilitic
Hornblende	0.3–1 mm - subhedral-euhedral - commonly resorbed - restricted to domains near MMEs	0.03–1.2 mm - subhedral-euhedral - interstitial or inclusion-rich forms - local ocelli-like rims around plagioclase	0.1–0.4 mm - prismatic to subhedral - both interstitial and poikilitic - forms aggregates <2 mm
Apatite	- acicular and stubby	- acicular - crosscuts adjacent grains - abundant	- acicular - in clusters and grain-crosscutting arrays

P₂O₅, and TiO₂ contents (ESM 2, Fig. 1). The monzogranite-granodiorite samples (D-1-9G, D-1-17-7-35, and D-1-8G) are magnesian, calc-alkalic, and metaluminous to weakly peraluminous (Fig. 7). The gneiss (D-1-22G) is marked by high SiO₂ (71.90 wt%), elevated Na₂O (3.93 wt%), and low K₂O (1.54 wt%) content.

Slavonija-Srijem igneous rocks also display a wide range in SiO₂ concentration, from quartz-alkali-feldspar syenite (B-3-5) with 61.05 wt % to alkali-feldspar granites with 72.59–77.89 wt%. They are ferroan but display different compositions with respect to MALI (modified alkali-lime index) and aluminium saturation, with quartz-alkali-feldspar syenite being alkalic and metaluminous, alkali-feldspar granite (B-1-3, B-1-4, B-1-5) alkali-calcic and metaluminous to slightly peraluminous, while alkali-feldspar granite (B-2-1) is calcic and peraluminous (Fig. 7a-c). The calcic composition of alkali-feldspar granite B-2-1 reflects very low K₂O content (1.41 wt%). The orthogneiss (B-5-2) had moderate SiO₂ (67.11 wt%), ferroan, alkali-calcic and peraluminous character (Fig. 7a-c). Slavonija-Srijem rocks mainly belong to the high-K calc-alkaline series, while Drava igneous rocks are calc-alkaline and subordinately high-K calc-alkaline (Fig. 7d).

The Drava igneous rocks have moderate to high Nb/Y ratios (0.5–1.1), indicating a general tendency towards alkaline affinities,

which is also the case for the Slavonija-Srijem (0.9–1.6, Fig. 7e). Primitive mantle-normalized spider diagrams show that the MMEs are enriched in Pb and slightly enriched in U and Th, with depletions in Nb, Ta, and Y and minor negative anomalies in Ba, Sr, and Eu in one sample (Fig. 8a). The IMR group exhibits more variable behaviour without consistent anomalies across all samples (Fig. 8b). Most, however, show enrichment in U, Th, and Pb and slight depletions in Ba, Nb, Sr, Eu, and Y. The monzogranite-granodiorite samples display enrichment in Th, U, Pb, Zr, and Hf, with moderate enrichment in Sr and Eu in certain cases, a pattern also observed in the gneiss (Fig. 8a). Alkali-feldspar granites display greater enrichment in trace elements, except for Ba, Sr and Eu, which display deep negative anomalies. Quartz-alkali-feldspar syenite is characterized by slight negative anomaly of Sr, and positive anomalies of Rb, Nb, Zr and Hf.

Chondrite-normalized REE patterns for Drava igneous rocks indicate moderate LREE/HREE fractionation ($La_N/Yb_N = 4.9–8.0$; Fig. 8c, d). Although absolute REE concentrations are higher in the MMEs and IMR relative to the monzogranite-granodiorite and gneiss, the most pronounced difference lies in the Eu anomaly. The MMEs and IMR exhibit weakly negative Eu anomalies ($Eu/Eu^* = 0.84–0.98$), whereas the monzogranite-granodiorite ($Eu/Eu^* = 1.07–1.33$) and gneiss ($Eu/Eu^* = 1.24$) have positive anomalies. The Slavonija-Srijem igneous rocks also display moderate LREE/HREE enrichment ($La_N/Yb_N = 6.0–7.4$; Fig. 8c, d), with pronounced negative Eu anomaly for alkali-feldspar granites (0.12–0.27) and no Eu anomaly for the quartz-alkali-feldspar syenite (1.00).

5.4. Zircon morphology and internal texture

Most zircons are euhedral to subhedral, colourless, and transparent, although milky grains are also present, especially in the alkali-feldspar granite B-2-1. The zircons from all samples contain inclusions and display complex internal textures, as revealed by CL imaging (ESM 2 Fig. 3). Granodiorite (sample D-1-17-7-35) also contains zircons with resorption embayments. Zircon typology is classified according to Pupin (1980).

Zircons from orthogneiss (B-5-2), are mainly elongated, subordinately stubby, corresponding to the P₅, P₄ and P₃ subtypes (ESM 2 Fig. 4a). Their aspect ratio ranges from 1.2:1 to 3.3:1 (average 2.4:1). CL images reveal oscillatory zoning, whereas convolute and sector zoning, and resorption are less common. Antecrystic/xenocrystic cores are present in some grains.

In the alkali-feldspar granite (sample B-1-5), zircons are mainly elongated, (mainly P₅ and D subtypes (ESM 2 Fig. 4b) with aspect ratio 1.2:1 to 2.6:1 (average of 2.3:1). Zircons from the alkali-feldspar granite (sample B-2-1) are mainly short prismatic, D subtypes, subordinately P₃₋₅ (ESM 2 Fig. 4c) and have aspect ratio from 1.1:1 to 3.2:1 (average 1.6:1). In quartz-alkali-feldspar syenite (samples B-3-5), zircons are both stubby and elongated, mainly S₂₄ and S₂₅, subordinately J₄ (ESM 2 Fig. 4c) and have aspect ratio from 1.1:1 to 3.6:1 (average 1.8). Their internal texture is characterized by oscillatory and sector zoning, with subordinate resorption and convolute zoning. Minor antecrystic cores are present in the alkali-feldspar granites (samples B-1-5 and B-2-1), whereas quartz-alkali-feldspar syenite (sample B-3-5) also contains homogeneous grains.

The zircons from the granodiorite (sample D-1-17-7-35) are mainly S₂₅, subordinately S₂₄₋₂₃ and J₅ (ESM 2 Fig. 4e), but S₁₋₆₋₁₁ are also present, as are P₁ types (ESM 2 Fig. 4f). Their aspect ratio ranges from 1:1 to 4.6:1 (average 1.7). Internal texture is characterized by oscillatory and convolute zoning with resorption (ESM 2 Fig. 3). Most of the grains contain xenocrystic cores.

5.5. Zircon U-Pb ages

The results of zircon U-Pb dating by LA-ICP-MS along with corresponding diagrams are presented in ESM 1 Table 3. The individual data

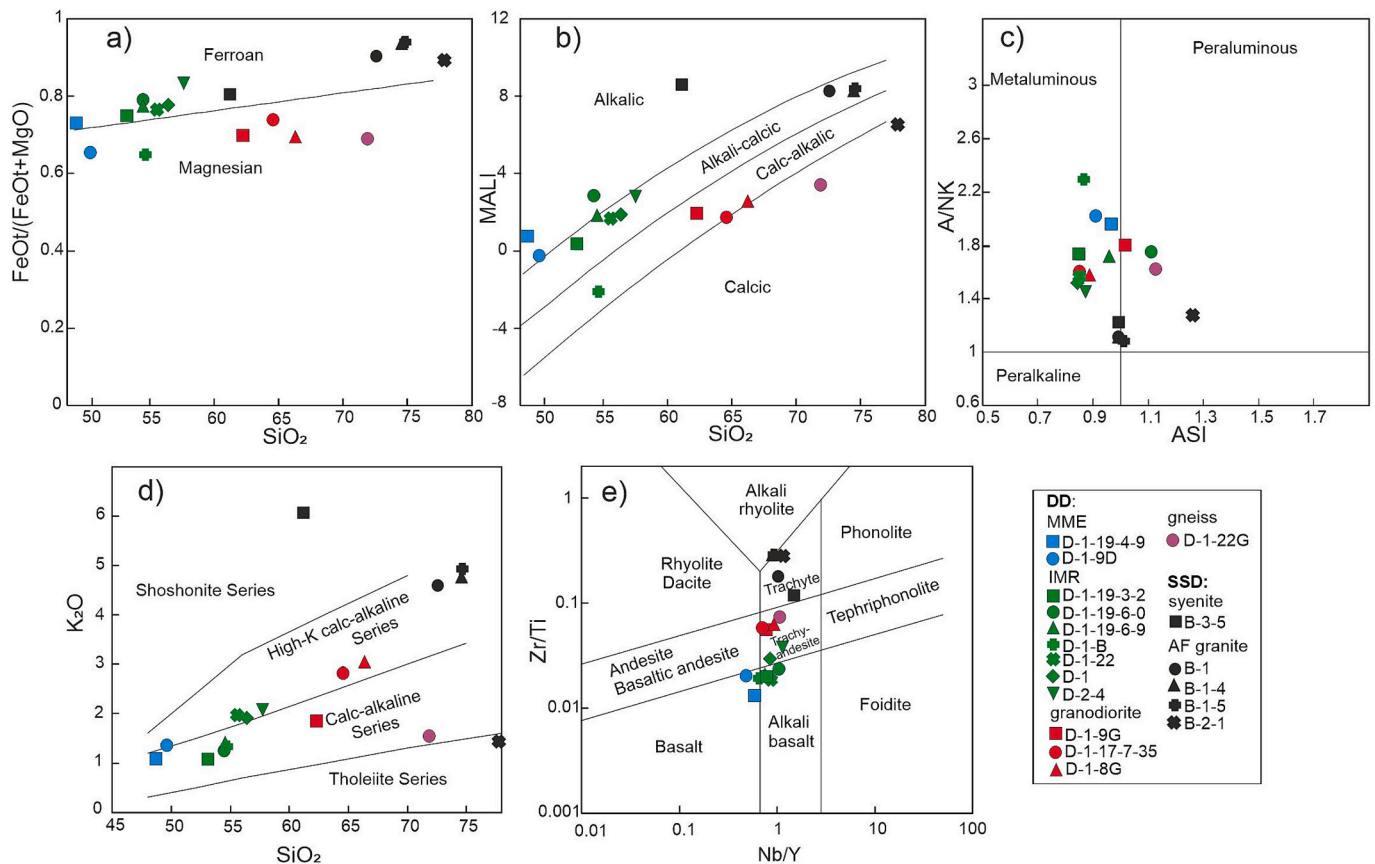


Fig. 7. Whole-rock classification diagrams: a) SiO_2 – $\text{FeOt}/(\text{FeOt}+\text{MgO})$; b) SiO_2 – $\text{Na}_2\text{O} + \text{K}_2\text{O}-\text{CaO}$; c) $\text{ASI} - \text{A/NK}$, after Frost et al. (2001) d) SiO_2 – Na_2O after Peccerillo and Taylor (1976); e) $\text{Nb/Y} - \text{Zr/Ti}$ after Pearce (1996).

for the orthogneiss (B-5-2) are mostly concordant (only two of them are discordant by more than $\pm 10\%$). However, they yield strong scatter, plotting along the concordia curve between 250 and 280 Ma; thus, the concordia age can be considered meaningless. Therefore, the weighted mean age of 257 ± 2.6 Ma was used. Aside from the Permian orthogneiss, all other samples resulted in Late Cretaceous ages. According to their ages and actinide element-based chemistry, these zircons formed in igneous bodies of different compositions and emplacement ages.

In the alkali-feldspar granite (sample B-1-5), no xenocrysts were found, but 8 out of 26 data are discordant at the $\pm 10\%$ level. The mean age can be calculated in three different ways: intercept age, weighted mean age, and concordia age. As they all yield values between 80.0 and 80.4 Ma, this value can be considered robust, and the weighted mean age of 80.0 ± 1.0 Ma is considered as the emplacement age.

In the alkali-feldspar granite (sample B-2-1), 6 of 22 analyses are discordant. This sample has the highest U concentrations (1000 to 4000 $\mu\text{g/g}$). The high alpha-dose, and thus the high degree of metamictization, is responsible for the discordant data and scatter. The weighted mean age of concordant data yields 83.7 ± 0.6 Ma.

In the quartz-alkali-feldspar syenite (sample B-3-5), only one of the 31 analyses is discordant. However, in this case, the weighted mean age algorithm and the $\pm 5\%$ concordant age yield significant differences. There is obvious clustering of the data around ca. 79 Ma and a tail of older ages that draws an average of ca. 80 Ma. The CL patterns of this sample are rather chaotic; thus, the weighted mean age of 78.8 ± 0.7 Ma could provide the most reliable age estimation.

In the granodiorite (sample D-1-17-7-35), of the 23 zircons analyzed, 9 resulted in much older ages than the Cretaceous (~ 284 Ma to > 2 Ga). These must be either xenocrysts or inherited cores. For the remaining 14 crystals, the scatter is too large for a reliable concordia age, but they supply a weighted mean age of 77.3 ± 1.1 Ma.

5.6. Hafnium isotopes in zircon

The Lu-Hf isotopic compositions of zircons, together with ϵHf and $\epsilon\text{Hf}_{(t)}$ values, are reported in ESM 1 Table 4 and Fig. 9. Zircons from all analyzed units show a wide $\epsilon\text{Hf}_{(t)}$ range but most of the Late Cretaceous magmatic grains record positive values (Fig. 9b).

The orthogneiss sample B-5-2, yielding Permian U-Pb crystallization ages, contains zircons with $\epsilon\text{Hf}_{(t)}$ values between +2.4 and -3.1 , with average value of -0.2 and median value -0.3 , after excluding outliers (+5.8 and -20.0). Xenocrystic cores, recalculated to their individual ages, yield $\epsilon\text{Hf}_{(t)}$ values of +0.9 and -8.8 .

Zircons from the Late Cretaceous Slavonia–Srijem igneous suite show consistently juvenile to slightly evolved signatures. After excluding the outliers, alkali-feldspar granite B-2-1 displays the highest $\epsilon\text{Hf}_{(t)}$ (+9.7 to +4.0), with average and median values of +6.4, followed by alkali-feldspar granite B-1-5 (+8.7 to -0.8) with average +4.7 and median value of +5.1. Quartz-alkali-feldspar syenite B-3-5 shows slightly lower values +6.5 to -0.2 , with average +3.4 and median +3.7.

The Late Cretaceous Drava granodiorite D-1-17-7-35 displays lower $\epsilon\text{Hf}_{(t)}$ values (+3.3 to -3.2 , after excluding the outlier +5.6). Xenocrystic zircons recalculated to their crystallization ages show a broad spread (+6.1 to -52.9) but are predominantly negative, as reflected by their average value of -0.3 and median -0.9 . When recalculated to ~ 77 Ma, approximating the time of granodiorite emplacement, all inherited zircons shift to negative $\epsilon\text{Hf}_{(t)}$.

6. Discussion

Our data demonstrate the presence of two distinct series of Late Cretaceous granitic rocks in the subsurface of the Pannonian Basin. Although broadly coeval, these rocks differ in their mode of occurrence,

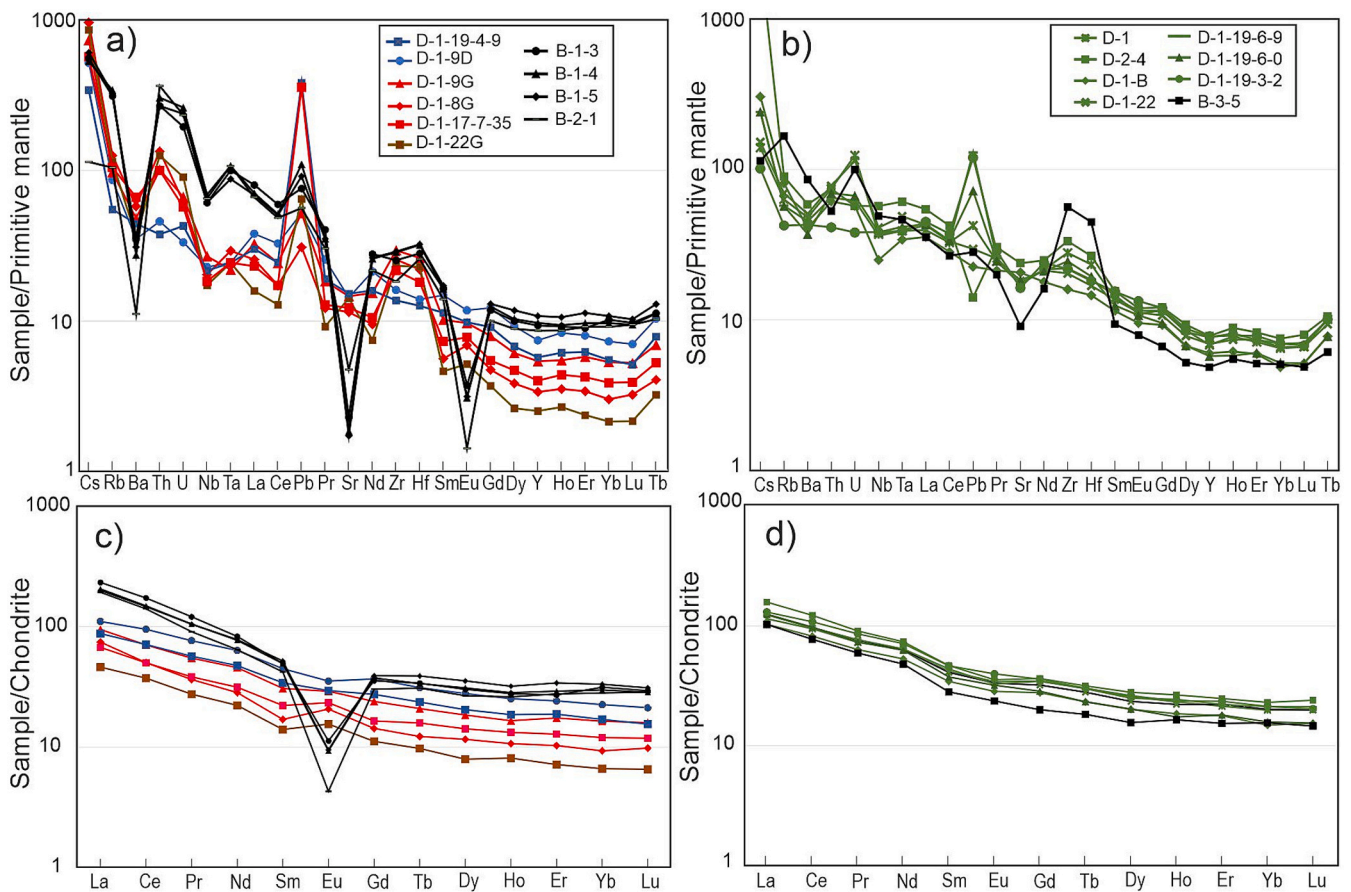


Fig. 8. Primitive mantle-normalized trace element signatures (Sun and McDonough, 1989) of MME, monzogranite-granodiorite and gneiss, as well as alkali-feldspar granites (a) and intermediate rocks (IMR), including quartz-alkali-feldspar syenite (b). Chondrite-normalized REE patterns (McDonough and Sun, 1995) of MME, monzogranite-granodiorite and gneiss, as well as alkali-feldspar granites (c) and intermediate rocks (IMR) including quartz-alkali-feldspar syenite (d). MME – microgranular mafic enclaves, IMR – intermediate rocks.

mineralogy, petrography, geochemistry and zircon Hf-isotope composition, implying different petrogenetic histories. We suggest that these differences primarily reflect variations in parental material composition and continental crustal thickness. Although the presence of secondary minerals points to partial alteration of analyzed rocks, the absence of cerium anomaly ($Ce/Ce^* = 0.97\text{--}1.06$), with consistent chondrite-normalized REE and primitive mantle-normalized trace element patterns (with the exception of Pb, Cs and U in certain samples) indicates that this alteration did not substantially affect trace element distributions (Polat et al., 2002), so they can be used for discussion of igneous processes.

6.1. Typology and classification of the Late Cretaceous igneous rocks

Among the many classification schemes proposed for granitic rocks, the traditional I – S – A-type subdivision (Chapell and White, 1974; Loiselle and Wones, 1979) remains widely used and is applicable to the rocks examined here. The more mafic samples were additionally classified using established scheme of Peccerillo and Taylor (1976).

The geochemical characteristics of Drava granodiorite-monzogranite, such as metaluminous compositions with $Na_2O > K_2O$, magnesian, calc-alkalic and metaluminous to weakly peraluminous character indicate an I-type affinity typical of continental-arc batholiths (Frost et al., 2001). Their trace-element signatures with enriched large-ion lithophile element (LILE) to high-field-strength element (HFSE) ratios and LREE-enriched REE patterns (Fig. 8) point to subduction-related and/or continental crustal magmatism (Pearce, 2008; Sun and McDonough, 1989). Associated hybrid IMR and MME display a

predominantly ferroan and alkali-calcic character, and elevated Nb/Y, pointing to more alkaline affinity (Fig. 7e). Hornblende in IMR is mainly Mg-rich, with transition to Fe-rich members. All igneous members of the Drava samples, including the MMEs belong to calc-alkaline to high-K calc-alkaline series (Fig. 7d).

In contrast, the Slavonia–Srijem alkali-feldspar granites are ferroan, alkali-calcic and metaluminous (Fig. 7a–c). Their high concentrations of high-field-strength elements (Zr, Nb, Y), elevated Ga/Al and strong depletions in Ba, Sr and Eu clearly point to an A-type affinity (Fig. 8), as previously recognized by Šuica et al. (2022). This is supported by the presence of Fe-rich hornblende and biotite and zircon typology indicative of crystallization from hot, alkali-rich magmas. The quartz-alkali-feldspar syenite shares many A-type features but lacks pronounced Ba–Sr–Eu anomalies and exhibits elevated K and Zr (Fig. 8b). Šuica et al. (2022) attributed these features to cumulate processes.

6.2. Crystallization conditions and shallow-level emplacement

The magmatic rocks from the Drava calc-alkaline to high-K calc-alkaline series probably crystallized from magma with relatively high-water contents, since this is the most effective way to overcome high viscosity and thermal contrast between basic and acid magma that could otherwise prevent effective mingling and mixing (Frost and Mahood, 1987). This is supported by hydrous ferromagnesian mineralogy, with the hornblende as a main mineral (> 30 vol%) in hybrid IMR and MME, followed by minor to accessory biotite. Pressure-temperature conditions of crystallization for Drava hybrid IMR can be estimated using calcic amphibole thermobarometry (Ridolfi, 2021). Most analyzed amphiboles

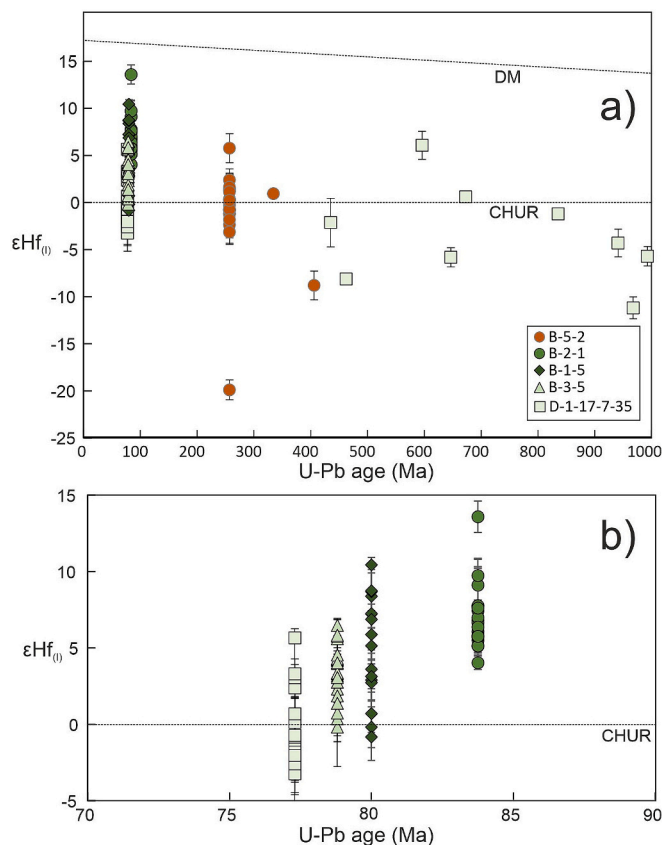


Fig. 9. Relation of hafnium isotopes ($\epsilon\text{Hf}_{(t)}$) in zircon crystals and the emplacement ages (U-Pb age) plots of zircons for analyzed orthogneiss (B-5-2), alkali-feldspar granites (B-1-5, B-2-1), quartz-alkali-feldspar syenite (B-3-5), granodiorite (D-1-17-7-35): a) age range of 0–1000 Ma; b) age range 70–90 Ma. Only grains with concordant ages were plotted.

are low-Mg so only suitable subset of grains yielding robust estimates were utilized for calculations. This produced pressures 67 ± 8 to 89 ± 11 MPa, indicating low-pressure crystallization, and temperatures $701\text{--}755 \pm 22$ °C. The granodiorite-monzodiorite yielded zircon-saturation temperatures of $782\text{--}829$ °C (Watson and Harrison, 1983) and $719\text{--}780$ °C (Boehnke et al., 2013). The presence of abundant inherited and xenocrystic zircon grains suggests either high pre-existing Zr saturation in the melt or temperatures insufficient to fully dissolve entrained zircons.

On the other hand, the Slavonia-Srijem A-type granites are hypersolvus, with one feldspar, perthite (B-1-3, B-1-4, B-1-5) and anthipertite (B-2-1), and interstitial late-stage biotite indicating crystallization from magma with low water content (Bonin, 2007). The granophyric intergrowths clearly point to magma undercooling, in line with low-pressure crystallization inferred from Al-in-hornblende barometry (Šuica et al., 2022). This is in accordance with the presence of miarolitic cavities in the B-1-5 A-type granite. Zircon typology (Pupin, 1980) indicates high temperature, consistent with >800 °C zircon saturation temperatures (Šuica et al., 2022). Comparable high temperatures have been reported for coeval rhyolites from Mt. Papuk (northern Croatia), where Ti-in-zircon thermometry yielded temperatures approaching 900 °C (Schneider et al., 2025). The A-type syenite sample (B-3-5) is subsolvus, with two feldspars, probably due to higher water-pressure compared to the A-type granites. But, according to zircon typology, it also crystallized from a high-temperature magma. Again, inherited cores in zircon grains were not found, testifying to high-temperature melting.

In summary, both the Slavonia-Srijem A-type and Drava I-type granitoids crystallized at shallow upper-crustal levels, but from compositionally and physically distinct magmas. The A-type granites

formed from high-temperature melts, whereas the I-type suite crystallized from comparatively cooler, more water-rich magmas, reflecting fundamentally different source regions and melting regimes.

6.3. Tectonic significance of the Permian-age orthogneiss

The Late Cretaceous Drava calc-alkaline to high-K calc-alkaline series intruded the upper crust of the Tisia mega-unit, representing the upper plate during Adria–Europe convergence (Schmid et al., 2008). Their emplacement into continental crust is evident from abundant inherited zircon, including pre-Variscan and Variscan components, and from evidence for magma chamber processes such as mixing and wall-rock assimilation. These features, together with ~ 30 km crustal thickness in the region during the Late Cretaceous (Schneider et al., 2025), indicate that magmatism occurred within a relatively thick continental lithosphere.

In contrast, the Slavonia-Srijem A-type rocks lie within the Sava Zone (Schmid et al., 2008), where the nature of the basement, continental versus oceanic, has long been debated (Prelević et al., 2017; Sokol et al., 2020; Toljić et al., 2018; Ustaszewski et al., 2009). The new data presented here allow a reassessment of this issue. Besides Late Cretaceous igneous rocks, orthogneiss from B-5 borehole (sample B-5-2), situated 15–20 km to the east southeast from our B-1 to B-3 boreholes with A-type rocks, occupying position within lower, Adriatic plate according to the tectonic map of Schmid et al. (2020) was analyzed. Zircon U-Pb dating of the orthogneiss yields an age of 257 ± 2.6 Ma. Major- and trace-element compositions point to an A-type granite protolith (Šuica et al., 2022), which is consistent with the zircon typology indicative of crystallization from high-temperature, alkali-rich melts.

Permian A-type granites are well documented both in ALCAPA and Tisia megaunits, across the Western Carpathians, Pannonian Basin, and Apuseni Mountains. SHRIMP U-Pb zircon ages reported by Ondrejka et al. (2021) from the Velence Hills (281 ± 3 Ma), Turčok (262 ± 4 Ma), Hrončok (267 ± 2 Ma), and Upohlav (264 ± 3 Ma) show relatively close match to the age of B-5-2 orthogneiss. Similarly, the Highiş granite in the Apuseni Mts. yields LA-ICP-MS ages between 267.8 ± 4.4 and 262.9 ± 4.1 Ma (Szemerédi et al., 2021), consistent with the CA-ID-TIMS age of Pană et al. (2002). Although B-5-2 is metamorphosed and slightly younger than most published ages, it overlaps with the regional Permian magmatic spectrum. Notably, rocks of this age have not been reported from Adria-derived units of the Dinarides (Schmid et al., 2020), indicating an origin within the Tisia mega-unit. The granite precursor was subsequently deformed and recrystallized probably during Alpine orogenesis. The occurrence of Permian orthogneiss within the Slavonia-Srijem boreholes therefore has significant implications for the configuration of the Sava Zone. First, it represents the first direct evidence that the northwestern Sava Zone contains continental basement with European affinity rather than oceanic lithosphere. Second, it places the Slavonia-Srijem A-type granites within the marginal part of the Tisia mega-unit, near the contact with Adria, where thinner crust would have favoured the ascent and shallow emplacement typical of A-type granites.

6.4. Coeval A-type and I-type granites: the role of mantle and crust in their parental material

The Slavonia-Srijem A-type granites and the Drava calc-alkaline to high-K calc-alkaline series record the same Late Cretaceous magmatic pulse but involving very different crust–mantle contributions: A-type bodies carry dominantly juvenile Hf signatures, whereas the Drava rocks possess mixed to predominantly crustal isotopic compositions.

The Slavonia-Srijem A-type granites are chemically highly evolved ($\text{SiO}_2 > 72$ wt%) yet yield the most juvenile zircon $\epsilon\text{Hf}_{(t)}$ values in our dataset, with more fractionated samples having higher zircon $\epsilon\text{Hf}_{(t)}$ values (e.g., $+9.7$ to $+4.0$ in B-2-1; B-1-5 and the syenite are slightly less radiogenic). Generally, A-type granites can form by two substantially different processes: i) a direct fractionation of alkali or transitional

basalts with addition of crustal material) or ii) partial melting of (calc-alkaline) quartzo-feldspathic meta-igneous rocks such as tonalites and granodiorites, with both mechanisms operating under relatively low-pressure conditions (Frost and Frost, 2011). Balen et al. (2020) interpreted (83.6 ± 1.5 Ma) Late Cretaceous A2-type granite of Požeška Gora as a product of lower-crustal melting under high-temperature conditions. The occurrence of coeval alkali to E-MORB-type mafic magmatism in the Sava Zone (Belak et al., 1998; Ustaszewski et al., 2009; Cvetković et al., 2014; Prelević et al., 2017; Schneider et al., 2025; Olić Peco et al., 2026) indicates the presence of shallow asthenosphere and a strongly attenuated crust during emplacement. These conditions, involving a high thermal flux from the asthenosphere and low-pressure melting of both mantle and lower crust, are optimal for the generation of A-type magmas. The strongly juvenile zircon $\varepsilon_{\text{Hf}(t)}$ signatures of A-type granites from this study are difficult to reconcile with derivation solely from partial melting of quartzo-feldspathic crust, since plausible source rocks (pre-Variscan, Variscan and Mid-Late Permian granitoids) would yield more evolved Hf isotopic compositions. Zircon trace-element data (high U, elevated Th/U), whole rock geochemistry with strong negative Eu anomalies and high zircon saturation temperatures indicate crystallization from very hot, fractionated, alkali-rich melts. The most consistent interpretation is that the Slavonia-Srijem granites represent highly fractionated derivatives of mantle-derived basaltic magmas, variably overprinted by assimilation of crustal partial melts. This interpretation accords with their A1-type geochemical affinity (Šuica et al., 2022).

By contrast, the samples from Drava calc-alkaline to high-K calc-alkaline granodiorite-monzodiorite record lower and more variable $\varepsilon_{\text{Hf}(t)}$ (+3.3 to −3.2). Zircon morphologies with both elongate prismatic (high-T) and stubby bipyramidal (low-T) forms, and complex zoning, indicate magma-mixing in granodiorite. The inherited zircon cores (~284 Ma to >2 Ga) and xenolithic enclaves, as well as trace-element patterns that closely resemble the local gneiss basement (including positive Eu anomalies), indicate a crustal assimilation and remelting of continental material. Together with abundant MMEs and hybrid IMR, it points to a hybrid system in which mantle input triggered extensive crustal melting and produced granitoids with mixed isotopic signatures. We exclude alternative fractional crystallization or assimilation-fractional crystallization processes, based on the lack of negative Eu anomalies that rules out dominant plagioclase removal, as well as the absence of middle rare earth element depletion (e.g., Dy) that precludes significant hornblende fractionation (Davidson et al., 2013). Collectively, these geochemical constraints combined with petrography confirm that magma mixing and assimilation represent the most robust model for these lithologies.

To illustrate these relationships, we modelled mixing/hybridization using our most evolved granite as the felsic endmember and published data from Late Cretaceous mafic lavas from the region as basic end-members (Sava Zone basalts from Klepa and Kozara; ABTS basalts; Fig. 10). The modelling shows that the HFSE-rich signatures of Drava rocks, the weak Nb-Ta anomalies, as well as the elevated Nb/Y and TiO_2 contents are not reproduced by ABTS-type mafic inputs. In contrast, mixing trajectories incorporating Sava-type basalts match the observed geochemical arrays and ratio-ratio trends. Thus, the most plausible juvenile contributors to the Drava melts are Sava-type (alkaline/transitional) magmas rather than ABTS arc basalts. However, as pointed out before, this modelling does not imply that geochemical variations within the suite resulted purely from mixing processes.

6.5. Late Cretaceous magmatism within the regional framework

In situ zircon U-Pb dating of zircons from igneous rocks in Slavonia-Srijem and Drava area yielded Late Cretaceous ages, namely 80.0 ± 1.0 Ma, and 83.7 ± 0.6 Ma for A-type granites, 78.8 ± 0.7 Ma for A-type syenite, and 77.3 ± 1.1 Ma for I-type granodiorite. These ages fit well both in the range of the Sava Zone and the ABTS. Due to overlapping age of Sava Zone and ABTS, the regional geological affiliation of the rocks from this study should be determined based on geochemistry. Despite numerous published data on both Sava Zone and ABTS, there is no systematic comparison between them nor established geochemical criteria for their distinction.

In order to make clear comparison belts and to resolve affiliation of igneous rocks from this study, representative datasets for both regions were compiled from literature (ABTS: Gallhofer et al., 2015; Sava Zone: Belak et al., 1998; Ustaszewski et al., 2009; Balen and Petrinec, 2011; Balen and Broska, 2011; Cvetković et al., 2014; Prelević et al., 2017; Sokol et al., 2020, 2025; Balen et al., 2020, Schneider et al., 2022, 2025).

Major-element data highlight the strongly bimodal character of the Sava Zone, unlike the more continuous basic–intermediate–acid series of ABTS (ESM2 Fig. 5). Trace-element systematics (Fig. 11) further underline the contrast: Sava Zone magmas have markedly lower LILE/HFSE ratios (lower La/Nb, higher Zr/La and Zr/Ba) and higher TiO_2 contents, consistent with minimal involvement of subduction-modified sources. In Th/Yb–Nb/Yb space, ABTS rocks closely follow the volcanic-arc array, reflecting a Th-enriched mantle wedge, whereas Sava Zone basic rocks plot along the mantle array, and only acid rocks show variable Th/Yb enrichments attributable to crustal melting or assimilation. Likewise, a major part of ABTS rocks lies in the field of orogenic rocks, while the Sava Zone including samples from this study

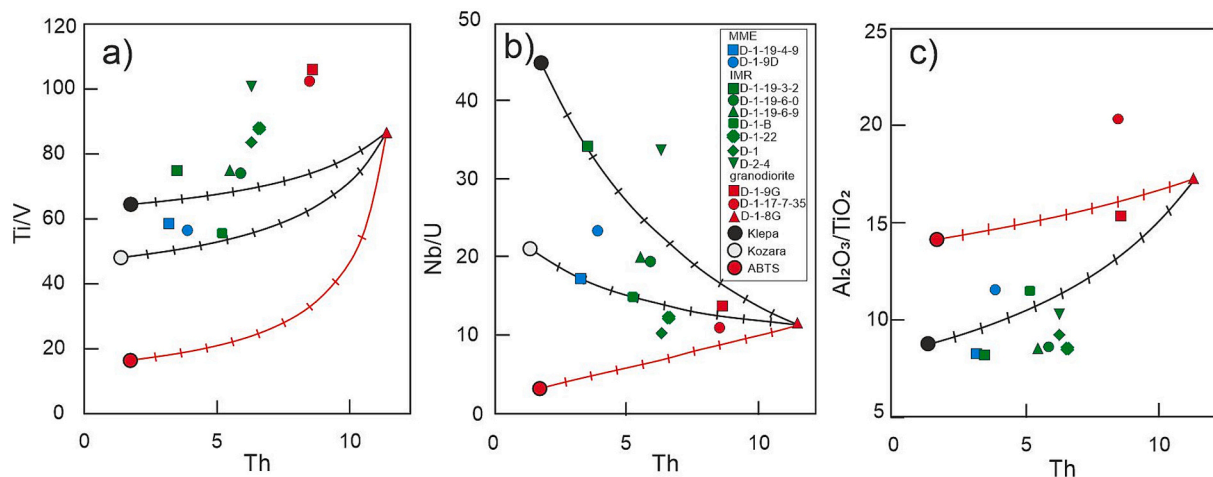


Fig. 10. Mixing models involving three candidate basic end-members, Klepa (Prelević et al., 2017), Kozara (Cvetković et al., 2014; Ustaszewski et al., 2009) and ABTS (compiled in Gallhofer et al., 2015), with the most evolved felsic member of Drava igneous rocks (D-1-8G) a) Th-Ti/V; b) Th-Nb/U; c) $\text{Al}_2\text{O}_3/\text{TiO}_2$ -Th, Klepa and Kozara end-members overlap, so only Klepa is displayed.

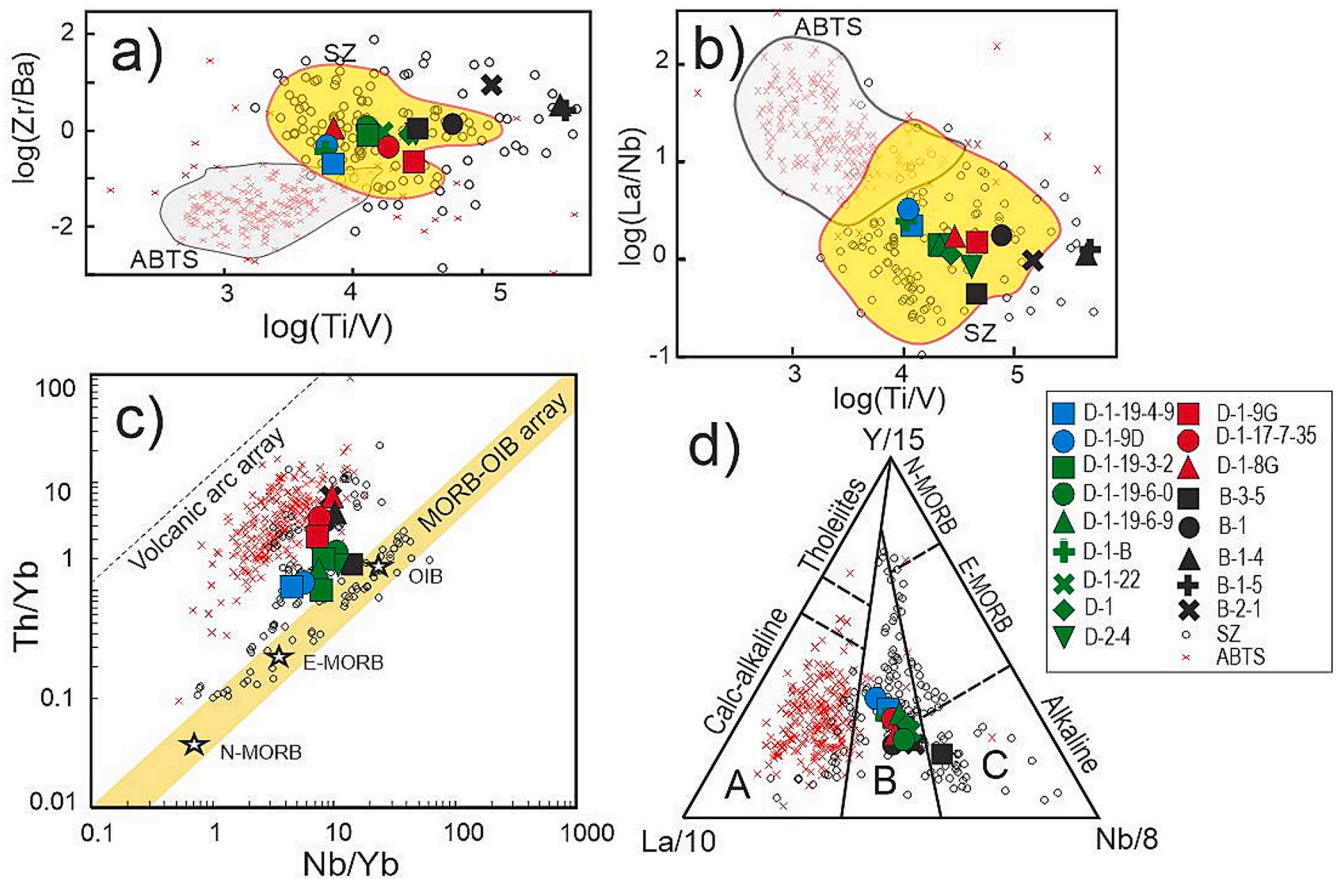


Fig. 11. Comparison of our data with Apuseni-Banat-Timok-Srednogorie (ABTS) and Sava Zone (SZ) magmatism. In a) and b), fields with >90% of samples for each group are outlined. a) $\log(\text{Ti/V})$ – $\log(\text{Zr/Ba})$; b) $\log(\text{La/Nb})$ – $\log(\text{Zr/Ba})$; c) Nb/Yb – Th/Yb (after [Pearce, 2008](#)); d) $\text{La}/10$ – $\text{Y}/15$ – $\text{Nb}/8$ after [Cabanis and Lecolle \(1989\)](#); A-orogenic (compressive) domains, B-late orogenic to post-orogenic intracontinental domains, C-anorogenic domains. ABTS: [Gallhofer et al. \(2015\)](#); Sava Zone: [Belak et al. \(1998\)](#); [Ustaszewski et al. \(2009\)](#); [Balén and Petrinec \(2011\)](#); [Balén and Broska \(2011\)](#); [Cvetković et al. \(2014\)](#); [Prelević et al. \(2017\)](#); [Sokol et al. \(2020, 2025\)](#); [Balén et al. \(2020\)](#), [Schneider et al. \(2022, 2025\)](#).

mainly falls into the late orogenic to post-orogenic and anorogenic fields as defined by [Cabanis and Lecolle \(1989\)](#); [Fig. 11d](#)).

The samples from this study match the Sava Zone trend within these geochemical parameters. High Ti/V ratios indicate a lower oxygen fugacity relative to ABTS, reinforcing the inference of a distinct, less arc-modified mantle source. Overall, the data imply that ABTS magmatism stems from melting of a subduction-metasomatized mantle, whereas Sava Zone magmatism reflects less metasomatized mantle with significant high-temperature crustal input. This source dichotomy is consistent with the contrasting thermal histories of high-temperature, low-pressure metamorphism in the Sava Zone ([Starijaš et al., 2010](#)) versus typical arc-like conditions in ABTS.

6.6. Implications for the Late Cretaceous tectonic setting

The obduction of ophiolites is generally considered as a marker for the closure of Neothetys in southeastern Europe, but intraoceanic interpretation of Sava Zone igneous rocks ([Ustaszewski et al., 2009](#); [Cvetković et al., 2014](#)) left the possibility for a partial preservation of oceanic domain. However, the growing number of petrological studies focused on Sava Zone, including this one, stresses out intracontinental extensional or transtensional setting of this magmatism ([Prelević et al., 2017](#); [Balén et al., 2020](#); [Schneider et al., 2022, 2025](#); [Sokol et al., 2020, 2025](#)). Furthermore, the Late Cretaceous basalts inside lower-plate units of Adria-derived nappes could hardly be explained by active subduction scenario ([Sokol et al., 2025](#); [Mladenović et al., 2026](#)). Besides this igneous event, lower-plate Adria records continuous compressional

tectonics during Cretaceous period ([Schmid et al., 2008](#); [Vukovski et al., 2024](#); [Šamarija et al., 2025](#)), resulting in development of syn-orogenic sedimentary basins ([Mikes et al., 2008](#); [Lužar-Oberiter et al., 2012](#)). Moreover, these syn-orogenic deposits record low-temperature thermochronological data pointing to Late Cretaceous exhumation event ([Mikes et al., 2008](#); [Lužar-Oberiter et al., 2012](#)).

Altogether, this line of evidence, along with the absence of Late Cretaceous ophiolites in the southeastern Europe, speak against the existence of oceanic crust in this region and point to complete ocean closure with ophiolite obduction as proposed by [Stanković et al. \(2023\)](#). Thus, the Late Cretaceous magmatism took place in intracontinental setting ([Fig. 12a](#)). Indirect arguments for an oceanic domain, such as contemporaneous calc-alkaline magmatism of the ABTS, do not necessarily require active subduction. Comparable calc-alkaline magmatism is well documented in post-collisional settings of the southeastern Europe ([Schefer et al., 2011](#)) and can be explained by complex post-collisional processes, including Jurassic slab break-off, rebound of previously subducted continental lithosphere, and subsequent lithospheric delamination ([Stanković et al., 2026](#)).

The granitic suites investigated here provide direct petrological and isotopic constraints on Late Cretaceous tectonic setting. The coexistence of high-temperature, strongly juvenile A-type granites in Slavonia-Srijem and more crust-influenced I-type granitoids in the Drava Depression is best explained by spatial variations in lithospheric thickness and thermal structure within an overall intracontinental convergent framework ([Fig. 12b](#)). Localized extension and asthenospheric upwelling, would have promoted high-temperature melting and

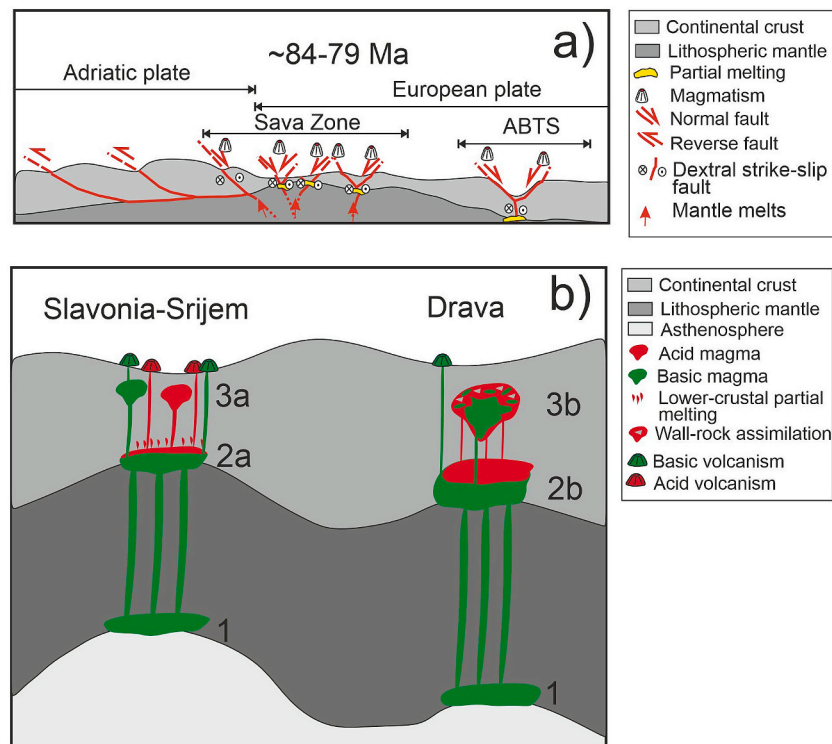


Fig. 12. a) Intracontinental tectonic scenario for Late Cretaceous magmatism in the southeastern Europe. b) Magmatic scenario for Slavonia-Srijem A-type and Drava I-type magmatism. 1 – partial melting in the mantle induced by localized extension and asthenosphere upwelling; 2a – low pressure fractionation of mantle-derived basic magma followed by high-temperature melting in the lower crust at the shallow crust-mantle boundary; 2b - repeated underplating of basic melts with relatively higher-pressure and lower-temperature fractional crystallization and longer-lived magma-crust interaction at the deeper crust-mantle boundary; 3a – shallow emplacement followed by fast crystallization; 3b – intrusion of basic magma in shallow chamber with acid partially-crystallized magma, followed by magma-mixing and wall-rock assimilation.

efficient mantle-crust hybridization beneath thinner lithosphere, favouring the generation of A-type magmas with minimal zircon inheritance. In contrast, beneath thicker crustal domains, repeated underplating of similar basic melts led to lower-temperature, longer-lived magma-crust interaction, extensive assimilation of heterogeneous basement, and the production of I-type granitoids with abundant inherited zircon due to a Late Cretaceous tectonic regime characterized by heterogeneous lithospheric architecture, variable thermal input, and post-collisional mantle dynamics rather than by a simple, long-lived subduction system.

7. Conclusions

This paper presents new data on previously unknown Late Cretaceous igneous rocks from the subsurface of the Drava and Slavonia-Srijem Depression, in the Croatian part of the Pannonian Basin. The affiliation in terms of tectonic units was clear for the Drava Depression, belonging to Tisia megaunit, while for the Slavonia-Srijem the presence of orthogneiss derived from Late Permian A-type granite (U-Pb zircon age 257 ± 2.6 Ma, $\epsilon_{\text{Hf}(i)} = +2.4$ to -3.1), indicate Tisian affinity, too. The Drava calc-alkaline to high-K calc alkaline (U-Pb zircon age 77.3 ± 1.1 Ma) igneous rocks are represented by I-type granodiorite-monzodiorite with microgranular mafic enclaves, in contact with intermediate rocks of broadly quartz-monzodioritic composition, all displaying clear petrographic evidence for magma-mixing and hybridization. The I-type granodiorite-monzodiorite displays high LILE/HFSE typical of subduction-related magmatism or continental crust, but less evolved members have elevated Nb/Y, TiO_2 contents and HFSE/LILE ratios, indicating involvement of relatively alkaline magma in their genesis. The Hf isotopic composition of zircons in the granodiorite from this suite ($\epsilon_{\text{Hf}(i)} = +3.3$ to -3.2) yield mixed to predominantly crustal

isotopic compositions, in line with the presence of numerous older cores. This points to a hybrid system where mantle-derived magmas with alkaline affinity triggered crustal melting and assimilation. The Slavonia-Srijem A-type rocks (80 ± 1.0 Ma, 83.7 ± 0.6 Ma and 78.8 ± 0.7 Ma) have ferroan character, high alkali and low LILE/HFSE. They crystallized from hot, fractionated, alkali-rich magmas, and lack inherited zircon cores. Zircon $\epsilon_{\text{Hf}(i)}$ values (+9.7 to -0.8) point to strong involvement of mantle-derived magmas that were mixed in variable proportions with crustal melts under low-pressure conditions. Both suites were emplaced in upper crustal levels of continental crust and display strong affinities towards magmatism of the Sava Zone. They point to intracontinental scenario and provide clear evidence for involvement of (post-)collisional processes in their petrogenesis.

CRediT authorship contribution statement

Sanja Šuica: Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Dejan Prelević:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **István Dunkl:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation. **Jin-Cheng Xie:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Vesnica Garašić:** Writing – review & editing, Supervision, Conceptualization. **Alan B. Woodland:** Writing – review & editing, Investigation, Data curation. **Nina Trinajstić:** Writing – review & editing, Investigation, Conceptualization. **Mihovil Brlek:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Funding

This work was supported by the the Science Fund of the Republic of Serbia, through project RECON TETHYS (7744807) and by the Croatian Science Foundation under projects “Miocene syn-rift evolution of the North Croatian Basin (Carpathian–Pannonian Region): a multi-proxy approach, correlation and integration of sedimentary and volcanic record” (PYROSKA, HRZZ UIP-2019-04-7761), “Sedimentary evolution of Late Cretaceous deep-water basins in the Dinarides” (SECret HRZZ IPS-2023-02-2683), and and internal research project “Global events in the Adriatic Carbonate Platform deposits” (GEACAP) at the Croatian Geological Survey, funded by the National Recovery and Resilience Plan 2021–2026 of the European Union – NextGenerationEU, and monitored by the Ministry of Science and Education of the Republic of Croatia. The use of equipment in the “Goettingen laboratory for correlative Light and Electron Microscopy” (GoeLEM) is partially funded by DFG (INST 186/1367-1 FUGG and INST 186/1522-1 FUGG). D.P. also thanks the Serbian Academy of Sciences and Arts, Projects F9 and F17.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

S.Š. would like to express her gratitude to the company INA-Industrija nafte d.d. for providing documentation and rock samples. Critical comments by Kristijan Sokol helped to improve an early version of the manuscript. We would like to express our gratitude to Milan Kohút and Branimir Šegvić for their helpful comments and suggestions, as well as Ali Polat for his editorial work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lithos.2026.108743>.

References

- Balen, D., Broska, I., 2011. Tourmaline nodules: products of devolatilization within the final evolutionary stage of granitic melt? In: Sial, A.N., Bettencourt, J.S., de Campos, C.P., Ferreira, V.P. (Eds.), *Granite-Related Ore Deposits*, 350. Geol. Soc. Spec. Publ., pp. 53–68. <https://doi.org/10.1144/SP350.4>
- Balen, D., Petrinec, Z., 2011. Contrasting tourmaline types from peraluminous granites: a case study from Moslavačka Gora (Croatia). *Mineral. Petrol.* 102, 117–134. <https://doi.org/10.1007/s00710-011-0164-8>.
- Balen, D., Schneider, P., Massonne, H.-J., Opitz, J., Luptáková, J., Putiš, M., Petrinec, Z., 2020. The Late Cretaceous A-type alkali-feldspar granite from Mt. Požeška Gora (N Croatia): potential marker of fast magma ascent in the Europe–Adria suture zone. *Geol. Carpath.* 71, 361–381. <https://doi.org/10.31577/Geol-Carp.71.4.5>.
- Belak, M., Halamić, J., Marchig, V., Tibljaš, D., 1998. Upper Cretaceous-Paleogene Tholeiitic Basalts of the Southern margin of the Pannonian Basin: Požeška gora Mt (Croatia). *Geol. Croat.* 51, 163–174.
- Berza, T., Constantinescu, E., Vlad, Ș.-N., 1998. Upper Cretaceous Magmatic Series and Associated Mineralisation in the Carpathian – Balkan Region. *Resour. Geol.* 48, 291–306.
- Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., Schmitt, A.K., 2013. Zircon saturation re-revisited. *Chem. Geol.* 351, 324–334. <https://doi.org/10.1016/j.chemgeo.2013.05.028>.
- Bonin, B., 2007. A-type granites and related rocks: evolution of a concept, problems and prospects. *Lithos* 97, 1–29. <https://doi.org/10.1016/j.lithos.2006.12.007>.
- Bortolotti, V., Chiari, M., Marroni, M., Pandolfi, L., Principi, G., Saccani, E., 2013. Geodynamic evolution of ophiolites from Albania and Greece (Dinaric-Hellenic belt): one, two, or more oceanic basins? *Int. J. Earth Sci.* 102, 783–811. <https://doi.org/10.1007/s00531-012-0835-7>.
- 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 Planet. Sci. Lett.* 273, 48–57. <https://doi.org/10.1016/j.epsl.2008.06.010>.
- Cabanis, B., Lecolle, M., 1989. Le diagramme La/10 – Y/15 – Nb/8: Un outil pour la discrimination des series volcaniques et en evidence des mélange et/ot de contamination crustale. *C. R. Acad. Sci.* 309, 2023–2029.
- Chapell, B.W., White, A.J.R., 1974. Two contrasting granite types. *Pac. Geol.* 8, 173–174.
- Čičulić-Trifunović, M., Galović, I., 1984. Osnovna geološka karta SFRJ 1:100 000: List Bačka Palanka [Basic Geological Map of SFRJ 1:100 000, Sheet Bačka Palanka]. Savezni geološki zavod, Beograd.
- Čičulić-Trifunović, M., Rakić, M.O., 1978. Osnovna geološka karta SFRJ 1:100 000: List Novi Sad [Basic Geological Map of SFRJ 1:100 000, Sheet Novi Sad]. Savezni geološki zavod, Beograd.
- Croatian Geological Survey, 2009. Geological Map of the Republic of Croatia M 1:300 000. Croatian Geological Survey, Department of Geology, Zagreb.
- Cvetković, V., Sarić, K., Grubić, A., Cvijić, R., Milošević, A., 2014. The Upper Cretaceous ophiolite of North Kozara – remnants of an anomalous mid-ocean ridge segment of the Neotethys? *Geol. Carpath.* 65, 117–130.
- Davidson, J., Turner, S., Plank, T., 2013. Dy/Dy*: variations arising from mantle sources and petrogenetic processes. *J. Petrol.* 54, 525–537. <https://doi.org/10.1093/petrology/egs076>.
- Dunkl, I., Mikes, T., Simon, K., von Eynatten, H., 2008. Brief introduction to the Windows program Pepita: data visualization, and reduction, outlier rejection, calculation of trace element ratios and concentrations from LA-ICP-MS data. In: Sylvester, P. (Ed.), *Laser ablation ICP-MS in the Earth Sciences: Current Practices and Outstanding Issues*, 40. Mineralogical Association of Canada, Short Course, pp. 334–340.
- Frei, D., Gerdes, A., 2009. Precise and accurate in situ U-Pb dating of zircon with high sample throughput by automated LA-SF-ICP-MS. *Chem. Geol.* 261, 261–270.
- Frost, C.D., Frost, B.R., 2011. On Ferroan (A-type) Granitoids: Their compositional variability and modes of origin. *J. Petrol.* 52 (1), 39–53. <https://doi.org/10.1093/petrology/egq070>.
- Frost, T.P., Mahood, G.A., 1987. Field, chemical, and physical constraints on mafic-felsic magma interaction in the Lamarck Granodiorite, Sierra Nevada, California. *Geol. Soc. Am. Bull.* 99, 272–291.
- Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. *J. Petrol.* 42, 2033–2048.
- Gallhofer, D., von Quadt, A., Peytcheva, I., Schmid, S.M., Heinrich, C.A., 2015. Tectonic, magmatic, and metallogenic evolution of the Late Cretaceous arc in the Carpathian-Balkan orogeny. *Tectonics* 34, 1813–1836. <https://doi.org/10.1002/2015TC003834>.
- Georgiev, S., Marchev, P., Jicha, B., Banushev, B., Raicheva, R., Peytcheva, I., von Quadt, A., 2021. ⁴⁰Ar/³⁹Ar age and petrology of magmatic rocks from East Balkan (Bulgaria) constrain the initiation of regional subduction in SE Europe. *Lithos* 398–399, 106302. <https://doi.org/10.1016/j.lithos.2021.106302>.
- Goričan, S., Đaković, M., Baumgartner, P.O., Gawlick, H.-J., Cifer, T., Djerić, N., Horvat, A., Kocjančić, A., Kukoč, D., Mrdak, M., 2022. Mesozoic basins on the Adriatic continental margin – a cross-section through the Dinarides in Montenegro. *Folia Biol. Geol.* 63, 85–150. <https://doi.org/10.3986/fbg0099>.
- Griffin, W.L., Pearson, N.J., Belousova, E., Jackson, S.E., van Acherbergh, E., O'Reilly, S.Y., Shee, S.R., 2000. The Hf isotope composition of cratonic mantle: LAM–MC–ICPMS analysis of zircon megacrysts in kimberlites. *Geochim. Cosmochim. Acta* 64, 133–147.
- Griffin, W.L., Wang, X., Jackson, S.E., Pearson, N.J., O'Reilly, S.Y., Xu, X., Zhou, X., 2002. Zircon chemistry and magma mixing, SE China: in-situ analysis of Hf isotopes, Tonglu and Pingtan igneous complexes. *Lithos* 61, 237–269.
- Jackson, S., Pearson, N., Griffin, W., Belousova, E., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chem. Geol.* 211, 47–69.
- Janoušek, V., Farrow, C.M., Erban, V., 2006. Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). *J. Petrol.* 47, 1255–1259.
- Karamata, S., Lovrić, A., 1978. The age of metamorphic rocks of Brezovica and its importance for the explanation of ophiolite emplacement. *Bull. T. LXI Acad. Serbe Sci. Arts Cl. Sci. Natur. Math. Sci. Natur.* 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 Planet. Sci. Lett.* 26, 271–276.
- Leake, B.E., Woolley, A.R., et al., 1997. Nomenclature of amphiboles: report of the Subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral names. *Can. Mineral.* 35, 219–246.
- Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. *Geol. Soc. Am. Abstr. Programs* 11, 468.
- Ludwig, K.R., 2012. User's manual for Isoplot 3.75: a geochronological Toolkit for Microsoft Excel. *BGC Spec. Publ.* 4, 70.
- Lužar-Oberiter, B., Mikes, T., Dunkl, I., Babić, L.J., von Eynatten, H., 2012. Provenance of Cretaceous synorogenic sediments from the NW Dinarides (Croatia). *Swiss J. Geosci.* 105, 377–399. <https://doi.org/10.1007/s00015-012-0107-3>.
- McDonough, W.F., Sun, S.-S., 1995. The composition of the Earth. *Chem. Geol.* 120, 223–253. [https://doi.org/10.1016/0009-2541\(94\)00140-4](https://doi.org/10.1016/0009-2541(94)00140-4).
- Mikes, T., Christ, D., Petri, R., Dunkl, I., Frei, D., Baldi-Beke, M., Reitner, J., Wemmer, K., Hrvatović, H., von Eynatten, H., 2008. Provenance of the Bosnian Flysch. *Swiss J. Geosci.* 101, 31–54. <https://doi.org/10.1007/s00015-008-1291-z>.
- Mladenović, A., Cvetković, V., Gajić, V., Sokol, K., Dunčić, M., Prelević, D., 2026. The Zvornik “Suture” in the Internal Dinarides: a key to understanding regional strike-slip structures in the Balkans. *Geol. An. Balk. Poluostrova*. <https://doi.org/10.2298/GABP260409009M>.
- Olić Peco, I., Matoš, B., Prelević, D., Petrinec, Z., Sokol, K., Kocjančić, A., Moro, A., Lužar-Oberiter, B., 2026. Late Cretaceous volcano-sedimentary complex along the

- Adria–Tisza boundary: new insights from the westernmost Sava Suture Zone. *Cretac. Res.* 183, 106340. <https://doi.org/10.1016/j.cretres.2026.106340>.
- Ondrejka, M., Uher, P., Putiš, M., Kohút, M., Broska, I., Larionov, A., Bojar, A.-V., Sobocký, T., 2021. Permian A-type granites of the Western Carpathians and Transdanubian regions: products of the Pangea supercontinent breakup. *Int. J. Earth Sci.* 110, 2133–2155. <https://doi.org/10.1007/s00531-021-02064-2>.
- Paces, J.B., Miller, J.D., 1993. Precise U–Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights into physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga midcontinent rift system. *J. Geophys. Res.* 98, 13997–14013.
- Pamić, J., Pécskay, Z., 1994. Geochronology of Upper Cretaceous and Tertiary igneous rocks from the Slavonija–Srijem Depression (Southern Pannonian Basin) and their basic petrological features. *Nafta* 45, 331–339.
- Pamić, J., Belak, M., Bullen, T.D., Lanphere, M.A., McKee, E.H., 2000. Geochemistry and geodynamics of a Late Cretaceous bimodal volcanic association from the southern part of the Pannonian Basin in Slavonia (Northern Croatia). *Mineral. Petrol.* 68, 271–296.
- Pană, D.I., Heaman, L.M., Creaser, R.A., Erdmer, P., 2002. Pre-alpine crust in the Apuseni Mountains, Romania: insights from Sm–Nd and U–Pb data. *J. Geol.* 110, 341–354. <https://doi.org/10.1086/339536>.
- Pearce, J.A., 1996. A User's Guide to Basalt Discrimination Diagrams. *Geol. Assoc. Can., Short Course Notes*, 12, pp. 79–113.
- Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos* 100, 14–48. <https://doi.org/10.1016/j.lithos.2007.06.016>.
- Peccerillo, A., Taylor, S.R., 1976. Geochemistry of Eocene calc alkaline volcanic rocks from Kastamonu area, Northern Turkey. *Contrib. Mineral. Petrol.* 58, 63–81. <https://doi.org/10.1007/BF00384745>.
- Polat, A., Hofman, A.W., Rosing, M.T., 2002. Boninite-like volcanic rocks in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: geochemical evidence for intra-oceanic subduction zone processes in the early Earth. *Chem. Geol.* 184, 231–254. [https://doi.org/10.1016/S0009-2541\(01\)00363-1](https://doi.org/10.1016/S0009-2541(01)00363-1).
- Popov, P., Berza, T., Grubic, A., Ionaș, D., 2002. Late Cretaceous Apuseni-Banat-Timok-Srednogie (ABTS) Magmatic and Metallogenic Belt in the Carpathian-Balkan orogen. *Geol. Balc.* 32, 145–163.
- Prelević, D., Wehrheim, S., Reutter, M., 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.
- Pupin, J.R., 1980. Zircon and granite petrology: contrib. *Mineral. Petrol.* 73, 207–220.
- Ridolfi, F., 2021. Amp-TB2: an updated model for Calcic Amphibole thermobarometry. *Minerals* 11, 324. <https://doi.org/10.3390/min11030324>.
- Šamarija, R., Lužar-Oberiter, B., Kukoč, D., Kocjančić, A., Gobo, K., Petrinjak, K., Bjelogrić, M., 2025. Carbonate platform margin evolution in a compressive tectonic setting: an example from the Cretaceous of the Pre-Karst Unit of the Dinarides (Gacko, Bosnia and Herzegovina): facies, 71, 9. <https://doi.org/10.1007/s10347-025-00699-0>.
- 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. *Int. J. Earth Sci.* 100, 1181–1206.
- 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 J. Geosci.* 101, 139–183.
- 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 Res.* 78, 308–374.
- Schneider, P., Balen, D., Opitz, J., Massonne, H.-J., 2022. Dating and geochemistry of zircon and apatite from rhyolite at the UNESCO geosite Rupnica (Mt. Papuk, northern Croatia) and the relationship to the Sava Zone. *Geol. Croat.* 75, 249–267. <https://doi.org/10.4154/gc.2022.19>.
- Schneider, P., Gallhofer, D., Skrzypek, E., Hauzenberger, C.A., Balen, D., 2025. Age and origin of a brief Late Cretaceous magmatic pulse based on geochemical data from accessory zircon: a case study from Mt. Papuk, Croatia. *Geol. Carpath.* 76, 277–299. <https://doi.org/10.31577/GeolCarp.2025.13>.
- Šegvić, B., Slovenec, D., Schuster, R., Babajić, E., Badurina, L., Lugović, B., 2020. Sm–Nd geochronology and petrologic investigation of sub-ophiolite metamorphic sole from the Dinarides (Krivaja-Konjuh, Ophiolite complex, Bosnia and Herzegovina). *Geol. Croat.* 73, 119–130. <https://doi.org/10.4154/gc.2020.09>.
- Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon - a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chem. Geol.* 249, 1–35.
- Slovenec, D., Šegvić, B., 2023. The evolution of the Mesozoic lithosphere of northwestern Neotethys: a petrogenetic and geodynamic perspective. *J. Geol. Soc. Lond.* 181, 132. <https://doi.org/10.1144/jgs2023-132>.
- Söderlund, U., Patchett, P.J., Vervoort, J.D., Isachsen, C.E., 2004. The ^{176}Lu decay constant determined by Lu–Hf and U–Pb isotope systematic of Precambrian mafic intrusions. *Earth Planet. Sci. Lett.* 219, 311–324.
- Sokol, K., Prelević, D., Romer, R.L., Božović, M., van der Bogaard, P., Stefanova, E., Kostić, B., Čokulov, N., 2020. Cretaceous ultrapotassic magmatism from the Sava–Vardar Zone of the Balkans. *Lithos* 354–355.
- Sokol, K., Prelević, D., Olić Peco, I., Cvetković, V., 2025. Current understanding of the Sava Zone of the Balkans: a magmatic perspective. *Geol. An. Balk. Poluostrova*. <https://doi.org/10.2298/GABP2511010125>.
- Spahić, D., Gaudenyi, T., 2022. On the Sava Suture Zone: post-Neotethyan oblique subduction and the origin of the Late Cretaceous mini-magma pools. *Cretac. Res.* 131, 105062. <https://doi.org/10.1016/j.cretres.2021.105062>.
- Šparica, M., 1986. Osnovna geološka karta SFRJ 1:100 000: List Slavonski Brod [Basic Geological Map of SFRY 1:100 000, Sheet Slavonski Brod]. Savezni Geološki Zavod, Beograd.
- Šparica, M., Juriša, M., Crnko, J., Šimunić, A., 1979. Osnovna geološka karta SFRJ 1:100 000: list nova Kapela [Basic Geological Map of SFRY 1:100 000, Sheet Nova Kapela]. Savezni geološki zavod, Beograd.
- Spencer, C.J., Kirkland, C.L., Taylor, R.J.M., 2016. Strategies towards statistically robust interpretations of in situ U–Pb zircon geochronology. *Geosci. Front.* 7, 581–589.
- Stanković, N., Gerya, T., Cvetkov, V., Cvetkovi, V., 2023. Did the Western and the Eastern Vardar ophiolites originate through a single intra-oceanic subduction? Insight from numerical modelling. *Gondwana Res.* 124, 124–140.
- Stanković, N., Cvetković, V., Mladenović, A., Cvetkov, V., Prelević, D., Gerya, T., 2026. Post-obduction slab dynamics in the Balkans and its role in Late Cretaceous magmatism: a numerical modelling approach. *Gondwana Res.* 151, 1–17. <https://doi.org/10.1016/j.gr.2025.10.015>.
- Starčijaš, B., Gerdes, A., Balen, D., Tibljaš, D., Finger, F., 2010. The Moslavačka Gora crystalline massif in Croatia: a Cretaceous heat dome within remnant Ordovician granitoid crust. *Swiss J. Geosci.* 103, 62–82.
- Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks. *Geol. Rundsch.* 63, 773–786.
- Šuica, S., Lugović, B., Kukoč, D., 2018. Tectono-magmatic significance of the pillow basalts from the ophiolitic mélange of the Dinarides. *Ofoliti* 43, 85–101.
- Šuica, S., Garašić, V., Woodland, A.B., 2022. Petrography and geochemistry of granitoids and related rocks from the pre-Neogene basement of the Slavonia–Srijem Depression (Croatia). *Geol. Croat.* 75, 129–144. <https://doi.org/10.4154/gc.2022.09>.
- Sun, S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, S.J., Norry, M.J. (Eds.), *Magmatism in the ocean basins*, 42. *Geol. Soc. Spec. Publ.*, pp. 313–345. <https://doi.org/10.1144/GSL.SP.1989.042.01.19>.
- Szemerédi, M., Varga, A., Dunkl, I., Lukács, R., Seghedi, I., Kovács, Z., Raucsik, B., Pál-Molnár, E., 2021. Petrology and zircon U–Pb dating of granitoid rocks in the Highis, massif (SW Apuseni Mts, Romania): insights into Permian plutonic–volcanic connections. *Geol. Carpath.* 72, 482–504.
- Toljić, M., Matenco, L., Stojadinović, U., Willingshofer, E., Ljubović-Obradović, D., 2018. Understanding fossil fore-arc basins: inferences from the Cretaceous Adria–Europe convergence in the NE Dinarides. *Glob. Planet. Chang.* 171, 167–184.
- Ustaszewski, K., Schmid, S.M., Lugović, B., Schaltegger, U., Bernoulli, D., Hottinger, L., Kounov, A., Fügenschuh, B., Schefer, S., 2009. Late cretaceous intra-oceanic magmatism in the internal Dinarides (northern Bosnia and Herzegovina): Implications for the collision of the Adriatic and European plates. *Lithos* 108, 106–125.
- 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>.
- Vermeesch, P., 2018. IsoplotR: a free and open toolbox for geochronology. *Geosci. Front.* 9, 1479–1493.
- Vernon, R.H., 1984. Microgranitoid enclaves in granites: globules of hybrid magma quenched in a plutonic environment. *Nature* 309, 438–439.
- Vukovski, M., Špelić, M., Kukoč, D., Troškot-Čorbić, T., Grgasović, T., Slovenec, D., Tomljenović, B., 2024. Unravelling the tectonic evolution of the Dinarides—Alps—Pannonian Basin transition zone: insights from structural analysis and low-temperature thermochronology from Ivanščica Mtn., NW Croatia. *Swiss J. Geosci.* 117, 16. <https://doi.org/10.1186/s00015-024-00464-5>.
- Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Planet. Sci. Lett.* 64, 295–304. [https://doi.org/10.1016/0012-821X\(83\)90211-X](https://doi.org/10.1016/0012-821X(83)90211-X).
- Wiedenbeck, M., Allé, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W., 1995. Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. *Geostand. Newslett.* 19, 1–23.