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Current understanding of the Sava Zone of the Balkans: a magmatic perspective

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Abstract. The Sava Zone (SZ) forms a key tectonic boundary between Europe-derived and Adria-derived continental units in the central Balkans and hosts a discontinuous belt of Late Cretaceous volcanic and plutonic rocks whose geodynamic significance remains strongly debated. Traditional interpretations viewed this belt as the youngest remnant of the Neotethyan Ocean, implying an oceanic environment and ophiolitic affinities. However, recent studies challenge this interpretation suggesting that much of the SZ magmatism has intracontinental origins. This revised perspective indicates that these magmatic rocks may not be associated with oceanic subduction, as previously thought, but rather with the tectono-magmatic evolution of the European (Tisza-Dacia) and Adria plates.

In this review we synthesize available petrological, geochemical, and geochronological data from all major localities where Upper Cretaceous magmatic rocks occur along the broader area of Sava Zone. Magmatic activity, constrained to ca. 87–76 Ma, spans tholeiitic to alkaline basalts and compositionally diverse felsic rocks. Two contrasting magmatic domains are evident. Adria-side localities host tholeiitic to transitional basalts with N- to E-MORB–like signatures derived from a relatively depleted spinel-bearing mantle. European-side occurrences contain enriched within-plate basalts and lamprophyres approaching OIB-like characteristics, requiring melting of a metasomatized lithospheric mantle extending into the garnet–spinel transition field. In our view, this asymmetry reflects lateral mantle heterogeneity rather than fundamentally different tectonic environments. The acidic rocks occurring within the European-affinity blocks display considerably greater diversity, including A1, A2, and S-type granitoid compositions, whereas the acidic rocks in the Dinarides (Adriatic plate) are predominantly restricted to the A2 subtype.

Regionally, Sava Zone magmatism was coeval with - but genetically distinct from - the Apuseni–Banat-Timok-Sredna Gora magmatic and metallogenic belt. Whereas the latter may have formed with or without invoking an actively subducting oceanic domain (e.g., the proposed “Sava Ocean”), the Sava Zone magmas in our view reflect lithospheric thinning, transtension, and mantle upwelling driven by slab rollback. These findings indicate that the Sava Zone records the transition from subduction-driven to post-collisional tectonics during the final reorganization of the Neotethyan margin. We therefore pro-

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pose redefining this system as part of the Central Balkan Late Cretaceous Magmatic Province - an intracontinental belt marking the waning stages of Tethyan closure.

Key words:
Sava Zone, Upper Cretaceous magmatism, Europe, Adria.

Апстракт. Сава зона представља кључну тектонску границу између континенталних јединица европског и јадранског афинитета. Ова хетерогена зона обухвата горњокредне седименте и магматске формације као и фрагменте јурских офиолита. Традиционално, Сава зона је интерпретирана као остатак најмлађег домена неотетиског океана затвореног у горњој креди, што подразумева постојање океанске литосфере у то време и офиолитски карактер магматских формација. Међутим, новија истраживања указују да значајан део магматизма има геохемијске и петролошке карактеристике интраконтиненталних стена.

У овом раду обједињени су постојећи подаци свих познатих локалитета у којима се појављују горњокредне магматске формације у ширем подручју Сава зоне. Сви испитивани локалитети показују уједначену старост, у интервалу од 87 до 76 милиона година. Горњокредни магматизам Сава зоне је литолошки и геохемијски разноврстан и укључује толеитске до алкалне базалте, лампрофире, риолите и гранитоиде.

Магматске стене Сава зоне показују јасне петролошке и геохемијске разлике, у зависности да ли су локалитети на континенталним јединицама европског или јадранског афинитета. Тако базалти из локалитета који се налазе у Динаридима (Јадранска плоча) претежно показују субалкални карактер, док базалти из локалитета који се појављују у блоковима европског афинитета (Српско-македонска маса, Дачија, Тиса) доминирају у пољу алкалних базалта. Геохемијски подаци указују да су базалти настали из три различита дела унутар омотача, односно на различитим дубинама: у зони стабилности граната (Топола), у зони коегзистенције граната и спинела (локалности око Београда, делимично Клепа) и у зони стабилности спинела (базалти из свих локалности у Динаридима (Јадранска плоча). Киселе стене које се појављују у блоковима европског афинитета показују знатно већу разноврсност, укључујући A1, A2 и S типове гранитоидних састава, док су киселе стене који се налазе у Динаридима (Јадранска плоча) ограничене углавном на A2 подтип.

На регионалном нивоу, магматизам Савске зоне је временски истовремен, али генетски различит од магматизма који се појављује у појасу Апусени–Банат–Тимок–Средногорје. Док се овај магматски и металогенетски појас може објаснити различитим моделима, укључујући и оне који подразумевају активну субдукцију, магматизам Сава зоне одражава деламинацију континенталног литосферског омотача, транстензију и локално издизање астеносферског омотача.

Уколико је ово тумачење тачно, такозвани „магматизам Сава зоне“ прецизније би се могао описати као Централнобалканска горњокредна магматска провинција (ЦБГМП).

Кључне речи: *Сава зона, горње кредни магматизам, Европа, Адрија.*

Introduction

The Sava Zone (SZ) occupies a pivotal position in the Alpine evolution of the Balkan segment of Alpine-Himalayan orogenic belt in the central Mediterranean (Schmid et al., 2020). As a major tectonic boundary between crustal domains of Europe and Adria affinities (Fig. 1), it comprises Upper Cretaceous sedimentary and magmatic formations together with older metamorphic and ophiolitic fragments (Dimitrijević

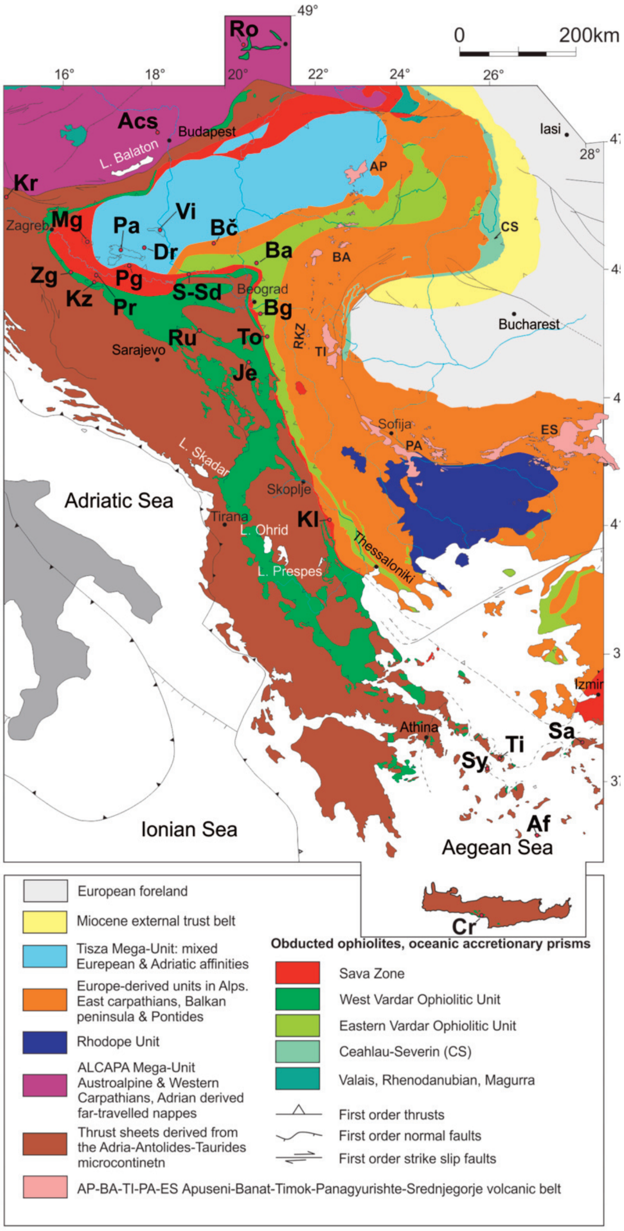


Fig. 1. Simplified tectonic map of the South–Eastern Europe (after Schmid *et al., 2020) with marked intrusives and volcanic bodies belonging to the Sava Zone (according to the Basic geological map of former Yugoslavia and* Sokol *et al., 2020).* ***Ro*** *– Rochovce,* ***Acs*** *– Alcsútdoboz,* ***Kr*** *– Krško,* ***Mg*** *– Moslavačka Gora,* ***Pa*** *– Papuk Mt.,* ***Pg*** *– Požeška Gora,* ***Dr*** *– Drava,* ***Vi*** *– Villányi Mt.,* ***Zg*** *– Zrinska Gora,* ***Kz*** *– Kozara Mt.,* ***Pr*** *– Prosara,* ***S-Sd*** *– Slavonija-Srijem depression,* ***Bč*** *– Bačka region,* ***Ba*** *– Banat region (Karađorđeva formation),* ***Bg*** *– Belgrade area (this area contains the following localities: Tešića Majdan, Resnik, Rušanj and Bela Reka),* ***To*** *– Topola,* ***Je*** *– Jelica Mt.,* ***Ru*** *– Rujevac,* ***Kl*** *– Klepa Mt.,* ***Sy*** *– Syros,* ***Ti*** *– Tinos,* ***Sa*** *– Samos,* ***Af*** *– Anafi,* ***Cr*** *– Crete (Asterousia Mt.).*

et al., 1975, 1997; Karamata et al., 1994; Pamić et al., 2000, Dimitrijević, 2001; Grubić 2002; Pamić, 2002; Hass et al., 2004; Schmid et al., 2008, 2020; Ustaszewski et al., 2009; Grubić et al., 2010; Csaszar et al., 2013; Cvetković et al., 2016; Prelević et al., 2017; Toljić et al., 2018). Despite extensive regional mapping and numerous local studies, the tectonic role of the Sava Zone during the latest Mesozoic - in particular the relation to the timing and mechanisms that led to final closure of the Neotethyan domains in this sector remains debated.

Several contrasting interpretations have been proposed. Pamić (2002) described parts of the Sava (Vardar) Zone as a narrow belt of variably metamorphosed Upper Cretaceous sedimentary and magmatic rocks that may record magmatic-arc processes (Karamata et al., 2000; Karamata, 2006) interpreted magmatic formations within the zone as ophiolites, i.e., representing remnants of an Upper Cretaceous oceanic domain. These and the later studies including Schmid et al. (2008, 2020) viewed the Sava Zone as the principal suture that marks the closure of a Late Cretaceous ocean (the "Sava Ocean"). In contrast, numerous regional studies have described Sava Zone as a narrow and repeatedly reactivated fault system having a transcurrent (strike-slip) character, operating within a dextral, obliquely convergent tectonic regime (e.g., Dimitrijević & Dimitrijević, 1975; Dimitrijević, 1997; Grubić, 2002; Köpping et al., 2019; Spahić & Gaudenyi, 2022). Several authors emphasized that many magmatic occurrences within the zone could instead reflect intracontinental extension or transtensional tectonics, rather than oceanic or arc-related volcanism (e.g., Prelević et al., 2017; Köpping et al., 2019; Sokol et al., 2020; Balen et al. 2020; Schneider et al., 2022, 2025).

There is a broad first-order agreement on the present-day configuration of Sava Zone: a major northwest-dipping suture separates Adria (Adria/"African" block) from Tisza–Dacia (Europe-derived) terrains. This structure extends roughly WNW–ESE from Zagreb to Belgrade, then trends toward the N–S direction between Belgrade and Thessaloniki. The suture is spatially associated with variously deformed Upper Cretaceous (± Paleogene) sediments, and contemporaneous magmatic rocks.

The aim of this paper is to reassess the competing interpretations of Sava Zone by synthesizing stratigraphic, petrographic, geochemical and geochronological evidence from key Sava Zone related magmatic localities (Kozara, Požeška Gora, Papuk, Topola, Jelica, Rujevac, Klepa, and adjacent sites). The localities included in our synthesis extend well beyond those originally outlines by Schmid et al. (2020), reflecting the much broader distribution of Upper Cretaceous magmatic occurrences now recognized in the wider Sava Zone region. The criteria by which we decided to include them is apart from Upper Cretaceous age, also their close relationship with Upper Cretaceous sediments with which they sometimes appear coevally. We particularly focus on petrogenetic and geochemical signatures that constrain mantle sources in the aforementioned localities. Our motivation is to put more constraints on the ultimate tectonic setting that generated the Late Cretaceous magmatism, and to clarify the role of Sava Zone during the final suturing and permanent closure of the last Neotethyan domain(s) in this area.

The paper is organized as follows: after a brief geological background, we summarize the distribution and stratigraphic context of Sava Zone magmatism, then present petrographic and geochemical datasets for previously documented occurrences, supplemented by new data from the following localities: the Belgrade area (Rušanj, Bela Reka, and Resnik), Jelica Mt., Topola, and Rujevac (please see Supplementary dataset). The discussion then integrates these data into a tectono-magmatic framework, which we ultimately compare with regional and global models of Neotethyan closure. Finally, we synthesize the evidence and propose a working geodynamic model that reconciles the spatial and geochemical heterogeneity of magmatic signatures across the Sava Zone.

Revisiting Tethyan ocean closure in the Balkans and the role of Sava Zone

The consumption of major Tethyan ocean(s) in the Balkans eventually led to the formation of the collisional orogenic belt, which represents a complex and long-lived convergent boundary between Eurasia and Africa that was active since the Jurassic (Dercourt et al., 1986, Schmid et al., 2008). The Vardar Zone (Kossmat, 1924), forming the central axis of the Balkans (Fig. 1), is a key segment of this part of the Alpine-Himalayan belt, recording the geological evolution of the Vardar branch of the Tethys ocean (Cvetković et al., 2016 and reference therein). The onset of convergence between the two major plates is constrained by metamorphic sole formations that date the initial obduction of oceanic lithosphere to 149–192 Ma (Karamata & Lovrić, 1978; Lanphere et al., 1975; Lugović et al., 1991; Robertson & Karamata, 1994; Pamić 2002). These ages mark the beginning of the progressive consumption of the Tethys in the Balkan region.

The timing and mechanism of the final closure of northwestern segment of Tethyan ocean, however, remain unresolved and continue to represent one of the most debated issues in the Alpine–Himalayan orogenic system (Prelević et al., 2017; Sokol et al., 2020; van Hinsbergen et al., 2020). The classical interpretation for a long time was that all oceanic segments of the Tethys were consumed by the Late Jurassic, implying complete obduction of ophiolites and no remaining oceanic lithosphere existed during the Cretaceous (Csontos et al., 2004; Bortolotti et al., 2013; Karamata, 2006; Robertson et al., 2009). This view was challenged by the discovery of Upper Cretaceous pillow basalts and sheeted dykes in the Kozara Mountains, interpreted as part of a dismembered ophiolitic succession (Karamata et al., 1997b, 2000, 2005; Grubić et al., 2009; Cvetković et al., 2014).

Similar magmatic occurrences of the same age have since been documented across the central Balkans, forming a relatively narrow WNW–ESE belt referred to as the Sava Zone. To explain these findings, several authors proposed that the Sava Zone preserves remnants of a Late Cretaceous oceanic domain — the "Sava Ocean" — that persisted until the latest Cretaceous (Schmid et al., 2008). In this model, the final closure of the last Tethyan oceanic domain occurred along the "Sava Zone" by complete subduction of its oceanic lithosphere (Karamata et al., 2000, Karamata, 2006; Robertson et al., 2009; Schmid et al., 2008; Ustaszewski et al., 2009; Gallhofer et al., 2015; van Hinsbergen et al., 2020).

The existence of Late-Cretaceous Apuseni–Banat–Timok–Panagyurishte–Sredno Gorie (ABTPS) magmatic and metallogenic belt (Fig. 1) is instrumental in this interpretation. The subduction-related geochemistry of its magmatic rocks and their association with porphyry copper deposits have been viewed as indisputable evidence of an Andean-type continental margin developed during north-eastward subduction of the "Sava Ocean" beneath the European plate (Berza et al., 1998; Ciobanu et al., 2002; Gallhofer et al., 2015; von Quadt et al., 2003, 2005; Kolb et al., 2012).

Recent studies, however, have provided alternative interpretations. Investigations of Upper Cretaceous basaltic occurrences in the Klepa inselberg (North Macedonia; Prelević et al., 2017) and Ripanj near Belgrade (Sokol et al., 2020) revealed clear intracontinental, within-plate geochemical signatures, inconsistent with ophiolitic or arc-related magmatism. These findings suggest that the Late Cretaceous volcanism in the Sava Zone was not related to active oceanic subduction (Prelević et al., 2017; Köpping et al., 2019; Sokol et al., 2020; Balen et al. 2020; Schneider et al., 2022, 2025) but instead to transtensional tectonics within a continental setting. (Prelević et al., 2017; Köpping et al., 2019; Sokol et al., 2020). Consequently, whether any true Tethyan oceanic crust persisted into the Late Cretaceous remains an open question.

Geology of the Sava Zone and its geodynamic significance

The Sava Zone (Fig. 1) is best defined as a narrow belt of Upper Cretaceous sedimentary and magmatic formations (Pamić, 2002), locally containing Jurassic ophiolitic fragments (Schmid et al., 2008, 2020; Prelević et al., 2017; Toljić 2018). It occupies a key structural position between crustal blocks of Adria affinity (Jadar–Kopaonik, Drina–Ivanjica, Pelagonides and Helenides) and those of European affinity (Tisza, Dacia (Serbian-Macedonian massif), Veles Series), all variably deformed and sheared (Köpping et al., 2019). The northwestern segment of the Sava Zone extends from the SW–NE-trending Mid-Hungarian plane toward the Zagreb area, and further toward Belgrade, then turns southward into North Macedonia and continues into western Turkey as the Bornova Flysch of the Izmir–Ankara Suture Zone (Okay et al., 2012). Prominent exposures occur in northern Bosnia and eastern Croatia (Kozara, Prosara, Motajica, Moslavačka gora and Požeška Gora), central Serbia (Belgrade area, Šumadija, along the Zvornik fault), and North Macedonia (Klepa; Fig 1).

The Upper Cretaceous to Paleogene sedimentary successions of the Sava Zone consist predominantly of siliciclastic flysch (Pamić et al., 2002), interbedded with mixed siliciclastic–carbonate rocks containing impure shales, sheared limestones (*Scaglia Rossa*-type; Karamata et al.,2000, 2005; Ustaszewski et al., 2009; Prelević et al., 2017; Gajić et al., 2024), sandstones, and conglomerates.

Late Cretaceous magmatism (Fig. 2) is expressed by small-volume transitional to alkaline basaltic lavas, gabbros, dolerites, subordinate rhyolites, A and S granites and rare ultrapotassic basalts (Pamić et al., 2000; Balen et al., 2003, 2020; Ustaszewski et al., 2009, 2010; Nédli et al. 2010; Starijaš et al., 2010; Cvetković et al., 2014; Prelević et al., 2017; Sokol et al., 2020; Šuica et al., 2022b; Schneider et al., 2022, 2025). Geochemical and isotopic data, although limited, indicate that these rocks are unlike typical ophiolitic basalts (Prelević et al., 2017). Instead, they exhibit transitional to Na-alkaline compositions, with mantle-like Sr–Nd isotope ratios, high HFSE/LILE values, and the absence of orogenic geochemical features (e.g., elevated LILE/HFSE ratios, positive Pb, and negative Ti–Nb–Ta anomalies). Such features point to melting of variably enriched mantle sources within an intracontinental setting, likely induced by extensional or transtensional tectonics (Prelević et al., 2017; Sokol et al., 2020; Spahić & Gaudenyi, 2022).

These enriched mantle sources underline the geodynamic importance of the Sava Zone as a key boundary between the Adria and European plates, recording the terminal stages of Neotethyan evolution in the Balkans. Three principal models have been proposed to explain its origin and role during the Late Cretaceous:

i) Remnant-ocean model. The Sava Zone represents remnants of the youngest domain of Neotethyan ocean, still open in the latest Cretaceous (Schmid et al., 2008; Ustaszewski et al., 2009, 2010; Gallhofer et al., 2015). It was formed as a part of an accretionary wedge containing relics of oceanic crust that were finally consumed by subduction in the Late Cretaceous (Karamata, 2006; Schmid et al., 2008, 2020; Robertson et al., 2009; Gallhofer et al., 2015; Toljić et al., 2018).

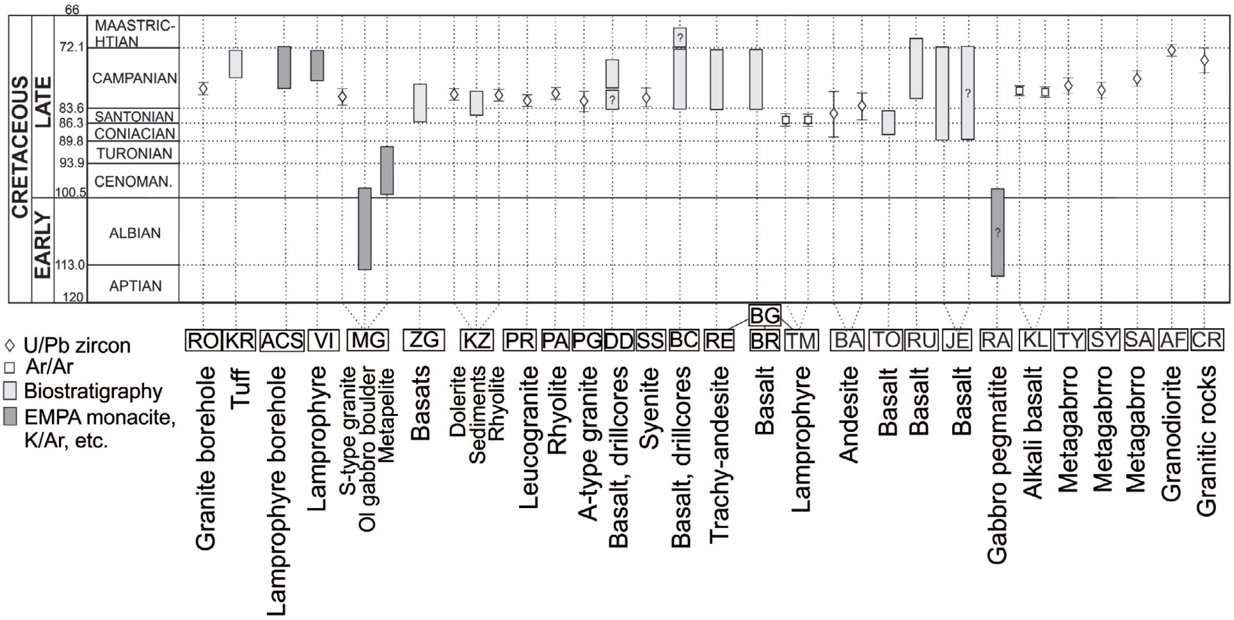


*Fig. 2. Time-chart of all magmatic occurrences within/in the vicinity of the Sava Zone in the Balkans (**Ro** – Rochovce (Haraško et al., 1997; Poller et al., 2001; Kohút et al., 2013), **Kr** – Krško (Gerčar et al., 2022), **Acs** – Alcsútdoboz (Szabó, 1985; Szabó et al., 1993), **Vi** – Villányi Mt. (Molnár & Szederkényi, 1996), **Mg** – Moslavačka Gora (Balen et al., 2003; Starijaš et al., 2010), **Zg** – Zrinska Gora (Šikić, 2014), **Kz** – Kozara (Ustaszewski et al., 2009), **Pr** – Prosara (Ustaszewski et al., 2010), **Pa** – Papuk Mt. (Pamić et al., 2000; Schneider et al., 2022, 2025), **Pg** – Požeška gora (Balen et al., 2020), **Dr** – Drava region (Pamić et al., 2000), **SS** – Slavonija-Srijem depression (Šuica et al., 2022b), **Bč** – Bačka region (Dunčić et al., 2017), **Ba** – Banat region (Karađorđeva formacija; Cvetković et al., 2022), **Bg** – Belgrade area (this area contains following localities: Tešića Majdan (Sokol et al., 2020), Resnik (Andjelković, 1973; Karamata et al., 1997, 1999), Rušanj (Andjelković, 1973; Marković et al., 1985) and Bela Reka (Andjelković, 1973, Ivković et al., 1975, Toljić et al., 2018), **To** – Topola (Toljić et al., 2020), **Je** – Jelica Mt. (Brković et al., 1978), **Ru** – Rujevac (Toljić et al., 2022), **Ra** – Rastište (Božović, unpublished), **Kl** – Klepa Mt.(Prelević et al., 2017), **Sy** – Syros (Tomaschek et al., 2003), **Ti** – Tinos (Bulle et al., 2010), **Sa** – Samos (Bröcker et al., 2014), **Af** – Anafi (Martha et al., 2016), **Cr** – Crete - Asterousia Mt. (Martha et al., 2017).*

ii) Fore-arc model. The Sava Zone developed as a fore-arc region during ongoing subduction of a residual Neotethyan basin. Some Late Cretaceous magmatic sequences may represent fore-arc volcanic or ophiolite-like assemblages produced by ridge subduction or slab rollback (Toljić et al., 2018; Sokol et al., 2020).

iii) Transtensional reactivation model. The Sava Zone marks a reactivated suture between Adria and Europe (Köpping et al., 2019; Sokol et al., 2020), which had already collided by the Late Jurassic–Early Cretaceous (Csontos & Vörös, 2004; Bortolotti et al., 2013). In this scenario, the zone functioned as a diffuse strike-slip and transtensional boundary within the continental lithosphere. The Late Cretaceous magmatic rocks are products of intracontinental volcanism triggered by transtensional deformation (Köpping et al., 2019; Sokol et al., 2020)

Sava Zone magmatism: localities and tectono-stratigraphic setting

Within the generally accepted Alpine framework (Schmid et al., 2008, 2020; Gallhofer et al., 2015; Ustaszewski et al., 2009, 2010; Toljić et al., 2018), the Neotethyan ocean(s) closed along an active margin that remained operative during the Late Cretaceous. In this configuration, the Tisza–Dacia / Serbo-Macedonian units of European affinity are regarded as an upper plate, and the Dinarides, derived from Adria–Africa, as a lower plate. Importantly, Late Cretaceous magmatism within the Sava Zone is distributed across both plates: Adria-side localities (lower plate): Rochovce, Alcsútdoboz, Kozara, Zrinska Gora, Prosara?, Rujevac, and Jelica, and European-side localities (upper plate): Villányi Mt., Moslavačka Gora, Papuk Mt., Požeška Gora, Drava Depression, Slavonia–Srijem Depression, Karađorđevo Formation, Belgrade area, Topola, and Klepa Mountain.

Late Cretaceous magmatism along the Sava Zone is dominantly basaltic and closely associated with sedimentary successions, many of which demonstrate syn-magmatic relationships.

In the **Villány Mountains** (Hungary), dykes of lamprophyric composition intrude Mesozoic limestones (Nédli & Tóth, 2007) and host abundant pyroxene and spinel lherzolite xenocrysts and xenoliths (Nédli & Tóth, 1999). Whole-rock K/Ar dating indicates a Late Cretaceous emplacement age of about 76 Ma (Molnár & Szederkényi, 1996). Comparable lamprophyric rocks containing xenoliths are also documented from the Late Cretaceous NE Transdanubian dyke system of the Alcapa microplate (Szabó, 1985; Szabó et al., 1993) in the **Alcsútdoboz-2 borehole** (Fig. 1).

Zrinska Gora (Croatia) comprises Variscan basement overlain by Late Paleozoic–Mesozoic–Paleogene successions. Its western part exposes a Jurassic ophiolitic mélange including sandstones, shales, cherts, marls, amphibolites, greenschists, peridotites, serpentinites, gabbros, and spilites. The central domain consists of Upper Cretaceous–Paleogene foreland-basin deposits: Campanian *Scaglia*-type pelagic carbonates overlain by Maastrichtian–Paleocene turbiditic sandstones and Eocene conglomerates. Spilites and basalts occur interbedded with Upper Cretaceous limestones and marls, locally accompanied by pyroclastic rocks (Šikić, 2014).

Kozara Mountain (Bosnia and Herzegovina) comprises of bimodal suites including gabbro, dolerite, basalt, and rhyolite occurring with Late Santonian–earliest Campanian *Scaglia Rossa* red pelagic carbonates (Karamata et al., 2000; Grubić et al., 2009;Ustazewski et al., 2009, Cvetković et al. 2014) (Fig. 3a, b).

Prosara Mountain (Bosnia and Herzegovina) exposes a metamorphic basement complex that grades from low-grade phyllites and sandstones in the south to amphibolite-facies gneisses in the north (Šparica et al., 1984). Granite bodies in northern Prosara yielded U–Pb zircon ages of ~82 Ma (Ustaszewski et al., 2010).

Požeška Gora (Croatia) preserves a bimodal complex dominated by rhyolites and alkali granites, with massive basalts and pillow lavas interbedded with Santonian–Maastrichtian limestones and shales (Pamić & Šparica, 1983; Belak et al., 1998). Granites yield U–Pb zircon ages of 83.6 ± 1.5 Ma (Balen et al., 2020) and display A2-type affinity consistent with an extensional, possibly back-arc, setting.

In the basement of the **Drava Depression**, north of the Slavonian Mountains, several oil wells have reached basalts and rhyolites interlayered with Upper Cretaceous sedimentary rocks, spatially associated with A-type granites (Pamić et al., 2000).

The southern part of the Tisia block includes the **Moslavačka Gora** Massif (Pamić, 2000). Its metamorphic envelope is dominated by felsic anatexites and granitic orthogneisses, with subordinate metapelites and amphibolites. Zircon ages of 486–491 Ma from metagranites indicate that this complex largely represents an Early Ordovician granitic protolith (Starijaš et al., 2010). The massif is intruded by a Cretaceous S-type granite pluton emplaced into a LP/HT metamorphic complex. Monazite ages constrain the LP/HT metamorphism to ~90–100 Ma (Starijaš et al., 2010), while zircon dating yields 82 ± 1 Ma for the Central Granite (Stari jaš et al., 2010).

Although **Mt. Papuk** is largely composed of pre-Alpine rock complexes, Cretaceous volcanic rocks occur in the northwestern area near Voćin (Pamić et al., 2000), where they intrude the pre-Alpine basement. The Voćin volcanic complex comprises basalts, rhyolites, and associated pyroclastic rocks of Cretaceous age (~81 Ma), as recently dated from zircon in an albite rhyolite at the Rupnica geosite (Schneider et al., 2022). At the Trešnjevica geosite, migmatitic gneiss and granitoids of the Variscan basement are cut by swarms of younger dikes, comprising rhyolite, andesite, basalt, and fine-grained dolerite (Schneider et al., 2025). Zircon dating from four rhyolite samples and one andesite sample yields ages of 81.1 ± 1.1 Ma and 81.5 ± 1.1 Ma, respectively (Schneider et al., 2025).

In the pre-Neogene basement of the **Slavonia–Srijem Depression**, boreholes have revealed the presence of alkali granite, granite, syenite, and rhyolite. Some of these rocks show close affinities with the Late Cretaceous A-type magmatic suite of the Slavonian region (Šuica et al., 2022a), with the syeni-

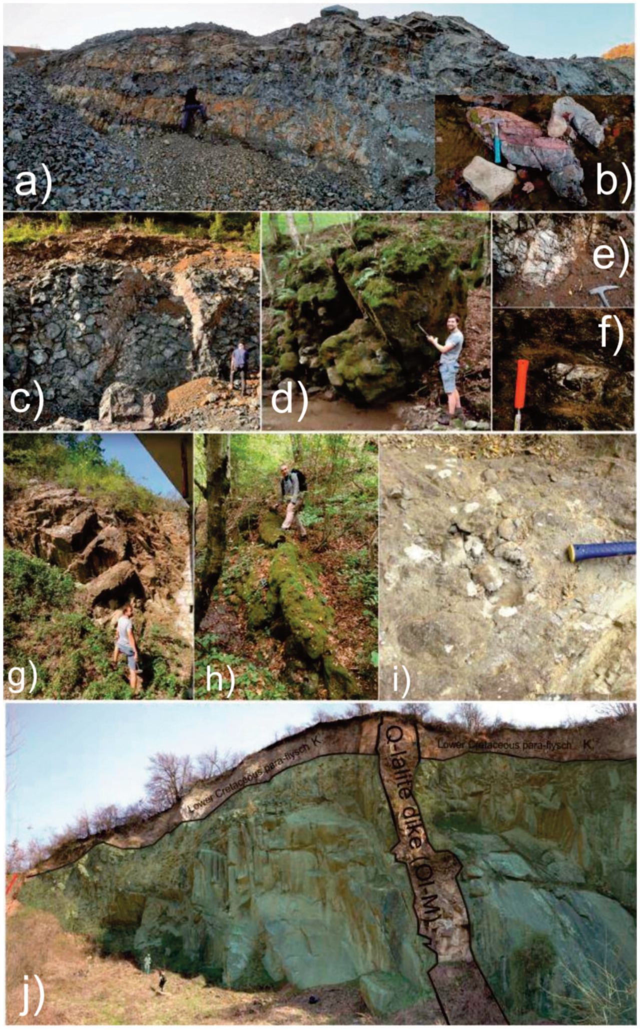


Fig. 3. Field photos of Sava Zone volcanic formations. ***a)*** *Kozara Mt., Trnova quarry with alternation of rhyolitic and basaltic dykes.* ***b)*** *Kozara Mt., deformed lenses of Scaglia Rossa red pelagic carbonates interstratified with basaltic pillow lavas outcrop at the confluence of the River Crna Reka and Krvavac creek. Interbedded pelagic carbonates contain microfossils, notably several species of Globotruncana, of Upper Santonian–Lower Campanian age, which was interpreted as an irrefutable proof for the Cretaceous ophiolites (Karamata et al., 2000; Grubić et al., 2009).* ***c)*** *Jelica Mt., pillow basalts at Crna stena quarry.* ***d)*** *Rujevac, Vukova reka, pillow basalts cut by a dyke of similar composition.* ***e)*** *Rujevac, the contact between basalts and Upper Cretaceous limestone.* ***f)*** *Rujevac, a block of Upper Cretaceous limestone in the basalt.* ***g)*** *Ripanj towards Bela Reka (Belgrade area), basaltic dyke cutting Lower Cretaceous sandstone (para-flysch unit).* ***h)*** *Rušanj (Belgrade area), basaltic dyke that cuts Lower Cretaceous para-flysch unit.* ***i)*** *Resnik (Belgrade area) cobbles sized trachyandesite volcaniclastites in the Upper Cretaceous marl.* ***j)*** *Tešića Majdan quarry (Belgrade area) showing the Late Cretaceous lamprophyre (vaugnerite-durbachites series) sill? intruding into Early Cretaceous para-flysch. The Oligocene quartzlatite (K-Ar 25 Ma; Vasković, 1990) cuts these two units.*

tes dated to approximately 83.0–80.5 Ma (Šuica et al., 2022b).

In **Serbia**, Sava Zone sequences are partly known from borehole samples beneath the Pannonian Basin sedimentary cover. In **Bačka**, Campanian–Maastrichtian pelagic limestones are interbedded with diabase, spilite and tuffs (Dunčić et al., 2017). Deeper boreholes from **South Bačka** and **Banat** intersected the **Karađorđevo Formation** (Kemenci & Čanović, 1987; Čanović & Kemenci, 1999), a volcaniclastic series containing sedimentary rocks with volcanic detritus. The clastic horizons are rich in angular fragments of andesite showing porphyritic textures with euhedral plagioclase phenocrysts. Many fragments are hydrothermally altered, with albitized and epidotized plagioclase and chloritized groundmass. Radiometric dating of zircon populations from borehole samples yielded Campanian ages (76.9±1.3 Ma, 82.8±2.2 Ma, 84.4±4.8 Ma; Cvetković et al., 2022), confirming coeval volcanism with sedimentation. Older zircon populations (300 Ma to 2.5 Ga) reflect recycled crustal sources.

In the **Belgrade area**, diverse Coniacian–Santonian magmatism includes lamprophyres, andesites, trachydacites, and syn-depositional basalts (Andjelković, 1973, 1953, 1975a,b, 1982, 1984; Andjelković & Milojević, 1964; Karamata et al., 1997a, 1999; Toljić et al., 2020), occurring as dykes (Fig. 3g,h), flows, sills (Fig. 3j) and volcaniclastic conglomerate in the Upper Cretaceous marls (Fig. 3i). In the **Ripanj** locality, there is a quarry of lamprophyre *(vaugnerite-durbachites series)*. Ar–Ar dating of phlogopite yielded age of ~86 Ma (Sokol et al., 2020) (Fig. 3j).

Further south, **Topola** (central Serbia) provides key evidence of syn-depositional Upper Cretaceous volcanism (Toljić et al., 2020). At Karađorđeva Česma, basalts are overlain by carbonates, while at Limovac they directly overlie marls and peperites. The peperites, with mingled lava and carbonate clasts, record lava–sediment interaction in a shallow-water setting. Foraminiferal assemblages (*Marginotruncana sigali, Dicarinella primitiva, D. concavata, Globotruncana spp., Whiteinella baltica*) constrain the age to the Upper Turonian–Lower Coniacian. Together, the Topola sections provide unambiguous evidence for shallow-marine, syn-sedimentary volcanism in an extensional basin.

Along the **Zvornik Suture** (Dimitrijević, 1972, 1997; Dimitrijević & Dimitrijević, 1975; Gerzina, 2010) (western Serbia) or fault, magmatism is closely associated with this major tectonic lineament of the Internal Dinarides. Its southern continuation is exposed in the **Jelica Mountain**, where basement rocks of Jadar–Kopaonik affinity (para-schists, marbles, metabasites) are overlain by Cretaceous volcano-sedimentary formations. Transitional subalkaline and tholeiitic basalts occur interbedded with hemipelagic limestones and clastics (Fig. 3c). At **Rujevac near Krupanj**, basaltic lavas, dykes and pillows (Fig. 3d,e) are associated with Coniacian–Santonian limestones containing *Marginotruncanids, Dicarinellids, Heterohelicids*, and other planktonic foraminifera (Toljić et al., 2022). These relationships confirm syn-sedimentary emplacement of basaltic lavas within Cretaceous basins.

In North Macedonia, **Klepa Mountain** exposes transitional subalkaline to alkaline volcanic rocks (microgabbros, trachyandesites, trachytes, and basalts) overlain by hemipelagic limestones and conglomerates. Ar–Ar ages of ~81 Ma (Prelević et al., 2017) overlap with Kozara magmatism. Unlike Kozara, however, the Klepa basalts lack MORB affinities, suggestng either a fore-arc or transtensional setting.

Beyond the core regions of Croatia, Bosnia and Herzegovina, Serbia and North Macedonia, additional Late Cretaceous occurrences include: the Rochovce granite (Slovakia; Kohút et al., 2013), bentonite layers near Krško (Slovenia; Gerčar et al., 2022) and metamorphic igneous rocks in Greece, including Asterousia meta-diorites and granodiorites (Martha et al., 2017), Anafi granodiorites (Martha et al., 2016), and meta-gabbro from Samos, Tinos, and Syros (Bröcker et al., 2014; Bulle et al., 2010; Tomaschek et al., 2003).

Petrography and available geochemical data

In our synthetic approach, we tentatively divide the rocks of Sava Zone into two groups, reflecting their tectonic position: (1) European-side (upper plate) localities (Villányi Mt., Moslavačka Gora, Papuk Mt., Požeška Gora, Drava Depression, Slavonia–Srijem Depression, Karađorđevo Formation, Belgrade area, Topola, and Klepa Mt.) and (2) Adria-side, that is, Dinarides (lower plate) localities (Alcsútdoboz, Kozara, Zrinska Gora, Rujevac, and Jelica). The petrographic descriptions and their corresponding references are presented in the section above.

Petrography

In the northern Sava Zone, notably at Kozara Mountain, Požeška Gora, and Zrinska Gora, bimodal igneous complexes include gabbros, dolerites, basalts, and rhyolites. Basaltic pillow lavas are closely associated with *Scaglia*-type pelagic limestones of Late Santonian–earliest Campanian age (Grubić et al., 2009). These basalts are strongly hydrothermally altered, typically porphyritic with intersertal to skeletal and aphanitic textures. Primary phases (plagioclase, clinopyroxene, Fe-oxides, volcanic glass) are variably altered, whereas albite, chlorite, epidote, calcite, quartz, and titanite define a zeolite–greenschist facies assemblage. Amygdales filled with calcite (rarely hematite) are ubiquitous. Together, the mineral assemblage and preserved basaltic textures identify these rocks as highly altered basalts (spilites; Cann, 1969). Plagioclase phenocrysts (labradorite to andesine) are variably sericitized and overgrown by albite, while clinopyroxenes are largely replaced by chlorite and epidote, with only rare augite preserved. Dendritic augite and skeletal plagioclase also occur.

The Villány lamprophyre shows a porphyritic to panidiomorphic texture with altered olivine and clinopyroxene phenocrysts set in a fine-grained, pyroxene-rich groundmass. Glomeroporphyritic aggregates and altered mafic–ultramafic xenoliths are observed. Olivine is entirely replaced by calcite, serpentine minerals and Fe–Ti oxides, while clinopyroxene occurs as zoned phenocrysts and euhedral augite, partly rimmed by amphibole. The groundmass contains plagioclase, amphibole, biotite, Fe–Ti oxides, and acicular apatite, with secondary chlorite, clays, and calcite filling the matrix.

Granite bodies occur in Prosara Mountain, whereas in Požeška Gora the bimodal association is dominated by rhyolites and alkali granites.

Serbian localities display considerable petrographic variation. In the Karađorđevo Formation, epiclastic and volcaniclastic material includes porphyritic andesites with euhedral, short-prismatic plagioclase phenocrysts. These are commonly hydrothermally altered, with albitized and epidotized plagioclase and chloritized groundmass. Fragmentation was most likely gravitational, though hyaloclastic processes cannot be excluded.

The Ripanj lamprophyres are kersantites with granular to weakly macrocrystic textures. They contain millimeter-sized poikilitic phlogopite, diopside, plagioclase, orthoclase, and abundant apatite. Phlogopite is mostly fresh with minor chloritization; diopside shows slight uralitization; plagioclase is consistently albitized and difficult to distinguish from alkali feldspar whereas orthoclase is intensely saussuritized and albitized. Modal reconstructions indicate that Ripanj rocks represent plutonic equivalents of phlogopite lamprophyres, i.e. vaugnerites (Rock, 1991; Le Maitre, 2002). The Bela Reka basalts (Fig. 3d) display a distinct porphyritic texture characterized by euhedral to subhedral olivine phenocrysts, which are commonly altered to secondary assemblages. The fine-grained groundmass is dominated by plagioclase laths, extensively albitized, and clinopyroxene that has undergone pervasive chloritization. Accessory minerals include zircon and apatite, both occurring as small, well-formed crystals dispersed throughout the matrix. Secondary mineral assemblages comprise Fe–Ti and Fe–Cr oxides, chlorite, calcite, and quartz, reflecting significant post-magmatic alteration.

At Topola, basalts (Fig. 3f) are heavily altered, hypocrystalline, and predominant aphyric, exhibiting vesicular–amygdaloidal textures filled with calcite and palagonitic groundmass. The rock is mainly composed of diopside, which locally forms glomeroporphyritic aggregates. These diopsides are characterized by high Ti content and show alteration to sphene and chlorite. Amphibole is also present, while the groundmass contains plagioclase that has undergone albitization. The secondary mineral assemblage includes Fe–Ti oxides, chlorite, calcite, and quartz.

The Resnik (Fig. 3b) samples comprise volcaniclastic rocks redeposited within marly sediments. These clasts, typically fist-sized, are predominantly trachyandesitic, with minor basaltic and basaltic–andesitic compositions. The trachyandesites are characterized by phenocrysts of plagioclase, sanidine, and biotite, all exhibiting intense alteration. Secondary minerals include epidote, chlorite, Fe–Ti oxides, barite, pyrite, and galena, whereas apatite and zircon occur as accessory phases. The groundmass is mainly glassy that has undergone devitrification. Samples displaying a glomeroporphyritic texture are comparatively unaltered, preserving fresh primary mineral assemblages. Basaltic varieties consist chiefly of augite and plagioclase, showing a hypocrystalline porphyritic texture and pervasive alteration, marked by chloritization and epidotization of clinopyroxene and albitization of plagioclase.

Along the Zvornik fault (Jelica Mountain and Rujevac), basalts are also hydrothermally altered, with porphyritic and intersertal to skeletal–aphanitic textures. Their mineralogy parallels that of northern localities, with primary plagioclase, clinopyroxene, spinel, Fe-oxides, and volcanic glass overprinted by albite, chlorite, epidote, calcite, quartz, and titanite. Rare olivine phenocrysts occur (relicts). Hyaloclastite has also been identified in thin section (Fig. 3g) in association with the basaltic rocks. Within this hyaloclastite, we recognized paragonite (Fig. 3h) and observed radiolarian remains (Fig. 3j), although the radiolaria have not been taxonomically determined.

Klepa Mountain (North Macedonia) contains subalkaline transitional and alkaline basalts, Ti-amphibole-bearing microgabbros, and trachyandesites/trachytes. These are porphyritic, with phenocrysts of pseudomorphed olivine, diopside, plagioclase, and in some cases amphibole. The groundmass comprises tabular/acicular plagioclase (partly albitized), amphibole, and altered glass. Secondary minerals include chlorite, calcite, epidote, sericite, albite, and clays.

Taken together, the magmatic sequences occurring in the European-side localities remain distinguished by their lithological and petrographic diversity, whereas their counterparts occurring in the Adria-side localities - although now including both mafic and felsic representatives - still show a

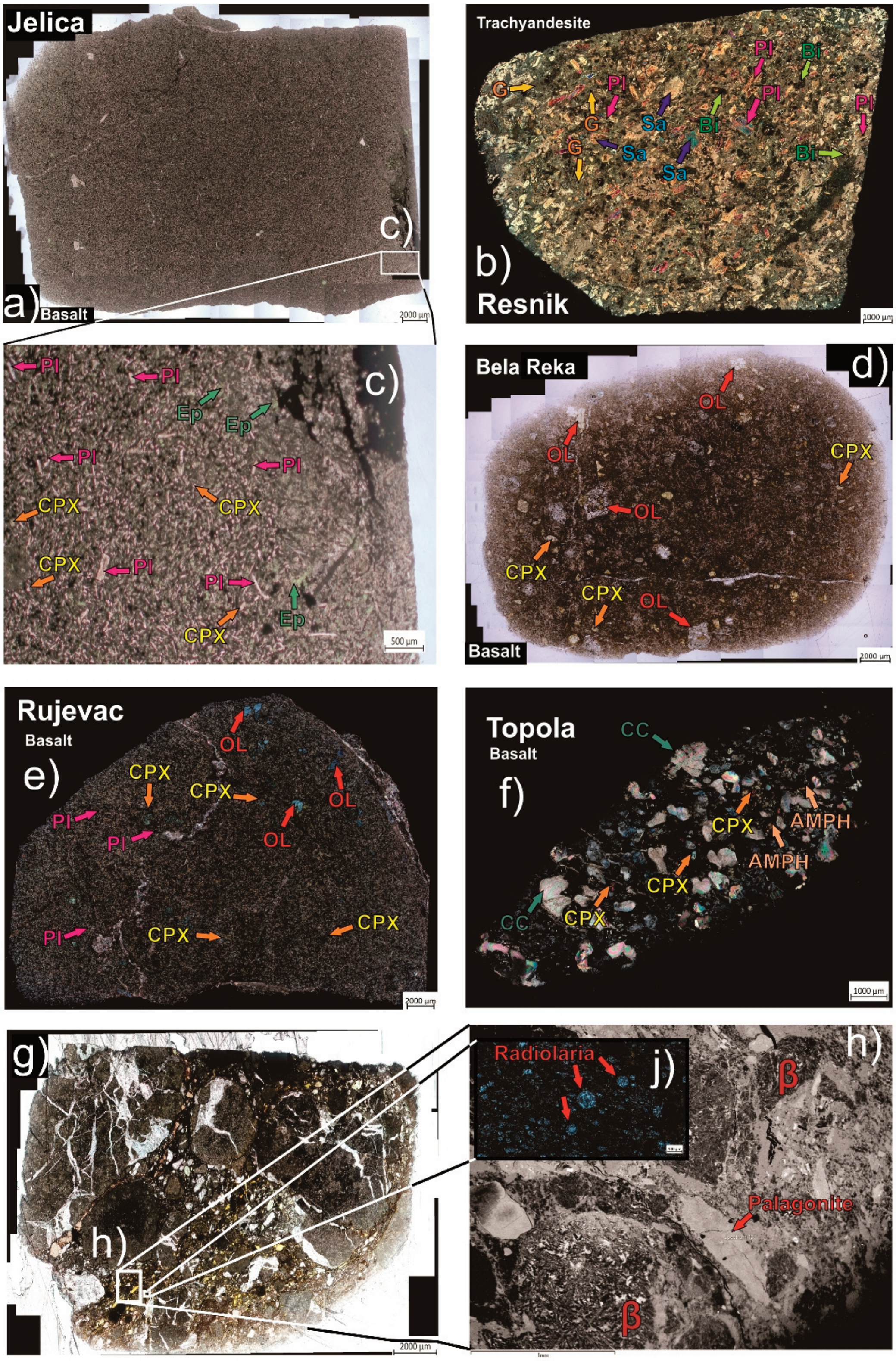


Fig. 4. *Photomicrographs of representative samples of the Late Cretaceous rocks from* ***a)*** *Jelica Mt. Cretaceous basalt.* ***b)*** *Resnik trachyandesite.* ***c)*** *shows a close up view of the area marked in a).* ***d)*** *Bela Reka basalt.* ***e)*** *Rujevac basalt.* ***f)*** *Topola basalt.* ***g)***, ***h)*** *and* ***j)*** *Jelica Mt. hyaloclastite. g) and j) provides a detailed view of the specific area indicated in g) illustrating paragonite and j) radiolaria. Mineral abbreviations are from* K*RETZ*, *1983. Note the following symbols denote: β – basaltic rock fragment, G – devitrified glass.*

more coherent set of textures and mineral–alteration features, dominated by systematically altered basalts and rhyolitic/rhyodacitic lavas.

Geochemistry

Extensive alteration, as indicated by consistently high LOI values, precludes reliable major-element classification of the Late Cretaceous lavas. Alteration strongly affected major elements and fluid-mobile LILE (Ba, Cs, K, Rb, Sr), but HFSE and REE remain relatively immobile (Pearce, 2014) and provide a basis for classification (Winchester & Floyd, 1977) (Fig. 5a).

Available data indicate basaltic compositions for majority of the locations where Late Cretaceous lavas occur with SiO_2 ranging 41–53 wt.% (Le Maitre, 2002). On Nb/Y vs. Zr/Ti (Winchester & Floyd, 1977) and Nb/Y vs. Ti/Y diagrams, all samples plot within the basalt field, spanning tholeiitic to alkaline affinities (Fig. 5a). Felsic rocks associated with the European-side occurrences display a greater geochemical and petrographic heterogeneity, with compositions spanning the trachyandesite, trachyte, and rhyolite fields. In contrast, the acidic rocks occurring on the Adria-side are comparatively homogeneous, clustering within a narrower compositional range, predominantly in the rhyodacite–dacite to rhyolite field.

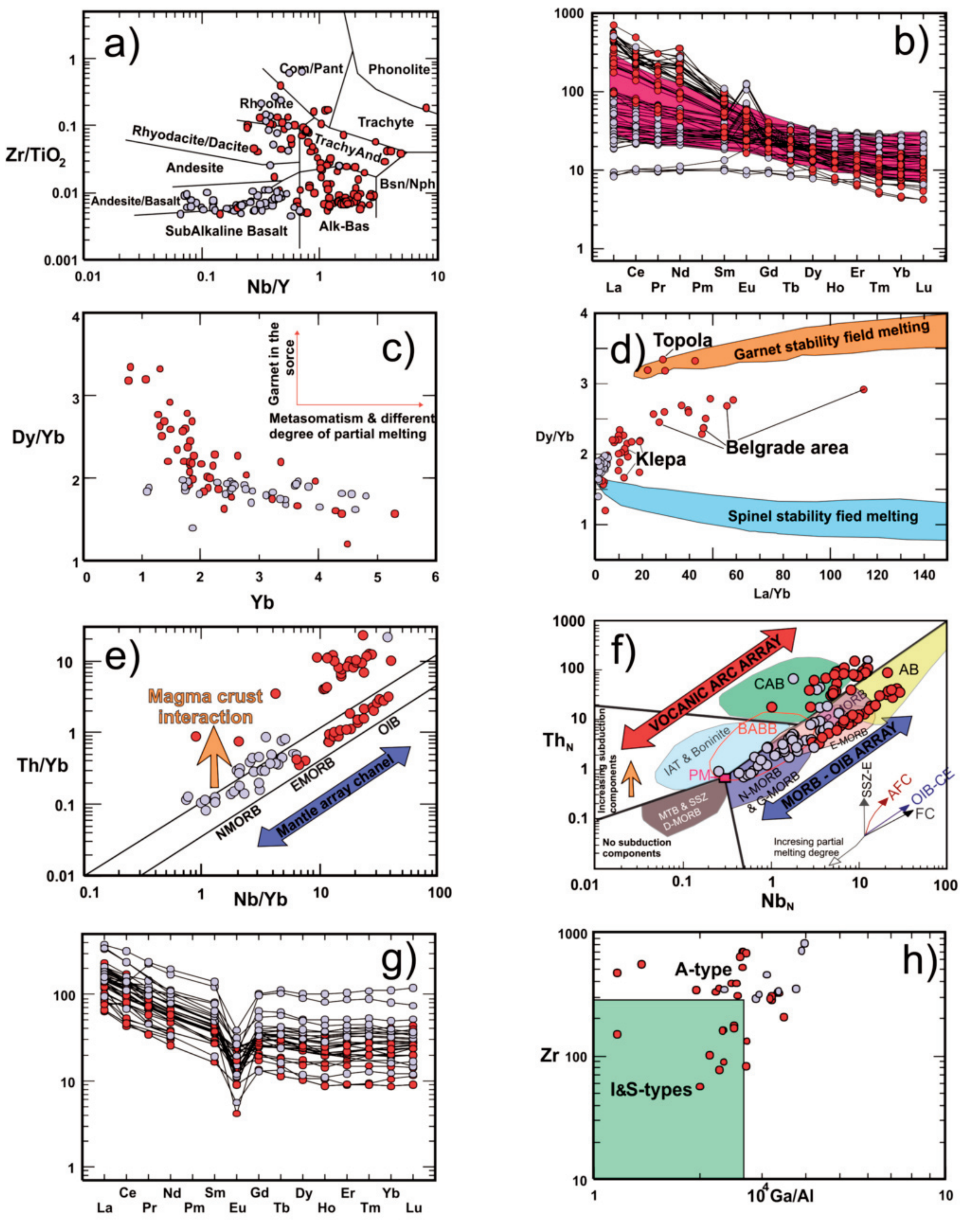
On average both basic and acidic rocks from European-side occurrences exhibit higher Nb/Y values than those occurring on the Adria side. This trend is consistent with either a more enriched mantle source or higher degrees of crustal contamination relative to the Adria-derived counterparts.

Basalts from the Adria-side localities are moderately enriched in LREEs (Fig. 5b), although notable exceptions exist (e.g., Alcsútdoboz). La_N/Yb_N values vary from 0.81–1.65 at Jelica and Rujevac to 1.7–3.9 at Kostajnica and Kozara. Corresponding La_N/Sm_N ratios (0.61–1.00 for Jelica/Rujevac; 1.20–1.92 for Kostajnica/Kozara) and Eu_N/Yb_N values (0.89–1.82, except dolerites from Kozara with markedly elevated values of 4.2–4.6) point to moderate HREE fractionation. Overall, the REE patterns from the Adria-side basaltic occurrences are more enriched than N-MORB and comparable to E-MORB, but much less enriched than typical OIB. Their primitive-mantle–normalized multi-element patterns also show E-MORB–like characteristics, including modest enrichment over N-MORB and mostly reduced or absent Ti anomalies.

In contrast, basalts from the European side show geochemical signatures typical of trace-element enriched within-plate magmas. Characteristic features

Fig. 5. *(next page). Blue dots represent Adria-derived Late Cretaceous magmatic rocks (Alcsútdoboz, Zrinska Gora, Kozara Mt., Rujevac and Jelica Mt.) while red dots represent Europe-derived magmatic rocks (Villanyi, Moslavačka Gora, Prosara?, Papuk Mt., Požeška Gora, Drava depression, Slavonia-Srijem, Tešića Majdan, Bela Reka, Resnik, Rušanj, Topola and Klepa).* ***a)*** *Classification diagram Nb/Y and Zr/Ti for volcanic rocks from Sava Zone (Winchester & Floyd, 1977).* ***b)*** *Chondrite-normalized REE diagram (Sun & McDonough, 1989) for basaltic rocks from Sava Zone (SiO_2 <53%) (Le Maitre, 2002), magenta colored field in the diagram represents whole rock samples from Klepa (Prelević et al., 2017).* ***c)*** *Dy/Yb vs. Yb whole rock data of basaltic rocks (SiO_2 <53%) (Le Maitre, 2002).* ***d)*** *Dy/Yb vs La/Yb the whole rock data of basaltic rocks (SiO_2 <53%) (Le Maitre, 2002) are plotted. Fields of melt compositions for melting in the garnet and spinel peridotite stability fields are from Prelević et al. (2012).* ***e)*** *Nb/Yb vs. Th/Yb Pearce et al. (2008) diagram for basaltic volcanic rocks (SiO_2 <53%).* ***f)*** *Th_N vs Nb_N N-MORB normalized discrimination diagram (after Saccani, 2015) whole rock data of basaltic rocks (SiO_2 <53%) (Le Maitre, 2002). Note abbreviations of the fields referenced in the diagram MTB, SSZ and D-MORB (Medium Titanium Basalts, Supra Subduction Basalts and Depleted Mid-Oceanic Ridge Basalts), NMORB (Normal Mid-Oceanic Ridge Basalts), E and G-MORB (Enriched and Garnet influenced Mid-Oceanic Ridge Basalts), PMORB (Plume influenced Mid-Oceanic Ridge Basalts), AB (Alkaline ocean-island Nasalts), IAT (low Ti, Island Arc Tholeiites), BABB (Back Arc Basin Basalts), PM (Primitive Mantle), CAB (Calk Alkaline Basalts). Vectors indicate the trends of compositional variations due to the main petrogenetic processes. Abbreviations: SSZ-E (Supra Subduction Zone enrichment), AFC (Assimilation-Fractionation Crystallization), OIB-CE (Ocean Island Basalt-type (plume-type) component enrichment, FC (Fractional Crystallization).* ***g)*** *Chondrite-normalized REE diagram (Sun & McDonough, 1989) for acidic rocks (SiO_2 >64).* ***h)*** *Zr vs. Ga/Al discrimination diagrams for granites after Whalen et al. (1987). I, S, and A granites. Geochemical data for acidic rocks (SiO_2 >64) for the Mt. Moslavačka Gora are from Starijaš et al. (2010), for the northern part of Mt. Kozara are from Ustaszewski et al., 2009 and Cvetković et al., 2014, Papuk (Pamić et al., 2000; Schneider et al., 2022), Požeška Gora (BALEN et al., 2020), Moslovačka Gora (Starijaš et al., 2010), Slavonia-Srijem depresion (Šuica et al., 2022). Data for basaltic rocks (SiO_2 <53%) from Alcsútdoboz (Szabo et al., 1993), Kozara (Ustaszewski et al., 2009; Cvetković et al., 2014), Villanyi (Nedli et al., 2007), Papuk (Pamić et al., 2000), Požeška Gora (Pamić et al., 2000), Drava depresion - Bizovac (Pamić et al., 2000) Zrinska Gora – Kostajnica (Olić Peco et al. submitted), Tešića Majdan (Sokol et al., 2020), Klepa (Prelević et al., 2017), and from this paper from Belgrade region (Bela Reka, Rušanj), Topola, Jelica and Rujevac.*

include low Zr/Nb ratios (4–8), high Zr/Hf (>40), Nb/Yb up to ~60, Nb/Ta up to ~20, and markedly variable La/Yb ratios. Their REE patterns are strongly fractionated, with LREE enrichment approaching OIB-like values (La_N/Yb_N >> E-MORB), suggesting derivation from an enriched mantle source (Fig. 5d). Primitive-mantle–normalized multi-element patterns display strong enrichment



relative to both N- and E-MORB and most closely resemble OIB, again without systematic Ti anomalies.

In Th/Yb–Nb/Yb diagram (Pearce, 2008), the two groups are clearly separated: European-side samples trend from the mantle array toward OIB compositions with or without crustal components, whereas Adria-side lavas cluster within the N-MORB (Jelica-Rujevac) to E-MORB field (Kostajnica-Kozara) (Fig. 5e).

The Dy/Yb–La/Yb and Dy/Yb–Yb systematics (Fig. 5c,d) reveal three distinct mantle melting regimes, which also correspond spatially to the two tectonic domains:

1) Deep melting in the garnet stability field – European side;

Basalts from the Topola area display high Dy/Yb and steep HREE slopes, indicating melting at depths of the garnet stability field. This signature reflects a relatively thick lithosphere and/or access to deeper asthenospheric mantle beneath the European domain.

2)Polybaric melting involving both garnet and spinel – European side;

Samples from the Belgrade area and, to a lesser degree, Klepa define intermediate Dy/Yb and La/Yb ratios, consistent with melting at the depths ranging across the garnet–spinel transition. This implies a polybaric melting path and variable contributions from deeper and shallower mantle sources.

3) Shallow melting in the spinel stability field – Adria side;

Basalts from Adria - side localities cluster near the spinel-field array, indicating melting at shallower depths where spinel is the dominant residual phase. This pattern matches a thinner lithosphere and more typical upper-mantle conditions beneath the Adria-derived units.

Taken together, these relationships show that the European-side magmas were generated from deeper and more compositionally variable mantle sources, whereas the Adria-side basalts reflect shallower melting of a comparatively uniform spinel-bearing mantle. This spatial organization of melting regimes reflects the broader petrological and geochemical contrasts between the two tectoni blocks.

Figure 5g shows chondrite-normalized REE patterns for rhyolites and granites. The samples from both Adria and Europe do not show pronounced differences, both showing enrichment in light REEs (LREEs) and comparatively lower, relatively flat heavy HREE patterns. A distinct negative Eu anomaly is present in all samples.

The Zr vs Ga/Al (Fig. 5h) discrimination diagram of Whalen et al. (1987) shows that the Mt. Moslavačka Gora sample plots within the I–S type field, whereas the rhyolites from N. Kozara and the Slavonia–Srijem area, as well as granites from Požeška Gora and rhyolites from Papuk, fall within the A-type field.

Based on the Y/Nb vs. Rb/Nb diagram Fig. 6 of Eby (1992), the granites from Požeška Gora and part of the Slavonia–Srijem (SS) granites, together with the rhyolites from Northern Kozara, plot within the A2 subtype field. In contrast, the remaining SS granites, along with the Papuk rhyolites, fall within

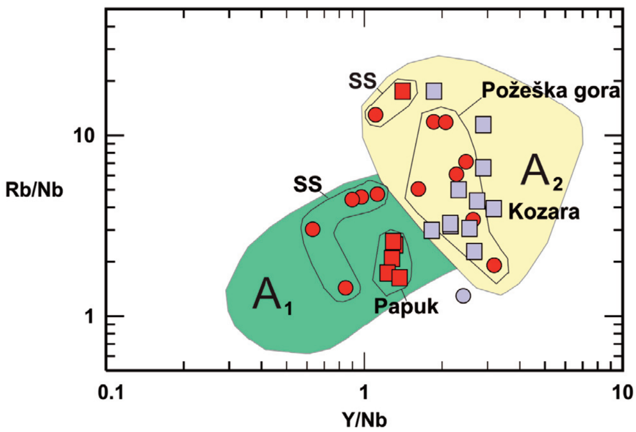


Fig. 6. *Y/Nb vs. Rb/Nb discrimination diagram after Eby (1992), using the same dataset as in Fig. 5h. Squares denote rhyolite samples, whereas circles denote granite samples. In the diagram, the green-shaded area corresponds to the A1 subtype, whereas the yellow-shaded area delineates the A2 subtype.*

the A1 subtype field. In summary, the Adriatic plate rhyolites plot within the A2 subtype field, whereas the European plate localities display a broader range, encompassing A1- and A2-type rhyolites and granites, as well as S-type granitoids.

Discussion

The data presented above provide important information about the major petrological and geochemical features of the magmatic formations comprising the Sava Zone. In the following subsections, we explore their implications for the Late

Mesozoic geodynamic evolution of the region, with particular attention to the timing and mechanism of Neotethyan ocean closure and whether the Sava Zone magmatism intruded oceanic or continental lithosphere.

Geodynamic Interpretation of Sava Zone magmatism

Radiometric ages and stratigraphic associations show that the bulk of magmatic activity within the Sava Zone clusters in the Late Santonian–Early Campanian (Kozara, Zrinska Gora, Papuk, Požeška Gora, Klepa, Jelica, Rujevac; (Belak et al., 1998; Pamić et al, 2000; Grubić et al., 2009; Ustaszewski et al., 2009; Prelević et al., 2017; Balen et al., 2020; Toljić et al., 2020). Locally older magmatic activity of Early Coniacian–Santonian (Topola; Toljić et al., 2020) or younger magmatic activity of Late Campanian–Early Maastichtian (Karađorđevo Formation; Dunčić et al., 2017; Cvetković et al., 2022) ages occur. The basalts reported by Dunčić et al. (2017) are not part of the Karađorđevo Formation; rather, only the volcaniclastic series – consisting of sedimentary rocks containing volcanic detritus – can be assigned to this formation.

In most localities, basaltic rocks are either closely associated and/or interstratified with the sedimentary successions. However, these sedimentary units within Sava Zone associated with basalts provide limited constraints. While dominated by clastic sediments, the diagnostic and widespread lithology is the pelagic *Scaglia Rossa* limestone. In many studies, this type of lithology was ascribed to deep oceanic (abyssal) type deposits, presenting an unambiguous evidence for the oceanic affinity for the whole Sava Zone volcanic and sedimentary association (Grubić et al., 2009). However, global studies of these limestones (Kuhnt, 1990; Kaminski & Gradstein, 2005) show that they are poor paleogeodynamic markers: they typically reflect deposition above the CCD with minimal detrital input, low organic flux, and well-oxygenated bottom waters, with hematite imparting their red color. Even the presence of abyssal agglutinated foraminifera does not necessarily indicate abyssal depths but rather oligotrophic conditions. Thus, the sedimentary record alone cannot resolve whether the Sava Zone basins were truly on the oceanic lithosphere.

Despite broad temporal overlap and similar stratigraphic contexts, the Late Cretaceous magmas are not homogeneous across the Sava Zone demonstrating systematic geochemical asymmetry between the two tectonic domains, as shown above: Adria - side units show basaltic compositions with MORB–to E-MORB-like signatures, modest LREE enrichment, and trace-element patterns consistent with melting of a depleted to mildly enriched mantle, whereas European - side units display stronger HFSE–LREE enrichment and within-plate/OIB-like characteristics, with melting extending into deeper mantle levels (mixed garnet–spinel or garnet-dominated fields).

This contrast may be interpreted as evidence for fundamentally different tectonic regimes operating across the Sava Zone. However, the variation of the canonical trace-element ratios (Th/Yb, Nb/Yb, La/Yb, Nb/U) applied in the discrimination diagrams often shows overlap for true oceanic basalts, within-plate melts and continental transtensional suites (Pearce, 2008). In addition, similar HFSE/REE signatures can arise from different processes: (a) variation in source composition (e.g., prior-subduction metasomatism), (b) differing degrees and depths of melting (spinel vs. garnet stability), or (c) different contributions from small volume mantle melts (e.g., OIB-type blobs) mixing with MORB-like melt. Thus, discrimination plots, while useful, are not irrefutable proof of a single tectonic mechanism.

An alternative and here preferred explanation is that both Adria- and European-side volcanic suites formed within a broadly uniform transtensional regime during the Late Cretaceous, but tapped compositionally different mantle domains. The geochemical disparity primarily records the lateral heterogeneity of the lithospheric mantle: relatively depleted or mildly enriched beneath the Dinarides but variably enriched beneath the European margin due to earlier subduction-related metasomatism. Consequently, similar tectonic forces, as a slab rollback and localized transtensional strain, could have tapped different mantle reservoirs, producing the observed spectrum from E-MORB-like to OIB-like magmatism (Prelević et al., 2017, 2024; Stanković et al., 2026).

The acidic magmas support this view. Although felsic units on the Adria side are compositionally restricted and fall consistently within the A2 field, those on the European side span A1, A2, and S-type compositions. We interpret this diversity not as evidence for separate tectonic environments, but as reflecting different proportions of mantle-derived versus crustal melts, variations in the depth of crustal melting, and contrasts in magma ascent paths. These processes may reflect multiple magmatic pulses, consistent with the broader 87–76 Ma range for the basaltic rocks and the narrower 80.5–83.6 ± 1.5 Ma interval recorded by the acidic rocks. However, to further clarify these relationships, additional radiogenic isotope work will be required (both basic and acidic rocks). Such analyses are essential for better understanding key questions regarding magma sources, degrees of crustal involvement, and timing of melt generation, and for determining whether a single regional magmatic event or multiple discrete processes produced the observed geochemical heterogeneity. It is important to note that the published studies on acidic rocks from the Sava Zone are not uniform in the level of available petrological and geochemical detail. Most localities have well-constrained geochronological data (Fig. 2); there are some works that provide insights into magma ascent rates Požeška Gora (Balen et al., 2020) whereas isotopic data are largely lacking. It is also important to note that these acidic rocks are spatially restricted to region between Slavonia and northern parts of Bosnia & Hercegovina (exception being Rochovce granite) not broadly documented elsewhere, which emphasizes their significance in understanding the unique thermal & tectono-magmatic evolution of the area.

In summary, the geochemical evidence reveals a complex and spatially heterogeneous Late Cretaceous magmatic system along the Sava Zone: E-MORB-like tholeiites in the Dinarides domain and enriched, within-plate/OIB-like basalts on the European side. This pattern is best explained by a tectonic scenario involving late-stage extension, slab rollback, and heterogeneous mantle composition, all acting along a reactivated suture zone during the final stages of Neotethyan evolution and transtensional tectonics. The following section examines how this interpretation fits within the broader regional and global framework of Mediterranean orogenesis and Tethyan ocean closure.

Broader regional and global geodynamic implications

This synthesis of geological and geochemical data from the Sava Zone magmatism tries to provide a step towards a comprehensive understanding of the terminal evolution of the Neotethyan realm in the Balkans. In our view, the Sava Zone magmatism records the post-collisional response of a lithosphere already sutured by the earlier convergence of Adria and Europe, rather than marking the site of a still-active oceanic subduction system during the Late Cretaceous (Prelević et al., 2017; Köpping et al., 2019; Sokol et al., 2020).

In this framework, the Sava Zone more probably represents a diffuse intracontinental corridor that accommodated transtensional strain during the reorganization of plate boundaries following the cessation of subduction (Dimitrijević & Dimitrijević, 1975; Dimitrijević, 1997; Grubić, 2002; Köpping et al., 2019). Localized extension within this corridor triggered asthenospheric upwelling and decompression melting of a heterogeneous lithospheric mantle, variably modified by earlier subduction episodes. The resulting magmas range from tholeiitic to highly enriched alkaline compositions, reflecting spatially variable lithospheric sources rather than distinct tectonic settings. The onset of lamprophyric magmatism at ~87 Ma (Ripanj) indicates that transtensional deformation began significantly earlier than previously recognized, predating the Oligocene onset of Pannonian extension.

Regionally, this intracontinental magmatism developed synchronously with the Upper-Cretaceous Apuseni–Banat–Timok–Panagyurishte–Sredno Gorie (ABTPS) magmatic and metallogenic belt to the northeast, a system commonly interpreted as an active Andean-type continental margin. However, already some parts of this belt, namely Sredno Gorie, is interpreted as being postcollisional resulted from the collapsing orogeny after latest Jurassic–Early Cretaceous collision (Burg, 2012; Jolivet et al., 2013).

Moreover, the Sava Zone suite differs fundamentally in both composition and tectonic position: it lacks arc-like LILE–HFSE signatures and was formed on both Adria- and Europe-derived crustal blocks, implying no single active subduction beneath the suture. Instead, these coeval magmatic belts may record lateral segmentation of the late Neotethyan system, in which rollback of the subducted slab and transtentional tectonics within the pull-apart basins produced localized transtension and partial melting across adjacent lithospheric fragments.

On a broader scale, the Sava Zone magmatism may represent a Mediterranean example of post-collisional extension following slab rollback and detachment, analogous to processes documented in the Rhodope (Brun et al., 2008; Burg, 2012; Jolivet et al., 2013), Anatolia (Uzel et al., 2020), and Tibet (Guo et al., 2015). If this interpretation is correct, then the so-called "Sava Zone" magmatism could be better named the Central Balkan Late Cretaceous Magmatic Province (CBLCMP).

Conclusion

The Sava Zone represents one of the most complex and debated tectonic domains of the Balkan Peninsula. Integrating geological, petrographic, geochemical, and geochronological evidence from key localities across Hungary, Croatia, Bosnia and Herzegovina, Serbia, and North Macedonia reveals that Late Cretaceous magmatism was neither uniform nor oceanic in character. Instead, it formed a discontinuous belt of volcanic and plutonic rocks emplaced within sedimentary basins that developed contemporaneously with extension and transtension during the latest Mesozoic.

Two principal magmatic domains can be distinguished:

(1) The Adria-side (Dinaridic) localities, characterized by tholeiitic to transitional basalts with E-MORB–like trace-element signatures, and

(2) The European-side (Tisza–Dacia / Serbo-Macedonian) localities, hosting enriched within-plate basalts and lamprophyres with OIB-like affinities.

These contrasts are best explained by melting of compositionally distinct lithospheric mantle domains under a common extensional regime, rather than by coexistence of different subduction systems. The Dinaridic mantle was relatively depleted, whereas the European mantle source was variably metasomatized by earlier subduction episodes, leading to distinct enrichment patterns during decompression melting.

The close stratigraphic association between magmatism and sedimentation, including shallow-marine peperites and volcaniclastic successions, indicates volcanism occurred in transtensional basins developed after the onset of continent–continent collision between Adria and Europe. The geochemical evidence thus supports an intracontinental rather than oceanic origin for the Sava magmatic system.

Regionally, the Sava Zone magmatism was broadly coeval with the Apuseni–Banat–Timok–Sredna Gora (ABTS) arc, yet genetically distinct. Whereas the ABTS magmatic complex reflects subduction-related processes, the Sava magmas record intracontinental extension and mantle upwelling in response to slab rollback at the retreating Neotethyan margin.

Accordingly, we propose that the so-called "Sava Zone magmatism" marks the transition from subduction-dominated to post-collisional, transtensional tectonics in the central Balkan region. Its formation records the final reorganization of the lithosphere following the closure of the Neotethys, establishing the structural framework upon which the Cenozoic evolution of the Pannonian Basin System was later superimposed.

Supplementary data

Supplementary data to this article can be found online at: https://doi.org/10.6084/m9.figshare.30719231

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Резиме

Магматске формације Сава зоне на централном Балкану

Сава зона представља кључну тектонску границу између континенталних јединица европског и јадранског афинитета (сл. 1) формирану током алпске еволуције балканског сегмента Алпско-хималајског орогеног појаса у централном Медитерану (Schmid et al., 2008, 2020). Ова хетерогена зона обухвата горњо-кредне седименте и магматске формације као и фрагменте јурских офиолита (Pamić et al., 2000, 2002; Ustaszewski et al., 2009; Cvetković et al., 2016; Prelević et al., 2017; Toljić et al., 2018). Сава зона (сл. 1) се пружа од СИ-ЈЗ усмерене Средњомађарске низије, преко Славоније и Београда, затим ка северној Македонији, и наставља се у западну Турску као Борнова флиш (Okay et al., 2012).

Имајући у виду централну позицију Сава зоне на Балкану, боље разумевање њене генезе помогло би решавању два суштинска питања која су и даље отворена: (1) када је дошло до коначног затварања неотетиских океанских домена, и (2) у каквом је тектоно–магматском окружењу настао горњокредни магматизам.

Тумачења улоге Сава зоне у овим процесима могу се груписати у три основна модела:

– као остатак најмлађег океанског домена (Karamata, 2006; Schmid et al., 2008; Robertson et al., 2009; Ustaszewski et al., 2009, 2010; Gallhofer et al., 2015),

– као фор–арк појас у време активне субдукције (Gallhofer et al., 2015; Toljić et al., 2018; Sokol et al., 2020),

– као зону транстензионе реактивације већ постојеће шавне зоне (Csontos & Vörös, 2004; Bortolotti et al., 2013; Köpping et al., 2019; Sokol et al., 2020).

У овом раду обједињени су постојећи подаци свих познатих локалитета у којима се појављују горњокредне магматске формације Сава зоне. Сви испитивани локалитети показују уједначену старост, у интервалу од 87 до 76 милиона година (сл. 2). Горњокредни магматизам Сава зоне је литолошки и геохемијски разноврстан и укључује толеитске до алкалне базалте, лампрофире, риолите и гранитоиде (Szabó, 1985; Szabó et al., 1993; Pamić et al., 2000; Nédli & Tóth, 2007; Nedli et al., 2010; Ustaszewski et al., 2009, 2010; Starijaš et al., 2010; Cvetković et al., 2014; Prelević et al., 2017; Balen et al. 2020; Sokol et al., 2020; Schneider et al., 2022, 2025; Šuica et al., 2022).

У већини локалитета стене су изузетно алтерисане што је јасно указано повишеним вредностима губитка жарењем. Ови процеси су значајно изменили садржаје главних (макро) и LILE елемената (Ba, Cs, K, Rb, Sr), док су HFSE и REE релативно немобилни (Pearce, 2014) што их чини поузданом основом за класификацију и петрогенетску дискусију (Winchester & Floyd, 1977) (сл. 5а).

Базалтоидне стене Сава зоне (садржај SiO_2 од 41–53 wt.%) на дијаграмима Nb/Y према Zr/Ti и Nb/Y према Ti/Y (Winchester & Floyd, 1977) показују од толеитског до алкалног афинитета (сл. 5а). Притом, базалти из локалитета који се налазе у Динаридима (Јадранска плоча) претежно показују субалкални карактер, док базалти из локалитета који се појављују у блоковима европског афинитета (Српско-македонска маса, Дачија, Тиса) доминирају у пољу алкалних базалта.

Геохемијски подаци указују да су базалти настали из три различита дела унутар омотача, односно на различитим дубинама (сл. 5ц,д): у зони стабилности граната (Топола), у зони коегзистенције граната и спинела (локалитети око Београда, делимично Клепа) и у зони стабилности спинела (базалти из свих локалности у Динаридима (Јадранска плоча).

Киселе стене које се појављују у блоковима европског афинитета показују знатно већу разноврсност, укључујући A1, A2 и S типове гранитоидних састава (сл. 5х, 6), док су киселе стене који се налазе у Динаридима (Јадранска плоча) ограничене углавном на A2 подтип (Eby, 1992; Whalen et al., 1987).

На основу интеграције геохемијских и петролошких података, сматрамо да је горњокредни магматизам Сава зоне настао локално у екстензионом режиму, али да суштинске разлике у саставу ових стена које су просторно контро-

лисане потичу из значајних разлика литосферског омотача у Динаридима (Јадранска плоча) и у блоковима европског афинитета (Српско-македонска маса, Дачија, Тиса): литосферски омотач Динарида је релативно осиромашен, док је литосферски омотач блокова европског афинитета значајно метасоматски обогаћен током ранијих субдукционих догађаја. Као резултат тога, исти тектонски услови – *slab rollback* и локализована транстензија у оквиру *pull-apart* басена – могле су активирати различите резервоаре у омотачу, генеришући спектар магматизма од N–MORB до OIB карактеристика (PRELEVIĆ et al., 2017, 2024; STANKOVIĆ et al., 2026).

У кори је вероватно дошло до топљења на различитим дубинама, што је довело до варијација у саставу киселих магми, слично процесима документованим у Родопима (BRUN et al., 2008; BURG, 2012), Анадолији (UZEL et al., 2020) и Тибету (GUO et al., 2015). Уколико је ово тумачење тачно, такозвани „магматизам Сава зоне“ прецизније би се могао описати као Централнобалканска горњокредна магматска провинција (ЦБГМП).

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