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A first attempt at a provenance study in the Jadar block (Serbia) by means of U-Pb zircon geochronology

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Abstract. U-Pb geochronology of zircon grains retrieved from magmatic rocks intruding the Jadar block terrane in the central Balkans is used here to add new constraints on the terrane accretion processes and the provenance of crustal sources of this potentially exotic crustal block. Using an unorthodox approach, we analyzed zircons extracted from the products of Cenozoic (Cer and Boranja granitoid massifs) and Triassic magmatism (Bobija andesitic tuff - *Pietra Verde*). In fourteen samples of granites and epiclastites, we analyzed about 600 grains, and of these, about 30-40% were derived from the basement and were used further for the geological interpretation.

Most samples show a similar Precambrian and Paleozoic age spectrum, including ubiquitous Neoproterozoic and well-defined Silurian-Ordovician populations. Only a few older zircons are present, composing minor populations at c. 1.2 Ga and 3.2 Ga. The younger zircons represent a ubiquitous Triassic population that is the strongest in all samples. This age population is most likely associated with local Permo-Triassic magmatism generated due to the opening of the Neotethys. In contrast to the magmatic rocks of Boranja and Bobija, the zircon age spectrum of the Cer polyphase pluton shows a strong Carboniferous peak, indicating a potentially important link to the Variscan margin of Eurasia. This supports opposing interpretations that either this part of the Jadar block terrane represents a southern continuation of the "Bükkium" and Sana-Una terranes comprising displaced fragments of the southern European Variscan foreland, or, more likely, that it has an Adria affinity and that these zircons are derived from Cretaceous sediments of the Sava Zone, i.e., the suture that separates European and Adriatic domains, which were assimilated during the intrusion of the Cer granitic magmas.

Key words:
Provenance study, Adria plate, Bükkium terrane.

Апстракт. У раду су коришћени U-Pb геохронолошки подаци добијени мерењем циркона из магматских стена које пробијају Јадарски блок. Ови подаци коришћени су да бисмо што ближе утврдили порекло циркона, и одатле донели закључке о геолошком развоју овог потенцијално "егзотичног" блока. Анализирани су циркони гранитоидних масива Цера и Борање као и циркона из епикластита *pietra verde* на планини Бобија, тријаске старости. У четрнаест узорака гранита и епикластита анали-

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зирано је око 600 зрна, од којих је око 30–40% зрна имало наслеђена језгра која су коришћена за даљу геолошку интерпретацију.
Већина узорака показује прекамбријски и палеозојски сигнал, укључујући свеприсутне неопротерозојске и добро дефинисане силурско-ордовицијумске популације. Присутно је само неколико старијих циркона, који показују старости око 1,2 Ga и 3,2 Ga. Млађи циркони представљају тријаску популацију која је најјача и свеприсутна у свим узорцима. Ова популација циркона је највероватније повезана са локалним пермо-тријаским магматизмом, насталим услед отварања Неотетиса. За разлику од магматских стена Борање и Бобије, спектар старости циркона церског полифазног плутона показује снажан карбонски импулс, што указује на потенцијално важну везу са варисцијским магматизмом који је најчешће везан за јужну маргину Евроазије у време херцинске орогенезе. Ови циркони највероватније воде порекло из кредних седимената Сава зоне, који су асимиловани приликом интрузије церске гранитоидне магме.

Кључне речи:
Порекло циркона,
Адрија плоча,
Bükkiит блок.

Introduction

The Alpine-Himalayan accretionary orogen represents a continent-scale diffuse and long-lived convergent boundary between Eurasia and Gondwana-derived plates that have been active since Permian–Mesozoic times (e.g., Dercourt et al., 1986; Schmid et al., 2008; Şengör & Yilmaz, 1981). Long-lived convergence involved the accretion of numerous continental slivers that mainly originated from late Permian times onwards (e.g., Palinkaš et al., 2008; Robertson et al., 2009) by continental rifting and subsequent seafloor spreading between Gondwana and its northern promontory (Adria) and Eurasia. Progressive plate convergence associated with ophiolite obduction eventually resulted in collision.

In the Balkan section of the Alpine-Himalayan orogen, plate convergence was linked to the closure of a branch of the Mesozoic Tethys located between Eurasia and Adria, called ‘Vardar Tethys’ (Cvetković et al., 2016) or ‘Northern branch of Neotethys’ (Schmid et al., 2008). In the Dinarides fold-thrust belt, the Late Cretaceous collision of Adria and Eurasia (Ustaszewski et al., 2010) and subsequent post-collisional shortening until the Oligocene to Miocene eventually formed a highly complex orogen with several out-of-sequence thrusts (e.g., van Unen et al., 2019a, b; Balling et al., 2021a). In combination with the subsequent extension of the internal parts of the thrust belt (e.g., Matenco & Radivojević, 2012), this resulted in a complex relationship between different pre-Alpine crustal fragments mixed with younger ones of various origins. Geological units pre-dating the opening of the Neotethys are dominantly represented by remnants of Adria and its distal parts, which are exposed within the Sava suture zone (Fig. 1; Schmid et al., 2008). This complicates and challenges a paleotectonic interpretation, especially without detailed provenance analyses. These processes eventually formed an orogenic system consisting of multiple belts during the late Mesozoic–Cenozoic times.

The Jadar block terrane of northern Serbia (Fig. 1) lies between the Neothethyan West Vardar zone and the Drina-Ivanjica block that represents a deformed segment of the Adriatic microplate (Spahić & Gaudenyi, 2020). The paleogeographic affinity of the Jadar block terrane has been a matter of debate, and two opposing models have been proposed:

1. The widely accepted opinion is that the Jadar block terrane, together with the Kopaonik Block, forms the Jadar-Kopaonik composite nappe that was thrust onto the Drina-Ivanjica composite nappe during the Late Cretaceous to Early Paleogene shortening, postdating the latest Jurassic obduction of the Western Vardar ophiolites (Schmid et al., 2020). The Jadar-Kopaonik composite nappe *sensu* Schmid et al. (2008) represents the most distal nappe of the internal Dinarides situated on the Adriatic microplate (Matenco & Radivojević, 2012). In more detail, this view suggests that the Jadar block terrane, the Bükk unit or “Bükkium terrane” (NE

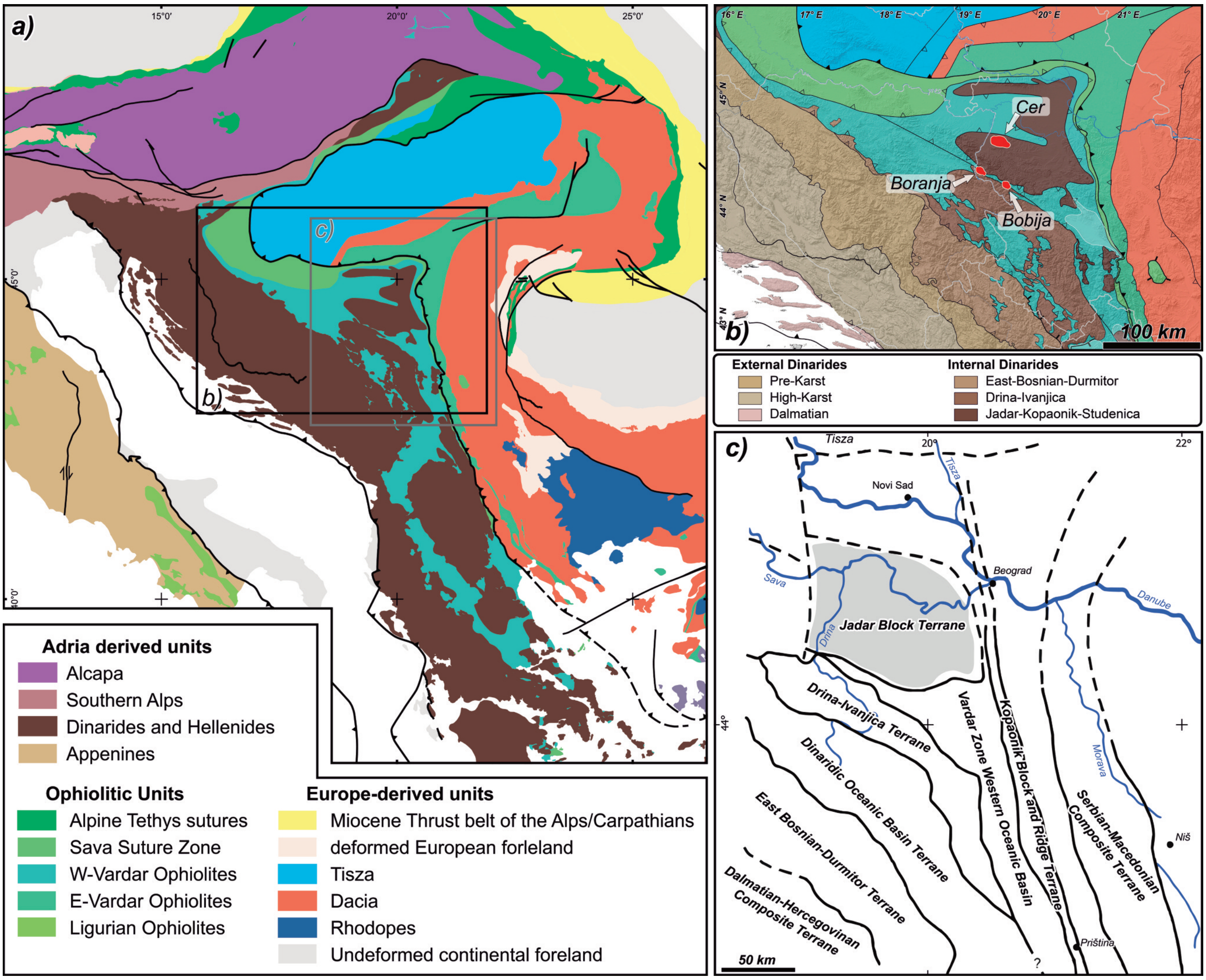

Fig. 1. *Geological and tectonic sketch of the Balkan Peninsula. The two maps illustrate two opposing models of the origin of the Jadar Block, which are discussed in more detail in the text.* ***a)*** *Tectonic sketch after* Schmid *et al. (2008) with the position of the study area (dark polygon).* ***b)*** *Simplified tectonic map of the delineated area showing the major geotectonic units (modified from* Karamata *et al., 1997).*

Hungary), and Sana–Una (NW Bosnia and Herzegovina) represent displaced fragments of the internal Dinarides (Kovács et al., 2011, 2000; Protić et al., 2000), with the Medvednica Mountain and neighboring inselbergs near Zagreb occupying an intermediate position (Schmid et al., 2008).

2. Based on similarities in the Variscan and Early Alpine evolution with “Bükkium” and Sana-Una terranes, it is proposed that the Jadar block terrane was emplaced into the area of the Vardar Suture Zone (Sava-Vardar suture zone *sensu* Schmid et al. 2008) during the Late Cretaceous from the neighborhood of the Sana-Una unit, where the original setting of the Bükk unit of NE Hungary can also be supposed (Filipović et al., 2003; Karamata et al., 1997; Protić et al., 2000; Spahić & Gaudenyi, 2020). According to this interpretation, these three blocks share close similarities with the Carboniferous-Permian succession of the Carnic Alps as well, implying a close palaeogeographic affinity within the western Paleotethyan domain and belonging to the southern European Variscan foreland (Filipović et al., 2003). Based on the presence of Carboniferous magmatic zircons, it was recently demonstrated that clastites from the Bükk Mts. (the Bükk unit) might be partially derived from Austroalpine and Southern

Alpine rocks (Zajzon et al., 2011), suggesting that this block, and presumably also the Jadar block terrane, was located in the foreground of the Alpine units. In other words, the Jadar block terrane may represent an exotic terrane whose geological differences from the neighboring blocks cannot be explained by lateral transitions in sedimentary facies, metamorphic history, structure, etc. It may be ultimately derived from the Gondwana-derived microcontinents included in the Variscan and Alpine collisional orogens (*sensu* von Raumer et al., 2003), that is the post-Variscan European margin (*sensu* Spahić & Gaudenyi, 2020).

In situ U–Pb dating of zircon grains has proven to be a powerful tool in provenance studies, providing information about the timing of the origin of lithologies in a source area, which has often been destroyed and recycled during preceding plate tectonic processes. Our pilot study aims to evaluate the palaeogeographic affinity of the Jadar block terrane, performing the very first provenance study of zircon grains (older than Cenozoic) derived from the basement of the most distal composite nappe of Adriatic affinity, the Jadar-Kopaonik thrust sheet (*sensu* Schmid et al., 2008), that is, the Jadar block terrane (*sensu* Filipović et al., 2003). Instead of studying detrital zircons in clastic sedimentary rocks, we utilize an unorthodox approach by analyzing zircons extracted from the products of Cenozoic and Triassic magmatism of three localities: Bobija (Sokolske Mts.), Boranja Mts. and Cer Mts. plutons. In the case of two localities (Cer and Boranja plutons), zircon xenocrysts that yielded ages older than the age of intrusion of the granitoid magmas have been discussed and plotted. In contrast, in the case of the third locality (volcaniclastics of *Pietra Verde*, Bobija), the entire zircon population was processed. This approach allows to obtain information on the provenance of the basement below the Mesozoic/Cenozoic sedimentary cover sequences, which are in many cases unknown as their base is seldomly exposed, therefore casting a new light on the origin of pre-Alpine basement units in the central Balkans. This has important implications for our in-depth understanding of the evolution of North Gondwana-derived terranes and, consequently, for Alpine plate-tectonic reconstructions.

Geological setting of the Jadar block and its magmatism

The internal Dinarides, in particular, the most-distal Jadar-Kopaonik nappe (*sensu* Schmid et al., 2008), occupy a significant part of northwestern Serbia and, in terms of pre-Alpine paleogeography represent the northeastern continuation of the Drina-Ivanjica composite nappe (Schmid et al*.,* 2008) (Fig. 1). The pre-Permian succession of the Jadar-Kopaonik thrust sheet comprises non- to low-grade metamorphic Paleozoic clastic sediments (e.g., Schefer et al., 2010; Sudar & Kovács, 2006). Devonian to Upper Carboniferous siliciclastic sediments and shallow-marine carbonates are overlain by fusulinid limestones and siltstones up to the earliest Permian. Sedimentation continued in the mid-Permian with the deposition of clastic sediments, passing into gypsum, dolomite, and limestone. Triassic lithologies include shallow-water carbonates often transformed into marbles and intercalated with rift-related basaltic-intermediate volcanic rocks (Protić et al., 2000). A presentation of the Jadar block's stratigraphy is beyond this study's scope, and the reader should refer to several detailed studies, (e.g., Filipović et al., 2003 and references therein).

Two major magmatic episodes characterize the internal Dinarides, Triassic rifting-related volcanism and Cenozoic magmatism, dominantly represented by plutonism (e.g., Schefer et al., 2011 and references therein).

The Triassic volcanism in the terrains with Gondwana affinity in the Balkans is related to riftogenesis, which led to forming a Red Sea-type basin (Robertson & Karamata, 1994). This type of magmatic product is widespread in the Jadar block terrane. It is mainly represented by remnants of lava flows and volcanoclastic and epiclastic deposits of the *Pietra Verde* type (Maurer et al., 2019). Bobija (Fig. 1) is located at the southwestern edge of the Jadar block terrane. However, its position needs to be clarified since it is located on the very border with the Drina-Ivanjica terrane to which it may also belong. The volcano-sedimentary succession in the Triassic strata comprises coherent lavas and volcaniclastic sediments (*Pietra Verde*) and also hosts stratabound sulphide mineralization. The Triassic volcanism at Bobija is characterized by an absolute U-Pb age of 239.4±1.4 Ma obtained on zircon (Maurer et al., 2019).

Boranja mountain is located at the nappe contact between the Jadar-Kopaonik thrust sheet (*sensu* Schmid et al*.,* 2008) in the east that was thrust onto the Drina-Ivanjica thrust sheet in the west and hosts a granodioritic pluton of Oligocene age (Delaloye et al., 1989) (Fig. 1). This intrusion represents an Oligo-Miocene phase of I-type granitoid magmatism situated mainly along the Central Balkans. It is interpreted to be related to the post-collisional tectonics (Cvetković et al., 2000). More recent work suggests a possible phase of mantle delamination below the internal Dinarides to represent the trigger for the magmatic activity (Balling et al., 2021). The Oligocene granodiorite pluton of Boranja intruded the basement, mainly composed of Triassic limestones and Palaeozoic black phyllites. Plutonism was accompanied by almost simultaneous intrusions of a swarm of dykes of dacitic and lamprophyric composition (Prelević et al., 2004).

Cer Mountain is located in a more internal position with respect to Bobija and Boranja and hosts a poly-phase pluton that intruded the Paleozoic basement, comprising metapsammites and metapelites. These metamorphic successions experienced intense contact metamorphism and were exhumed as a metamorphic core complex together with the plutonic rocks along an extensional mylonitic shear (Löwe et al., 2021; Stojadinović et al., 2017). The pluton comprises an I-type Qz-monzonite to Qz-monzodiorite, subsequently intruded and enveloped by a peraluminous S-type granite (Cvetković et al., 2002; Koroneos et al., 2011). U-Pb zircon ages of the I-type intrusion constrain crystallization to Early Oligocene times (31.36±0.49 Ma to 32.21±0.30 Ma) (Stojadinović et al., 2017), whereas K-Ar and Ar-Ar cooling ages from muscovite of the S-type granite range between 15.96±0.64 Ma and 16.48±0.65 Ma (Koroneos et al., 2011; Löwe et al., 2021).

Sample selection and analytical methods

Detailed maps with sampling locations are shown in the electronic appendix (Supplementary Datasets 1–3). A complete dataset, including detailed results of the zircon analyses for each site, can also be accessed in the electronic appendix (Supplementary Datasets 4–6). Kernel density estimation (KDE) with the concordant measurements for each location plotted in the diagrams are presented in the electronic appendices (Supplementary Datasets 7–11). Finally, a table with coordinates and descriptions of sampling locations and the exact percentage of inherited grains is presented (Supplementary Dataset 12).

Supplementary Datasets 1–12

Samples were crushed to grain sizes below 500 µm and elutriated to remove small particles (<63 µm), except for samples representing the S-type intrusion in Cer, where zircons were almost exclusively recovered from the fraction <63µm. Zircon grains were separated from the bulk samples using standard techniques (jaw crusher, Frantz isodynamic magnetic separator, heavy liquids). They were finally handpicked under a binocular with the help of UV light. Zircon grains were mounted in epoxy resin, polished to their centers, carbon coated, and imaged by cathodoluminescence (CL) and back-scattered electron (BSE) using a scanning electron microscope (SEM; JEOL JSM-6610LV with an EDS analytical system) at the University of Belgrade.

Zircon U–Pb age determination was performed using the LA-ICPMS at the Department of Geosciences, University of Mainz, with an ESI NWR193 ArF 193 nm excimer laser system equipped with a TwoVol2 ablation cell coupled to an Agilent 7500ce quadrupole ICPMS. Ion intensities for the following isotopes were measured by LA-ICPMS applying a pulse repetition rate of 10 Hz and an energy density of about 3 J cm^{-2}: ^{202}Hg, ^{204}(Pb, Hg), ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U. Background measurements of 15 s were followed by 30 s ablation and 20 s wash-out time. The laser was operated at a repetition rate of 10 Hz and a nominal energy output of 40%, corresponding to a laser energy of 0.006 mJ and a laser fluency of 0.8 J cm^{-2}. All data were acquired with single-spot analyses on individual zircon grains using a 20–30 μm spot size. Helium gas was used for flushing the sample cell and was mixed downstream with the Ar sample gas of the mass-spectrometer. The washout time for this configuration is\15 s. The total acquisition time for each analysis was 60 s, with the first 30 s used to measure the gas blank. The instrument was tuned to give large, stable signals for the ^{206}Pb and ^{238}U peaks, low background count rates (typically around 150 counts per second for ^{207}Pb), and low oxide production rates ($^{238}U^{16}O/^{238}U$ generally below 0.2%). Single spot measurements with a diameter of 30 μm were arranged along transects through the zircon crystals, emphasizing sampling rim and core regions (all analysis spot locations are marked in Online Resource 4). Ablation locations were selected based on CL images. For calibration of the LA-ICP-MS measurements, either 91500 or GJ1 zircon was used, while Plesovice zircons were used as QCM to monitor the accuracy and precision of the measurements.

Data reduction was performed using Iolite in combination with the Isoplot (4.15) add-in for Excel (Ludwig, 2003) and IsoplotR (Vermeesch, 2018). Obtained data for the zircon age standard 91500 and GJ1 agree with published ages (see QAQC data in Supplementary Datasets 4–6).

Results of zircon dating

About 210 zircon grains were analyzed from the three investigated localities, but the largest number of zircons was retrieved from the Cer pluton (both I and S types). The results of the U–Pb zircon analyses are provided in Figures 2–4, and a more detailed presentation of the data, including concordia diagrams and Kernel Density Estimations, is presented as electronic appendices (Supplementary Datasets 4–6).

In all three localities, the age spectrum (Kernel density estimation, KDE) of the basement zircons is dominated by Permo-Triassic ages, ranging between 259 and 220 Ma with significant peaks at 220 and 239 Ma (Figs. 2–4). A considerably smaller amount of the analysed zircons yielded Ordovician Late Neoproterozoic ages covering Cryogenian, Ediacaran,

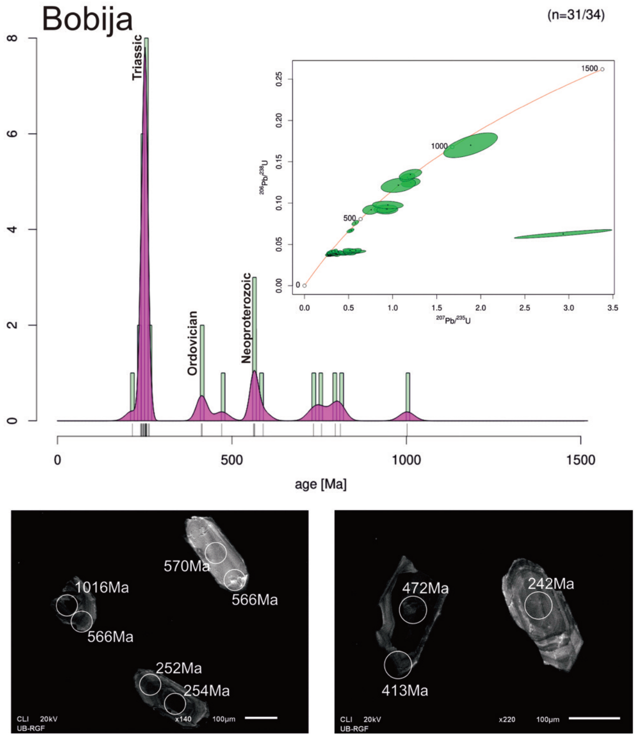

Fig. 2. *KDE plot (kernel density estimation) and concordia diagram illustrating the results of U-Pb dating of zircon from Bobija. Bottom: CL immages of representative polygenetic zircons.*

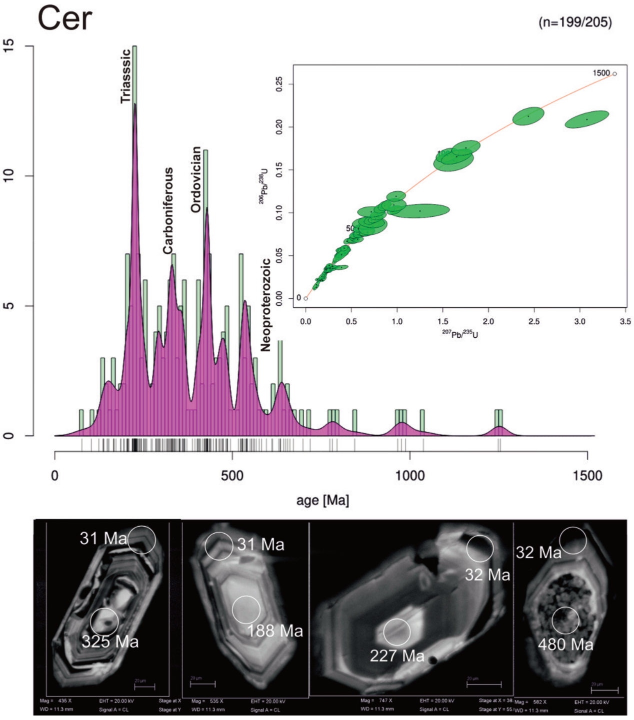

Fig. 3. *KDE plot (kernel density estimattion) and concordia plots illustrating the results of U-Pb dating of zircons from Cer. Bottom: CL images of representative polygenetic zircones. Note in the oscillatory zoning.*

and Tonian, with significant peaks at 424–468, 550–650, and 750 Ma. Interestingly, zircons from Cer additionally yield Carboniferous and Jurassic ages with peaks at 338 and 153.

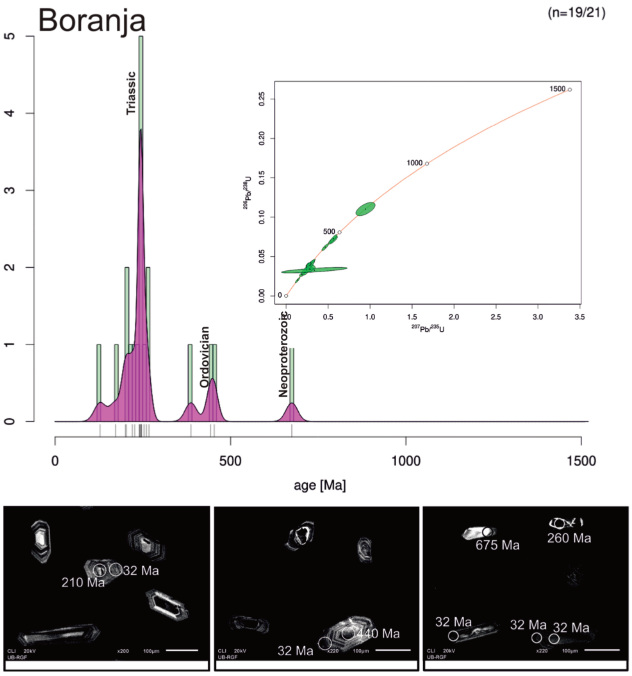

Fig. 4. *KDE plot (kernel density estimation) and concordia diagram illustrating the results of U-Pb datinf of zircins from Boranja. Bottom: CL images of representatice polygenetic zircons. Note the oscillatory zoning.*

Analyses indicated U contents of 100–1000 ppm and Th contents of 30–550 ppm (Supplementary Datasets 4–6). They dominantly plot within the field of magmatic zircons (Fig. 5) and are most likely the result of crystallization from felsic melt composition with minor mafic influences.

Discussion

Pre-Mesozoic formations occur as basement units throughout the entire Alpine–Himalayan belt. Most of these Paleozoic units were dismembered as thrust sheets due to the breakup of Pangea and the following convergence between Eurasia and Africa (Pamić & Jurković, 2002). Within the Gondwana-affinity terrains in the Balkans (e.g. Dinarides), mainly Devonian to Permian successions are found that are usually overlain by Triassic sedimentary rocks (Hrvatović & Pamić, 2005).

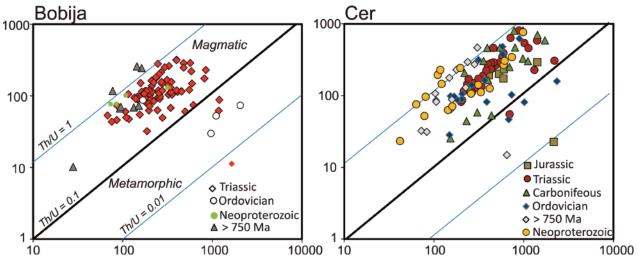

Fig. 5. *Th and U concentrations of different zircon age group, modified after Meinhold et al. (2008).*

In the following, our data on zircon age distributions are compared to regional studies of the lithostratigraphic development during a similar age span. This helps to constrain the provenance, emplacement, and geodynamic evolution of the basement that constitutes the most internal Dinarides.

Geodynamic provenance of the investigated zircons

Our study's earliest concordant zircon ages can be reduced to late Neoproterozoic ages, followed by Ordovician and Triassic ages. These age spectra are typical for all three locations. However, only zircon grains retrieved from the Cer poly-phase pluton yielded Carboniferous and Jurassic ages.

Late Neoproterozoic, Ordovician, and Triassic age spectra typical for all three locations

The **Late Neoproterozoic ages** are most likely to the Cadomian–Pan-African orogeny that is generally manifested by a series of tectonic events, which took place along the northern margin of Gondwana from ca. 750 to 540 Ma, leading to the formation of the Avalonian–Cadomian belt (Nance & Murphy, 1994) and to the opening of the Iapetus Ocean (Grunow et al., 1996; Nance et al., 2010; Linnemann et al., 2008). The origin of many European basement units lay in the lateral alignment of several microcontinents at the northern margin of Gondwana from the Late Neoproterozoic to the Ordovician (von Raumer et al., 2002). The separation of the Avalonian terrane from the northern margin of Gondwana started in the Early Ordovician and was induced by a subduction zone within the Prototethys (Stampfli & Borel, 2002; von Raumer et al., 2002, 2003; Meinhold et al., 2010). As a result of this active continental margin, a back-arc basin opened, creating the Rheic Ocean (Meinhold et al., 2010). The northern drift of Avalonia and its subsequent docking with Laurentia and Baltica induced the formation of Laurussia (Stampfli & Borel, 2002), and the southward subduction of Rheic ultimately caused the opening of Palaeotethys.

U-Pb analyses on zircons of all samples yielded several zircon grains demonstrating concordant ages with **Ordovician to Early Silurian** peaks that coincide with the opening of the Paleotethys. Due to the renewed subduction and slab roll-back of the Rheic Ocean under Gondwana, the Paleotethys was opening (410–380 Ma) as a back-arc and forming the Hun terrain that comprised parts of Europe and Asia (*sensu* Stampfli & Borel, 2002; von Raumer et al., 2002), that is Galatia superterrane (*sensu* Stampfli et al., 2013), resulting in the generation of a volcanic arc. Late Ordovician peraluminous granitoids from the Alpine domain most probably originated within the European Hun terrane. They accreted onto the southern margin of Laurussia in the Devonian, resulting in the Variscan orogeny in Europe (Stampfli & Borel, 2002).

The Ordovician peak of concordant zircon ages obtained on our samples coincides with Ordovician–Silurian thermal events reported in several regional provenance studies. Carrigan et al. (2005) investigated inherited cores of Variscan zircons (metagranites) in central Bulgaria that show Ordovician ages (445–467 Ma). Titorenkova et al. (2003) present the ages of metagranites from the Serbo-Macedonian Massif from 459.9±7.6 Ma. Himmerkus et al. (2002, 2009) reported zircons of igneous origin of Silurian age (428.2±1.2 Ma and 433±4.2 Ma) within the Serbo-Macedonian Massif. A zircon age of 462 Ma from orthogneisses is reported by Özmen & Reischmann (1999) in NW Turkey. Meinhold et al. (2007) analysed olistostrome blocks of cherts, carbonates, and fossiliferous siliciclastic rocks in eastern Greece (Chios Island); the olistolith formations implied several ages, including the Silurian. The Ordovician ages record the opening of the Rheic Ocean in the Early Ordovician by separating several arc terranes (Avalonia) from the north-western margin of Gondwana (Nance et al., 2010) and the subsequent opening of the Paleotethyan Ocean by the detachment of peri-Gondwanan terranes (Hun terrane) in the eastern direction (Stampfl & Borel, 2002).

Bearing in mind the paleogeographic development of the terranes that make up the Balkan Peninsula, it was expectable that the two age sequences mentioned above occur universally in all parts of its continental crust. This has been confirmed recently in the basement of Adria-derived units below the ophiolites (The Mid-Bosnian Schist Mountains), where similar igneous and detrital ages have been reported (Garašić et al., 2015; Hrvatović, 2022) as well as by previous provenance studies (Antić et al., 2016a,b, 2017; Meinhold et al., 2010, 2007). Unpublished data (Prelević et al.) also show these two significant peaks for the eastern parts of Serbia (Cretaceous sediments from the Timočka eruptive area) (Supplementary Dataset 10).

The Permotriassic age signal represents the strongest basement signature in all investigated samples. These zircons demonstrate the magmatic activity associated with the break-up of Pangea after the convergence between Eurasia and Africa (Pamić & Jurković, 2002), which is ubiquitous in the Gondwana-affinity terrains of the Balkans. These Permotriassic ages are generally either absent in the Europe-affinity terrains (Supplementary Dataset 10) or quite rare (Antić et al., 2016a).

Carboniferous and Jurassic ages recorded in the zircons from Cer: their significance and presumed origin

Carboniferous thermal events are frequently encountered within the Circum-Mediterranean region (Fig. 6). These events signify the collision between Gondwana and Laurussia that started in the Late Carboniferous, which eventually led to the formation of Pangaea. In contrast, the Paleotethys was

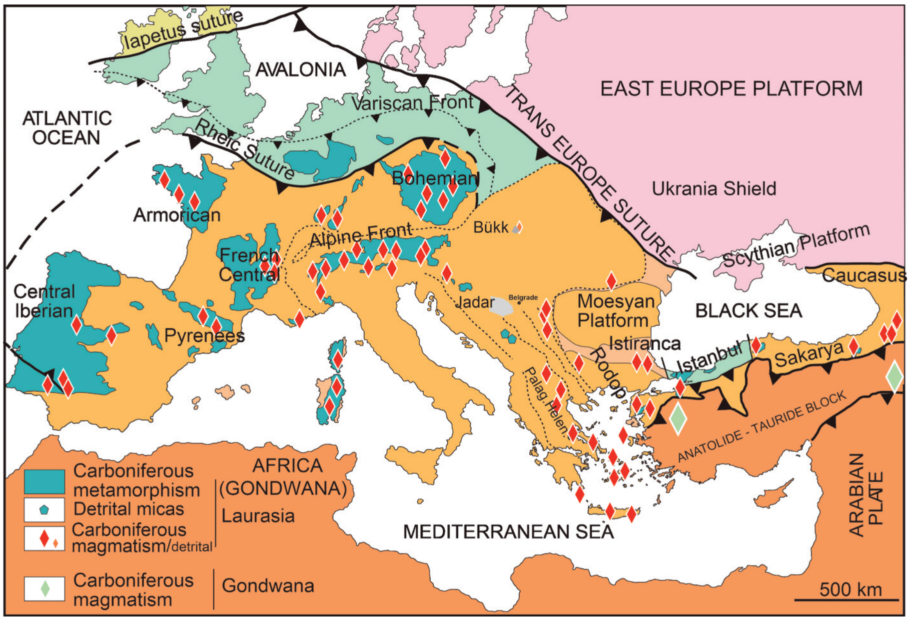

Fig. 6. *Simplified map of Circum-Mediterranean area with the general distribution of Carboniferous to Permian magmatic and metamorphic rocks and detrital zircons and micas in Laurasia- and Gondwana-derived terrains. Modified from* Candan *et al. (2016). Detrital micas and zircons from Dinarides and Bükk from* Ilić *et al. (2005) and* Zajzon *et al. (2011), respectively.*

furthermore replaced by the Neotethys later on (Stampfli & Borel, 2002). Carboniferous arc-type granites (350–320 Ma) are reported in the terrains that belong to the southern margin of the Laurussia and are dominantly distributed within the European Variscan and Alpine mountain chains of Circum-Mediterranean area, which represent collisional orogens built up of pre-Variscan "building blocks" which, in most cases, originated from the Gondwana margin (Candan et al., 2016, von Raumer et al., 2003). In the Balkans, these units are related to the European Variscan basement, which originated during Variscan orogeny (Supplementary Dataset 10; Antić et al., 2016a). The Variscan sequences include the Slavonian Mountains in northern Croatia, where the Barrovian-type metamorphics, as well as I- and S-type granites and migmatites, are reported (Pamić & Lanphere, 1991, Pamić et al., 1996). Similarly, slightly peraluminous Variscan granitoid plutons intrude the Getic and the Danubian units of the East Serbian Carpatho-Balkanides (Jovanović et al., 2019). They are dominantly formed under post-collisional conditions ranging between 323 and 290 Ma. On the other hand, in the Dinarides, only a significant thermal influence of Variscan deformation has been reported (Ilić et al*.,* 2005), as well as a relatively weak signal recorded in the Bosnian flysch (Mikes et al., 2008). In contrast, magmatism is not reported (Fig. 6).

An important observation from our study is that both I- and S-type granitoids of the Cer composite pluton contain zircons of Carboniferous age. In contrast, this age signal is absent in other localities. Our data in this group (370–330 Ma) can be correlated with the zircons mentioned above from the Southern and Eastern Alps. The concordant zircon age obtained from the inherited grains from the Cer granitoid of 338 Ma (Supplementary Dataset 8) is in good agreement to the above mentioned data and therefore indicates an association with post-Variscan formations originating in the Late Carboniferous.

At first glance, this could point to an apparent affinity of the Jadar Block to Variscan (Alpine) Europe, as Field Spahić & Gaudenyi (2020) suggested. However, the absence of Variscan zircons in the other two localities excludes such a possibility.

A much more likely explanation is that the zircons are retrieved from the metasediments considered to be of the Paleozoic age with which the granites have intensively interacted during their emplacement (Löwe et al., 2021). These lithologies were metamorphosed under up to amphibolite-facies grade conditions and subsequently exhumed in response to the opening of the northerly adjacent Pannonian Basin during Miocene times, giving rise to the Cer metamorphic core complex (Löwe et al., 2021; Stojadinović et al., 2017) and other core complexes of the internal Dinarides (Marovic et al., 2007a,b; Ustaszewski et al., 2010; Schefer et al., 2011; Toljic et al., 2013; Erak et al., 2017). Inherited zircon grains in the Cer granites that most likely originate from these sediments yield ages as young as the Cretaceous. An additional sample targeting the metamorphic basement of Cer yielded Mesozoic to Neoproterozoic ages, with Jurassic ages representing the youngest one, indicating the timing of deposition (Supplementary Dataset 11). Therefore, the basement of Cer that was previously mapped to represent Devonian to Carboniferous strata could be much younger and needs to be reevaluated, as speculated (Stojadinović et al., 2017). This is also indicated by the presence of Jurassic zircons (Supplementary Dataset 11).

The scarcity of geochronological studies from the areas in the Dinarides below the ophiolites greatly hinders provenance studies. Therefore, at this point of our research, the preliminary nature of our data prohibits ample understanding of the origin and significance of the obtained age spectra, and future more thorough research, primarily on the metasediments in the vicinity of the Cer pluton, will undoubtedly provide more details and comprehensive insights.

Conclusions

In this study, we applied in situ U–Pb dating of zircons by laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) to analyze zircons extracted from magmatic products of Cenozoic and Triassic age that intruded the Jadar block terrane in northwestern Serbia. In this unorthodox approach, we used data from the xenocrystic zircon grains derived from basement lithologies to add new constraints on the terrane accretion processes and the provenance of crustal sources of this potentially exotic crustal block.

The main findings are as follows.

1. Neoproterozoic, Ordovician, and Triassic age signals are common in all three studied locations. In contrast, Carboniferous, and further Jurassic age zircons, were encountered only among grains retrieved from the Cer poly-phase pluton.

2. Although, at first glance, the Carboniferous signal obtained from the Cer samples could point to an affinity of the Jadar Block to Variscan (Alpine) Europe, a much more likely explanation is that the zircons originate from sedimentary sequences that were assimilated by the granitic magma.

3. In summary, our preliminary data suggest an Adriatic- affinity for the Jadar Block Terrane.

4. Although with a small number of data and a relatively restricted spatial coverage, this pilot study demonstrates the great potential that provenance studies have in providing information about the origin of different crustal blocks in complex areas such as the Balkans and ultimately improving our in-depth understanding of the evolution of North Gondwana-derived terranes.

Data Availability Statement

Supporting Information, including Supplementary Datasets 1–12, is available at https://figshare.com/s/e6a86950af2e6a4d0089 with DOI: 10.6084/m9.figshare.22210447

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Резиме

Порекло циркона из Јадарског блока, Србија

Јадарски блок у северозападној Србији лежи између неотетиске западновардарске зоне и Дринско-ивањичког блока који представља деформисани сегмент Јадранске микроплоче. Палеогеографски афинитет и геолошка историја Јадарског блока предмет су дугогодишње дебате, а предложена су два супротстављена модела:

1. Широко прихваћено мишљење је да Јадарски блок заједно са Копаоничким блоком чини Јадарско-копаоничку композитну навлаку која је навучена на Дринско-ивањички блок током горње креде (Schmid et al., 2020). Јадарско-копаоничка композитна навлака (*sensu* Schmid et al., 2008) представља најдисталнији део унутрашњих Динарида који, опет, представљају део Јадранске микроплоче (Matenco & Radivojević, 2012).

2. На основу сличности варисцијског и раноалпског геолошког развоја са „ Bukkium” блоком (североисточна Мађарска), предлаже се да је Јадарски блок смештен у подручје Вардарске зоне током горње креде, из околине Санско-унског блока, где је првобитно био смештен и „Bükkium“ теран (Filipović et al., 2003; Karamata et al., 1997; Protić et al., 2000; Spahić & Gaudeni, 2020). Према овом тумачењу, ова три блока показују сличности и са карбонско-пермском сукцесијом карнијских Алпа, што имплицира палеогеографску позицију унутар западног палеотетиског домена и припадност јужноевропском варисцикуму (Filipović et al., 2003). Као подршка овој тези, недавно је потврђено, на основу присуства карбонских циркона, да кластити са планине Bükk („Bükkium“ теран) у Мађарској делимично воде порекло из делова стена аустроалпских и јужноалпских формација (Zajzon et al., 2011).

Основни мотив ове пилот студије јесте да процени палеогеографски афинитет Јадарског блока. По први пут су коришћени U-Pb геохронолошки подаци циркона са задатком одређивања њиховог порекла, а са циљем да применом нове методологије допринесемо дебати о пореклу Јадарског блока. Анализирани су циркони које смо сепарисали из магматских стена: гранодиорита Борање, гранитоида Цера и епикластита Бобије (Pietra Verde). Од око 600 анализираних зрна, тридесетак процената потиче из старијих формација које се могу сматрати подлогом Јадарског блока.

Већина узорака показује прекамбријски и палеозојски сигнал, укључујући свеприсутне неопротерозојске и добро дефинисане силурско-ордовицијумске популације. Присутно је само неколико старијих циркона, који показују старости око 1,2 Ga и 3,2 Ga.

Неопротерозојски циркони су највероватније настали током кадомско-панафричке орогенезе која се манифестује низом тектономагматских догађаја који су се одиграли дуж северне границе Гондване од око 750 до 540 Ma. Ови догађаји су довели до формирања Авалонско-кадомијског појаса (Nance & Murphi, 1994) и до отварања океана Јапетус (Grunov et al., 1996; Nance et al., 2010; Linnemann et al., 2008).

Силурско-ордовицијумски циркони настали су током тектоно-магматских догађаја везаних за отварање Палеотетиса. Овај океан је настао као последица субдукције Реичког океана испод Гондване (410-380 Ma) током чега је у изалучном басену настао читав низ блокова који обухватају делове Европе и Азије (*sensu* Stampfli & Borel, 2002; von Raumer et al., 2002), односно Галатиа супертеран (*sensu* Stampfli et al., 2013). Силурско-ордовицијумски пералуминијски гранитоиди из алпског домена највероватније су настали унутар тих блокова. Ова старост циркона потврђена је и током неколико регионалних студија. Тако су Carrigan et al. (2005) нашли у варисцијским метагранитима у централној Бугарској цирконе који показују ордовицијумску старост (445–467 Ma). Слични су налази Titorenkove et al. (2003), Himmerkus et al. (2002, 2009) и Ozmen & Reischmann (1999) у Бугарској одн. у северозападној Турској.

Циркони пермотријаске старости чине најјачи геохронолошки сигнал у свим испитиваним узорцима који је вероватно свеприсутан у свим геолошким јединицама са афинитетом Гондване на Балкану. Ови циркони настали су током тектономагматских догађаја везаних за распад Пангее након конвергенције између Лауразије и Гондване (Pamić & Jurković, 2002). Циркони пермотријаске старости су генерално или одсутни на теранима са тзв. европским афинитетом или су прилично ретки (Antić et al., 2016a).

Карбонски тектоно-магматски догађаји означавају конвергенцију између Гондване и Лауразије, која је започела у касном карбону, што је на крају довело до формирања Пангее, док је Палеотетис касније замењен Неотетисом (Stampfli & Borel, 2002). Када је реч о Циркум-медитеранском подручју, карбонски гранити (350–320 Ma) нађени су на теранима који припадају јужном ободу Лауразије и доминантно су распрострањени унутар европских варисцијских и алпских орогених терена (Candan et al., 2016; von Raumer et al., 2003). На Балкану карбонски гранити се проучавани у Славонским планинама у северној Хрватској (Pamić & Lanphere, 1991; Pamić et al., 1996), у Карпато-Балканидима у Србији (Jovanović et al., 2019). У Динаридима је забележен само значајанији термички утицај варисцијских деформационих фаза (Ilić et al., 2005), као и релативно слаб сигнал у босанском флишу (Mikes et al., 2008) присуством циркона карбонске старости, док магматизам није констатован.

Резултати нашег истраживања указују да испитивани узорци из I- и S-типа гранитоида Цера садрже цирконе карбонске старости, док је овај сигнал у потпуности одсутан на другим локалитетима. Добијене старости (370–330 Ma) могу се повезати са горе наведеним цирконима из јужних и источних Алпа. Ови циркони највероватније воде порекло из кредних седимената Сава зоне, који су асимиловани приликом интрузије церске гранитоидне магме. У закључку можемо да кажемо да не постоје недвосмислени геохронолошки докази који би могли да упућују на палеогеографску позицију Јадарског блока унутар западног палеотетиског домена и припадност јужноевропском варисцикуму.

Недостатак геохронолошких студија у Динаридима испод офиолита у великој мери омета проучавање порекла циркона. Прелиминарна природа наших података онемогућава довољно разумевање порекла и значаја добијених старосних сигнала. Очекујемо да ће будућа детаљнија истраживања, пре свега метаседимената у околини церског плутона, свакако дати свеобухватнији увид у порекло Јадарског блока.

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