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Variscan granitoids of the East Serbian Carpatho-Balkanides: new insight inferred from U–Pb zircon ages and geochemical data

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Abstract

The study reports and discusses new LA–ICP–MS zircon U–Pb data and major and trace element analyses for 16 samples from nine different plutons intruding the Getic (Brnjica, Neresnica, Ziman, Gornjane–Tanda–Blizna), and the Danubian (Aldinac, Janja, Ravno Bučje, Plavna and Suvodol) units of the East Serbian Carpatho-Balkanides (ESCB). Within the entire ESCB belt predominate slightly peraluminous granitoids, ranging in composition from biotite–hornblende tonalite through granodiorite to monzogranite. They contain mafic enclaves and are often cut by lamprophyre shallow intrusions and show gradual transitions to, or are cut by muscovite-bearing granitoids. All the above mentioned rocks formed under post-collisional conditions with some of them displaying evidence of post-emplacement shearing and recrystallization. By contrast, the garnet-bearing muscovite granite of Ziman (Getic unit) is distinctively peraluminous and shows evidence of syn-collisional emplacement and crystallization. The most reliable U–Pb zircon ages on the post-collisional granitoids show an age range between ~ 323 and ~ 290 Ma. The granitoids of the Getic unit reveal better concordia ages suggesting that Variscan magmatism lasted longer than previously thought, i.e., even until Permian times. On the other hand, the concordia age of 325.8 ± 1.2 Ma for the syn-collisional Ziman granitoid likely represents a minimum age for the collision event in this part of the Variscan belt. The ages of the Danubian plutons at least allow for discussing still open questions, such as (1) whether the Danubian intrusives are systematically older than those intruding the Getic basement, (2) if Variscan syn-collisional plutons do exist in the Danubian unit, and (3) what role the Variscan magmatism played in the formation of uranium mineralization in the area.

Keywords Danubian · Getic · Hercynian magmatism · Paleozoic · Post-collisional granitoids

1 Introduction

Variscan orogeny in Europe records the merging of Laurasia and Gondwana and the establishment of the Pangea supercontinent (e.g. Tait et al. 1997; Pharaoh et al. 2006). This orogenic belt is composed of a complex terrane collage of both oceanic and continental origin, and can be traced from the Pyrenees to Turkey (Ziegler 1986; Matte 1991; Franke 1989, 1992, 2000; von Raumer et al. 2003). During the period from latest Neoproterozoic to Paleozoic times these terranes detached from the northwestern margin of Gondwana and migrated toward Laurasia (Tait et al. 2000; Nance et al. 2008). Their accretion to Laurasia culminated during the Variscan collision that was accompanied by widespread granitoid magmatism.

It is generally agreed that the European Variscan plutons were emplaced roughly between 350 and 270 Ma, in a syn-

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to post-collisional setting (e.g. Finger et al. 1997). They are exposed as numerous granitoid massifs occurring from Iberia through the Massif Central and Black Forest up to the Bohemian Massif (Gleizes et al. 1998; Altherr et al. 2000; Janoušek et al. 2000; Gerdes et al. 2003; see inset a in Fig. 1).

Part of the eastern branch of the European Variscan orogeny belongs to the Carpathian–Balkan sector that can be traced from the South Carpathians in Romania to the Black Sea in east Bulgaria (the major part of the belt is shown in Fig. 1, inset b). In the South Carpathians, it comprises a north–south trending belt of composite plutons that intrude the pre-Alpine basement (Balica et al. 2007; Duchesne et al. 2008; Plissart et al. 2012; Balintoni et al. 2014). Further to the south, in Serbia, the Variscan intrusives occur in a > 200 km long, N–S to NNW–SSE elongated belt that belongs to the so-called East Serbian Carpatho-Balkanides (hereafter ESCB). The belt continues in Bulgaria, forming a W–E stretching chain of granitoids that intrude the Balkan, Sredna Gora (Kamenov et al. 2002; Carrigan et al. 2003, 2005) and Rhodope mountains (Peytcheva and von Quadt 1995; Cherneva et al. 2002). The studies for the Romanian and Bulgarian Variscan sectors report and discuss a relatively large number of high-precision radiometric and geochemical data, whereas for the ESCB part such data are substantially lacking.

The only systematic study of the ESCB Variscan intrusives was performed in the 70-ties and the early 80-ties, in the frame of the large-scale project of the Basic Geological Mapping 1:100.000 of the Social Federal Republic of Yugoslavia (SFRY). The mapping involved comprehensive field and petrographic investigations and brought valuable information about size, stratigraphic position and petrography of each Variscan pluton, including the relative proportions of different types of granitoids. The project also involved first attempts to date the plutons radiometrically, mainly by the old Rb–Sr method and by so-called “chemical zircon dating” (Larsen et al. 1952). These data are reported in Explanatory Sheets for the Basic Geological Map of SFRY (see further text for references) and in some separate publications (e.g., Deleon et al. 1962, 1965; Deleon 1969). Given that these old publications are not readily available electronically, the authors are committed to provide scanned copies, upon request. Kräutner and Krstić (2003) updated and synthesized the available geological information about the entire ESCB, and produced a compiled geological map of the Carpatho-Balkanides in the scale 1:300.000.

In the last two decades only two studies addressed the ESCB Variscan granitoids. Vaskovic et al. (2004) reported a petrological study for the Brnjica pluton based on major and trace element whole-rock XRF analyses, whereas Vasković et al. (2012) published a short abstract with several LA–ICP–MS ages obtained on zircons from the Gornjane–Tanda–Blizna massif, albeit with incomplete information about analytical conditions and data quality.

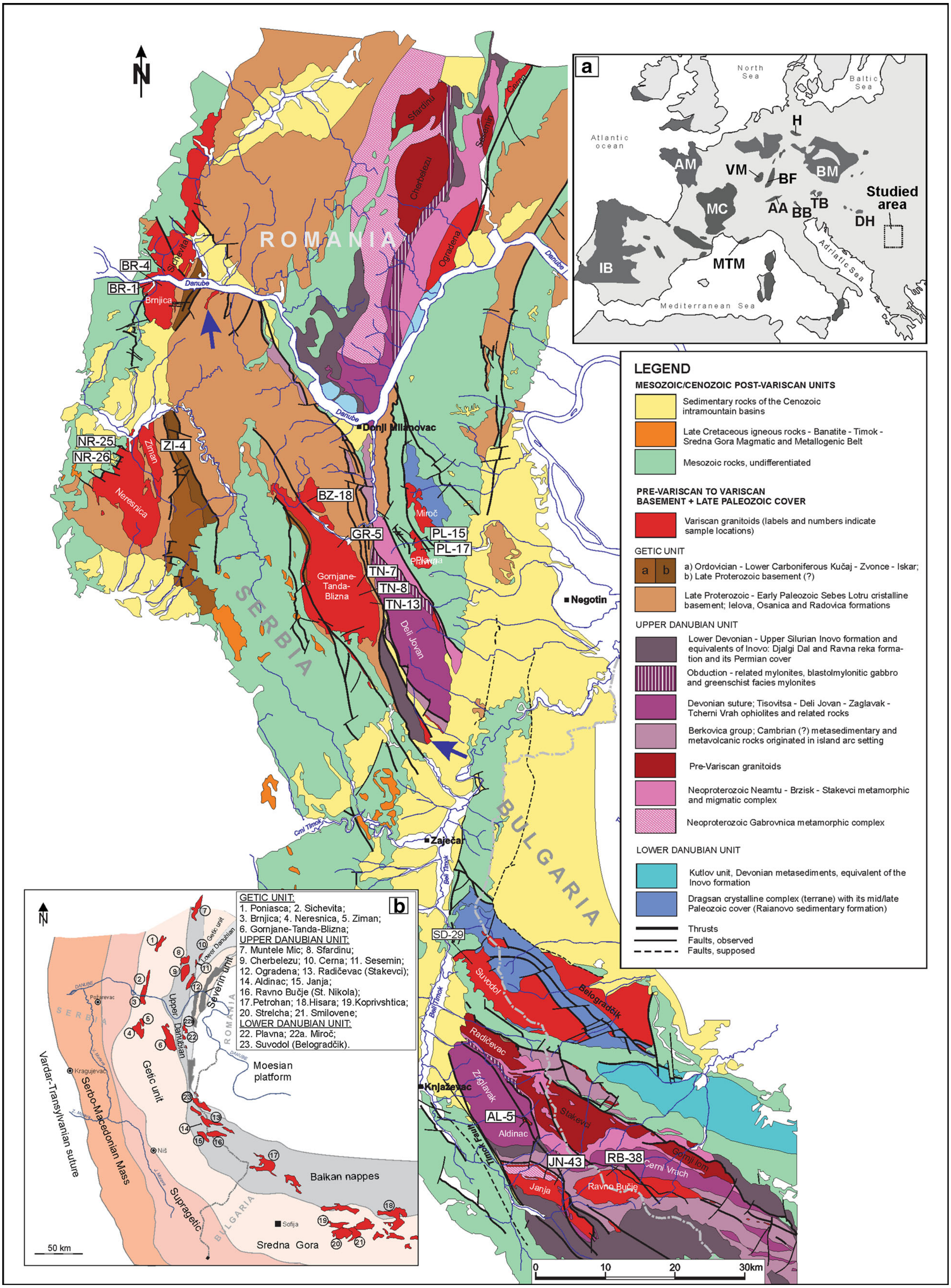
This study aims at filling an obvious gap in knowledge concerning the Variscan Carpathian–Balkan sector exposed in Serbia. First, we summarized data from the Basic Geological Mapping Project of the SFRY and completed them with our own field and petrographic observations, in order to understand the general petrology of each intrusive. In addition, we then collected zircons from nine different plutons or smaller granitoid occurrences and carried out laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) zircon dating and produced whole rock major and trace elements including rare earth trace elements (REE) analyses for the same sample suite. The principal objective of our research was to provide the first coherent data basis of radiometric ages, using a modern geochronological technique in order to establish the general age range of the ESCB Variscan plutons and to bring new light into the Variscan collisional events in the Carpathian–Balkan sector.

2 Regional geological framework

Geotectonically, the East Serbian Carpatho-Balkanides (ESCB) are located between the Alpine Vardar–Transylvanian suture and the Moesian platform. They are part of the long Carpathian–Balkan mountain chain that moulds around the Moesia and includes also the NE–SW elongated South Carpathians in Romania and the E–W oriented Balkan–Sredna Gora mountains in Bulgaria (inset b in Fig. 1). This entire Carpathian–Balkan chain acquired its present day configuration in response to Alpine tectonics (e.g., Ratschbacher et al. 1993; Gallhofer et al. 2015, 2017), which involved substantial clockwise rotations of the northern segments. The rotation was accommodated by orogen-parallel dextral transtension along the Cerna-Jiu and Timok faults (Berza and Drăgănescu 1988; Kräutner and Krstić 2003; Fügenschuh and Schmid 2005).

The ESCB consist of two major late Mesozoic eastward-facing nappe systems: the Getic–Supragetic including the Serbo-Macedonian Massif and the Danubian units in the west and east, respectively. These include pre-Alpine basement rocks and a Late Paleozoic–Mesozoic sedimentary cover (Schmid et al. 2008 and references therein).

Most authors agree that the pre-Alpine basement of the Getic–Supragetic and the Danubian units consists of lithospheric fragments that originated from the northern margin of Gondwana (sensu Nance et al. 2008). However, a precise correlation of these terranes for the entire Carpathian–Balkan mountain chain is not possible yet, because the studies in the different sectors of the Carpathian–


N
ROMANIA
SERBIA
BULGARIA
Danube
Donji Milanovac
Negotin
Zaječar
Knjaževac
Crni Timok
Beli Timok
BR-4
BR-1
Brnjica
Sichevita
NR-25
NR-26
ZI-4
Ziman
Neresnica
BZ-18
GR-5
Gornjane-Tanda-Blizna
TN-7
TN-8
TN-13
Deli Jovan
PL-15
PL-17
Miroč
Plavna
Sfardinu
Cherbelezu
Sesemin
Cerna
Ogradena
SD-29
Suvodol
Belogradčik
Radičevac
Zaglavak
AL-5
Aldinac
Stakevci
JN-43
RB-38
Janja
Ravno Bučje
Gornji lom
Cerni Vrach
Timok Fault
0 10 20 30km
a
North Sea
Baltic Sea
Atlantic ocean
H
AM
VM
BF
BM
MC
AA
BB
TB
Studied area
DH
IB
MTM
Adriatic Sea
Mediterranean Sea
LEGEND
MESOZOIC/CENOZOIC POST-VARISCAN UNITS
Sedimentary rocks of the Cenozoic intramountain basins
Late Cretaceous igneous rocks - Banatite - Timok - Sredna Gora Magmatic and Metallogenic Belt
Mesozoic rocks, undifferentiated
PRE-VARISCAN TO VARISCAN BASEMENT + LATE PALEOZOIC COVER
Variscan granitoids (labels and numbers indicate sample locations)
GETIC UNIT
a b
a) Ordovician - Lower Carboniferous Kučaj - Zvonce - Iskar; b) Late Proterozoic basement (?)
Late Proterozoic - Early Paleozoic Sebes Lotru cristalline basement; Ielova, Osanica and Radovica formations
UPPER DANUBIAN UNIT
Lower Devonian - Upper Silurian Inovo formation and equivalents of Inovo: Djalgi Dal and Ravna reka formation and its Permian cover
Obduction - related mylonites, blastolmylonitic gabbro and greenschist facies mylonites
Devonian suture; Tisovitsa - Deli Jovan - Zaglavak - Tcherni Vrah ophiolites and related rocks
Berkovica group; Cambrian (?) metasedimentary and metavolcanic rocks originated in island arc setting
Pre-Variscan granitoids
Neoproterozoic Neamtu - Brzisk - Stakevci metamorphic and migmatic complex
Neoproterozoic Gabrovnica metamorphic complex
LOWER DANUBIAN UNIT
Kutlov unit, Devonian metasediments, equivalent of the Inovo formation
Dragsan crystalline complex (terrane) with its mid/late Paleozoic cover (Raianovo sedimentary formation)
Thrusts
Faults, observed
Faults, supposed
b
GETIC UNIT:
1. Poniasca; 2. Sichevita;
3. Brnjica; 4. Neresnica, 5. Ziman;
6. Gornjane-Tanda-Blizna;
UPPER DANUBIAN UNIT:
7. Muntele Mic; 8. Sfardinu;
9. Cherbelezu; 10. Cerna; 11. Sesemin;
12. Ogradena; 13. Radičevac (Stakevci);
14. Aldinac; 15. Janja;
16. Ravno Bučje (St. Nikola);
17. Petrohan; 18. Hisara; 19. Koprivshtica;
20. Strelcha; 21. Smilovene;
LOWER DANUBIAN UNIT:
22. Plavna; 22a. Miroč;
23. Suvodol (Belogradčik).
Getic unit
Lower Danubian
Severin unit
Upper Danubian
DANUBE
Požarevac
SERBIA
ROMANIA
BULGARIA
Moesian platform
Kragujevac
V. Morava
Z. Morava
J. Morava
Niš
Vardar-Transylvanian suture
Serbo-Macedonian Mass
Supragetic
Balkan nappes
Sofija
Sredna Gora
50 km

◀**Fig. 1** Simplified geological map after Kräutner and Krstić (2003). Inset **a** distribution of the European Variscan complexes (Carrigan et al. 2005; Duchesne et al. 2013, and references therein), *AM* Armorica massif, *IB* Iberian massif, *MC* Massif Central, *MTM* Maures–Tanneron massif, *VM* Vosges massif, *BF* Black Forest massif, *H* Harz massif, *BM* Bohemian massif, *DH* Dinarides–Hellenides. Inset **b**: A geotectonic sketch of the Carpathian–Balkan sector with locations of the pre-Alpine granitoids (Krstic and Karamata 1992; Karamata 2006)

Balkan chain only provide incomplete data sets obtained by various approaches of terrane analyses (e.g., Krstic and Karamata 1992; Yanev 2000; Kräutner and Krstic 2002; Balintoni et al. 2009, 2014).

Therefore, and for the sake of simplicity, we use an Alpine geotectonic subdivision for providing a regional overview. From west to east the major units are: Getic,

Table 1 Geotectonic correlation of the three different sectors of the Carpathian–Balkanides mountain chain

Romanian South Carpathians[a]		**East Serbian Carpatho-Balkanides (ESCB)**[b]		**Bulgarian Balkan Mountains**[c]	
Alpine unit	**Pre-Alpine basement**	**Alpine unit***	**Pre-Alpine basement**	**Alpine unit**	**Pre-Alpine basement**
Median Dacides – Getic	Sebes – Lotru terrane (Ordovician, North African orogen, magmatic arc)	Getic	Kučaj terrane (Late Proterozoic to Early Cambrian volcanic arc)	Sredna Gora nappes	Iskar – Svoge (?)
Marginal Dacides – Danubian	Tisovita (Devonian oceanic suture)	Upper Danubian	Stara Planina – Poreč terrane (Proterozoic/?/ to Neoproterozoic, and Early-Mid Paleozoic, island arc + ophiolites /Deli Jovan/)	Balkan nappes	Island arc /Berkovica Group/ + ophiolites /Tcherni Vrah/ Balkan terrane
	Dragsan terrane (Early Neoproterozoic, Avalonia)	Lower Danubian	Vrška Čuka – Miroč terrane (Neoproterozoic volcanic arc)		Late Proterozoic, Cadomian, Gondwana – derived
	Lainici-Paius terrane (Neoproterozoic, Amazonian Cadomian rejuvenation)				

For each sector the available nomenclature of Alpine units and pre-Alpine basement is given

[a] Săndulescu (1994) and Balintoni et al. (2014)

[b] Krstic and Karamata (1992) and Kräutner and Krstić (2003)

[c] Haydoutov (1989), Georgiev et al. (2001), Yanev (2000), Kräutner and Krstić (2003) and Yanev et al. (2005)

[d] The names of the tectonic units used in this study

Upper Danubian, and Lower Danubian units (e.g. Berza et al. 1994; Schmid et al. 2008). Table 1 summarizes the existing terminology and nomenclature for these Alpine units, including the information about the pre-Alpine basement, which is available from various tectonostratigraphic reconstructions and terrane analyses (see Table 1 for references). Note that we do not address the Supragetic unit and the Civcin–Severin ophiolites (both shown in inset b, Fig. 1), because they are not intruded by Variscan granitoids and are, therefore, not of interest for this study.

The Getic unit is in an upper structural position with respect to the Danubian nappes, and is also called Median Dacides in Romania (Săndulescu 1994) and Sredna Gora in Bulgaria (Ivanov 1988). This complex Alpine unit contains old continental fragments represented by the Sebes–Lotru terrane in the Romanian South Carpathians, which was interpreted as part of an Ordovician orogen detached from north Africa (Balintoni et al. 2014). This Sebes–Lotru terrane can be roughly correlated with the Kučaj terrane of Krstic and Karamata (1992) in the ESCB and, most likely, with the Iskar–Svoge zone in Bulgaria (Kräutner and Krstić 2003).

The structurally lower Upper Danubian and Lower Danubian units were thrusted over the stable Moesian platform. These tectonic units are also known as south-facing Marginal Dacides in Romania (Săndulescu 1994), whereas in Bulgaria they are represented by the north-facing Balkan nappes (Haydoutov 1989; Georgiev et al. 2001). The pre-Alpine basement in the Marginal Dacides contains the early Neoproterozoic Lainici-Paius terrane and the Neoproterozoic–Cadomian Dragsan terrane representing old crustal fragments in the Lower Danubian (e.g. Balintoni et al. 2009, 2014 and references therein). These terranes were correlated to the Vrška Čuka–Miroč terrane in Serbia, which is interpreted to be a Neoproterozoic volcanic arc (Krstic and Karamata 1992), whereas a similar Cadomian basement was found in the Balkan terrane in Bulgaria (Yanev 2000; Yanev et al. 2005). Within the Upper Danubian an apparent correlation exists between the Tisovita terrane in the South Carpathians, believed to be a Devonian oceanic suture (Balintoni et al. 2014; Kiselinov et al. 2017; Plissart et al. 2017) and the Stara Planina–Poreč terrane (including Deli Jovan opholites) in the ESCB (Krstic and Karamata 1992; Kräutner and Krstić 2003) as well as with the Berkovica Group (island arc + ophiolites of Tcherni Vrah) in the Balkan terrane (Yanev 2000; Yanev et al. 2005). Note, however, that the formation of this same oceanic slice was also dated as being of Cadomian age (von Quadt et al. 1998; Kounov et al. 2012).

The distribution of the ESCB plutons is given in Fig. 1 (modified after Kräutner and Krstić 2003). Four plutons intrude the Getic unit: Brnjica (samples BR-1, BR-4), Neresnica (NR-25, NR-26), Ziman (ZI-4) and Gornjane–Tanda–Blizna (GR-5, TN-7, TN-8, TN-13, BZ-18). Another four plutons intrude the Upper Danubian unit: Radičevac, Aldinac (AL-5), Janja (JN-43) and Ravno Bučje (RB-38), whereas three intrusives occur inside the Lower Danubian nappes: Miroč, Plavna (PL-15, PL-17) and Suvodol (SD-29). In Fig. 1 all massifs are mapped as Variscan granitoids, except for the Radičevac granite that is considered pre-Variscan (Cadomian), in keeping with the interpretation of Carrigan et al. (2003), Kräutner and Krstić (2003) and Plissart et al. (2012). Note, however, that we consider the Janja massif as a Variscan pluton (based on data from the current study), which conflicts with the view of Kräutner and Krstić (2003), who consider this pluton as Caledonian (see below).

3 Analytical techniques

3.1 Zircon dating

Sixteen samples were processed according to the standard zircon separation techniques at the University of Belgrade—Faculty of Mining and Geology. About 10 kg of each sample was crushed to sand size grains and sieved to a 100–300 μm fraction. The zircon concentrates were produced by using shaking table, magnetic separation and heavy liquids techniques. Mounts of 20–30 zircons were embedded into epoxy resin, polished and covered with carbon using a BALTEC-SCD-005 sputter coating device. CL imaging was done by the MiniCL (Gatan) detector attached to a SEM (model JEOL JSM-6610LV).

U–Pb isotope analyses for samples BR-1, BR-4, GR-5, TN-7, TN-8, TN-13, BZ-18, PL-15, PL-17, NR-25 and NR-26 were measured by LA–ICP–MS at the Geological Institute of the Bulgarian Academy of Science. The system comprises a New Wave Research (NWR) 193 nm excimer laser UP-193FX connected to the Perkin-Elmer ELAN DRC-e quadrupole inductively coupled plasma-mass spectrometer. An in-laboratory designed ablation cell with lowered position effects, “squid” smoothing device, energy density on sample ca. 8.5–8.8 J/cm^2, repetition rate of 8, and ablation craters of 35 μm were used. The GJ1 and Plesovice zircons were analysed as primary and secondary SRM (standard reference material), respectively. During the analyses the secondary Plesovice SRM was dated at 337.2 ± 1.6 Ma (internal error; published value of Sláma et al. 2008 is 337.13 ± 0.37 Ma). The results were calculated using Iolite combined with VizualAge to obtain ages and ratios corrected for instrumental drift and down hole fractionation (Paton et al. 2010, 2011). For each sample, all concordant zircons were used to calculate a concordia age, or a mean ^{206}Pb/^{238}U age, or probability density plots. As many zircons revealed a combination of lead inheritance and loss, ^{207}Pb correction (Andersen 2002; Paton et al. 2010, 2011) was applied to all analyses but then used only for information, as data became inverse discordant (around 3–4% lower ^{207}Pb/^{235}U ratios, assuming concordance). The plots were processed using ISOPLOT 3.0 (Ludwig 2003).

U–Pb isotope analyses for samples JN-43, ZI-4, SD-29, AL-5 and RB-38 were carried out using a New Wave Research (NWR) Excimer 193 nm laser-ablation system attached to a Perkin-Elmer ELAN inductively coupled plasma mass spectrometer (LA–ICP–MS) at the Johannes Gutenberg, University of Mainz. Laser spot size was 30 µm, 10 Hz laser repetition rate and yielded flux 3.22 J/cm^2 on the ablation site. All sample analyses for age determination were followed by measurement of referent SRM GJ1 and 91500 (primary and secondary standards). Places for analyses are carefully chosen by observation of BSE images, avoiding visible inclusions and cracks. Iolite 2.5 combined with VizualAge was used for data reduction (Paton et al. 2010, 2011). The plots were processed using ISOPLOT 3.75 (Ludwig 2013).

3.2 Major and trace element geochemistry

All samples dated by U–Pb zircon geochronology were also studied for major and full-range trace elements at the ACME Laboratories Ltd. Vancouver, Canada (now Bureau Veritas). Major element oxides were determined by ICP-AES (detection limits around 0.001–0.04%) after fusion with $LiBO_2$. Trace element and REE concentrations were acquired using ICP-MS (detection limits 0.01–0.5 ppm). STD SO-17 was certified in-house against 38 Certified Reference materials including CANMET SY-4 and USGS AGV-1, G-2, GSP-2 and W-2 (cf. Karsli et al. 2007). The analyses are considered accurate within the following limits: 2–5% for major elements, 10–15% or better for trace elements and 1–5% for REEs.

4 Results

4.1 Geology and petrology of the studied plutons

In the following, we report the main petrological characteristics of the ESCB Variscan granitoids. We also describe the Radičevac pluton, although we still do not have solid evidence to argue that this intrusive may also be Variscan in age. All relevant data from the Basic Geological Map of the SFRY 1:100.0000 (sheets Žagubica—Antonijević et al. 1970; Zaječar, Veselinović et al. 1975; Bor, Kalenić et al. 1976; Knjaževac and Belogradčik, Krstić et al. 1976; Kučevo, Kalenic et al. 1980; Donji Milanovac, Oršova, Baja De Arama and Turnu Severin, Bogdanović and Rakić 1980) were synthesized and completed by our own field observations and additional petrographic investigations.

4.1.1 Granitoids of the Getic unit

The Brnjica massif (Fig. 1) is an N–S stretching intrusion (25 km^2) whose northern continuation is found in the Sichevita–Poniasca intrusives in the South Carpathians (Duchesne et al. 2008). In the south-west it is covered by Cenozoic and Mesozoic sediments, whereas in the east, it is in contact with a Cambrian volcano-sedimentary series metamorphosed under greenschist facies conditions (Kalenic et al. 1980). The metamorphic series show thermal effects caused by the pluton (Karamata and Krstic 1996; Vaskovic and Matovic 1997; Vasković et al. 2012).

The pluton is composed of biotite (± hornblende) tonalite–granodiorite with subordinate two-mica granite and leucogranite. The main tonalite–granodiorite mass contains abundant mafic enclaves and is often cut by aplitic and pegmatitic veins. Two-mica granite shows gradual transitions to the main mass, but in some places intrusive contacts are also observed.

The tonalite–granodiorite is a medium-grained, equigranular and non-deformed rock with plagioclase, quartz, K-feldspar (in interstices only), biotite, and hornblende as main constituents, and primary epidote, apatite, zircon and magnetite as accessories. The two-mica granite has similar textures and is composed of quartz, K-feldspar, plagioclase, muscovite and biotite. Old Rb–Sr and K–Ar ages for Brnjica range between 272 and 259 and 291 and 342 Ma, respectively (Deleon et al. 1965; Deleon 1969; Kalenic et al. 1980).

The Neresnica massif is a larger (90 km^2) pluton located only several kilometres southwards from Brnjica (Fig. 1), where it intrudes Neoproterozoic to Lower Paleozoic metamorphic rocks. The contacts with the surrounding rocks are sharp and the pluton margins exhibit only a weak foliation. At some places a contact-metamorphic aureole is developed with andalusite-bearing rocks that are often injected by granite porphyry dykes and aplite and pegmatite veins.

The Neresnica granitoid rocks are petrographically indistinguishable from those of Brnjica and are represented by granodiorite that grades southwards to monzogranite and to subordinate two-mica granitoids that sometimes display effects of post-magmatic shearing and recrystallization. During shearing, even interstitial microcline underwent fracturing and annealing (Fig. 2a). The old radiometric ages range between 291 and 332 Ma (zircon U–Pb, Deleon et al. 1962; Kalenic et al. 1980), and 294–305 Ma (Kalenic et al. 1980).

The Ziman massif is a small (< 15 km^2) and elongated body separated from the Neresnica massif by a narrow

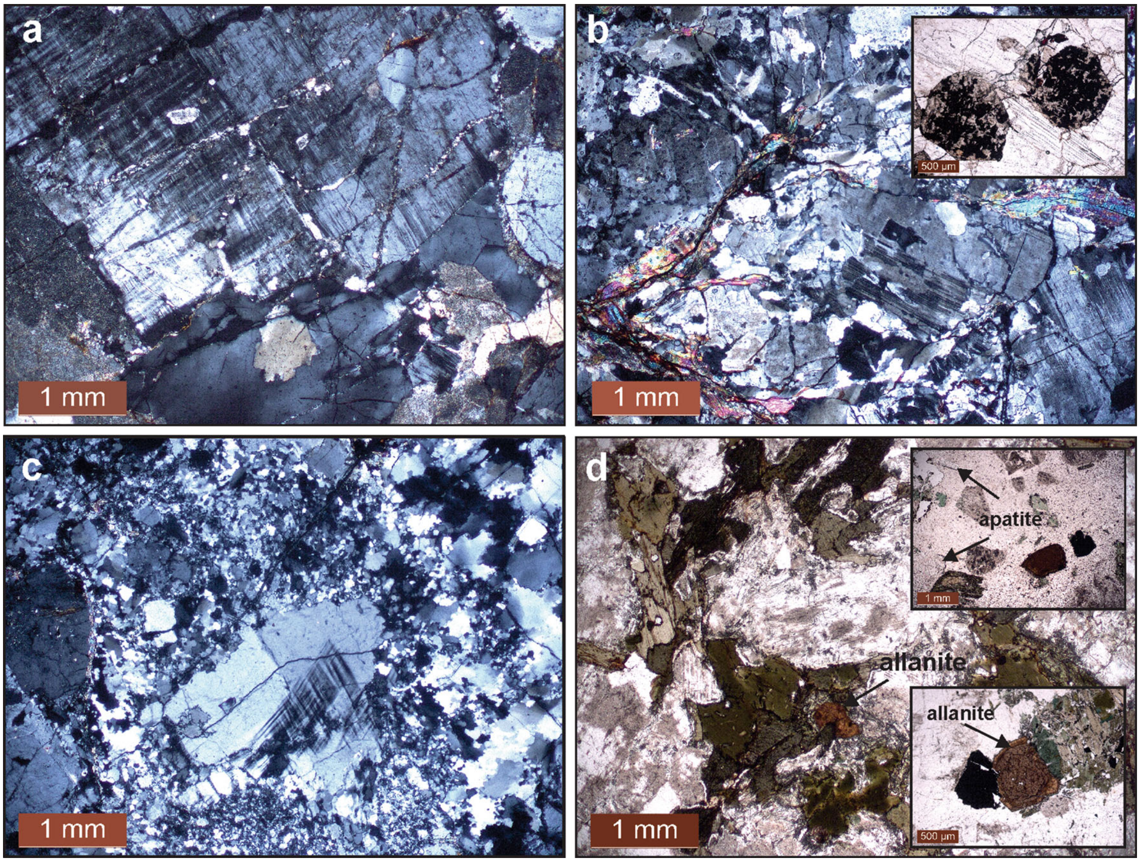


Fig. 2 Petrographic characteristics in thin-section. **a** Brittlely deformed microcline with cracks filled with secondary recrystallized quartz and K-feldspar (NR-25). **b** Texture evidencing syn-kinematic crystallization with ductilely deformed feldspar and muscovite (ZI-3, inset ZI-5). **c** Syn-kinematically grown feldspar and mica surrounded by fine-grained aggregates of secondary recrystallized quartz (RD-35). **d** Equigranular syenodiorite from the Janja massif (JN-43) containing large (~ 0.5 mm) allanite with epidote overgrowths (arrow); the insets show similar allanite from Ravno Bučje (lower inset; RB-37) and allanite and apatite (arrows) crystals from Aldinac (upper inset; AL-7)

(< 1 km) stripe of pre-Paleozoic two-mica gneisses (Fig. 1). The Neoproterozoic to Lower Paleozoic metamorphic rocks adjacent to the Ziman granite lack a contact metamorphic aureole and display effects of migmatization. According to our field observations, the migmatized gneisses in the surroundings are structurally concordant with the foliation displayed by the Ziman granite.

The intrusive is composed of inequigranular muscovite granite with quartz, plagioclase, microcline, muscovite, biotite, garnet, apatite and opaques. The rock displays evidence of syn-kinematic crystallization with ductilely deformed plagioclase, K-feldspar and muscovite (Fig. 2b). Some samples show an advanced stage of post-tectonic recrystallization, most likely due to the closeness of the Neresnica pluton, and most of them contain post-kinematically grown garnet that was transformed into fine-grained aggregates of chlorite and iron-oxide during a retrograde overprint. As mentioned above, Kalenic et al. (1980) interpreted this intrusion as a Cambrian pluton, whereas later authors considered it Variscan in age (e.g., Kräutner and Krstić 2003; Karamata 2006).

At least two smaller bodies of petrographically similar, foliated muscovite granites also occur in the ESCB basement (see blue arrows in Fig. 1). A 4 km long and around 500 m wide body is found on the right bank of the Danube, a few kilometres east from Brnjica. Another body of a similar size and orientation occurs ~ 10 km south from the Gornjane–Tanda–Blizna massif, (see below) where it cuts westernmost part of the Upper Danubian unit. Both of these smaller bodies were considered Cambrian in age (Antonijević et al. 1970; Kalenic et al. 1980).

The Gornjane–Tanda–Blizna massif is the largest (150 km^2) Variscan pluton in the ESCB (Fig. 1). It was emplaced along the easternmost part of the Getic unit, where it produced strong contact metamorphic effects occasionally associated to skarn-related ore occurrences. The main granitoid mass is quartz-monzonite, whereas granodiorite–diorite occurs along the pluton margins, and syenite, aplite–granite, aplite, pegmatite and lamprophyre form separate dykes or irregular bodies. The syenite bodies are concentrated along a few hundreds of meters wide and more than 10 km long zone that is elongated concordantly with major tectonic structures around the pluton. Lamprophyres are petrographically similar to mafic microgranular enclaves that are frequently found in the main granitoid mass.

The Gornjane–Tanda–Blizna quartz-monzonite and granodiorite–diorite are medium- to fine-grained rocks that generally consist of quartz, plagioclase, K-feldspar, biotite and amphibole (in various proportions), along with apatite, zircon, sphene, allanite and magnetite as accessories. Syenite is usually coarser-grained, contains oikocrysts of reddish K-feldspar and is usually carbonate-bearing. The carbonate often fills interstitial space and forms typical negative shaped crystals, which is commonly interpreted as evidence for its late magmatic origin (e.g., Gozzi et al. 2014). In the northern part of the massif two-mica granitoids are found; they show compositional transitions into the rest of the granitoids.

Deleon et al. (1965) and Deleon (1969) published first U–Pb zircon age determinations of ~ 277 Ma and 324 Ma. Vasković et al. (2012) reported LA–ICP–MS U–Pb data for zircons: 307.1 ± 4.5 Ma for the monzogranite, 307.6 ± 2.5 Ma and 323.3 ± 2.6 Ma for the fine-grained granite, 307.1 ± 2.9 Ma for the medium-grained granodiorite and 305.8 ± 3.6 Ma for the fine-grained diorite. The latter also argued that some zircons had inherited cores of different origin and age: Neoproterozoic (701–672 Ma), Cambrian (502–407 Ma) and Devonian–Early Carboniferous (378–342 Ma).

4.1.2 Granitoids of the Upper Danubian unit

The Radičevac massif is an NW–SE elongated intrusion that was concordantly emplaced into Neoproterozoic and Cambrian metamorphic rocks of the Stara Planina anticlinorium (Krstić et al. 1976). On the Bulgarian side, the body is referred to as Stakevci and Gornji Lom (Carrigan et al. 2003) granite, whereas its counterpart in Romania is called Sesemin granite (Kräutner and Krstić 2003). The metamorphic rocks in the surroundings are partly migmatized in a similar fashion that was observed in the rocks around the Ziman massif.

The Radičevac intrusive predominantly consists of two-mica gneiss-like granite that is accompanied by aplite, pegmatite and quartz veins. Field observations confirm the view of Krstić et al. (1976) who regarded the Radičevac massif as a typical synkinematic intrusion. In addition, our own microscopic investigations revealed the presence of sinkinematically grown feldspar and mica (Fig. 2c). The Radičevac massif, along with its counterparts in Bulgaria, is interpreted as Cadomian in age by all authors (Krstić et al. 1976; Kräutner and Krstić 2003; Carrigan et al. 2003; Plissart et al. 2012).

The Aldinac massif comprises a few small and one larger (1–2 km^2) dyke-like magmatic bodies emplaced into the Zaglavak (Iuti–Deli Jovan–Zaglavak–Tcherni Vrah) ophiolites whose age was either interpreted as Late Proterozoic-Cambrian (von Quadt et al. 1998; Savov et al. 2001; Kounov et al. 2012) or Devonian (Zakariadze et al. 2006; Plissart et al. 2017). The Aldinac rocks range in composition from monzogranite and monzogranite porphyry to holocrystalline rhyodacite. Inequigranular to porphyritic shallow intrusive types predominate, composed of euhedral plagioclase and subhedral quartz, biotite and hornblende, all set in a fine-grained quartz-feldspar matrix. Epidote, allanite (overgrowths over epidote), apatite (> 0.5 mm) and sphene are common accessory phases.

These shallow intrusions have so far not been radiometrically dated, but most authors considered them Variscan (e.g. Krstić et al. 1976; Kräutner and Krstić 2003) or even Permian in age (Kovačević et al. 2009).

The Janja massif is a W–E trending body (40 km^2) located ~ 5 km south from the Zaglavak ophiolites (Fig. 1). In the northern part it intrudes the Neoproterozoic complex of Gabrovnica, which displays effects of contact metamorphism. It also shows intrusive contacts against the Upper Danubian metamorphic rocks of the Berkovica group. Foliation associated with cataclastic deformation is occasionally developed but mostly along the margins, where the pluton is in physical contact with serpentinite and gabbro-diabase bodies. According to our observations, these mafic–ultramafic rocks show clear evidence of low to medium-grade metamorphism, whereas the host granite is fresh. The Janja intrusive is also cut by dykes and veins of lamprophyric composition, very similar to those found inside the Gornjane–Tanda–Blizna intrusive.

The Janja pluton displays biotite-rich granodiorite rims and K-feldspar-rich monzogranite to syenodiorite internal parts. The internal parts are composed of quartz, plagioclase, K-feldspar (microcline, rarely orthoclase) and biotite, with accessory phases represented by sphene, lots of apatite (> 1 mm), magnetite, zircon and allanite (Fig. 2d). The lamprophyres are fine-grained granular to slightly porphyritic and to a certain extent schistose.

Kräutner and Krstić (2003) interpreted the Janja massif to be Cadomian in age, mainly because the so-called Silurian–Devonian (?) Inovo series contains pebbles of similar magmatic rocks.

The Ravno Bučje massif (Fig. 1) intrudes a north-facing antiform and intersects the Lower Paleozoic metamorphic rocks of the Berkovica group. The intrusion produced an up to 300 m wide contact metamorphic aureole that consists of biotite-amphibole-andalusite hornfelses. Both aureole and pluton margins are intersected by small-sized shallow intrusions of granite porphyry, lamprophyre, aplite and pegmatite. According to our field observations, some parts of the pluton underwent shearing that postdates the intrusion of lamprophyres.

The Ravno Bučje massif is mainly composed of biotite tonalite–granodiorite, whereas varieties with amphibole are subordinate. Epidote, allanite (with overgrowths around epidote), apatite (> 1 mm), zircon and magnetite are the most abundant accessories (Fig. 2d). The rock is very often inequigranular with porphyritic varieties that are more abundant along the margins. The main granitoid mass contains numerous mafic enclaves.

Krstić et al. (1976) reported an Rb–Sr age of 283 Ma for the Ravno Bučje intrusion. It is noteworthy that the Ravno Bučje granitoid, along with the Janja massif and the Aldinac shallow intrusives, are petrogenetically associated to radioactive mineralization apparently related to a high abundance of accessory phases and high whole-rock contents of U and Th (Kovačević et al. 2009).

4.1.3 Granitoids of the Lower Danubian unit

The Plavna massif is a small granitoid body ($\leq$ 10 km^2) occurring ~ 7 km eastward from the Gornjane–Tanda–Blizna massif (Fig. 1). Geotectonically, it belongs to the western part of the Lower Danubian unit and its northern continuation is known as the Miroč granitoid (Kalenić et al. 1976). The Plavna massif intrudes the core of an antiform and is transgressively covered by Mesozoic sediments. It predominantly consists of mostly equigranular hornblende-biotite quartz-monzonite to granodiorite.

The Plavna intrusive has not yet been dated radiometrically, but was from most authors considered Variscan in age (see Kräutner and Krstić 2003).

The Suvodol massif (Fig. 1) is a NW–SE elongated body (~ 40 km^2) that intrudes the same Lower Danubian metamorphic rocks as the Plavna intrusive (Veselinović et al. 1975; Krstic and Karamata 1992). Actually, the Suvodol massif represents the larger part of the same anticline which was cut by the Timok fault and displaced ~ 100 km to the south. The eastward continuation of Suvodol is represented by the Belogradčik intrusive in Bulgaria.

The Suvodol massif is composed of biotite- and biotite-amphibole tonalite to granodiorite with subordinate monzogranite, aplite and granite porphyry. Monzogranite predominates in the northwestern part of the massif. It is composed of quartz, plagioclase, K-feldspar, hornblende and biotite, primary epidote, sphene, apatite, zircon and rare allanite. Although the association of accessory phases is similar to the one found in the Upper Danubian intrusives (see above), these REE–U–Th-rich minerals are neither equally abundant nor do they appear in remarkably large crystals as was observed in the Janja, Aldinac and Ravno Bučje rocks. The main tonalite–granodiorite massif shows compositional transitions to aplitic (muscovite-bearing) granite; however, the latter also appears as individual dykes and veins inside it. The leucocratic rocks usually show effects of shearing and recrystallization. Inside the pluton small-sized (a few meters thick) moderately to strongly altered lamprophyre dykes as well as dm-sized mafic enclaves of similar composition do occur.

Veselinović et al. (1975) considered the Suvodol pluton pre-Variscan in age, whereas, Kräutner and Krstić (2003) included this intrusion into the Variscan plutons.

4.2 U–Pb zircon dating

Information about the petrography of 16 samples that were radiometrically dated is given in Table 2. The results of LA–ICP–MS zircon analyses including zircon images and concordia diagrams are graphically shown in Figs. 3, 4 and 5, respectively, whereas the full zircon analytical data are given as Supplementary material (Table 1—supplement).

4.2.1 Getic unit

Most zircon crystals from the granitoid samples of the Getic unit are colourless and clear, but grains from some Gornjane–Tanda–Blizna samples exhibit pale pink colour, as well. Elongated crystals (about 250–300 μm in length), with aspect ratios more that 1:3 prevail, whereas non-elongated and tiny, needle-like crystals are extremely rare. Most grains show characteristic cathodoluminescence oscillatory zoning, indicating magmatic growth, but in several grains sector zoning can be also observed (Fig. 3).

Zircons of the Brnjica massif (BR-1 and BR-4) are mostly slightly to considerably discordant. The only four concordant grains of sample BR-1 define a concordia age of 302.7 ± 5.2 Ma (2 sigma, decay-const. errs included, MSWD of concordance = 1.5; Fig. 4a). The other grains do not lie on a discordia line and suggest domains or grains with different common lead composition and inheritance but also lead loss (apparent ^{206}Pb/^{238}U ages from 231 to 310 Ma). After the application of ^{207}Pb Andersen correction (Andersen 2002) a mean age of 291.0 ± 3.5 Ma (internal error, 95% conf. level) can be calculated (Fig. 4b), which coincides with the mean ^{206}Pb/^{238}U age for concordant zircons of sample BR-4 (only after Andersen correction). However, for further comparison we will use only concordant zircon ages (BR-1) without correction to keep them in agreement with data for other plutons.

Zircons of Neresnica massif NR-25 and NR-26 reveal similar phenomenon of inheritance and lead loss. Ten concordant grains/domains of sample NR-25 and two of sample NR-26 yield a concordia age of 294.6 ± 2.4 Ma

Table 2 Description of samples of the ESCB Variscan rocks studied by U/Pb zircon geochronology

Name of the pluton	Sample no.	Sample location	Petrography
Brnjica	BR-1	–	Biotite tonalite–granodiorite, equigranular, undeformed to only slightly deformed (postmagmatic), fresh to slightly sericitized
	BR-4	–	
Neresnica	NR-26	44°24.275′ 21°44.070′	Biotite granodiorite, equigranular, slightly deformed. Very similar to the Brnjica samples with more abundant microcline in the interstitial spaces (see Fig. 2a)
	NR-25	44°24.275′ 21°44.070′	
Ziman	ZI-4	44°23.393′ 21°45.654′	Garnet-bearing muscovite granite with textural relationships that suggest synkinematic crystallization, ductile deformation and recrystallization (see Fig. 2b)
Gornjane–Tanda–Blizna	BZ-18	44°21.074′ 22°01.759′	Biotite quartz-monzonite with oikocrysts of K–F and traces of muscovite; slightly inequigranular, postmagmatically sheared and recrystallized
	GR-5	44°14.910′ 22°09.062′	Hornblende-biotite granodiorite to quartz-monzonite, coarse-grained and slightly banded and schistose; probably cummulitic in character
	TN-13	–	Biotite–hornblende granodiorite, fine- to medium-grained, equigranular
	TN-7	44°13.848′ 22°08.100′	Biotite syenite to syenogranite, large K-feldspar, rich in apatite and primary epidote; TN-8 also contains primary calcite
	TN-8	44°13.848′ 22°08.100′	
Aldinac	AL-5	43°30.975′ 22°27.538′	Biotite (± hornblende) granodiorite porphyry-rhyodacite, undeformed, very rich in accessory phases (apatite, allanite, epidote and sphene) (see Fig. 2d)
Janja	JN-43	43°25.117′ 22°31.420′	Hornblende-biotite syenodiorite, equigranular, very rich in accessory phases (apatite, allanite, epidote and sphene) (see Fig. 2d)
Ravno Bučje	RB-38	43°25.583′ 22°32.836′	Biotite granodiorite with traces of muscovite, inequigranular, slightly recrystallized, very rich in accessory phases (apatite, allanite, epidote and sphene) (see Fig. 2d)
Plavna	PL-17	44°17.706′ 22°15.591′	Biotite (± hornblende) granodiorite to monzogranite, equigranular with K-feldspar both in interstices and as poikilitically enclosing plagioclase.
Suvodol	SD-29	43°42.361′ 22°22.928′	Hornblende-biotite (spessartite) lamprophyre, slightly schistose, moderately to intensively chloritized, very similar in composition to lamprophyres associated with other plutons studied here

(internal and external error; 95% conf., decay-const. errs included; MSWD of concordance = 19; Fig. 4c). A similar lower intercept age 290.5 ± 4.5 Ma (Fig. 4d) can be calculated using a Discordia line and analyses without Pb-loss for zircons of sample NR-25.

The samples from the Gornjane–Tanda–Blizna massif cover a wider range of ages. TN-7 and TN-8 are closely dated at 294.2 ± 4.5 Ma and 294.2 ± 4.4 Ma, respectively (Fig. 4e, f, respectively). An older concordia age of 312.1 ± 3.4 Ma is defined for sample TN-13 (Fig. 4g) with two possible clusters of ages: one at ~ 300 Ma and a second at ~ 320 Ma. Samples TN-7 and TN-8 also include older grains and domains, but there they can be referred to as inheritance and/or antecrysts (sensu Miller et al. 2007) as the corresponding analyses are slightly to clearly discordant. The Blizna zircons (BZ-18) are dated closer to TN-7 and TN-8 with a concordia age (defined on only three grains) at 300.4 ± 3.2 Ma (Fig. 4h) and a lower intercept age of 296.5 ± 3.0 Ma. For the Gornjane sample (GR-5) we defined a concordia age of 309.3 ± 4.2 Ma using fifteen analyses (Fig. 4i).

The Ziman sample ZI-4 of the group of granitoids that intrude the Getic unit is well dated at 325.8 ± 1.2 Ma (Fig. 4j).

Inherited zircon cores are detected in samples GR-5, BZ-18 and BR-4. Although most of these cores are smaller than 20 μm and not suitable for reliable analyses, the apparent $^{206}Pb/^{238}U$ ages of the coarser ones are Early Paleozoic (mostly around 410–530 Ma).

4.2.2 Danubian unit

Zircons from all the three granitoid samples of the Upper Danubian unit exhibit a similar crystal shape and morphology. They are about 100–150 μm in length, commonly zoned, frequently display metamorphic cores and are characterized by tiny bright rims on CL images (Fig. 3). A concordia age of 321.7 ± 1.8 Ma (Fig. 5a) was obtained

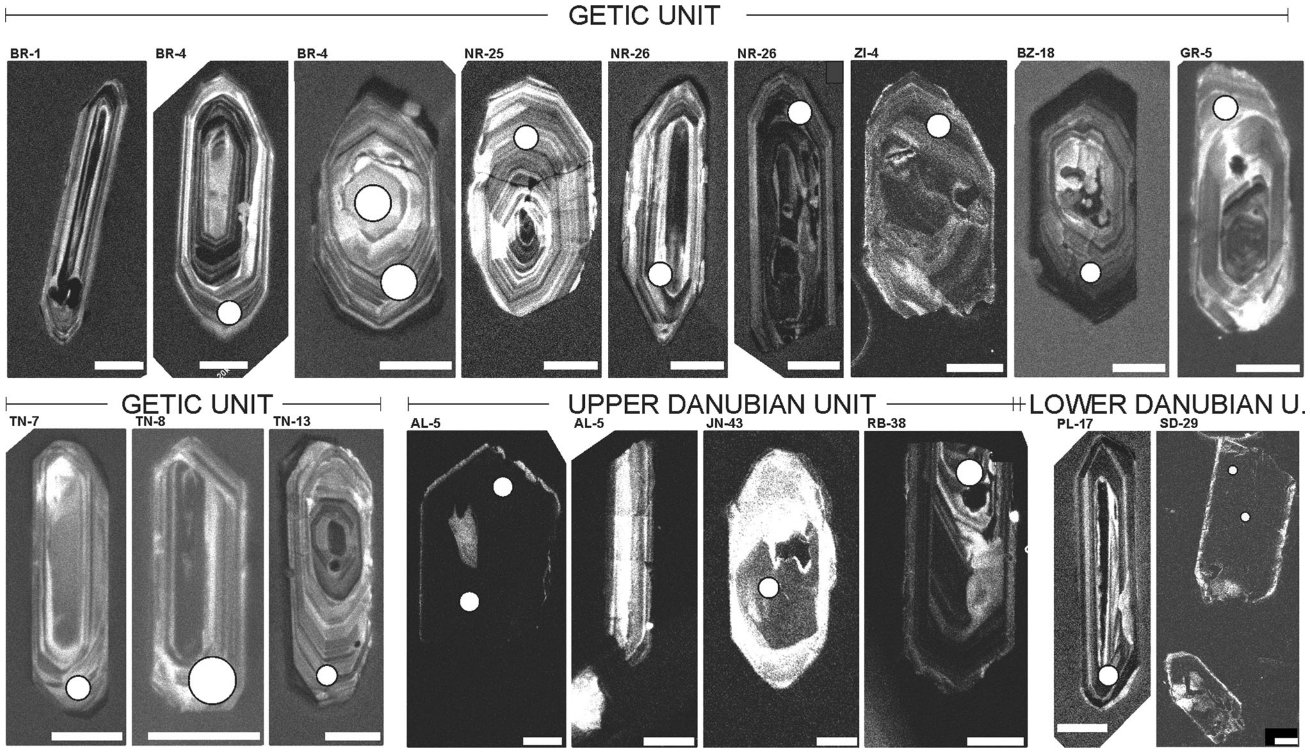


Fig. 3 Cathodoluminescence images illustrating the morphology and zoning of the analysed zircon grains; bar length is 50 µm

for the Janja syenodiorite (JN-43) using only four concordant points, whereas for samples from the Ravno Bučje massif and a dyke of Aldinac only lower intercepts ages can be taken into consideration: 324 ± 10 Ma (RB-38, Fig. 5b) and 319 ± 20 Ma (AL-5, Fig. 5c). It is noteworthy that zircons from Aldinac show a concordia age of 665.9 ± 4.0 Ma (Fig. 5d), which likely represents the inherited record of a Neoproterozoic (Cadomian?) event.

Zircons from the Plavna intrusive (Pl-15 and PL-17) appear as regularly shaped and well developed crystals, usually less than 150 µm in length, with bright rims and tiny inclusions. Only two zircon grains of PL-15 yield a poorly defined concordia age of 301.9 ± 12 Ma (Fig. 5e). If we combine the data from both samples and use ten of the concordant and negligible discordant analyses (marked on Table 1—supplement), a lower intercept age of 303.1 ± 8.5 Ma (Fig. 5f) can be calculated, which is in agreement with ^{207}Pb corrected (Andersen 2002) ages of PL-17 zircons (^{206}Pb/^{238}U mean age 296.2 ± 7.3 Ma, Fig. 5g). Zircons from Suvodol derive from the only non-granitoid sample that corresponds to a spessartite lamprophyre (SD-29), crosscutting the Plavna intrusive. The crystals are coarser (150–200/250 µm) than those from Plavna, and contain inclusions of other not-identified minerals. These zircons are specific, because they lack zoning and usually appear as dark-colored, homogeneous crystals surrounded by narrow bright-colored rims that could not be measured. No zircon grains yield Variscan or younger ages, instead, the analyses define a concordia age of 675.8 ± 2.2 Ma (Fig. 5h) and likely reflect the age of host rocks.

4.3 Geochemistry of the studied granitoids

Major and trace element contents for 15 studied samples from nine different massifs are shown in Table 3. In addition to the rocks dated by the U–Pb method, two samples of Radičevac (unpublished data) are also plotted on diagrams for correlation. Although these analyses are insufficient to fully characterize the studied plutons, especially given the fact that most intrusives consist of various rock types, we believe that they can help in establishing at least to a first approximation the relationship between the age and the petrology of the dated granitoid rocks.

Except for spessartite lamprophyre belonging to the Suvodol massif (SD-29: ~ 48 wt% SiO_2, ~ 8 wt% CaO and ~ 4 wt% Na_2O), syenodiorite from Janja (JN-43: ~ 54 wt% SiO_2, ~ 8 wt% $Na_2O + K_2O$) and two samples from Gornjane–Tanda–Blizna, one primary carbonate-bearing syenite (TN-8: ~ 51 wt% SiO_2, ~ 9 wt% $Na_2O + K_2O$, 7.6 wt% LOI) and a hornblende-biotite granodiorite cumulate (?) (GR-5: ~ 61 wt% SiO_2, > 9 wt% $Na_2O + K_2O$, 1.3 wt% LOI), all other rocks display relatively uniform granitoid compositions with

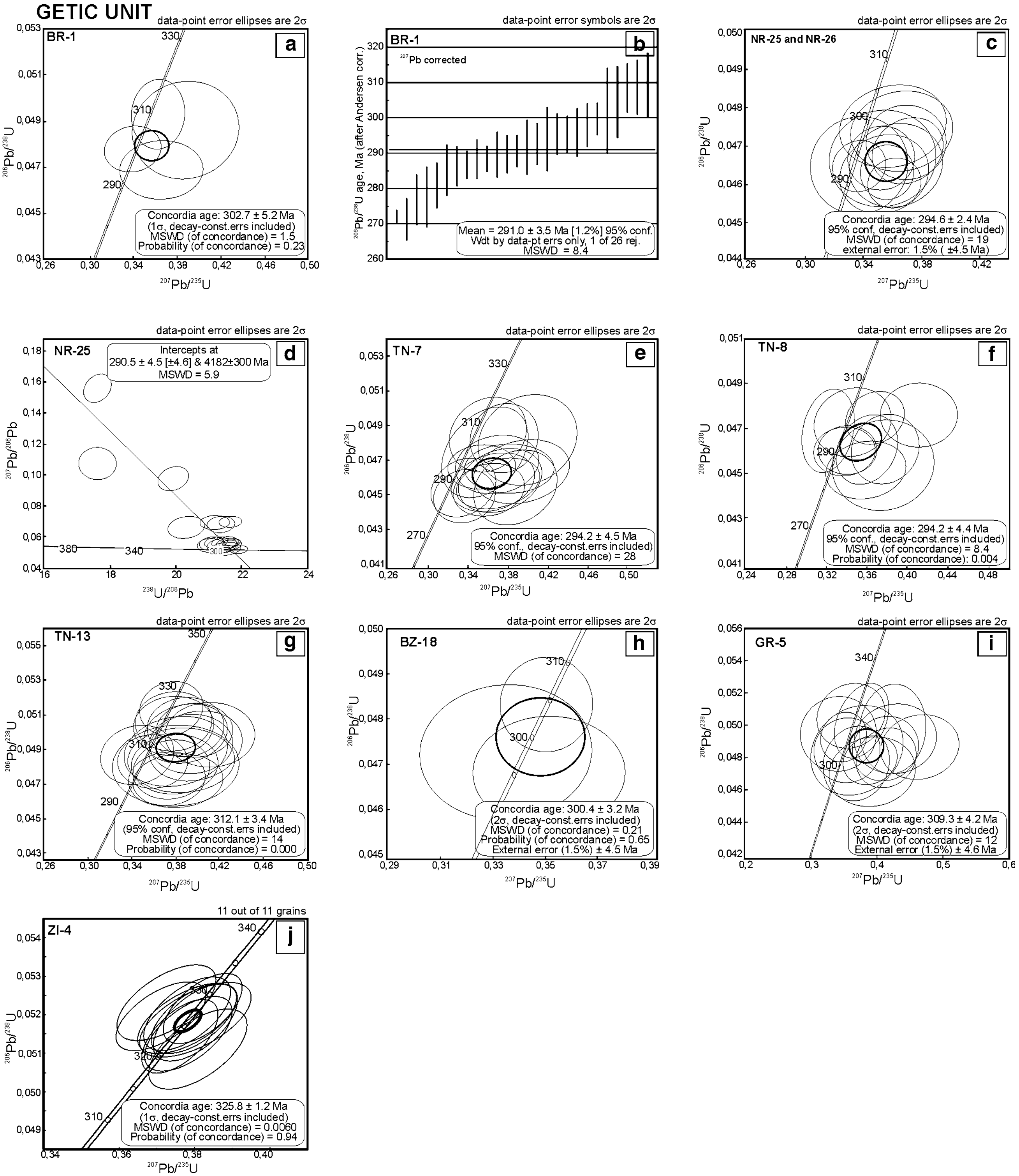


Fig. 4 Concordia diagrams, mean values and intercepts ages for the analyzed zircons from the Getic unit. **a**, **b** Brnjica; **c**, **d** Neresnica; **e**–**i** Gornjane-Tanda-Blizna; **j** Ziman

silica contents > 65 wt% SiO_2 and total alkalis above 7 wt%. As it can be seen in Fig. 6, a majority of the samples are slightly peraluminous with ASI = 1–1.1 [ASI = molecular $A1_2O_3/(Na_2O + K_2O + CaO)$]. By contrast, the garnet-bearing muscovite granite of Ziman and one sample from the Radičevac massif are strongly peraluminous (ASI > 1.1).

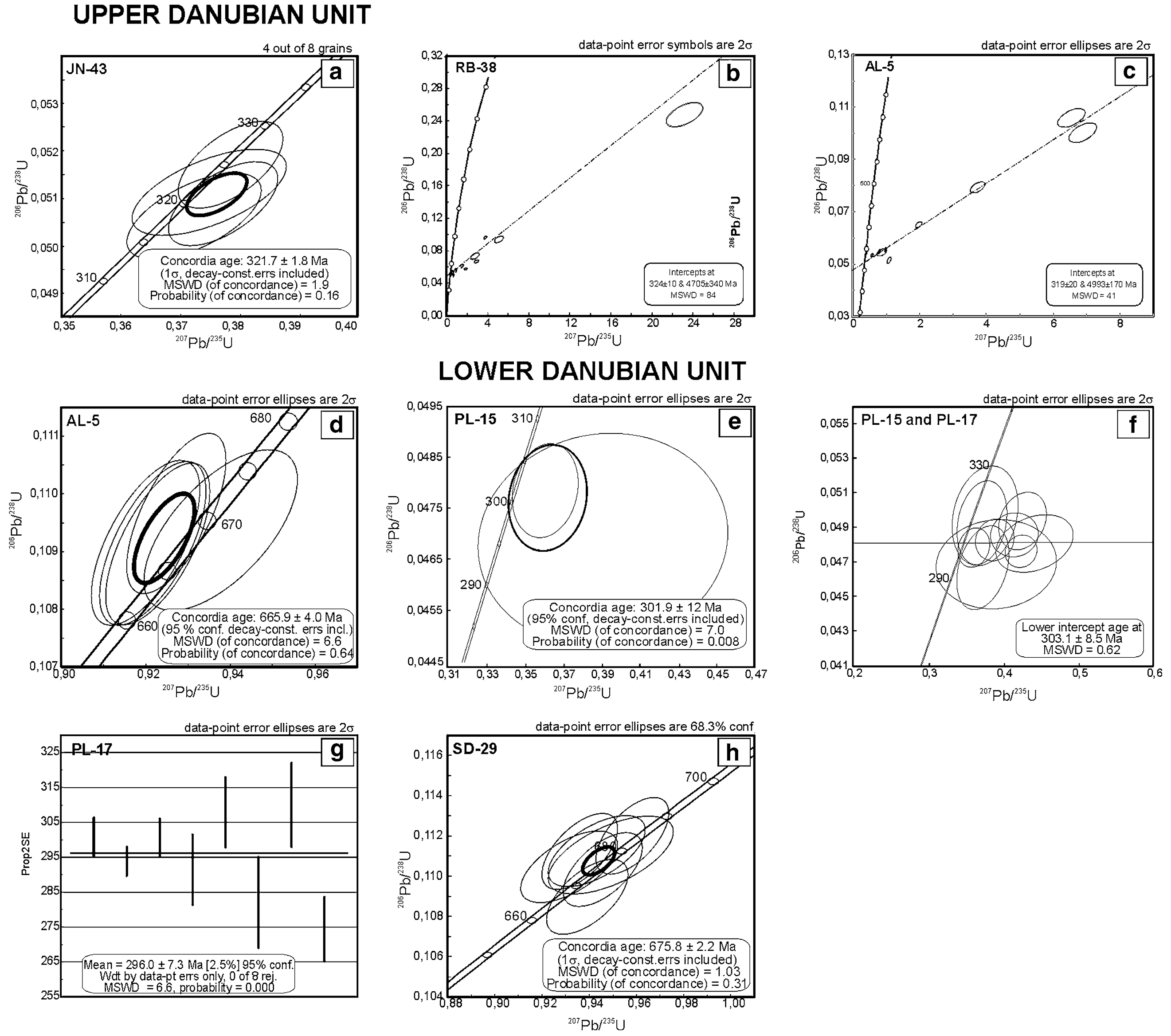


Fig. 5 Concordia diagrams, mean values and intercepts ages for the analyzed zircons from the Danubian units. **a** Janja; **b** Ravno Bučje; **c**, **d** Aldinac; **e–g** Plavna; **h** Suvodol

Primitive mantle-normalized trace element and chondrite-normalized REE patterns are shown in Fig 7a, b, respectively. Again, by setting aside the four above mentioned samples and focusing on the rocks with > 65 wt% SiO_2, it can be seen that samples of strongly peraluminous Ziman and Radičevac granites have mutually similar patterns that crosscut with the general pattern shown by other granitoids (Fig. 7a, b; upper left). The former exhibit the least light REE-enriched chondrite-normalized patterns with La/Lu below 45 and have low U, Th and Zr contents. In particular, the Ziman granite has 5–10 times lower Th contents (35× primitive mantle values—PM), generally lower U concentrations (98× PM) as well as significantly lower U/Nb (0.2) and U/Th (0.28) ratios than most slightly peraluminous granitoids which, in turn, are light REE-enriched (La/Lu = 50–115) with high thorium (Th = 70–270× PM) and uranium (U = 100–240× PM) concentrations as well as with high U/Nb and U/Th (up to 0.5 and 5, respectively) values. Samples from Ravno Bučje and Aldinac show remarkably similar trace element and REE patterns (Fig. 7a, b; upper right) in keeping with their same geotectonic and geological position and petrographic characteristics, which suggests that they likely belong to a single intrusive event. On the other hand, the slightly peraluminous massifs cutting the Getic basement (Brnjica, Neresnica and Gornjane–Tanda–Blizna) show similar REE patterns but with a different extent of fractionation.

Table 3 Major (wt%), trace and rare earth element (ppm) analyses of East Serbian Variscan rocks

	Getic										Upper Danubian			Lower Danubian	
	BR-1	BR-4	NR-26	NR-25	ZI-4	BZ-18	GR-5	TN-13	TN-7	TN-8	AL-5	JN-43	RB-38	PL-17	SD-29
SiO_2	66.72	67.99	67.12	68.67	70.38	69.24	61.44	65.22	70.25	51.93	69.01	54.26	66.33	69.72	48.77
TiO_2	0.42	0.41	0.48	0.28	0.07	0.24	0.62	0.42	0.24	0.25	0.31	0.74	0.46	0.31	1.14
Al_2O_3	16.12	16.01	16.11	15.65	16.83	15.42	16.3	15.63	13.98	16.16	14.75	19.66	15.21	15.05	18.87
Fe_2O_3(t)	4.64	3.93	4.65	4.46	0.99	3.46	5.97	4.81	3.19	3.23	3.21	5.59	3.72	3.84	10.10
MnO	0.07	0.05	0.07	0.06	0.04	0.05	0.11	0.08	0.05	0.17	0.04	0.08	0.08	0.07	0.19
MgO	1.26	1.17	1.39	0.74	0.15	1.08	3.59	2.36	1.56	3.10	0.80	2.71	1.29	0.88	3.98
CaO	3.16	3.04	3.31	2.13	0.81	1.90	3.61	3.12	1.60	7.57	1.97	4.41	3.24	2.32	8.07
Na_2O	4.20	4.17	4.31	4.07	4.06	3.83	3.69	3.54	2.7	4.14	3.42	4.59	3.51	4.03	4.15
K_2O	2.43	2.35	1.89	3.46	4.71	4.05	3.02	3.59	5.53	5.59	4.61	3.96	2.94	3.14	0.59
P_2O_5	0.12	0.12	0.14	0.09	0.16	0.17	0.12	0.11	0.07	0.08	0.12	0.46	0.23	0.11	0.41
LOI	0.70	0.60	0.40	0.20	1.60	0.50	1.30	0.90	0.70	7.60	1.50	2.90	2.60	0.40	3.40
Total	99.84	99.84	99.87	99.81	99.80	99.94	99.77	99.78	99.87	99.82	99.74	99.36	99.61	99.87	99.67
Ba	605	608	499	1357	612	505	817	592	725	932	1213	3129	1414	572	380
Cs	3.3	3.9	5.2	4.8	3.5	10.1	3.1	4	6.8	1.4	1.1	3.3	1.1	5.2	0.8
Ga	17.5	17.3	17	16	17.1	17.2	17.6	16.5	13.6	15.6	16.8	20.7	15.7	16	21.1
Hf	3.1	3.3	3.6	3.3	1.5	2.6	7.5	3.1	3.6	3.5	4.5	12.2	6.4	3.6	3.5
Nb	11	8.1	9.4	10.5	10.0	9.7	9.6	8.6	7.3	8.4	14.2	4.4	10.7	10.4	6.2
Rb	95.9	89.7	89.8	106.5	152.3	191.4	136.8	163.6	209.7	172.7	122.0	103.8	76	133.3	15.3
Sn	5	4	6	5	7	8	5	5	4	3	3	1	1	6	1
Sr	346.7	351.1	345	284.7	226.6	176.4	388.2	360.6	196.8	164.3	418.7	1182.1	678.5	254.7	1014.3
Ta	1	0.8	0.8	0.8	3.0	1.4	0.9	1.1	1.3	1	2.7	0.3	1.2	1.2	0.2
Th	14.4	10.2	5.7	14.2	2.8	8	24.8	14.5	7.3	13.8	21.6	36.2	24	13.2	1
U	3.1	1.8	2.6	2.3	2.0	3.5	4.6	2.4	3.5	2.7	5.3	7.1	3.7	4.9	0.4
V	41	41	43	30	<8	34	109	73	43	39	50	99	61	35	200
W	0.8	0.8	0.7	1.3	423.0	1.5	1.6	0.9	1.6	1.9	449.0	< 0.5	0.6	1.2	< 0.5
Zr	127.5	111.6	144	104.3	37.9	81.2	279.5	99.6	123.6	116.3	154.4	477.7	248.3	126.8	144.9
Y	8.7	8.1	11.3	12	15.6	15.5	22.2	14.5	11.6	20.1	16.0	10.4	22.2	15.2	21.8
La	32	27.9	16.1	29	8.9	13.8	27	21.1	10.5	12.6	33.2	133	49.5	20.4	22.5
Ce	60.1	52.4	32.1	60.3	16.7	28.4	58.7	42	23.3	30.2	56.8	209.1	99.6	42	51.7
Pr	5.92	5.23	3.43	6.5	2.07	3.19	6.44	4.32	2.58	3.39	6.64	19.42	9.75	4.6	7.33
Nd	19.8	17.5	12.3	22.6	6.8	11.3	23.4	15.5	9.7	12.5	22.1	58.3	33.6	16.3	30.9
Sm	3.05	2.82	2.36	4.08	1.81	2.34	4.67	3.09	2.11	2.97	3.90	7.01	5.58	3.12	6.14
Eu	0.84	0.83	0.79	0.93	0.52	0.66	0.97	0.8	0.61	0.74	1.04	1.9	1.34	0.62	1.83
Gd	2.43	2.1	2.21	3.24	2.06	2.35	4.33	2.81	2.05	3.08	3.24	4.8	4.95	2.81	5.43
Tb	0.32	0.29	0.36	0.46	0.46	0.44	0.7	0.45	0.34	0.56	0.55	0.49	0.67	0.44	0.73
Dy	1.57	1.47	1.92	2.27	2.67	2.61	3.82	2.47	1.78	3.17	2.65	2.21	3.58	2.45	4.04
Ho	0.29	0.28	0.37	0.41	0.61	0.5	0.75	0.53	0.38	0.66	0.62	0.34	0.73	0.47	0.79
Er	0.76	0.76	1.04	1.08	1.53	1.33	2.18	1.43	1.16	2.03	1.64	0.91	2.21	1.36	2.07
Tm	0.11	0.11	0.16	0.16	0.32	0.2	0.34	0.24	0.2	0.34	0.33	0.14	0.36	0.22	0.3
Yb	0.71	0.66	0.97	1.08	1.63	1.27	2.19	1.52	1.34	2.39	1.91	0.97	2.63	1.42	1.89
Lu	0.12	0.11	0.16	0.16	0.21	0.19	0.31	0.23	0.21	0.4	0.31	0.18	0.43	0.23	0.28
Mo	0.9	0.7	0.9	1.5	0.5	0.7	0.7	0.7	0.7	0.3	1.2	0.1	< 0.1	1	0.2
Cu	22.9	23.7	23.1	44.1	5.8	26.9	41.2	21.5	36.9	13.2	18.4	14.3	4.8	28.3	70.9
Pb	5.4	6	5.8	9.3	13.0	11.8	18.8	8.1	15.7	6.4	9.2	22.3	9.9	8.9	2.4
Zn	89	64	75	45	24	25	44	41	58	41	21	93	40	48	121
Ni	15.8	14.2	20.1	14.7	10.0	17.6	35.7	25.7	21.8	20.1	9.7	18.8	3.5	15.2	4

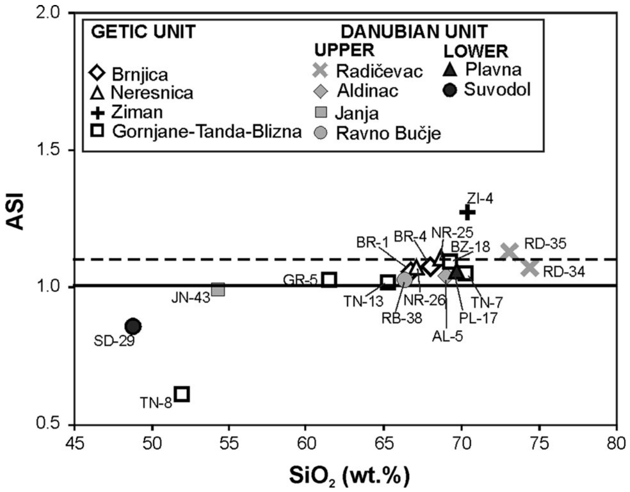


Fig. 6 Silica (wt%) vs aluminum-saturation index [molecular $A1_2O_3/(Na_2O + K_2O + CaO)$] diagram (Shand 1943) for samples of the ESCB Variscan granitoids, which were radiometrically dated; note that two samples of the Radičevac granitoid are plotted for correlation, although they are missing in Table 3

5 Discussion

Given a complex and presumably polyphase character of most of the studied plutons, it is sure that the above presented geochronological and geochemical data are still incomplete for enabling a comprehensive and detailed reconstruction of ESCB Variscan magmatism. In spite of this, the study certainly brings sufficient information for providing deeper insight into the origin and evolution of this part of the South European Variscan belt. The following discussion is structured such, that we start with the plutons inside the Getic unit, because our radiometric dating for these intrusives was more successful in producing meaningful ages. Then, we discuss the obtained data for the Danubian units and underline new information and its implications. Eventually, we summarize important open questions that will be addressed in the nearest future.

5.1 The Getic unit: what is the correct age range of Variscan magmatism in the ESCB?

In general, the new obtained range of U–Pb zircon ages (319–281 Ma, including error bars) for intrusives of the Getic unit is similar to the age range of the previously dated plutons from the Carpathian–Balkan sector (see Table 4 and Fig. 8 for references). The main difference is that our study reveals many ages that are younger than 300 Ma. In the case of the Neresnica and Brnjica plutons, we obtained several concordia ages that range between 284 Ma and 292 Ma. This is some 20 m.y. younger than, for instance, the age of the Poniasca biotite diorite of 311 Ma (SHRIMP II on zircons, Duchesne et al. 2008). Although two samples from Brnjica likely record some Pb loss (the corresponding points are discordant with apparent $^{206}Pb/^{238}U$ ages), three other samples from various granitoids of the Getic unit gave reliable emplacement ages of ~ 290 Ma. Two syenite samples from the adjacent Gornjane–Tanda–Blizna pluton show very similar Permian concordia ages (294.2 ± 4.4 Ma and 294.2 ± 4.5 Ma). The latter two samples are taken from syenite bodies that in places display sharp contacts with the main granitoid mass, confirming that they are likely related to a relatively younger magmatic event. By contrast, the samples from the predominating lithology of the Gornjane–Tanda–Blizna granitoid massif gave a relatively narrow older age range of

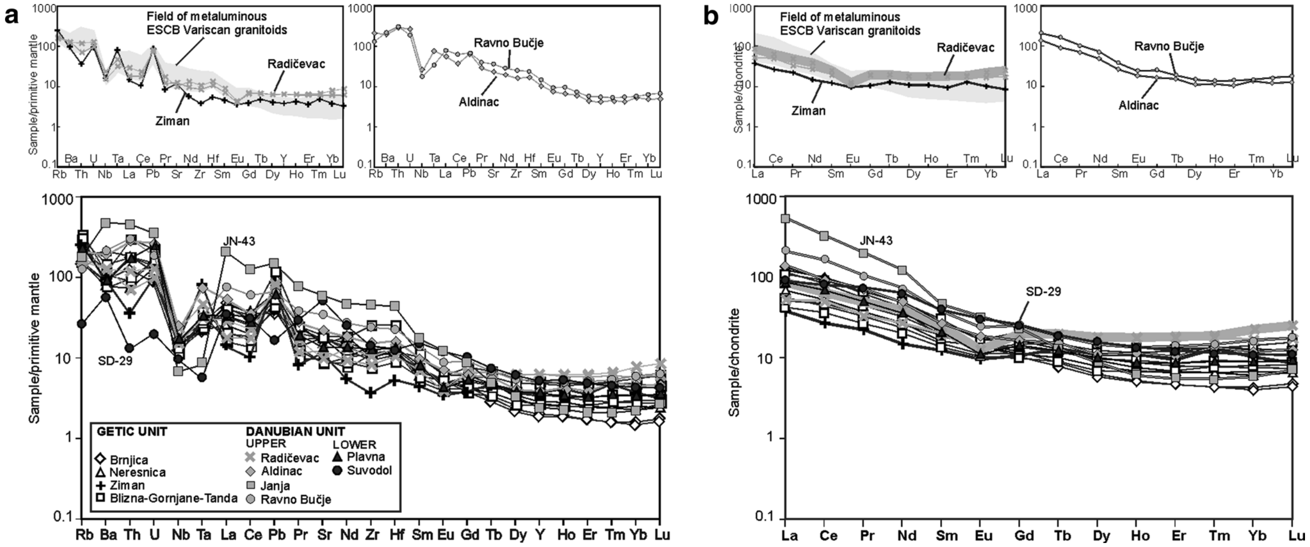


Fig. 7 **a** primitive mantle-normalized trace element concentrations, **b** chondrite-normalized REE contents (normalization coefficients after McDonough and Sun 1995); see the caption for Fig. 6

Table 4 Published radiometric data for Variscan granitoids of the East Serbian Carpatho-Balkanides

Locality	Rock type	Material	Method	Age (Ma)	References
Getic unit					
Brnjica	Main granodiorite	Biotite, zircon	Rb/Sr	259	Deleon et al. (1965) and Deleon (1969)
	Red granodiorite	Biotite	Rb/Sr	272	
	Granitoid	not given	K/Ar	291–342	Lovrić et al. (1973)—from Kalenic et al. (1980)
Neresnica	Granodiorite	Biotite	Rb/Sr	237–275	Deleon et al. (1965) and Deleon (1969)
	Granodiorite	Zircon	Pb/U	332–291	
	Granitoid	Not given	K/Ar	294–305	Lovrić et al. (1973)—from Kalenic et al. (1980)
Ziman	Granite	Muscovite	Rb/Sr	295	Deleon et al. (1965)
Gornjane	Granodiorite	Biotite	Rb/Sr	304	Deleon et al. (1965) and Deleon (1969)
	Granodiorite	Zircon	Pb/U	324	
	Porphyritic monzogranite	Zircon	LA–ICP–MS	307.1 ± 4.5	Vasković et al. (2012)
	Fine-grained granite	Zircon	LA–ICP–MS	307.6 ± 2.5; 323.3 ± 2.6	
	Medium-grained granodiorite	Zircon	LA–ICP–MS	307.1 ± 2.9	
	Fine-grained diorite	Zircon	LA–ICP–MS	305.8 ± 3.6	
Upper Danubian unit					
Aldinac	Granite	Zircon	Pb/U	287	Deleon et al. (1965) and Deleon (1969)
Janja	Metadiorite	Biotite	Rb/Sr	240	
Ravno Bučje	Granite	Biotite	Rb/Sr	283	
	Granite	Biotite	Pb/U	372	
Stara Planina	Granite	Biotite	Rb/Sr	300 ± 11	Cervenjak et al. (1963)
	Granite	Biotite	Rb/Sr	282 ± 10	
Lower Danubian unit					
Plavna	Granodiorite	Biotite	Rb/Sr	178	Deleon et al. (1965) and Deleon (1969)
Suvodol	Granite	Zircon	Pb/U + Th	332	

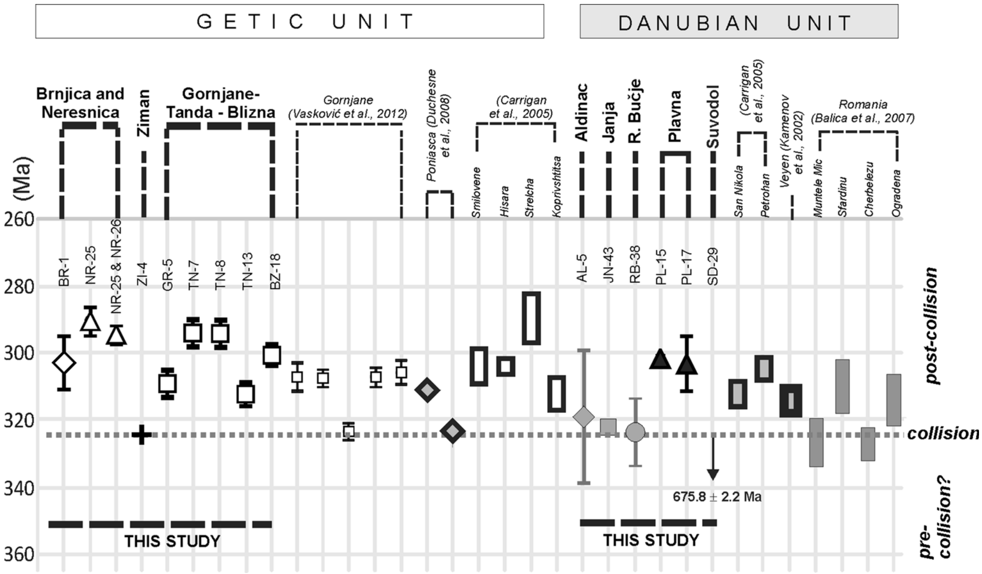


Fig. 8 Overview of the available zircon U–Pb ages for Variscan granitoids of the Carpatho-Balkan sector (this study and literature data, see also Table 4)

312.1 ± 3.4 to 300.4 ± 3.2 Ma, which conforms with the LA–ICP–MS zircon ages reported for the same pluton by Vasković et al. (2012) (Fig. 8).

Similar age ranges to those reported in this study are available for the plutons that intrude the Sredna Gora unit in Bulgaria. Carrigan et al. (2005) published an age of 312 ± 5.4 Ma for the Koprivshtitsa granitoid and around 304 Ma for the massifs of Smilovene and Hisara. However, for the Strelcha pluton they reported an age of 289.5 ± 7.8 Ma (Fig. 8).

All the above age data derive from zircons mostly extracted from slightly peraluminous to metaluminous granites that intrude the Getic basement. In this context, our data indicate that the Getic unit underwent Variscan magmatism which lasted longer than originally thought. The Getic and Danubian nappe systems are characterized by the development of Late Carboniferous ("Westphalian") to Permian post-tectonic sedimentary basins dated with palynological floras (Iancu et al. 2005; Cortesogno et al. 2004, and references therein). It thus seems that at least the youngest dated post-collisional granitoids are "post-Variscan" in the sense that they post-date Variscan orogeny. Given the wider ESCB region, it should be mentioned that similar late Carboniferous/early Permian concordia age (291.1 ± 1.1 Ma—LA–ICP–MS and 296.6 + 5.7/− 6.2 Ma—ID) are reported for the peraluminous Muntele Mare pluton in the Apuseni Mts., interpreted as an anatectic pluton generated by lithospheric delamination after the cessation of continental collision (Balintoni et al. 2009). Products of post-collisional magmatism of similar age were also found on the Iberian Peninsula (Dias et al. 1998; Fernandez-Suarez et al. 2000) as well as in SE France (Duchesne et al. 2013).

Important new information was provided by zircons from the Ziman garnet-bearing muscovite granite, which gave a concordia age at 325.8 ± 1.2 Ma. This age is associated to an intrusion that is structurally and compositionally different from the previously mentioned plutons. The Ziman intrusion is spatially associated with migmatites and lacks a contact metamorphic aureole, and its fabric implies syntectonic crystallization. It is strongly peraluminous in composition and its trace element and REE patterns differ from the patterns displayed by the predominantly slightly peraluminous granitoids. Hence, Ziman is very akin to typical syn-collisional granitoid intrusives (Pearce et al. 1984; Maniar and Piccoli 1989). Although the presence of syn-collisional granites so far has never been reported in the Getic unit, generally similar ages were detected in zircons from the presumably younger metaluminous granites of Poniasca (324 ± 4 Ma; Duchesne et al. 2008), Gornjane (323.3 ± 2.6 Ma; Vasković et al. 2012) and Koprivshtitsa (327.1 ± 5.9 Ma; Carrigan et al. 2005). These older ages were interpreted as reflecting an earlier partial melting event by all previous authors (e.g., Duchesne et al. 2008).

It is, therefore, appropriate to assume that the Ziman granite records the last compressional-collisional events of Variscan orogeny in the ESCB sector. This is in accordance with existing evidence about the age of peak metamorphism in the Getic metamorphic basement showing an age range between 358 and 323 Ma (Ledru et al. 1997; Dragusanu and Tanaka 1999; Medaris et al. 2003) as well as crustal melting events in South Bohemia dated 327 ± 1 Ma (Gerdes et al. 2003).

In summary, the presented data allow for concluding that the studied part of the Getic basement underwent a collisional phase associated with the intrusion of strongly peraluminous granitoids at ~ 325 Ma. This followed by the emplacement of post-collisional plutons associated with local extension as is documented by the formation of Late Carboniferous to Permian post-tectonic sedimentary basins associated with volcanism. These post-collisional predominantly metaluminous to slightly peraluminous plutons are heterogeneous in composition and often exhibit transitions to more peraluminous, muscovite-bearing or two-mica granitoids. Note, however, that these post-collisional muscovite-bearing granitoids should not be confused with the garnet-bearing Ziman-type muscovite granite that shows syn-collisional characteristics.

5.2 The Danubian units: how many Variscan plutons are there?

Although the ages recorded by zircons from the Danubian basement are of lower quality, they allow for constraining at least some important issues. Interestingly, the most reliable concordia age of 321.7 ± 1.8 Ma is recorded by zircons from syenodiorite of the Janja massif, earlier considered as Caledonian, mainly by its geological relationships to the Silurian-Devonian Inovo formation (Kräutner and Krstić 2003). These authors actually followed the interpretation of Krstić et al. (1976) who argued that the Janja pluton is coeval with the accompanying mafic–ultramafic rocks. However, our field observations suggest that these mafic–ultramafic rocks had already undergone (ocean floor?) metamorphism before they came into contact with the granitoid magma. This further implies that these mafic–ultramafic rocks either represent part of the Berkovica island-arc group (Kräutner and Krstić 2003) or they represent southern small-scale continuations of the Zaglavak ophiolites. The other three U–Pb analyses of the Danubian granitoid rocks failed to produce concordia ages, hence, our age estimates only serve as first approximations. Zircons from the Ravno Bučje intrusive gave a lower intercept at 324 ± 10 Ma, which is older but comparable to the age of the San Nikola pluton (311.9 ± 4.1 Ma;

Carrigan et al. 2005). Those from the Aldinac rhyodacite gave an age with an even larger error: 319 ± 20 Ma. These albeit rough age constraints can at least serve as indications that these magmatic bodies may belong to the same intrusive phase. It is corroborated by petrological characteristics, because the Aldinac and Ravno Bučje samples display almost indistinguishable primitive mantle- and chondrite-normalized REE and trace element patterns (see Fig. 7).

Although it is possible that the above discussed plutons are not petrogenetically related, we argue that the concordia age of the Janja pluton of 321.7 ± 1.8 Ma may be used for further constraining the age of the Aldinac and Ravno Bučje intrusives. In this context, we suggest that all plutons in the ESCB Upper Danubian basement may have been emplaced at around 320 Ma. This remains to be supported by further petrological studies, but we emphasize that the studied samples of Janja, Aldinac and Ravno Bučje show remarkable enrichments in accessory minerals, primarily apatite, allanite (see Fig. 2), sphene and zircon and have the highest contents of LREE, U, Th and Zr in comparison to all non-cumulitic ($>$ 65% of SiO_2) granitoids from the studied sample suite. The enrichment in radioactive elements in granitoid rocks of SE Serbia has long been known (Gertik 2003; Kovačević et al. 2009). The ore formation processes were usually explained by post-magmatic sedimentary processes, but these granitoids were always considered important sources for uranium (Kovačević 1997; Gertik 2003). Accordingly, the enrichment in radioactive elements is possibly a common feature of the Upper Danubian Variscan intrusives in Serbia.

The age of the Lower Danubian Variscan intrusives in Serbia remains poorly constrained. Zircons from the Suvodol lamprophyre (SD-29) revealed an early Cadomian concordia age of 675.8 ± 2.2 Ma, but due to too narrow rims that could not be measured (see Figs. 3, 5), it does not give the crystallization age of the lamprophyre. Relatively fast crystallizing melts usually have only inherited zircons, hence, it is reasonable to assume that this age likely reflects a Cadomian event already recorded by other inherited cores (e.g., Neresnica: 681.8 ± 7.2 Ma and Ziman: 654.17 ± 6.4 Ma). However, it can at least be speculated that this pluton also belongs to the Variscan intrusives on the basis of the petrographic similarity between the Suvodol lamprophyre and lamprophyres associated with other Variscan massifs studied here. This is supported by the general petrological features exhibited by the Suvodol granitoid itself, such as: the presence of mafic enclaves and evidence of post-tectonic crystallization and/or post-magmatic shearing and recrystallization.

This view is roughly supported by the age of 301.9 ± 12 Ma given by zircons from the Plavna massif. As previously mentioned, the Plavna granitoid mass most likely belongs to the northwesternmost part of the same antiform structure intruded by the Suvodol granitoid. During the Cenozoic, part of the anticline in which the Plavna body had already been emplaced, was cut off by the Timok fault and horizontally displaced by some 100 km northwards.

5.3 A snapshot into Variscan events in the ESCB realm: open questions

There is a number of open questions that require further consideration and must be addressed by future studies. In the following we discuss only two issues.

First, it is necessary to constrain the age of the Radičevac massif that also intrudes the Upper Danubian basement. This pluton, along with its counterparts: Stakevci, Gorni Lom, and Brzisik (Bulgaria) and Sesemin (Romania), has so far been regarded pre-Variscan in age by all authors (e.g., Carrigan et al. 2003). The Radičevac massif was not dated in this study, but there are some indications that this pluton may also be Variscan in age. If our conclusion that the Ziman granite is a syn-collisional intrusion is correct, it is likely that relicts of other plutons produced by syn-collision may exist in the area. The petrological similarities between the Ziman and Radičevac granite, namely: the presence of migmatized aureoles, their strongly peraluminous composition (Fig. 6), and textural evidence of syn-kinematic crystallization (Fig. 2), all imply the possibility that these two intrusions may have emplaced during the same geodynamic event. This primarily means that the Radičevac pluton must be accurately dated, despite the observation that magmatic zircons in such syn-collisional granitoids are commonly rare (e.g., Carrigan et al. 2003). Further research should also focus on studying smaller masses of the same geological position and similar petrography to those of Ziman and Radičevac, which occur in other places of the ESCB sector (see section on petrography).

A second issue is to prove or disprove the indication that there is a systematic age difference between the Variscan intrusions from different geotectonic units of the ESCB. Despite the fact that the available radiometric data still do not have sufficient resolution, there is evidence that the plutons occurring in the Danubian–Balkan terranes are systematically older than those intruding the Getic–Sredna Gora basement. If this turns out to be true, this may impose significant implications for the geodynamic reconstruction of the Variscan events in the entire Carpatho-Balkan sector.

6 Conclusions

On the basis of new LA–ICP–MS zircon U–Pb data and petrological characteristics of the nine investigated plutons of the Variscan basement of the Getic and Danubian units of the ESCB the following conclusions can be derived:

1. Our results confirm the general picture obtained from earlier studies that metaluminous (in our case only slightly peraluminous) granitoids, which occasionally show transitions to two-mica or muscovite-bearing peraluminous granitoids, strongly predominate in the ESCB sector. These types of granitoids solidified under post-collisional conditions, sometimes displaying evidence of post-emplacement shearing and recrystallization.
2. The most reliable U–Pb zircon ages belonging to the above mentioned post-collisional granitoids gave a range between ~ 323 and ~ 290 Ma for the entire ESCB belt.
3. The granitoids of the Getic unit reveal better concordia ages suggesting that Variscan and Permian magmatism lasted longer than previously thought, i.e., that they last into a period of post-Variscan extension.
4. The garnet-bearing muscovite granite of Ziman, previously considered a part of the Neresnica pluton, represents a strongly peraluminous intrusion that shows evidence of syn-tectonic crystallization. The concordia age of 325.8 ± 1.2 Ma for this granite is interpreted as marking a minimum age for collision in this part of the Variscan belt.
5. The obtained ages of the Danubian plutons are less reliable, but underline some still open questions, such as: (a) are the Danubian intrusions really systematically older than those intruding the Getic basement? (b) are there Variscan syn-collisional plutons in the Danubian unit at all (e.g., Radičevac–Stakevci)? and (c) was the formation of uranium mineralization exclusively related to Variscan magmatism in the Upper Danubian unit?

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