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Constraints on Ordovician and Carboniferous magmatism in the Carpathian–Pannonian region: New petrological and geochronological insights from the Tisza–Dacia and ALCAPA Mega-units (Hungary and Romania)

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Abstract: Carboniferous–Permian magmatic rocks are common in the Carpathian–Pannonian region, whereas Cambrian–Devonian (meta)igneous associations are less frequent and not yet confirmed by radiometric data in the basement of the Pannonian Basin. The major goal of this study was to constrain Ordovician zircon U–Pb ages from (meta)igneous rocks representing three prospective study areas in the inner Carpathian–Pannonian region: the Bihor Mts (Apuseni Mts, Tisza–Dacia Mega-unit), the eastern Mecsek Mts (southern Transdanubia, Tisza–Dacia Mega-unit), and the Balaton Highland (central Transdanubia, ALCAPA Mega-unit). Metagranitoids from the Bihor Mts yielded an Early Ordovician protolith age of 478.0+3.2/−2.5 Ma which, supported by bulk-rock geochemistry and deformation, suggests they belong to the ~495–477 Ma extensional bimodal magmatism of the Biharia terrane and may be related to back-arc rifting along the northeastern margin of Gondwana. These rocks were later overprinted by multiple Alpine shearing events within the Highiş–Biharia Shear Zone. A Middle Ordovician age of 464.8+3.0/−3.1 Ma, from one of the lower magmatic sections of the Kékkút-4 borehole in the Balaton Highland, is most plausibly attributed to the Alsóörs Metarhyolite and identifies it as the oldest known igneous formation within Hungary confirmed by numerical age data. Contrary to being overlain by Silurian slate, monzonites from the Szalatnak-3 borehole in the eastern Mecsek Mts yielded a Carboniferous age of 332.7+2.1/−1.6 Ma. These subvolcanic rocks exhibit alkaline, apparently shoshonitic characteristics and are slightly younger than the nearby I-type Mórágy Metagranite (~354–338 Ma). Supported by bulk-rock geochemical similarities, this may indicate that the two formations originated along the same active continental margin, representing different phases of a complex Variscan geodynamic evolution: subduction followed by post-collisional extension.

Keywords: zircon U–Pb dating, Ordovician magmatism, Biharia terrane, Kékkút, Carboniferous magmatism, Szalatnak, monzonite

Introduction

During the last ~25 years, numerous Paleozoic igneous periods were revealed in the Carpathian–Pannonian region (East-Central Europe) and placed within the geodynamics of the Variscan Belt in Central Europe based on various mineralogical, petrological, geochemical, and geochronological analyses carried out on a wide range of (meta)igneous formations in the region. The latter include those of the Western Carpathians (e.g., Broska & Uher 2001; Putiš et al. 2008, 2009; Kohút et al. 2009, 2024; Vozárová et al. 2009, 2010; Broska et al. 2013, 2022; Ondrejka et al. 2021; Villaseñor et al. 2021), central Transdanubia (e.g., Broska & Uher 2001; Lelkes-Felvári & Klötzli 2004; Uher & Ondrejka 2009; Szemerédi et al. 2020; Ondrejka et al. 2021), southern Transdanubia (e.g., Buda et al. 2004; Király & Koroknai 2004; Klötzli et al. 2004; Gerdes 2006; Buda & Pál-Molnár 2012; Szemerédi et al. 2020), the eastern Pannonian Basin (e.g., Buda et al. 2004, 2012; Buda & Pál-Molnár 2012; Szemerédi et al. 2020, 2023), the Apuseni Mts (e.g., Pană et al. 2002; Balintoni et al. 2009, 2010; Nicolae et al. 2014; Szemerédi et al. 2021, 2023), and the Slavonian Mts (e.g., Horvat & Buda 2004; Horvat et al. 2018).

Permian rift-related felsic volcanic and volcaniclastic rocks (e.g., Vozárová et al. 2009; Nicolae et al. 2014; Szemerédi et al. 2020, 2023) as well as anorogenic A-type (Pană et al. 2002; Uher & Ondrejka 2009; Bonin & Tatu 2016; Ondrejka et al. 2021; Szemerédi et al. 2021) and post-collisional (specialized) S-type granitoids (Broska & Uher 2001; Kubiš & Broska 2010; Villaseñor et al. 2021) are relatively frequent in the Carpathian–Pannonian region, including the ALCAPA Mega-unit

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(Western Carpathians, central Transdanubia) and the Tisza–Dacia Mega-unit (southern Transdanubia, eastern Pannonian Basin, and Apuseni Mts), most of which were generated ~285–260 Ma ago. Upper Devonian to Lower Carboniferous (~375–335 Ma) S- and/or I-type granitoids (Buda et al. 2004, 2012; Klötzli et al. 2004; Gerdes 2006; Kohút et al. 2009, 2024; Broska et al. 2013, 2022; Broska & Svojtka 2020; Kohút & Larionov 2021) also occur in various parts of both the Tisza–Dacia (southern Transdanubia, eastern Pannonian Basin, and Apuseni Mts) and the ALCAPA Mega-units (Western Carpathians). However, older, Cambrian to Devonian (meta)igneous rocks are relatively rare in the Carpathian–Pannonian region and, so far, have not been confirmed by radiometric age data in the basement of the Pannonian Basin, including the entire area of Hungary (see e.g., Babinszki et al. 2024 and references therein). Felsic metaigneous rocks of the pre-Alpine Biharia terrane in the Apuseni Mts yielded late Cambrian to Ordovician ages (~495–459 Ma; Pană & Balintoni 2000; Balintoni et al. 2010). These rocks are interpreted to have formed in an initial extensional environment, followed by subduction-related processes, reflecting the evolution of the northeastern margin of Gondwana (Pană & Balintoni 2000; Balintoni et al. 2010). Similar Cambrian–Ordovician protolith ages (~510 to 440 Ma) were constrained in the case of the orthogneisses in the Western Carpathians, including those in the Tríbeč, the Low Tatra, and the Vepor Mts (Méres & Hovorka 1992; Gaab et al. 2005, 2006; Petrík et al. 2006; Putiš et al. 2008, 2009). Early Ordovician volcanic activity has also been constrained by the dating of felsic metavolcanic rocks in the basement of the Western Carpathians, which yielded ages of 482±6 Ma and 476±7 Ma (Putiš et al. 2008, 2009). Late Cambrian to Early Ordovician protolith ages (491±1, 486±6, and 483±6 Ma) were also documented for the metagranites of the Moslavačka Gora Massif in the south-western Pannonian Basin (Starijaš et al. 2010).

The major goal of this study is the further examination of Ordovician magmatism in the Carpathian–Pannonian region, by selecting three prospective study areas (Bihor Mts, southern Transdanubia, and Balaton Highland) and their felsic (meta)igneous rocks (Fig. 1). (1) The Bihor Mts in the central Apuseni Mts has been selected based on the local occurrence of Upper Cambrian to Ordovician felsic metaigneous rocks (Pană & Balintoni 2000; Balintoni et al. 2010), which may deserve further petrological, geochemical, and geochronological investigations. (2) In southern Transdanubia, felsic rocks from the Szalatnak–3 borehole have been selected because of their lithostratigraphic position, being overlain by the Silurian Szalatnak Slate Formation (e.g., Árkai et al. 1995; Mészáros et al. 2019), which may indicate their Cambrian or Ordovician emplacement age, however their subvolcanic (dyke) origin or tectonic process cannot be excluded either as possible reasons for the current position of these rocks. (3) The Kékkút–4 borehole in the Balaton Highland was also prospective due to the local occurrence of rhyolitic metavolcaniclastic rocks, with subordinate subvolcanic rocks and lavas, known as the Alsóörs Metarhyolite Formation in the Hungarian lithostratigraphy (Babinszki et al. 2024 and references therein), which is supposed to be Ordovician without any geochronological evidence.

Geological background

The Pannonian Basin is a Neogene basin in East-Central Europe, and its pre-Neogene basement consists of two mega-units (MUs), the Tisza–Dacia MU and the ALCAPA MU of different geological histories, which are separated by the Mid-Hungarian Line (Fig. 1; Haas et al. 1999; Szederkényi et al. 2013a, b). Paleozoic (meta)igneous rocks occur as outcrops in both mega-units, e.g., in the Apuseni Mts, the Mecsek Mts, and the Slavonian Mts in the Tisza–Dacia MU as well as the Eastern Alps, the Western Carpathians, and the Transdanubian Mts (Velence Hills) in the ALCAPA MU (Fig. 1). They were also pierced by numerous boreholes of hydrocarbon or uranium ore exploration works in the eastern–central Pannonian Basin and southern Transdanubia (e.g., Babinszki et al. 2024 and references therein).

The current structure of the Apuseni Mts is the complex result of Alpine nappe stacking. Based on this, four NE–SW-trending nappe systems can be distinguished in the area, from bottom to top: the Bihor Autochtone Unit, the Codru Nappe System, the Biharia Nappe System, and the Mureş Zone Unit (e.g., Csontos et al. 1992; Csontos & Vörös 2004; Matenco & Radivojević 2012; Szederkényi et al. 2013a). The pre-Alpine basement of the Apuseni Mts also comprises three terranes, the Someş, the Baia de Arieş, and the Biharia terranes (e.g., Ianovici et al. 1976; Dallmeyer et al. 1999; Balintoni et al. 2006, 2009, 2010). According to Balintoni et al. (2006, 2010), zircon U–Pb data suggest two distinct early Paleozoic igneous periods in these basement terranes: an older (495–477 Ma) extension-related bimodal magmatism in the Biharia terrane and a younger (470–459 Ma) subduction-related igneous period in the Baia de Arieş and Someş terranes. Younger, Devonian or upper Paleozoic igneous formations in the Apuseni Mts include the Upper Devonian (~372 Ma; Pană et al. 2002) or Lower Carboniferous (~350 Ma; Balintoni et al. 2007) Codru granodiorites, the Lower Permian (~297 Ma) Muntele Mare granite (Balintoni et al. 2009), the Middle Permian (~268–263 Ma) Highiş granitoids and associated mafic–intermediate rocks (Pană et al. 2002; Bonin & Tatu 2016; Szemerédi et al. 2021) and the Middle Permian mafic to felsic volcanic and volcaniclastic rocks (Nicolae et al. 2014; Szemerédi et al. 2023). The western–central part of the Apuseni Mts is cut across by the greenschist facies Highiş–Biharia Shear Zone (Fig. 1; Pană & Erdmer 1994; Pană et al. 2002; Reiser et al. 2017), which has often affected the rock associations of the Biharia Nappe System through Alpine deformation and/or hydrothermal overprint (see e.g., Szemerédi et al. 2023).

In the Hungarian part of the Tisza–Dacia Mega-unit, three NE–SW-trending Alpine tectonic units are distinguished, from north to south and bottom to top: the Mecsek Unit,

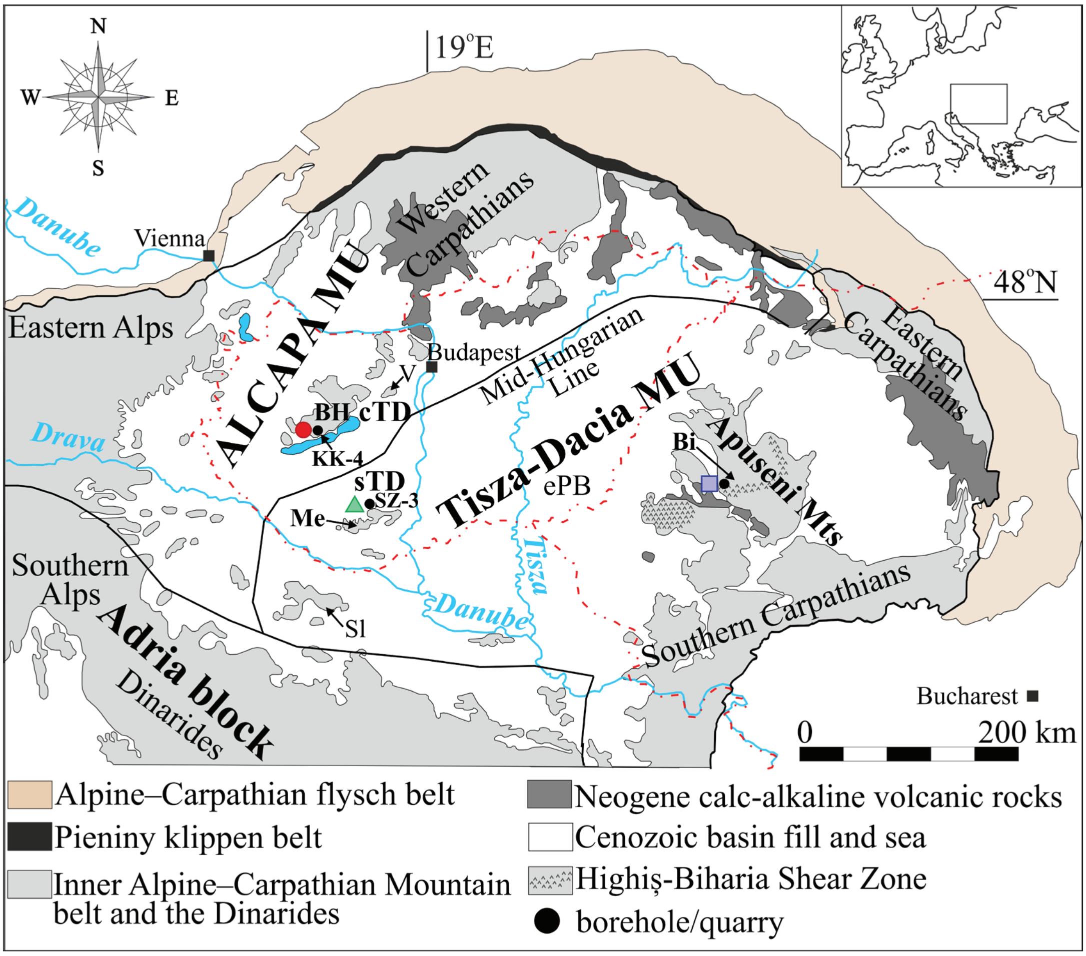

Fig. 1. Simplified geological map of the Carpathian–Pannonian region (modified after Csontos & Vörös 2004; Szemerédi et al. 2020), showing the distribution of the investigated Paleozoic (meta)igneous rocks in the Tisza–Dacia and ALCAPA Mega-units. Abbreviations: *BH*=Balaton Highland, *Bi*=Bihor Mts, *cTD*=central Transdanubia, *ePB*=eastern Pannonian Basin, *KK-4*=Kékkút–4 (borehole), *Me*=Mecsek Mts, *Sl*=Slavonian Mts, *sTD*=southern Transdanubia, *SZ-3*=Szalatnak–3 (borehole), *V*=Velence Hills.

the Villány–Bihor Unit (called Bihor Autochtone Unit in the Apuseni Mts), and the Békés–Codru Unit (called Codru Nappe System in the Apuseni Mts; e.g., Csontos et al. 1992; Csontos & Vörös 2004; Matenco & Radivojević 2012; Szederkényi et al. 2013a). Early Paleozoic magmatic ages have not been reported from southern Transdanubia (see e.g., Babinszki et al. 2024 and references therein). Carboniferous (~354–339 or ~338 Ma according to Klötzli et al. 2004 and Gerdes 2006, respectively) granitoids (dominantly granites or monzogranites) occur in the eastern Mecsek Mts (Mecsek Unit) and are classified as Mórágy Metagranite Complex in the Hungarian lithostratigraphy (Babinszki et al. 2024 and references therein). It also contains hybrid quartz syenite, quartz monzonite, or quartz diorite lenses, segregations, and dykes as well as mafic (amphibole and/or biotite-rich) enclaves. Mineralogical, petrological, and geochemical studies (e.g., Buda et al. 2004; Király & Koroknai 2004; Klötzli et al. 2004) have revealed the I-type character and the hybrid origin of the Mórágy Metagranite. As another felsic intrusion at the northern foreland of the Mecsek Mts (Mecsek Unit), the so-called Szalatnak Syenite (formerly Szalatnak Syenite Porphyry) is known from the Szalatnak–3 and –4 boreholes underlying the Silurian Szalatnak Slate Formation (Babinszki et al. 2024 and references therein). However, only a restricted amount of petrographic information is available about this syenitic or monzonitic igneous body and bulk-rock geochemical data and zircon U–Pb ages have not been published so far. The youngest Paleozoic igneous formation in southern Transdanubia is the Middle Permian (~270–260 Ma) rift-related Gyűrűfű Lapilli Tuff (Szemerédi et al. 2020, 2023), which is also known from many other areas of the Tisza–Dacia MU (eastern Pannonian Basin, Apuseni Mts) in all its Alpine structural zones.

In the Balaton Highland, central Transdanubia (ALCAPA MU), Paleozoic igneous formations include the Alsóörs Metarhyolite (supposed to be Upper Ordovician, based on the host Lovas Formation; Babinszki et al. 2024 and references therein) and the Lower Permian Felsősomlyó Rhyolite (Lelkes-Felvári & Klötzli 2004; Szemerédi et al. 2020; Józsa 2024). The Alsóörs Metarhyolite consists of rhyolitic metavolcanic and metavolcaniclastic rocks (lapilli tuffs, tuffs, tuffites), which were affected by very low-grade metamorphism. The Felsősomlyó Rhyolite, formerly named as "Kékkút Dacite" or "Kékkút quartz porphyry", was pierced only by a few boreholes in the Balaton Highland (e.g., Kékkút–4, Tótvázsony–1); however, petrologically and geochemically similar felsic dykes are also known from the Lower Devonian metamorphic limestone quarry near Polgárdi, central Transdanubia. In the case of the strongly altered porphyritic lavas in the Kékkút–4 borehole, Lelkes-Felvári & Klötzli (2004) reported a Cisuralian (~291 Ma) zircon U–Pb age, while the dating of the abovementioned dykes resulted a slightly younger (~282 Ma) age (Szemerédi et al. 2020).

Materials and methods

Felsic metaigneous rocks in the Bihor Mts (central Apuseni Mts, Romania) were collected from outcrops near Băiţa (Fig. 1). Petrographic analyses were carried out on three oriented thin sections at the Department of Geology, University of Szeged, Hungary and one of these samples (sample 474) has been selected for bulk-rock major and trace element geochemistry and zircon U–Pb dating. From the felsic intrusion drilled in the Szalatnak–3 (SZ–3) borehole (between 508.8 and 576.4 m depths), southern Transdanubia (Hungary, Fig. 1), numerous archive thin sections were provided by the MECSEKÉRC Ltd., Pécs, Hungary (23 pieces) and by Gyöngyi Lelkes-Felvári (57 pieces) representing the entire section of the igneous body, and four additional thin sections were made at the Department of Geology, University of Szeged. Bulk-rock major and trace element geochemical analyses were performed on seven representative samples from various depths. Zircon U–Pb dating was performed on one representative sample (SZAL), collected from a depth of 572.9–576.4 m. From the Kékkút–4 borehole (KK–4), Balaton Highland, central Transdanubia (Hungary, Fig. 1) drill cores were unfortunately not available for further petrographic and geochemical analyses, however, separated fine-to-coarse grained fractions, which had been used for the previous geochronological study of Lelkes-Felvári & Klötzli (2004) were provided by Gyöngyi Lelkes-Felvári from various depths. Zircon U–Pb dating was carried out on crystals from 450 m depth (sample KK-4). The most significant information about the samples studied is summarized in Table 1.

Petrographic studies were carried out at the Department of Geology, University of Szeged. Microstructural analysis of the deformed and metamorphosed 474 sample (Băiţa, Apuseni Mts) was carried out following Blenkinsop (2000) and Passchier & Trouw (2005). Bulk-rock geochemical analyses (see results in Table 2) were performed at the Bureau Veritas Mineral Laboratories, Acmelabs, Vancouver, Canada by ICP-ES and ICP-MS for major and trace elements, respectively. Laboratory conditions were the same as in Szemerédi et al. (2020, 2023). Zircon crystals were analyzed from 63–250 µm sized heavy mineral fractions of the three studied samples (474, SZAL, and KK-4) separated by the standard process of heavy mineral separation including crushing, sieving, heavy liquid separation, magnetic separation, and hand-picking. Cathodoluminescent images of the zircon crystals were captured by an AMRAY 1830 scanning electron microscope equipped with a GATAN MiniCL detector at the Department of Petrology and Geochemistry, Eötvös Loránd University, Budapest, Hungary. In-situ zircon U–Pb dating was carried out at the GÖochron Laboratories, Georg-August University, Göttingen, Germany using laser-ablation single-collector sector-field inductively coupled plasma mass spectrometry (LA–SF–ICP–MS). Data reduction, processing, and evaluation followed the procedures described in Szemerédi et al. (2020, 2023).

Results

Petrography

Băiţa, Bihor Mts (central Apuseni Mts)

Felsic metaigneous rocks in the Bihor Mts (Fig. 2) are strongly deformed and dominated by dynamically recrystallized sigmoidal and elongated quartz porphyroclasts (0.5–8 mm; Fig. 2a–f) along with lesser amounts of altered K-feldspar (0.5–5 mm; Fig. 2a, c, e, and f) and plagioclase (0.5–2 mm; Fig. 2a, c, e, and f). The recrystallized matrix exhibits a disjunctive foliation defined by bands of fine-grained micas (sericite±muscovite, some highlighted by pink dashed lines in Fig. 2), stretched quartz porphyroclasts (some highlighted by light blue dashed lines in Fig. 2) and quartz ribbons (Fig. 2d) as well as pressure-solution seams (Fig. 2c–e). The primary magmatic mineralogy and texture are obliterated due to intense deformation and the replacement of feldspar phenocrysts by micas. However, relics of rock-forming minerals indicate a felsic plutonic (granitoid) protolith.

Szalatnak–3, eastern Mecsek Mts (southern Transdanubia)

Felsic subvolcanic rocks in the lower section of the Szalatnak–3 borehole (Fig. 3) exhibit an aphanitic, fine-to-medium-grained, inequigranular, porphyritic, microholocrystalline texture with variable phenocryst content. In both the lower and the upper parts of the intrusion, felsitic and spherulitic textures were also observed. The phenocryst content and the grain size gradually increase toward the inner part of the intrusion from ~20 to ~85 vol.%. The main rock-forming minerals (Fig. 3a–f) include K-feldspar (33–55 vol.%), plagioclase (34–49 vol.%), and biotite (6–25 vol.%). Minor quartz (~1–9 vol.%; Fig. 3a–f), altered pyroxene, secondary sericite ±muscovite (Fig. 3c–f), carbonate, chlorite (Fig. 3a, c, and d–f), and rutile also occur within the microcrystalline groundmass or occasionally as alteration products of the phenocrysts. K-feldspar (0.8–5.0 mm; Fig. 3a, c, and d) dominantly occurs as subhedral to anhedral orthoclase, while microcline is rare. Plagioclase (0.6–3.8 mm) crystals (Fig. 3a, b, and d–f) are subhedral to anhedral and slightly to strongly sericitized. Biotite

Table 1: Summary of the studied Paleozoic (meta)igneous rock samples from the Tisza–Dacia and ALCAPA Mega-units, with X marks indicating the analytical methods applied to each sample.

Sample	Area	Locality	Petrography	Bulk-rock geochem.	Zircon U–Pb dating
474	Bihor Mts, Apuseni Mts	Băiţa	3 thin sections (Dept. Geol.)	X	X
SZ-3-2	southern Transdanubia	Szalatnak–3 (515.5 m)	23 thin sections (MECSEKÉRC Ltd.) +57 thin sections (Gy. Lelkes-Felvári) +4 thin sections (Dept. Geol.), representing the whole section	X	
SZ-3-3	southern Transdanubia	Szalatnak–3 (526.9–527.0 m)		X	
SZ-3-4	southern Transdanubia	Szalatnak–3 (534.5 m)		X	
SZ-3-5	southern Transdanubia	Szalatnak–3 (538.0 m)		X	
SZ-3-6	southern Transdanubia	Szalatnak–3 (565.0 m)		X	
SZ-3-7	southern Transdanubia	Szalatnak–3 (570.5 m)		X	
SZ-3-8/SZAL	southern Transdanubia	Szalatnak–3 (572.9–576.4 m)		X	X
KK-4	central Transdanubia	Kékkút–4 (450.0 m)			X

(0.1–2.5 mm; Fig. 3a–f) is subhedral to anhedral and is variably replaced by chlorite. Common accessory minerals are zircon, apatite (Fig. 3e), and opaque minerals, which occur in the groundmass and as inclusions. The samples are often crosscut by carbonate (Fig. 3f), quartz, and quartz±K-feldspar ±carbonate±chlorite veins. According to the modal composition, the studied rocks are classified as monzonites or subordinate quartz monzonites.

Bulk-rock major and trace element geochemistry

Major and trace element analyses (Figs. 4, 5, Table 2) were carried out on seven samples representing various depths of the Szalatnak–3 borehole (southern Transdanubia) and on one additional sample from the Băiţa locality, Bihor Mts. In the total alkali-silica diagram (Middlemost 1994; Fig. 4a), samples of the Szalatnak–3 borehole fall into the syenite and quartz monzonite fields with 61.2–66.3 wt.% SiO_2 and high alkali (8.0–9.3 wt.%) contents and alkaline character. Sample 474 (Băiţa) plotted in the granite field with significantly high SiO_2 content (82.8 wt.%), relatively low alkali content (4.5 wt.%), and subalkaline character. For the further geochemical classification, particularly in the case of the alkaline rocks, the samples were also plotted in the K_2O vs. SiO_2 diagram (Peccerillo & Taylor 1976; Fig. 4b), where rocks from the Szalatnak–3 borehole belong to the shoshonitic series (except for one quartz monzonite sample which falls into the high-K calc-alkaline series field), while sample 474 (Băiţa) falls into the calc-alkaline series field.

Szalatnak–3 samples are enriched in rare earth elements (REEs), with ΣREE concentration ranging from 383 to 556 ppm, whereas sample 474 (Băiţa) has a significantly lower ΣREE concentration of 127 ppm. In the chondrite-normalized REE diagram (Sun & McDonough 1989; Fig. 4c), samples from the Szalatnak–3 borehole display fractionated REE patterns (La_N/Yb_N=21.5–35.3), characterized by strongly enriched light REE (La_N/Sm_N=5.6–6.9) and near-flat heavy REE patterns (Gd_N/Yb_N=2.1–2.6) with an insignificant to slightly positive Eu anomaly (Eu/Eu*=0.9–1.4). Sample 474 (Băiţa) is also characterized by a fractionated REE pattern (La_N/Yb_N=9.2), and displays enriched light REE (La_N/Sm_N=4.4) and near-flat heavy REE patterns (Gd_N/Yb_N=1.5) with a negative Eu anomaly (Eu/Eu*=0.5). In the primitive mantle-normalized multi-element spider diagram (Sun & McDonough 1989; Fig. 4d), samples from the Szalatnak–3 borehole display local positive anomalies in Cs, Rb, Ba, Th, U, K, and Zr and negative anomalies in Nb, Ta, P, and Ti. In contrast, sample 474 (Băiţa) displays positive anomalies in Cs, Rb, Th, U, and K and negative anomalies in Ba, Nb, Ta, Sr, P, and Ti.

In the Ta vs. Yb (Fig. 5a; Pearce et al. 1984) and Hf–Rb–Ta (Fig. 5b; Harris et al. 1986) geotectonic discrimination diagrams, which are commonly used for felsic igneous rocks, all studied samples plot within the volcanic arc granite fields. This suggests that they are associated with active continental margins or could be generated by melting of material derived from such setting.

Zircon U–Pb geochronology

The studied zircons (some representative crystals from the 474 and the KK-4 samples are displayed in Fig. 6) are ~100–300 µm long crystals or fragments. Euhedral bipyramidal (or rarely prismatic) and subhedral (variably resorbed) zircons are present equally, and crystal shapes vary from relatively isometric to moderately elongated in the case of all the three studied samples. All of them display cathodoluminescent intensity and oscillatory zoning typical for magmatic zircon. Twenty-five to forty-one laser spots were analyzed per sample, targeting mostly the mantle part of the crystals to avoid cracks, inclusions, or inherited cores (Fig. 6). Dates were not used for age calculations if >5 % discordance was detected (see in Electronic Supplementary Material S1). Concordant dates (~85 % of all dates) yielded large age ranges in the case of the 474 (Băiţa) and the KK-4 samples, suggesting older inherited (xenocrystic/antecrystic) cores (Fig. 7). For the interpretation of the Paleozoic ages the $^{206}Pb/^{238}U$ data were considered, which have an average 2 s uncertainty between 1.4 and 1.7 %. The average Th/U ratios (0.3–0.4) within the samples do not show any systematic connection to the $^{206}Pb/^{238}U$ data. Age calculations were carried out according to two distinct methods. (1) We calculated TuffZirc ages based on the algorithm of Ludwig (2012) modified after Ludwig & Mundil (2002), which selects the youngest coherent group of concordant $^{206}Pb/^{238}U$ dates. (2) $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ concordia

Table 2: Bulk-rock major and trace element geochemical data of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia Mega-unit (474=Băiţa locality; SZ-3=Szalatnak–3 borehole). Major element concentrations and loss on ignition (LOI) values are given in wt.%, while trace element concentrations are given in ppm. Fe content is expressed as total Fe_2O_3. Rare earth element ratios presented in the table were calculated as follows: $(La/Yb)_N=La_N/Yb_N$; $(La/Sm)_N=La_N/Sm_N$; $(Gd/Yb)_N=Gd_N/Yb_N$; $Eu/Eu^*=Eu_N/\sqrt{(Sm_N \times Gd_N)}$.

Sample	474	SZ-3-2	SZ-3-3	SZ-3-4	SZ-3-5	SZ-3-6	SZ-3-7	SZ-3-8
SiO_2	82.84	62.06	61.19	61.38	62.01	66.34	62.51	62.39
TiO_2	0.21	0.83	0.75	0.81	0.74	0.67	0.63	0.69
Al_2O_3	9.80	18.02	18.83	18.31	18.16	16.56	17.74	18.29
Fe_2O_3t	2.19	5.67	5.24	6.03	5.44	4.58	5.96	5.01
MnO	0.01	0.08	0.14	0.08	0.10	0.05	0.07	0.06
MgO	0.35	1.39	1.66	1.79	1.92	1.83	1.60	1.71
CaO	0.08	2.48	2.95	2.03	2.41	1.78	2.08	2.39
Na_2O	2.10	3.91	3.86	3.64	3.50	3.50	3.51	3.62
K_2O	2.37	5.30	5.13	5.67	5.50	4.48	5.71	5.63
P_2O_5	0.04	0.26	0.24	0.26	0.23	0.21	0.19	0.22
LOI	1.50	3.30	2.30	2.70	2.30	1.70	1.90	2.30
sum	99.96	99.66	99.68	99.55	99.55	99.70	99.47	99.55
Ba	180	1406	1451	1687	1609	1308	2643	1930
Sc	4	10	10	10	9	9	10	9
Rb	80.5	125.0	134.4	155.9	121.9	112.6	137.9	142.4
Cs	2.9	7.6	7.6	6.7	6.5	6.2	5.6	6.7
Y	20.3	18.0	16.8	16.5	15.9	16.4	16.4	17.0
La	26.5	73.2	85.6	79.1	82.9	71.0	59.4	77.0
Ce	56.1	133.9	154.8	146.0	151.3	136.5	107.4	137.2
Pr	5.59	15.18	17.21	16.55	15.73	14.45	11.84	15.04
Nd	20.2	54.8	61.5	58.1	55.7	53.5	44.8	50.2
Sm	3.89	7.66	8.32	7.87	7.75	7.46	6.80	7.44
Eu	0.64	2.36	1.98	2.16	2.11	2.00	2.64	1.94
Gd	3.74	5.37	5.56	5.39	5.03	5.09	4.96	5.11
Tb	0.61	0.64	0.63	0.60	0.60	0.59	0.55	0.63
Dy	3.56	3.52	3.17	3.15	3.24	3.11	3.17	3.29
Ho	0.74	0.68	0.61	0.59	0.61	0.56	0.58	0.61
Er	2.24	1.97	1.64	1.61	1.75	1.72	1.84	1.62
Yb	2.06	1.97	1.74	1.75	1.75	1.70	1.98	1.66
Lu	0.31	0.29	0.25	0.28	0.24	0.26	0.30	0.28
Th	9.8	27.6	31.1	39.1	31.4	25.2	23.1	27.2
U	1.1	8.0	7.3	7.1	7.4	6.6	6.5	7.2
V	21	46	56	54	52	42	31	47
Co	4.3	8.1	8.8	7.7	9.7	5.3	6.9	6.8
Ni	<20	<20	<20	<20	<20	<20	<20	<20
Zr	92.0	630.2	456.4	549.9	506.8	528.3	665.1	488.1
Nb	5.0	15.8	16.9	16.7	14.5	13.9	12.2	16.9
Hf	2.9	15.0	11.4	13.1	11.3	12.1	13.7	11.3
Ta	0.5	1.1	0.9	1.1	0.8	1.0	0.8	1.1
Ga	9.4	20.9	23.0	21.1	20.7	18.5	21.0	19.9
Be	1.0	<1	4	5	4	3	4	7
Sn	2	3	1	2	1	<1	1	1
Sr	15.3	383.3	528.2	474.8	474.7	396.9	555.5	516.3
W	1.1	1.0	0.6	0.7	1.0	1.0	1.3	<0.5
Tm	0.34	0.29	0.25	0.28	0.24	0.26	0.30	0.28
$(La/Yb)_N$	9.23	26.65	35.29	32.42	33.98	29.96	21.52	33.27
$(La/Sm)_N$	4.40	6.17	6.64	6.49	6.91	6.14	5.64	6.68
$(Gd/Yb)_N$	1.50	2.25	2.64	2.55	2.38	2.48	2.07	2.55
Eu/Eu*	0.51	1.12	0.89	1.01	1.03	0.99	1.39	0.96
ΣREE	126.52	301.83	343.26	323.43	328.95	298.20	246.56	302.30

ages were also calculated using the IsoplotR software (Vermeesch 2018), omitting older, inherited (474 and KK-4; Fig. 7a, c) as well as younger outlier (possibly Pb loss affected) dates (474 and SZAL; Fig. 7a, b). Both methods yielded very similar ages for the samples studied, and the TuffZirc and the concordia ages are presented in Fig. 8 and Table 3. For the sake of simplicity, the TuffZirc ages were used in the subsequent discussion to represent the comparable results. Contrary to most common age calculation methods, TuffZirc ages have asymmetric uncertainties.

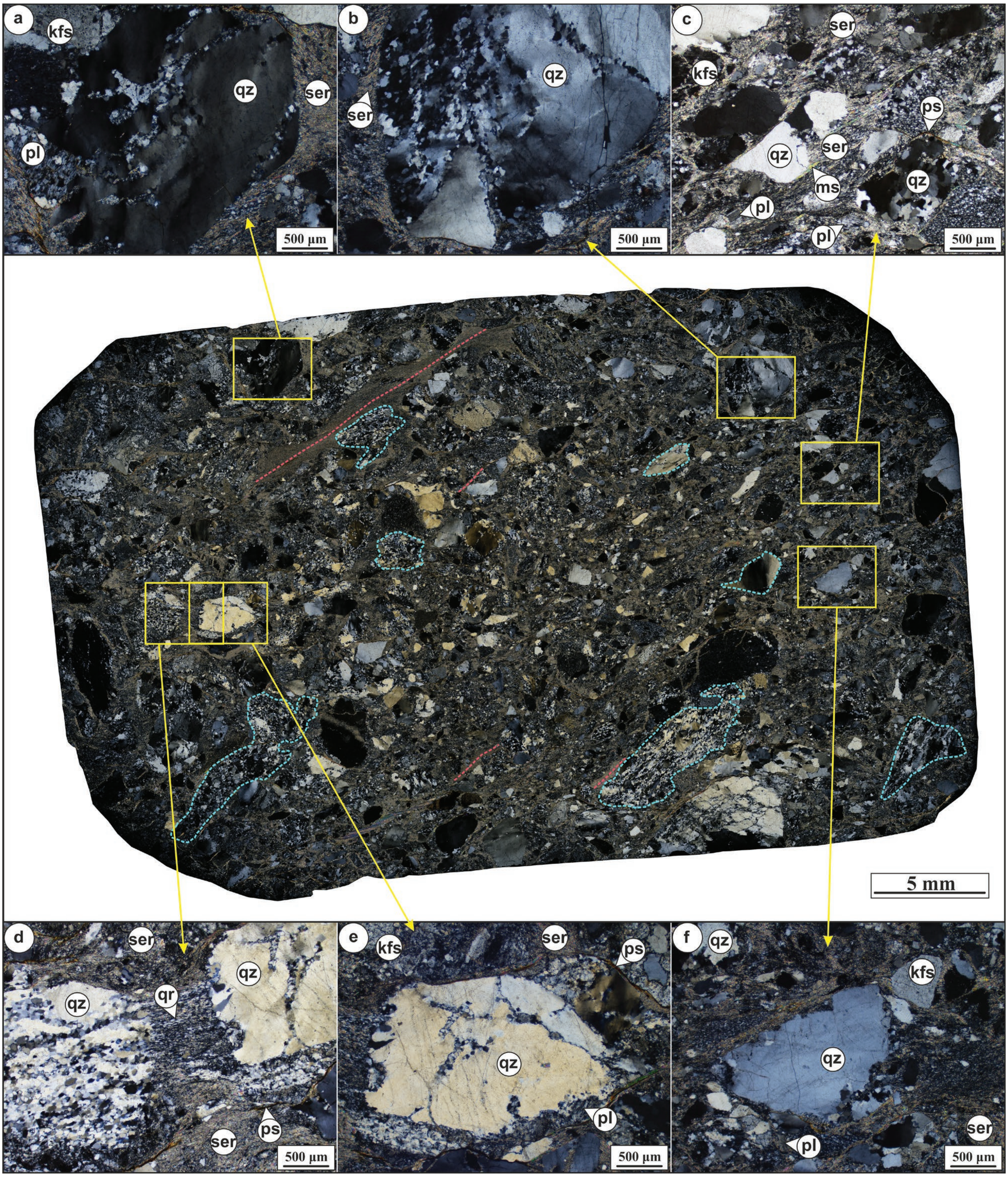

Fig. 2. Representative photomicrographs (taken under crossed polars) of felsic metaigneous rock (sample 474) from the Băiţa locality, Apuseni Mts (Tisza–Dacia Mega-unit), highlighting the major rock-forming minerals and key textural features. Some of the stretched quartz porphyroclasts are outlined with light blue dashed lines, while foliation, defined by bands of fine-grained micas, is marked with pink dashed lines in parts of the sample. Abbreviations: *ms* = muscovite, *kfs* = K-feldspar, *pl* = plagioclase, *ps* = pressure-solution seam, *qz* = quartz, *qr* = quartz ribbon, *ser* = sericite.

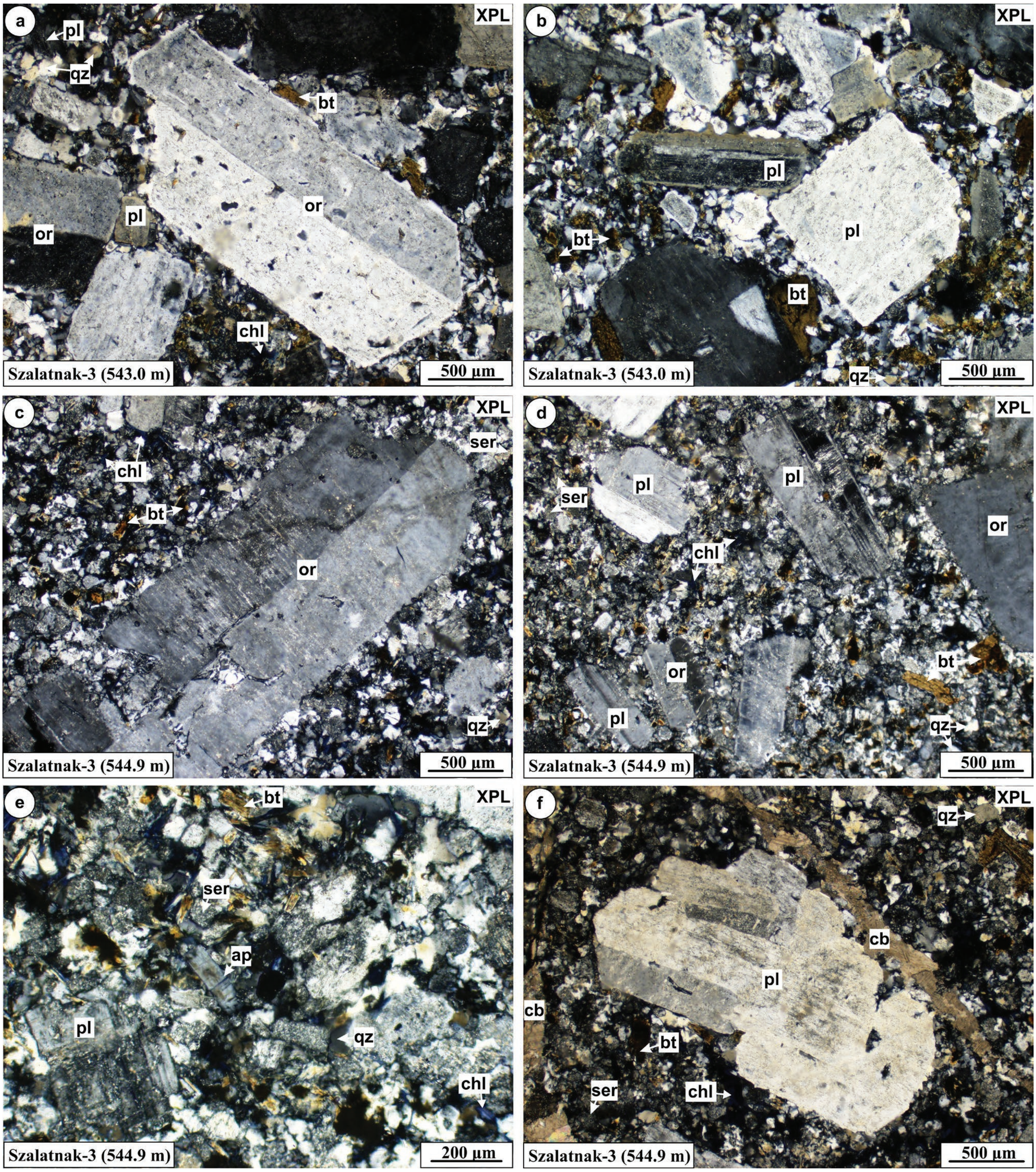

Fig. 3. Representative photomicrographs (taken under crossed polars) of subvolcanic monzonites from two different depths of the Szalatnak–3 borehole, southern Transdanubia (Tisza–Dacia Mega-unit), highlighting the major rock-forming minerals and key textural features. Abbreviations: *ap*=apatite, *bt*=biotite, *cb*=carbonate, *chl*=chlorite, *or*=orthoclase, *pl*=plagioclase, *qz*=quartz, *ser*=sericite.

Băiţa, Bihor Mts (central Apuseni Mts)

Twenty-five spot analyses were carried out in the case of the felsic metaigneous rock from the Bihor Mts (sample 474), most of which (>90 %) resulted in concordant dates (Fig. 7a). However, nine of the concordant $^{206}Pb/^{238}U$ dates have inherited, xenocrystic domains (from 1799.9±21.9 to 562.1±7.6 Ma) and are significantly older than the majority, which are late Cambrian to Late Ordovician (from 500.8±6.9 to 454.9 ±6.3 Ma). Two slightly older (~500 Ma) spot data are also considered to be affected by inherited zircon domains. The TuffZirc age algorithm (Ludwig 2012) selected 10 of the concordant $^{206}Pb/^{238}U$ dates as the youngest coherent group and calculated 478.0+3.2/−2.5 Ma (Fig. 8a), indicating an Early Ordovician main zircon crystallization period in the studied granitoid magma reservoir. $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ concordia age calculations yielded a similar result (476.0±3.2 Ma) marked by a moderate mean square weighted deviation (MSWD) value (2.5), considering 11 concordant dates (Fig. 8a).

Szalatnak–3, eastern Mecsek Mts (southern Transdanubia)

In the case of the monzonite from the Szalatnak–3 borehole (sample SZAL), 41 spot analyses were carried out and most of them (>75 %) resulted in concordant dates (Fig. 7b). Significantly older inherited crystals (or domains) were not identified and most of the concordant $^{206}Pb/^{238}U$ dates are Carboniferous (Mississippian), forming a coherent, relatively large group of data from 347.3±5.9 to 326.1±5.7 Ma. However, a few younger outlier dates differ from this main group, which range between 317.4±5.3 and 293.1±5.5 Ma and were most possibly affected by Pb loss. The TuffZirc age algorithm (Ludwig 2012) selected 30 of the coherent concordant $^{206}Pb/^{238}U$ dates and calculated 332.7+2.1/−1.6 Ma (Fig. 8b), indicating a Mississippian (Visean) emplacement age of the monzonitic intrusion. Similar, Visean concordia age was calculated (333.9±1.1 Ma) marked by a relatively low MSWD value (1.2), considering 27 concordant dates (Fig. 8b).

Kékkút–4, Balaton Highland (central Transdanubia)

Thirty-three spots were analyzed in the case of the KK-4 sample, most of which (>90 %) yielded concordant dates (Fig. 7c). Four of these $^{206}Pb/^{238}U$ dates are significantly older, suggesting their xenocrystic origin ranging from 1005.0±14.2 to 581.5±9.1 Ma. All the other 26 concordant dates are Ordovician (from 485.4±7.2 to 451.9±7.3 Ma) and generally overlap with each other. Twenty dates were selected by the TuffZirc age algorithm (Ludwig 2012) as the youngest coherent group (Fig. 8c) and the calculated result indicates a Middle Ordovician main zircon crystallization period (464.8+3.0/−3.1 Ma). Similar concordia age (465.6±2.4 Ma) marked by a moderate MSWD value (2.8) was calculated considering 25 coherent concordant dates (Fig. 8c).

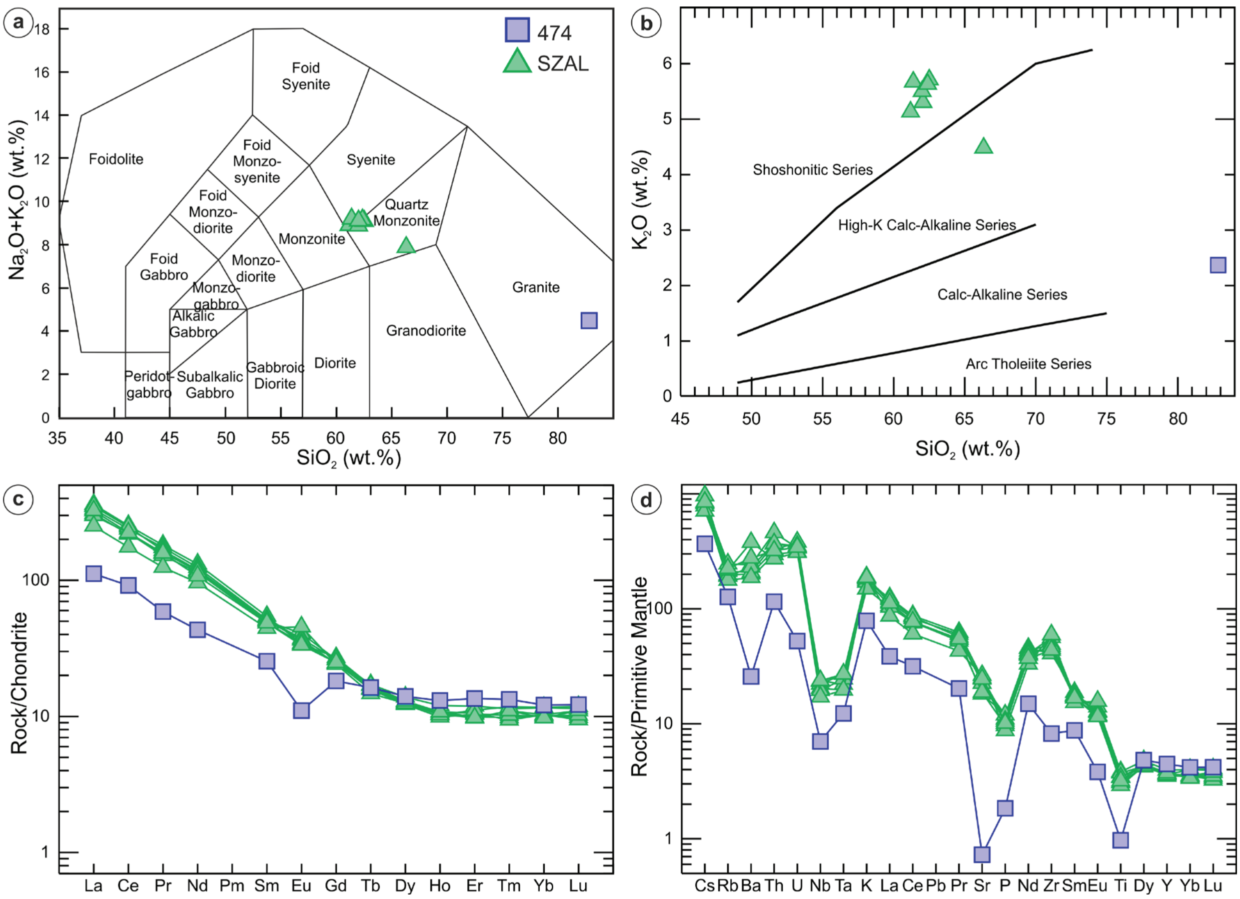

Fig. 4. Bulk-rock major element geochemistry of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia Mega-unit (474=Băiţa locality; SZAL=Szalatnak–3 borehole), presented in the following diagrams: **a** — total alkali-silica diagram (Middlemost 1994); **b** — K_2O vs. SiO_2 diagram (Peccerillo & Taylor 1976); **c** — chondrite-normalized REE diagram (Sun & McDonough 1989); **d** — primitive mantle-normalized multi-element spider diagram (Sun & McDonough 1989).

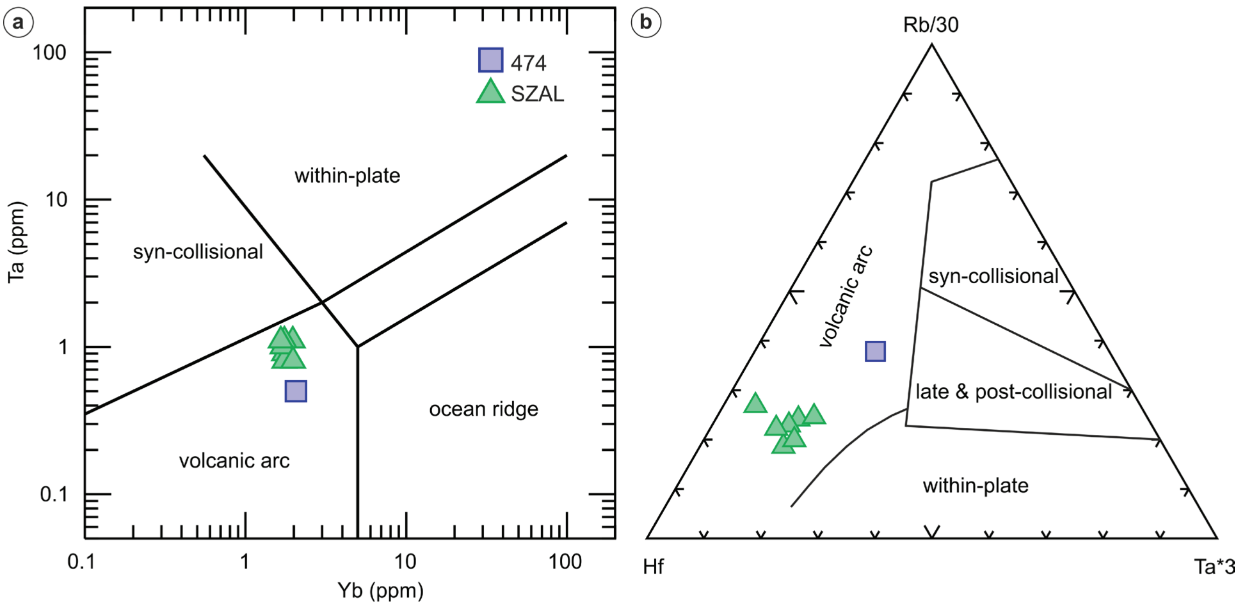

Fig. 5. a — Ta vs. Yb (Pearce et al. 1984) and **b** — Hf–Rb–Ta (Harris et al. 1986) discrimination diagrams, illustrating the geotectonic implications of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia Mega-unit (474=Băiţa locality; SZAL=Szalatnak–3 borehole).

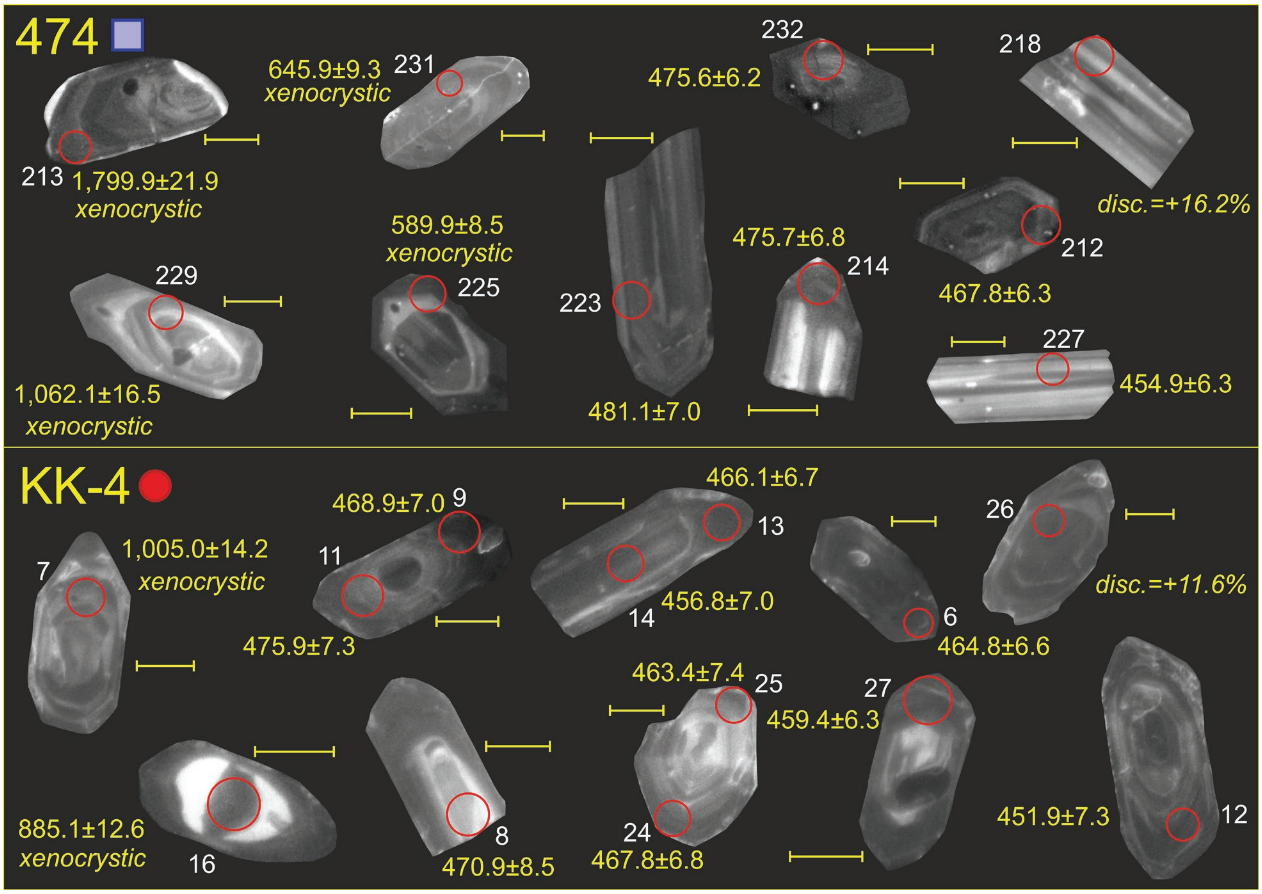

Fig. 6. Cathodoluminescence (CL) images of selected representative zircon crystals, including grains that yielded older, xenocrystic, or discordant dates, from two analyzed samples (474=Băiţa locality; KK-4=Kékkút–4 borehole). In-situ U–Pb dating results are presented as $^{206}Pb/^{238}U$ dates (Ma), with associated analytical uncertainties. Yellow scale bars represent 50 µm; red circles mark the 33 µm diameter laser ablation spots. Spot IDs (shown as white numbers) correspond to those in Electronic Supplementary Material S1.

Discussion

Effects of post-magmatic alterations

A variety of mineral-scale alterations, as well as textural and structural modifications, was identified through the petrographic analyses of the samples. In the Băiţa samples (474) from the Apuseni Mts, quartz occurs as dynamically recrystallized sigmoidal and elongated porphyroclasts (Fig. 2a–f), while bands of fine-grained secondary micas (sericite±muscovite) constitute a significant portion of the matrix (Fig. 2). Similarly, slight to strong sericitization of feldspar (particularly in the groundmass) is a common feature in the samples from the Szalatnak–3 borehole (southern Transdanubia), accompanied by secondary chlorite and carbonate as alteration products (Fig. 3a–f). Moreover, these samples are crosscut by veins composed of carbonate, quartz, and quartz±K-feldspar ±carbonate±chlorite (Fig. 3f). Altogether, these features indicate that the studied rocks from the Tisza–Dacia Mega-unit were affected by hydrothermal overprint and that the meta-igneous rocks from the Apuseni Mts underwent intense deformation, as well. To assess and quantify the type and intensity of the alterations and their impact on the bulk-rock chemistry, the Alteration Index (Ishikawa et al. 1976) was plotted against the Carbonate–Chlorite–Pyrite Index (Large et al. 2001) and applied as a quantitative evaluation tool. In this diagram, all the analyzed samples fall within the 'unaltered' or 'normal' igneous domains, corresponding to the rhyolite (474) and dacite (Szalatnak–3) fields (Fig. 9). Therefore, despite the various types of mineralogical, textural, and structural modifications, the major and trace element data of the studied rocks remain essentially suitable for petrogenetic interpretations.

New findings on Ordovician felsic magmatism in the Carpathian–Pannonian region

Cambrian–Ordovician (~530–440 Ma) metaigneous rocks (e.g., metagranitoids, metavolcanic and metavolcaniclastic rocks, orthogneisses, and amphibolites) occur in several distinct areas of the Carpathian–Pannonian region and its surroundings, including the Apuseni Mts (Tisza–Dacia Mega-unit; Balintoni et al. 2006, 2010), the Western Carpathians (ALCAPA Mega-unit; Vozárová & Ivanička 1996; Hovorka & Méres 1997; Gaab et al. 2005, 2006; Petrík et al. 2006; Putiš et al. 2008, 2009), and the Eastern Alps (Austroalpine Unit, ALCAPA Mega-unit; Siegesmund et al. 2006, 2021; Mandl et al. 2018; Huang et al. 2021; Neubauer et al. 2022, 2024). These rocks are geodynamically related to the active continental margin of northern Gondwana and record a series of multiphase rifting and subduction events between ~530 and 460 Ma. These include (1) the initial development of a back-arc rift basin in the late Cambrian; (2) the subsequent spreading and closure of the Crypto-Rheic Ocean during the Early Ordovician, involving arc accretion and amalgamation, associated with the continuing southward subduction of Proto-Tethys oceanic crust ("Cenerian orogeny" according to Zurbriggen

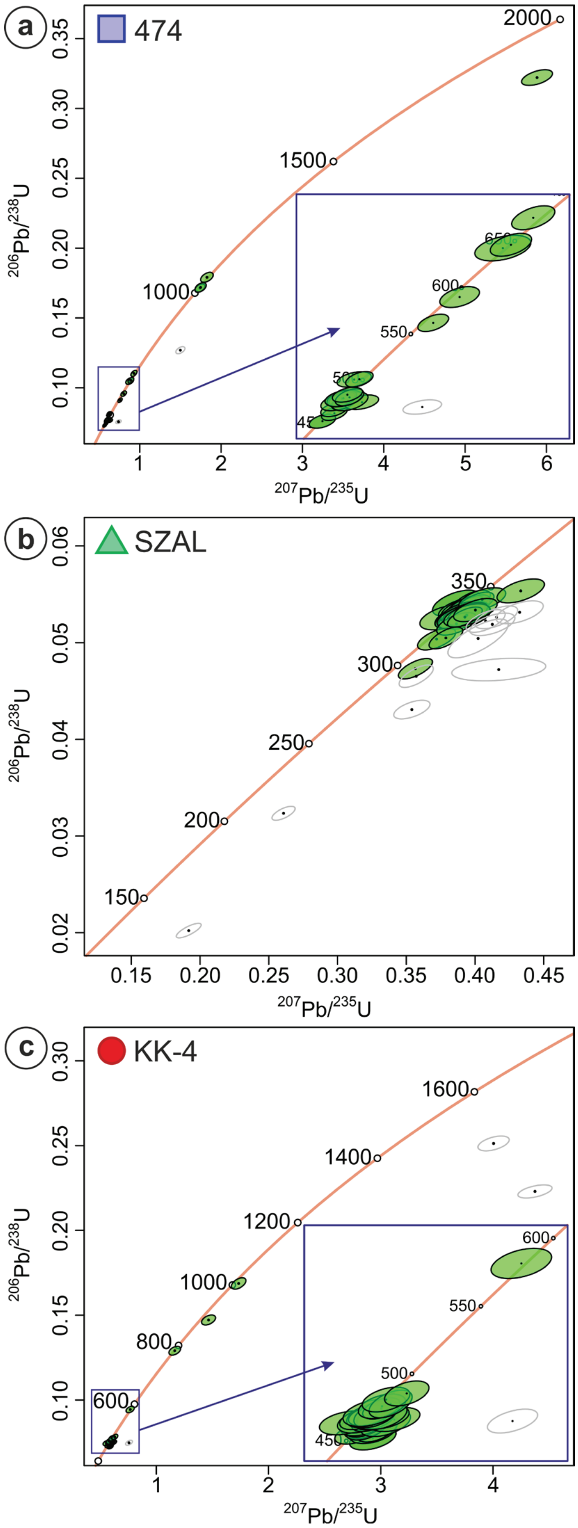

Fig. 7. Concordia diagrams (Vermeesch 2018) of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia and ALCAPA Mega-units (474=Băiţa locality; SZAL=Szalatnak–3 borehole; KK-4=Kékkút–4 borehole). Green ellipses represent concordant analyses, while white ellipses indicate discordant dates. Note: (1) the presence of older inherited zircon domains in samples from the Apuseni Mts (474) and central Transdanubia (KK-4); (2) three younger outliers (possibly Pb loss affected) and ten discordant dates in the sample from southern Transdanubia (SZAL).

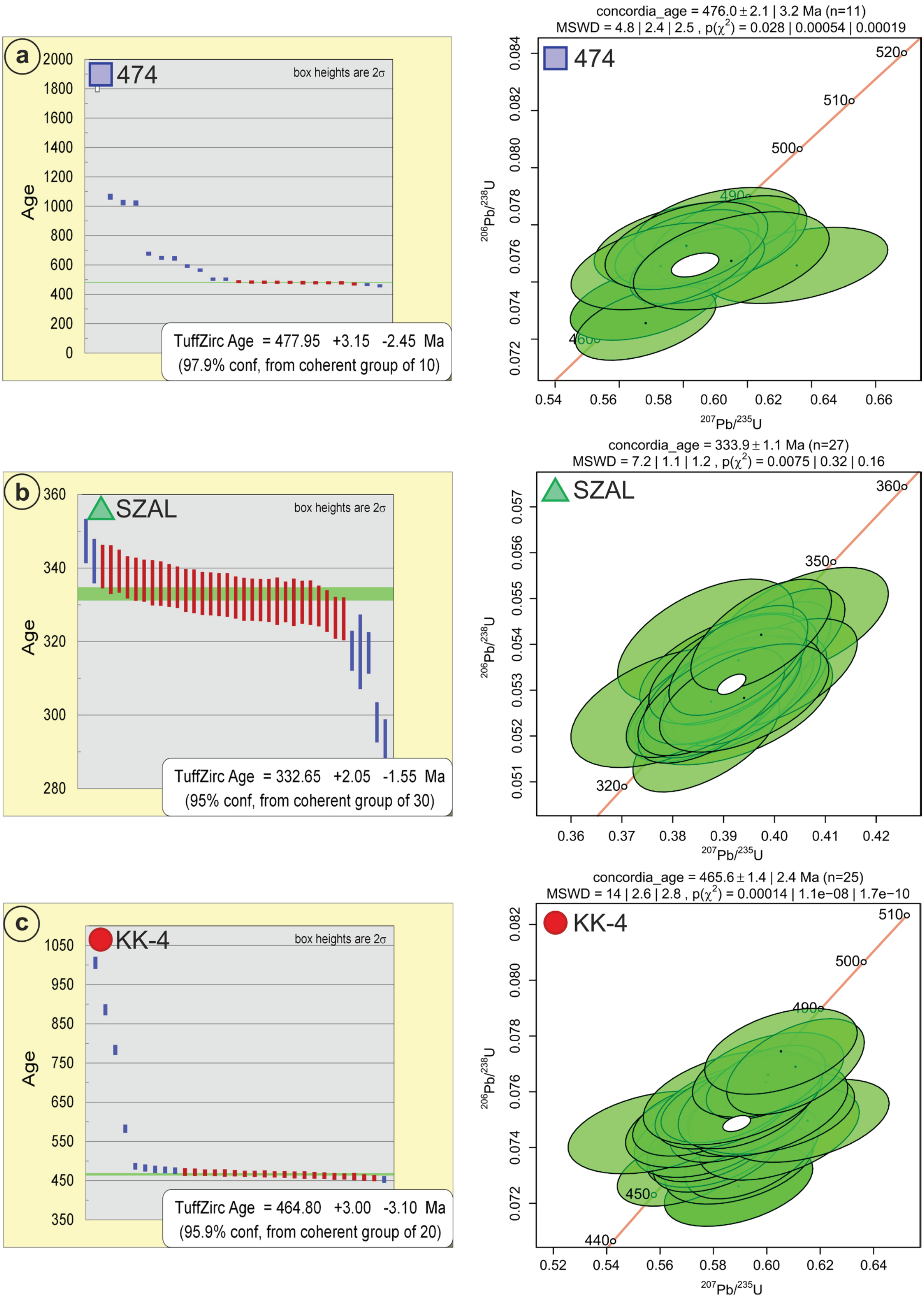

Fig. 8. Zircon U–Pb geochronological results of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia and ALCAPA Mega-units (474=Băiţa locality; SZAL=Szalatnak–3 borehole; KK-4=Kékkút–4 borehole), including TuffZirc ages (left column) calculated following Ludwig (2012), and concordia ages based on $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ plots (right column), calculated following Vermeesch (2018).

Table 3: Zircon U–Pb geochronological results for the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia and ALCAPA Mega-units, with ages calculated using the TuffZirc age algorithm (Ludwig 2012) and concordia plots based on $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ ratios (Vermeesch 2018).

Locality/borehole, area	Sample	Concordant/all spots	Th/U range	TuffZirc age in Ma (no. of analyses)	Concordia age in Ma (no. of analyses)
Băiţa, Bihor Mts	474	23/25	0.1–1.0	478.0+3.2/−2.5 (10)	476.0±3.2 (11)
Szalatnak–3, eastern Mecsek Mts	SZAL	31/41	0.3–0.7	332.7+2.1/−1.6 (30)	333.9±1.1 (27)
Kékkút–4, Balaton Highland	Kk-4	30/33	0.0–1.1	464.8+3.0/−3.1 (20)	465.6±2.4 (25)

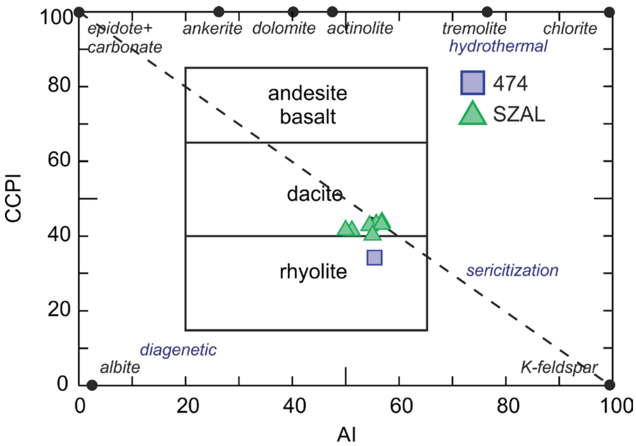

Fig. 9. Alteration Index (AI; Ishikawa et al. 1976) vs. Carbonate–Chlorite–Pyrite Index (CCPI; Large et al. 2001) diagram, illustrating the potential effects of post-magmatic alteration in the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia Mega-unit (474=Băiţa locality; SZAL=Szalatnak–3 borehole); however, no conclusive evidence for such alteration was identified based on the plotted geochemical data.

2017); and (3) a final phase of post-collisional extension in the Late Ordovician (Siegesmund et al. 2006, 2021; Putiš et al. 2008, 2009; Balintoni et al. 2010; Mandl et al. 2018; Huang et al. 2021; Neubauer et al. 2022, 2024).

Metaigneous rocks from the Băiţa locality in the Apuseni Mts (sample 474) yielded an age of 478.0+3.2/−2.5 Ma (Fig. 8a, Table 3), indicating Early Ordovician granitoid magmatism in the Biharia terrane, most likely associated with an active continental margin (arc setting) based on the trace element concentrations (Fig. 5). According to Balintoni et al. (2006, 2010), zircon U–Pb data suggest two distinct late Cambrian–Ordovician igneous periods in the northeastern Gondwana-derived basement terranes of the Apuseni Mts: an older (495–477 Ma) extensional, bimodal magmatic phase in the Biharia terrane and a slightly younger (470–459 Ma) subduction-related igneous period in the Baia de Arieş and Someş terranes (Balintoni et al. 2010). Based on the obtained age, the bulk-rock geochemistry, and the strongly deformed texture of the rocks (e.g., disjunctive foliation and intense ductile deformation of quartz), it is proposed that the felsic magmatic protolith of the studied metagranitoid corresponds to the older extensional magmatic period (most likely related to back-arc rifting) and represents the initial phase of the late Cambrian–Ordovician events on the northern Gondwana margin. Its age is slightly younger than the dominant late Cambrian ages of the back-arc rift-related rocks, suggesting that the initial phase may have lasted longer along the northern margin of Gondwana. Within the Highiş–Biharia Shear Zone (Pană & Erdmer 1994; Reiser et al. 2017), these rocks were affected by multiple Alpine shearing events, which led to their deformed, foliated structure (Fig. 2).

The sample studied from the Kékkút–4 borehole (Balaton Highland, central Transdanubia) yielded a similar but slightly younger age of 464.8+3.0/−3.1 Ma (Middle Ordovician; Fig, 8c, Table 3). Considering all available lithostratigraphic data from central Transdanubia, this age is most plausibly attributed to the Alsóörs Metarhyolite Formation, whose Ordovician age has not previously been supported by radiometric evidence. This new result therefore establishes it as the oldest known igneous formation in the territory of Hungary confirmed by numerical age data (Babinszki et al. 2024 and references therein). The Middle Ordovician age, together with the petrological characteristics of the Alsóörs Metarhyolite (acidic metavolcanic and metavolcaniclastic rocks; Babinszki et al. 2024 and references therein), suggest that the volcanic activity represents post-collisional extension, marking the final phase of late Cambrian to Ordovician events. Based on the previously obtained, significantly younger zircon U–Pb age of 291.4±4.7 Ma from the lower part of the studied metavolcanic unit (865–866 m depth), the entire igneous section of the Kékkút–4 borehole was interpreted as the product of Cisuralian post-collisional acidic volcanism (Lelkes-Felvári & Klötzli 2004). However, the newly obtained Middle Ordovician age (464.8+3.0/−3.1 Ma) of the sample from a depth of 450 m indicates that two completely different Paleozoic felsic metavolcanic rocks are present in the borehole (within unit U2 according to Lelkes-Felvári & Klötzli 2004). Interestingly, the older, Middle Ordovician formation overlies the younger, Lower Permian one, a structural relationship that might be explained by Alpine tectonic processes such as tectonic inversion or reverse faulting.

On a regional scale, these newly explored Ordovician rocks from the Apuseni Mts and the Pannonian Basin have also been compared with metaigneous formations of similar age in the Western Carpathians. These included calc-alkaline metavolcanic rocks in the basement of the Gemeric Unit. Metarhyolites and metadacites were dated at 482±6 Ma and 476±7 Ma, respectively by Putiš et al. (2008). Other metavolcanics (Vozárová & Ivanička 1996; Hovorka & Méres 1997) were

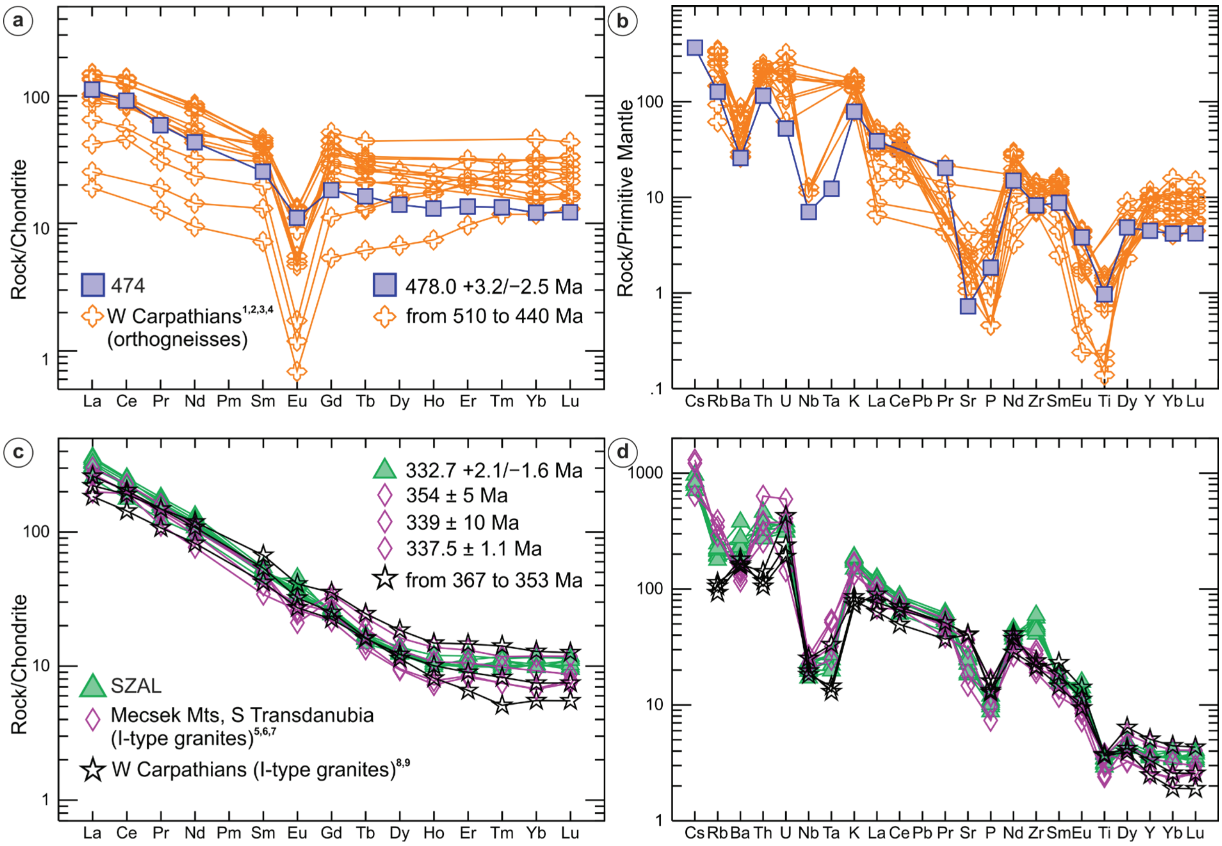

Fig. 10. Potential local to regional correlations of the studied Paleozoic (meta)igneous rocks from the Tisza–Dacia Mega-unit (474=Băiţa locality; SZAL=Szalatnak–3 borehole) based on bulk-rock trace element geochemistry and zircon/monazite U–Pb geochronology. Note that Ordovician granitic orthogneisses from the Western Carpathians exhibit slightly different geochemical characteristics compared to the meta-granitoid sample (474) from the Apuseni Mts (**a**–**b**), whereas Carboniferous subvolcanic monzonites from southern Transdanubia (Szalatnak–3) show several geochemical similarities with I-type granitoids from the same area (Mórágy Metagranite) and from the Western Carpathians (**c**–**d**). References: [1]Méres & Hovorka (1992); [2]Majdán et al. (2004); [3]Gaab et al. (2006); [4]Putiš et al. (2008); [5]Klötzi et al. (2004); [6]Gerdes (2006); [7]Buda & Pál-Molnár (2012); [8]Broska & Uher (2001); [9]Broska et al. (2013).

dated in a wider interval of 500–450 Ma by Vozárová et al. (2010). Granitic orthogneisses of similar ages (~510–440 Ma) also occur in the Tatric and Veporic Units (Majdán et al. 2004; Gaab et al. 2005, 2006; Putiš et al. 2008, 2009). Despite the similar, partially overlapping ages, the studied metagranitoid from the Apuseni Mts (sample 474) displayed slightly different bulk-rock geochemistry from the Ordovician orthogneisses in the Western Carpathians (Méres & Hovorka 1992; Majdán et al. 2004; Gaab et al. 2006; Putiš et al. 2008). Specifically, the Băiţa sample (474) exhibits a less pronounced negative Eu anomaly and a slightly lower enrichment in HREEs compared to the Western Carpathian orthogneisses (Fig. 10a–b). Based on the bulk-rock geochemistry, the obtained ages, and previous interpretations (e.g., Gaab et al. 2006; Putiš et al. 2008, 2009; Balintoni et al. 2010), it is feasible that the studied sample from the Apuseni Mts represents an older phase of extensional magmatism, consistent with the first magmatic event from ~520 to 480 Ma by Putiš et al. (2008, 2009) and Vozárová et al. (2010). Whereas, the Kékkút–4 sample from central Transdanubia corresponds to the second magmatic event from ~470 to 440 Ma detected in the Inner Western Carpathian basement (Putiš et al. 2008, 2009; Vozárová et al. 2010). The Muráň subalkaline A-type orthogneiss was dated at 511±6 Ma and represents an early extensional magmatic period (Putiš et al. 2009). However, a reliable comparison requires further geochemical study of the Ordovician metavolcanic rocks in central Transdanubia.

Carboniferous alkaline felsic subvolcanic rocks in southern Transdanubia

Upper Devonian to Carboniferous granitoids, dated to ~375–335 Ma, occur in several parts of the Carpathian–Pannonian region, including the Apuseni Mts (Pană et al. 2002; Balintoni et al. 2007), southern Transdanubia (Buda et al. 2004; Király & Koroknai 2004; Klötzli et al. 2004; Gerdes 2006; Buda & Pál-Molnár 2012), and the Western Carpathians (Broska & Uher 2001; Kohút et al. 2009; Broska et al. 2013, 2022; Broska & Svojtka 2020; Kohút & Larionov 2021). These formations are geodynamically related to Variscan magmatism, either to Late Devonian to Mississippian subduction-related (I-type granitoids, e.g., Broska & Uher 2001; Buda et al. 2004; Király & Koroknai 2004; Buda & Pál-Molnár 2012; Broska et al. 2013) or Carboniferous (post-)collisional magmatic events (S-type granitoids, e.g., Broska & Uher 2001; Broska et al. 2022). However, some studies suggest that the Carboniferous I- and S-type granitoids formed synchronously (e.g., Kohút et al. 2009, 2024; Broska & Svojtka 2020; Kohút & Larionov 2021). The Mórágy Metagranite Complex in southern Transdanubia (Tisza–Dacia Mega-unit) belongs to the first group, interpreted as a Carboniferous (~354–338 Ma; Klötzli et al. 2004; Gerdes 2006) granitic or monzogranitic intrusion of hybrid origin (Buda et al. 2004; Király & Koroknai 2004; Buda & Pál-Molnár 2012).

The studied sample of the Szalatnak–3 borehole in the eastern Mecsek Mts (southern Transdanubia) yielded a Carboniferous age of 332.7+2.1/−1.6 Ma (Fig. 8b, Table 3), similar to that of the Mórágy Metagranite, but significantly younger than expected based on its stratigraphic position, where it is overlain by the Silurian Szalatnak Slate. The latter, supported by textural observations (i.e., the porphyritic, microholocrystalline texture and the gradual increase in grain size and crystal content toward the inner part of the magmatic section), indicates that the felsic intrusion may represent a dyke or another type of shallow-level subvolcanic body. Based on their mineralogical composition, the felsic rocks in the Szalatnak–3 borehole are classified as monzonites, whereas their bulk-rock geochemistry classifies them as syenites or quartz monzonites with alkaline characteristics, possibly with shoshonitic affinity (Fig. 4a–b). The latter is also supported by their high K_2O content, high K_2O/Na_2O ratio, low TiO_2 content, variable but high Al_2O_3 content (Table 2), strong enrichment in LREEs (Fig. 4c), and local positive anomalies in Cs, Rb, Ba, and K (Fig. 4d, see e.g., Morrison 1980). However, despite the apparently unmodified or only slightly altered bulk-rock geochemical composition of these rocks (Fig. 9), a K-metasomatic overprint cannot be completely ruled out, and it may have contributed to their high-K shoshonitic character. Considering the subvolcanic origin of the rocks, the petrography-based classification as monzonite is probably more reliable, which contradicts the current lithostratigraphic name of the formation, Szalatnak Syenite (Babinszki et al. 2024).

Shoshonitic rocks are commonly associated with island arcs and post-collisional settings inboard from subduction zones and are typically attributed either to partial melting of a metasomatized lithospheric mantle source or to the subsequent generation of felsic melts within the continental crust (e.g., Conticelli & Peccerillo 1992; Guo et al. 2004; Gao et al. 2007; Conticelli et al. 2009; Pe-Piper et al. 2009; Zhu et al. 2021). The Szalatnak samples are slightly younger than the Variscan subduction-related I-type, high-K calc-alkaline Mórágy Metagranite in southern Transdanubia (~332 Ma vs. ~354–338 Ma; this study; Klötzli et al. 2004; Gerdes 2006) yet show some significant similarities in bulk-rock geochemistry, particularly in trace element concentrations (this study; Buda & Pál-Molnár 2012; Fig. 10c–d). They also resemble analogous Carboniferous (~367–353 Ma) I-type granitoids from the Western Carpathians (Broska & Uher 2001; Broska et al. 2013; Fig. 10c–d). Although the I-type granitoids and the studied felsic subvolcanic rocks most likely formed in distinct geotectonic settings, and differ in age and source, it cannot be excluded that they originated along the same active continental margin and represent different phases of a complex Variscan geodynamic evolution.

Conclusions

This study reveals three distinct Paleozoic igneous episodes in the Carpathian–Pannonian region, including the areas of both the Tisza–Dacia and the ALCAPA Mega-units.

- Felsic metaigneous rocks from the Băiţa locality in the Bihor Mts (central Apuseni Mts) yielded an Early Ordovician protolith age of 478.0+3.2/−2.5 Ma. Based on this age, their bulk-rock geochemistry, and strongly deformed texture, it is feasible that the studied metagranitoids correspond to the ~495–477 Ma extensional bimodal magmatism in the Biharia terrane. Geodynamically, this igneous event may be related to back-arc rifting along the northeastern margin of Gondwana. These rocks were later overprinted by multiple Alpine shearing events within the Highiş–Biharia Shear Zone, resulting in their deformed, foliated structure.
- A Middle Ordovician age of 464.8+3.0/−3.1 Ma was obtained from one of the lower igneous sections of the Kékkút–4 borehole in the Balaton Highland (central Transdanubia). This result contradicts the previously published Permian (Cisuralian) age from the same lithological unit, which had been assigned to the Felsősomlyó Rhyolite. The older age is most plausibly attributed to the Alsóörs Metarhyolite, for which an Ordovician origin had not previously been supported by radiometric data. This new result thus identifies it as the oldest known igneous formation in Hungary confirmed by numerical age data.
- Felsic subvolcanic rocks from the Szalatnak–3 borehole in the eastern Mecsek Mts (southern Transdanubia) have been classified as monzonites with alkaline, apparently shoshonitic characteristics. These rocks yielded a Carboniferous age of 332.7+2.1/−1.6 Ma, which is slightly younger than the crystallization age of the subduction-related I-type Mórágy Metagranite in the same area (~354–338 Ma). This, together with certain geochemical similarities between the Mórágy Metagranite and the studied monzonites, may suggest that the two formations originated along the same active continental margin, representing different phases of a complex Variscan geodynamic evolution, namely subduction and subsequent post-collisional extension.

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