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S-type granitoids in the Tisza Mega-unit: Geochronological constraints and implications for the Paleozoic magmatic evolution of the Central European Variscides

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ABSTRACT

Integrated mineralogical, petrological, geochemical, and geochronological investigations of S-type granitoids and their variably deformed or metamorphosed equivalents reveal three distinct Paleozoic magmatic episodes in the Tisza Mega-unit of the Carpathian–Pannonian region. (1) Early Ordovician (~480–470 Ma) ages were obtained from orthogneisses of Papuk Mt. (Slavonian Mts), which are interpreted as products of syn-collisional to post-orogenic processes along the northern Gondwanan margin. (2) Late Devonian–Early Carboniferous (~370–340 Ma) magmatism is represented by the Codru granodiorites from the SW Apuseni Mts and granitoids from the Battonya–Pusztaföldvár Basement Ridge (eastern Pannonian Basin). These rocks exhibit mixed arc-related and syn-collisional signatures, consistent with the Variscan subduction-to-collision transition and possible slab break-off. Mineralogical, geochemical, and geochronological data support correlations between these igneous bodies. (3) Middle Permian (~270 Ma) magmatism is recorded by monzogranitic pebbles from Lower Miocene siliciclastic deposits in the western Mecsek Mts and is interpreted as post-collisional crustal magmatism coeval with rift-related A-type magmatism and associated volcanic activity in the region. On a regional scale, Paleozoic igneous rocks of the Tisza Mega-unit correlate with those of the Western Carpathians, where comparable Early Ordovician, Early Carboniferous, and Middle Permian magmatic events have been documented. These similarities indicate a broadly shared Paleozoic tectono-magmatic evolution along the northern margin of Gondwana and later within the Central European Variscides.

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1. Introduction

Large granitoid intrusions ranging in age from Late Devonian to the Middle Permian are widespread across the Central European Variscan Belt. These magmatic rocks are associated with successive stages of Variscan geodynamic evolution, including subduction, continental collision during the convergence of Gondwana and Laurussia (and intervening microcontinents), followed by post-collisional extension and rifting processes (e.g., Broska et al., 2022; Janoušek et al., 2026; Klomínský et al., 2010; Ondrejka et al., 2021; Schulmann et al., 2014; Villaseñor et al., 2021).

In contrast to the well-exposed segments of the Variscan Belt in western and central Europe, including Iberia, the Armorican Massif, the French Massif Central, the Vosges–Schwarzwald region, Sardinia–Corsica, and the Bohemian Massif, the eastern continuation of Variscan crust is less well constrained (e.g., Janoušek et al., 2026; Kroner and Romer, 2013; Schulmann et al., 2014). In the Carpathian–Pannonian region, including the Western Carpathians and the Tisza Mega-unit

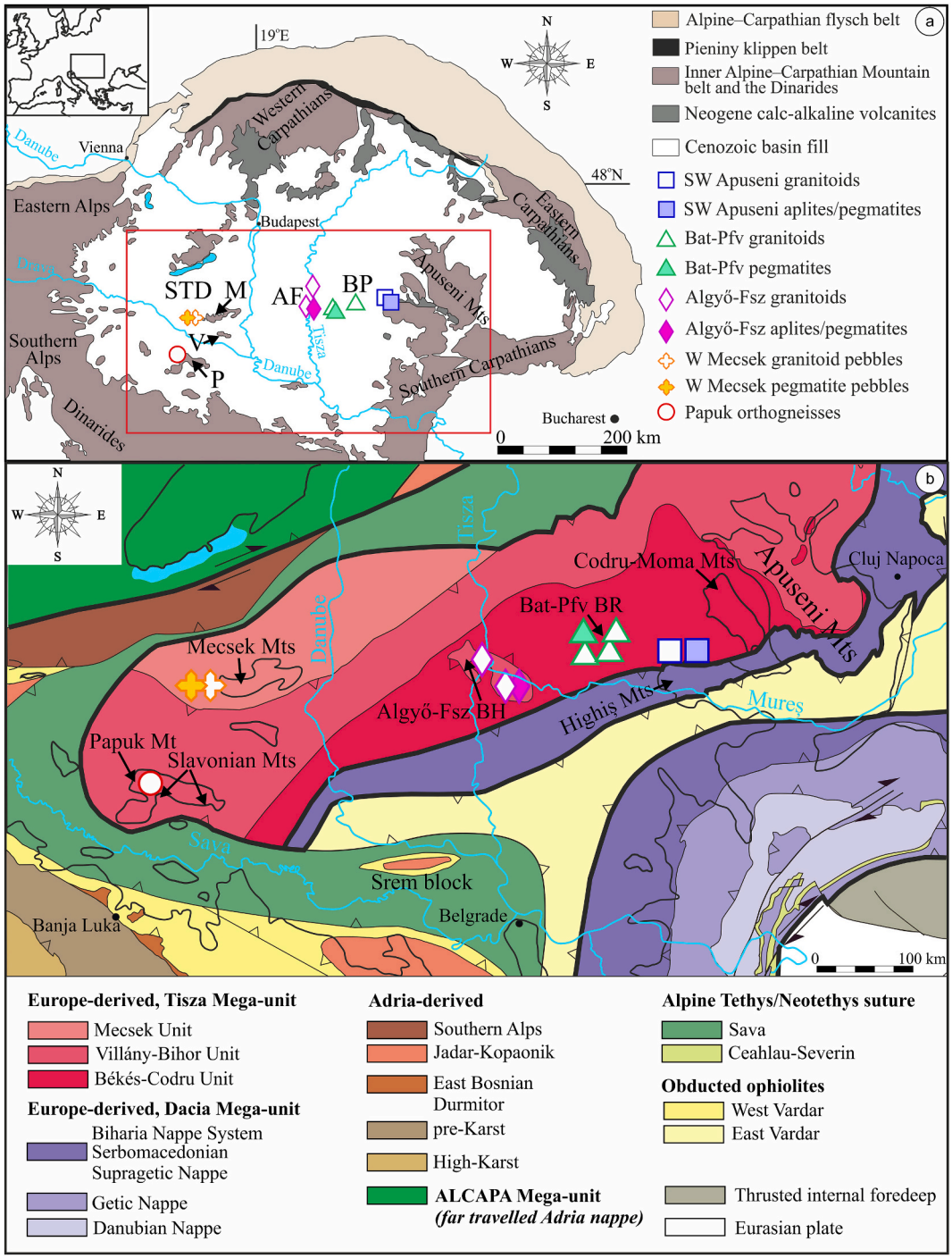


Fig. 1. Simplified geological map of the Carpathian–Pannonian region (a; modified after Csontos and Vörös, 2004; Szemerédi et al., 2020), showing occurrences of the studied S-type granitoids and highlighting the Tisza Mega-unit (b) and nearby tectonic units (modified after Matenco and Radivojević, 2012; Schmid et al., 2020). Abbreviations: *AF/Algyő–Fsz BH* Algyő–Ferencszállás Basement High, *BP/Bat–Pfv BR* Battonya–Pusztaföldvár Basement Ridge, *M* Mecsek Mts, *STD* southern Transdanubia, *P* Papuk Mt., *V* Villány Mts.

(Fig. 1), the Variscan basement is overprinted and obscured by Alpine tectonism and incorporated into Cretaceous nappe systems, which complicates the reconstruction of Paleozoic tectono-magmatic processes (e.g., Csontos and Vörös, 2004; Janoušek et al., 2026; Szederkényi et al., 2012).

Recent comparative studies between the Bohemian Massif and the Central Western Carpathians, based on petrochemical and geochronological data, suggest that these domains represent two contrasting segments of the Variscan crust (Janoušek et al., 2026). However, comparative datasets from the more southern and eastern Tisza Mega-unit (MU) remain sparse, particularly regarding S-type granitoids, limiting robust regional correlations and leaving its Paleozoic evolution poorly constrained. This uncertainty is relevant for assessing its affinity with either the Bohemian Massif or the Western Carpathians, as previous correlations with the latter have been based mainly on Permian magmatic rocks (Szemerédi et al., 2020, 2021, 2023). This raises broader questions regarding the age, petrogenesis, and tectonic significance of S-type granitoid magmatism along the Central European Variscan Belt, including whether the Tisza MU represents a crustal fragment genetically linked to the Western Carpathians or a distinct crustal domain.

In the Western Carpathians (ALCAPA Mega-unit) and the Tisza MU, S-type granitoids are particularly abundant and are generally related to Early Carboniferous to Late Permian syn- to post-collisional magmatism (Broska et al., 2022; Broska and Svojtka, 2020; Broska and Uher, 2001; Kubiš and Broska, 2010; Pál-Molnár et al., 2001a, 2001b).

While some igneous bodies have been well studied and integrated into the Paleozoic geodynamic framework of East-Central Europe (e.g., Lower Carboniferous and Permian S-type granitoids in the Western Carpathians; Kubiš and Broska, 2010; Broska et al., 2022), S-type granitoids in the Tisza MU lack reliable radiometric age constraints and remain poorly understood in terms of geotectonic interpretations. As a result, local to regional correlations are still uncertain.

Two-mica S-type leucogranites and granodiorites, together with their variably deformed or metamorphosed equivalents, occur in several areas of the Tisza MU (Fig. 1a–b). These include the Apuseni Mts (Balintoni et al., 2007; Pană et al., 2002), basement areas in the eastern Pannonian Basin (Battonya–Pusztaföldvár Basement Ridge and Algyő–Ferencszállás Basement High; Pál-Molnár et al., 2001a, 2001b; Buda et al., 2004, 2012, 2014), as well as pebbles in Miocene conglomerates from the western Mecsek Mts (Jámbor and Szabó, 1961; Józsa et al., 2009). Further occurrences are reported from the Papuk Mt. (Slavonian Mts; Pamić and Lanphere, 1991; Pamić et al., 1996; Horvat and Buda, 2004) and from the southwestern Pannonian Basin (N-NE of the Slavonian Mts) and the Slavonia-Srijem Depression (Pamić, 1999; Šuica et al., 2022).

Early 2000s petrological, bulk-rock geochemical (Buda et al., 2004; Pál-Molnár et al., 2001a, 2001b), and mineral chemical studies (Buda et al., 2012, 2014) interpreted these basement rocks as syn-collisional continental crustal granitoids related to the Variscan orogeny. However, their Variscan age remains unconfirmed, except for a few unpublished K/Ar ages, whose reliability in igneous rocks of the Tisza MU has been questioned (e.g., Szemerédi et al., 2020).

The first objective of this study is to characterize the age and petrogenesis of two-mica granitoids from the Tisza MU basement based on detailed petrographic observations, bulk-rock major and trace element geochemistry, and zircon U—Pb geochronology. The studied rocks occur in both surface and subsurface settings across Romania, Hungary, and Croatia, within several distinct Mesozoic structural zones (Fig. 1a–b). Local to regional correlations represent a central aspect of the study.

The second objective is to compare and correlate five main groups of S-type granitoids within the Tisza MU (SW Apuseni Mts, Battonya–Pusztaföldvár Basement Ridge, Algyő–Ferencszállás Basement High, western Mecsek Mts, and Papuk Mt., Fig. 1a–b) based on integrated petrographic, mineralogical, geochemical, and geochronological data.

The third objective is to place the magmatic events into a broader regional framework in order to better understand the Paleozoic tectono-magmatic evolution of the Variscan crustal fragment forming the basement of the Tisza MU. This is achieved by comparison with coeval granitoid suites in the Central European Variscides, particularly those of the Western Carpathians (e.g., Broska et al., 2022; Broska and Svojtka, 2020; Broska and Uher, 2001), and subordinately the Bohemian Massif (e.g., Janoušek et al., 2026; Klomínský et al., 2010) as key reference domains of the Variscan crust. This comparison also builds on previous studies suggesting correlations between the Tisza MU and the Western Carpathians in terms of Permian rift-related magmatism (Szemerédi et al., 2020, 2021, 2023).

2. Geological background

The Tisza Mega-unit represents a $> 100{,}000$ km^2-scale lithospheric fragment forming part of the basement of the Pannonian Basin, south of the Mid-Hungarian Tectonic Zone (Fig. 1b; e.g., Csontos et al., 1992; Matenco and Radivojević, 2012; Schmid et al., 2020). It is interpreted as a fragment derived from the southern margin of Variscan Europe, detached during Jurassic tectonic processes and subsequently translated to its present-day position during the Early Miocene (e.g., Csontos et al., 1992; Csontos and Vörös, 2004; Szederkényi et al., 2012). The pre-Mesozoic basement of the Tisza MU represents a composite terrane assembled during the Variscan orogenic cycle (e.g., Szederkényi et al., 2012).

Its crystalline basement is exposed in several areas, including the Apuseni Mts, the Mecsek Mts, and the Slavonian Mts, and was drilled as part of hydrocarbon exploration (e.g., eastern Pannonian Basin) and uranium ore exploration (e.g., southern Transdanubia), mostly during the second half of the 20th century. The structural subdivision of the mega-unit is based on its Alpine evolution and four main NW-vergent, NE–SW trending nappe systems are distinguished (Fig. 1b): (1) the Mecsek Unit, (2) the Villány–Bihor Unit (called Bihor Autochtone Unit in the Apuseni Mts), (3) the Békés–Codru Unit (called Codru Nappe System in the Apuseni Mts), and (4) the Biharia Nappe System, from north to south and bottom to top (e.g., Csontos et al., 1992; Csontos and Vörös, 2004; Matenco and Radivojević, 2012; Szederkényi et al., 2012). According to some studies, the Biharia Nappe System is not the highest Alpine tectonic unit in the Tisza MU, but it belongs to the Dacia MU (e.g., Schmid et al., 2020).

Two-mica S-type granitoids and related deformed or metamorphosed rocks occur all over the Tisza MU (Fig. 1) in various forms (e.g., in large outcrops; drilled in the basement at depths of several thousand metres; or as pebbles in younger sedimentary formations).

In the Apuseni Mts, two-mica granitoids are exposed in the western–southwestern part covering relatively large areas in the Codru-Moma Mts and have a few outcrops in the Highiş Mts (Codru Nappe System, Fig. 1b). Despite their common occurrence, detailed petrographic and geochemical information is barely available about the Codru granitoids. Zircon U—Pb dating resulted in a Late Devonian age (~372 Ma) by Pană et al. (2002), however, Balintoni et al. (2007) reported a younger, Early Carboniferous age (~350 Ma) by the same method and they connected the Codru granitoids to a Variscan subduction event based on the metaluminous, magnesian, and calc-alkaline character of the rocks.

In the eastern Pannonian Basin, Variscan granitoids are the most common in the Battonya–Pusztaföldvár Basement Ridge (Békés–Codru Unit, Battonya Granite Complex in the Hungarian lithostratigraphy, Fig. 1b; Babinszki et al., 2024) where they were exposed by numerous boreholes. Previous studies have shown that the Battonya granitoids include syenogranites, monzogranites, and granodiorites, which are characterized by subalkaline, calc-alkaline, and peraluminous geochemical properties. These features led to their interpretation as syn-collisional granitoids (Pál-Molnár et al., 2001a). However, reliable age

data are still lacking, with the exception of a K/Ar age of ~320 Ma reported by Buda et al. (2004). Buda et al. (2012, 2014) classified the Battonya granitoids as monazite-type granitoids and described metaluminous amphibole-bearing mafic enclaves in some drill cores, which raised the potentially mixed I-S-type origin of these rocks. Buda et al. (2004) found notable bulk-rock geochemical similarities between the Battonya granitoids and the analogous igneous rocks in the Western Carpathians.

In the eastern Pannonian Basin, S-type granitoids also occur in the Algyő–Ferencszállás Basement High (Biharia Nappe System or Villány–Bihor Unit, according to Matenco and Radivojević, 2012; and Schmid et al., 2020, respectively, Fig. 1b), including the Deszk and Ferencszállás areas and similar rocks were also drilled in the nearby Makó Trough. Pál-Molnár et al. (2001b) separated two main groups of S-type syenogranites in this basement area between which the only difference is the presence/lack of a preferred orientation. On the other hand, the mineralogical composition, the subalkaline, peraluminous character and the orogenic, continental collisional interpretation of these rocks closely resemble those of the Battonya granites.

In the western Mecsek Mts (Mecsek Unit, Fig. 1b), two-mica granitoids are found as pebbles within the conglomerate sequences of the Lower Miocene fluvial Szászvár Formation (Józsa et al., 2009), notably near Bükkösd and in the Sormás creek valley. These granitoid pebbles have also been encountered in boreholes in the Bükkösd, Cserdi, and Korpád areas. Locally, fine-grained aplite pebbles with similar composition but lacking biotite were also described in the western Mecsek Mts. No comparable igneous bodies are known from southern Transdanubia, either at the surface or from drill cores; however, Jámbor and Szabó (1961) proposed that the leucogranite pebbles were derived from the basement of the Tisza MU and transported from a source area located approximately 15–35 km south of the Mecsek Mts.

In the Papuk Mt. (Fig. 1b), granitoids appear as bodies or veins within a large migmatite complex in the western–central part (Papuk Complex according to Jamičić et al., 1987, 1989), however, similar lithologies were also drilled in the Pannonian Basin (N-NE of the Slavonian Mts) and the Slavonia-Srijem Depression (Pamić, 1999; Šuica et al., 2022). Those are most commonly S-type, peraluminous two-mica monzogranites and granodiorites with mostly homogeneous and less porphyritic structures, but recrystallization or cataclasis and various foliations are also common (Pamić et al., 1996; Pamić and Lanphere, 1991). S-type granitoids and migmatites in the Papuk Mt. are interpreted to have formed through partial melting of metapelites and metapsammites during the Variscan orogeny, along with associated regional metamorphism under isochemical conditions (Pamić and Lanphere, 1991). However, the available K/Ar data (Pamić et al., 1988) yield a wide range of ages between 336 and 272 Ma that do not convincingly constrain the age of the tectonomagmatic event. Horvat and Buda (2004) reported some I/S-type occurrences, as well. Jamičić (2001), based on petrographical and structural data, distinguished three series of basement rocks: Psunj-Krndija Complex, Papuk Complex, and Radlovac Complex, and interpreted the geological evolution of the Slavonian Mts through three phases of sedimentation and metamorphism from the presumed Precambrian to the Late Permian. The migmatization, granite intrusions and metamorphism in the Papuk Complex are interpreted as pre-Variscan. Late Devonian magmatic activity has been suggested by the application of the in-situ laser ablation U—Pb zircon dating method, which provided a 382 ± 2 Ma intrusion age of the S-type monzogranite from W Papuk Mt. (Šandrovac quarry; Horvat et al., 2018). The mildly peraluminous orthogneiss from Papuk Mt. (Trešnjevica quarry) has recently been reported as S-type granite in which igneous zircon crystallized at 498.9 ± 6.9 Ma (Gallhofer et al., 2026).

3. Materials and methods

In the Apuseni Mts granodiorite, pegmatite, and aplite samples were collected in the abandoned Galşa quarry, near Şiria, Highiş Mts (W Romania). Granitoids of the eastern Pannonian Basin were studied in drill cores originating from the Battonya–Pusztaföldvár Basement Ridge (SE Hungary) and the Algyő–Ferencszállás Basement High (S Hungary). Two-mica granitoid pebbles were collected from the Miocene Szászvár Formation (Sormás creek valley, western Mecsek Mts) and from boreholes in southern Transdanubia (SW Hungary). Five outcrop samples were collected in the abandoned Trešnjevica quarry, Papuk Mt., Slavonian Mts (N Croatia). Drill cores are stored at the Department of Geology, University of Szeged collection, and were provided by MOL Hungarian Oil and Gas Plc and MECSEKÉRC Ltd. Sample IDs, localities, and applied methods are summarized in Supplementary Table 1.

Petrographic studies were carried out on 72 hand specimens and 66 thin sections, using all available drill cores and representative outcrop samples. Modal mineralogical compositions were estimated by point counting using JMicroVision software (Roduit, 2019), with 3–16 samples per study area and ≥500 points counted per thin section. These observations were complemented by scanning electron microscope (SEM) analyses at the HUN-REN Centre for Energy Research, Budapest.

Forty-three samples (Electronic Supplementary Material 1) were analyzed for bulk-rock geochemistry at Bureau Veritas Mineral Laboratories (Acmelabs, Vancouver, Canada) using ICP-ES for major elements and ICP-MS for trace elements, under conditions described by Szemerédi et al. (2020). Additionally, two Papuk Mt. samples (PP-13/1 and PP-13/6) were analyzed at XRAL Laboratories (Don Mills, Toronto, Canada) by XRF and INAA for major and trace elements, respectively, following Horvat and Buda (2004).

Heavy mineral analyses were conducted on nine representative samples. Standard heavy mineral separation techniques (crushing, sieving, and heavy liquid separation with sodium polytungstate, ~2.90 g/cm^3) were applied to the 63–250 μm fractions, which were analyzed by polarizing microscope. Two hundred to three hundred transparent grains were 'ribbon-counted' at regular spacing on each grain mount (Mange and Maurer, 1992). Sample preparation was carried out at the Department of Petrology and Geochemistry, Eötvös Loránd University, Budapest, and at the Archaeometry Laboratory, National Institute of Archaeology of the Hungarian National Museum, Budapest. Analyses were performed using a polarizing microscope.

U—Pb dating was carried out on 63–250 μm zircon crystals separated from seven representative samples, following the procedures described in our previous studies (Szemerédi et al., 2020, 2021, 2023). Crystals were hand-picked under a binocular microscope at the Department of Petrology and Geochemistry, Eötvös Loránd University, Budapest. Cathodoluminescence mapping was also carried out at the same institute using an AMRAY 1830 SEM equipped by a GATAN MiniCL detector. In-situ zircon U—Pb dating was conducted at the GÖochron Laboratories, Georg-August University, Göttingen, Germany, by laser-ablation single-collector sector-field inductively coupled plasma mass spectrometry (LA-SF-ICP-MS).

K/Ar dating was performed on two altered samples at the Geochronology Lab, HUN-REN Institute for Nuclear Research, Debrecen. Samples were crushed, sieved, and grain-size fractions of 5, 2, 1, and 0.5 μm were separated by decantation and centrifugation following the USGS procedures (https://pubs.usgs.gov/of/2001/of01-041/htmldocs/methods/), and then dried at 70 °C. Potassium content was measured on 50 mg aliquots after HF and HNO_3 dissolution using a Sherwood-400 flame spectra-photometer with an accuracy better than ±1%. Mineral splits were heated at 100 °C under vacuum for 24 h to remove adsorbed atmospheric Ar. Argon was extracted by high-frequency induction fusion at 1300 °C and purified in a two-step low-blank vacuum system with cold St-707 and hot Ti-getter. Argon isotope compositions were measured using an Argus VI© multi-collector noble gas mass spectrometer and corrected for atmospheric $^{40}Ar/^{36}Ar = 295.5$ (Steiger and Jäger, 1977). Analyses followed the unspiked Cassignol-Gillot technique (Cassignol and Gillot, 1982; Gillot et al., 2006). Accuracy and reproducibility were monitored with HD-B1 and GL-O reference materials (Hess and Lippolt, 1994; Odin, 1982). Decay constants of Steiger and

Jäger (1977) were used for age calculation (overall error ± 1%), and sample errors were calculated following Quidelleur et al. (2001).

4. Results

4.1. Petrography

4.1.1. SW Apuseni Mts (Békés–Codru Unit)

In the Galşa quarry, the granodioritic body is crosscut by pegmatite and aplite veins and locally contains biotite-rich metasedimentary xenoliths. The granodiorites (Fig. 2a–b, Supplementary Figs. 1a–b, 2) are medium-grained, equigranular, subhedral granular, and weakly oriented, composed of plagioclase, quartz, K-feldspar, muscovite, and biotite (Table 1). Plagioclase is euhedral to subhedral, often sericitized in the core with albite rims, and may occur as small inclusions in K-feldspar. Quartz is subhedral to anhedral and variably deformed. K-feldspar is mainly subhedral to anhedral microcline; however, subhedral orthoclase also occurs. Myrmekitic and granophyric intergrowths are common. Muscovite and biotite are euhedral, often clustered, variably deformed, and oriented in two roughly perpendicular directions. Pegmatites and aplites (Supplementary Fig. 3a–b) are compositionally similar but less altered, with more quartz, microcline, and muscovite, less plagioclase and no biotite; aplites also contain Mn-rich garnet as an accessory mineral.

4.1.2. Battonya–Pusztaföldvár Basement Ridge (BR in the Békés–Codru Unit)

Drill cores from the Battonya–Pusztaföldvár BR are mainly medium- to coarse-grained monzogranites or granodiorites (Supplementary Fig. 2), with equigranular to inequigranular, subhedral granular texture and variable orientation (Fig. 2c–d, Supplementary Figs. 1c–d, 3c–d). They consist of plagioclase, quartz, K-feldspar, muscovite, and (chloritized) biotite (Table 1). Plagioclase is euhedral to subhedral, commonly sericitized in the core with albite rims, and often affected by carbonatization and argillic alteration; however, less altered, homogeneous crystals also occur, sometimes with myrmekitic textures. Small plagioclase inclusions occur in K-feldspar. Quartz is subhedral to anhedral and variably deformed, while K-feldspar is mostly subhedral to anhedral microcline with minor subhedral orthoclase. Muscovite and biotite are often clustered, deformed, and oriented in two roughly perpendicular directions. Some drill cores are crosscut by blocky carbonate veins, and locally tonalites and pegmatites were also encountered (Supplementary Table 1).

4.1.3. Algyő–Ferencszállás Basement High (BH in the Villány–Bihor Unit or Biharia Nappe System)

Drill cores from this area are medium-grained, equigranular, subhedral granular granitoids (Fig. 2e–f, Supplementary Fig. 1e–f) composed of quartz, plagioclase, K-feldspar, muscovite, and biotite (Table 1). All samples, ranging from monzogranites to granodiorites (Supplementary Fig. 2), were moderately to strongly deformed and metamorphosed, developing foliated, gneissic structures (S1 schistosity) and are thus interpreted as orthogneisses. Quartz is anhedral and strongly deformed. Plagioclase is subhedral to anhedral, mostly unaltered and homogeneous, though sericitization occurs locally. In the Deszk area (Supplementary Fig. 3e), plagioclase was replaced by sericite in thin, anastomosing bands forming a mylonitic S—C fabric. K-feldspar occurs as subhedral to anhedral orthoclase and microcline in similar proportions. Micas, often clustered (chloritized or hematitized) biotite and muscovite, are commonly deformed. Pegmatites and aplites were also drilled in the Ferencszállás area (Supplementary Fig. 3f).

4.1.4. Western Mecsek Mts (Mecsek Unit)

Samples from the western Mecsek Mts (Fig. 2g, Supplementary Figs. 1g, 3g) are medium-grained, inequigranular, subhedral granular monzogranites (Supplementary Fig. 2) composed of quartz, plagioclase, K-feldspar, muscovite, and biotite (Table 1). Quartz is subhedral to anhedral and variably deformed. Plagioclase is euhedral to subhedral, either intact or locally sericitized, with smaller euhedral inclusions in K-feldspar. K-feldspar is mainly subhedral orthoclase, often perthitic, with rare microcline. Micas form clusters of euhedral to subhedral (occasionally hematitized) biotite and muscovite, oriented in two roughly perpendicular directions, defining the weakly oriented structure. Andalusite occurs alongside muscovite. Some pebbles are pegmatites with similar monzogranite composition.

4.1.5. Papuk Mt (Villány–Bihor Unit)

In the Trešnjevica quarry, the studied samples (Fig. 2h, Supplementary Figs. 1h, 3h) are medium-grained, equigranular, subhedral granular monzogranites (Supplementary Fig. 2) with a foliated, gneissic structure and are therefore interpreted as orthogneisses. They consist of quartz, plagioclase, K-feldspar, and minor biotite, and muscovite (Table 1). Quartz is anhedral and deformed. Plagioclase is euhedral to subhedral, variably deformed, and commonly sericitized. K-feldspar is often clay-mineralized, subhedral to anhedral microcline or subordinate subhedral orthoclase. Feldspars are generally larger than other minerals, commonly forming porphyroclasts that give the rock a scaly structure. Biotite is euhedral, strongly chloritized, and commonly associated with euhedral to subhedral muscovite.

4.2. Heavy mineral analyses

A total of 5041 grains were counted from nine samples, of which 1954 were non-opaque, transparent heavy minerals (excluding micaceous and authigenic phases). The heavy mineral spectra were diverse, with each study area exhibiting different degrees of variation (Supplementary Fig. 4, Supplementary Table 2).

Sample GAG5 (SW Apuseni Mts) contains anhedral to subhedral, colorless to pale yellowish-green epidote-zoisite/clinozoisite (58%) and subhedral apatite (42%), often containing inclusions (Supplementary Fig. 4a).

DEH DNy-4 and BAT-MOL samples (Battonya–Pusztaföldvár BR) are dominated by subhedral to euhedral apatite (99%) with common inclusions. Other minerals include subhedral to euhedral, colorless zircon (0–1%) and rutile (0–1%) (Supplementary Fig. 4b–c).

Granitoids from the Algyő–Ferencszállás BH contain anhedral, colorless to pale pink garnet (88–89%) and subhedral apatite (5–12%) with abundant inclusions. Zircon (0–5%) is subhedral and colorless (Supplementary Fig. 4d–e).

Two-mica granitoid pebbles (western Mecsek Mts) show variable compositions, dominated by subhedral to euhedral, colorless, inclusion-free apatite (5–77%), anhedral to subhedral, colorless to pinkish andalusite (2–34%), and subhedral tourmaline with brown to colorless pleochroism (1–91%). Minor phases include euhedral, elongated, inclusion-free zircon (0–2%), titanite (0–2%), rutile (0–1%), garnet (0–1%), kyanite (0–1%), and epidote-zoisite/clinozoisite (0–1%) (Supplementary Fig. 4g–h).

DJE1.1 sample (Papuk Mt) contains subhedral, inclusion-free apatite (73%), subhedral to euhedral, inclusion-free zircon (24%), and pseudomorphs after pyroxene (3%), exhibiting hacksaw terminations and pale brown to pale green pleochroism (Supplementary Fig. 4f).

4.3. Bulk-rock major and trace element geochemistry

All the studied granitoids are peraluminous (A/NK = 1.1–2.0; A/CNK = 1.1–1.7, except for a few altered samples) with aluminum saturation (ASI; Frost and Frost, 2008) values of 1.1–1.6. Most are alkali-calcic or calc-alkalic (MALI = 2.1–8.6, Fig. 3a; Frost et al., 2001) and display either a magnesian character (Fe/Fe + Mg = 0.6–0.8; SW Apuseni Mts, Battonya–Pusztaföldvár BR, Papuk Mt) or a ferroan character (Fe/Fe + Mg = 0.8–0.9; Algyő–Ferencszállás BH, western Mecsek Mts, aplites/pegmatites from SW Apuseni Mts; Fig. 3b; Frost et al., 2001;

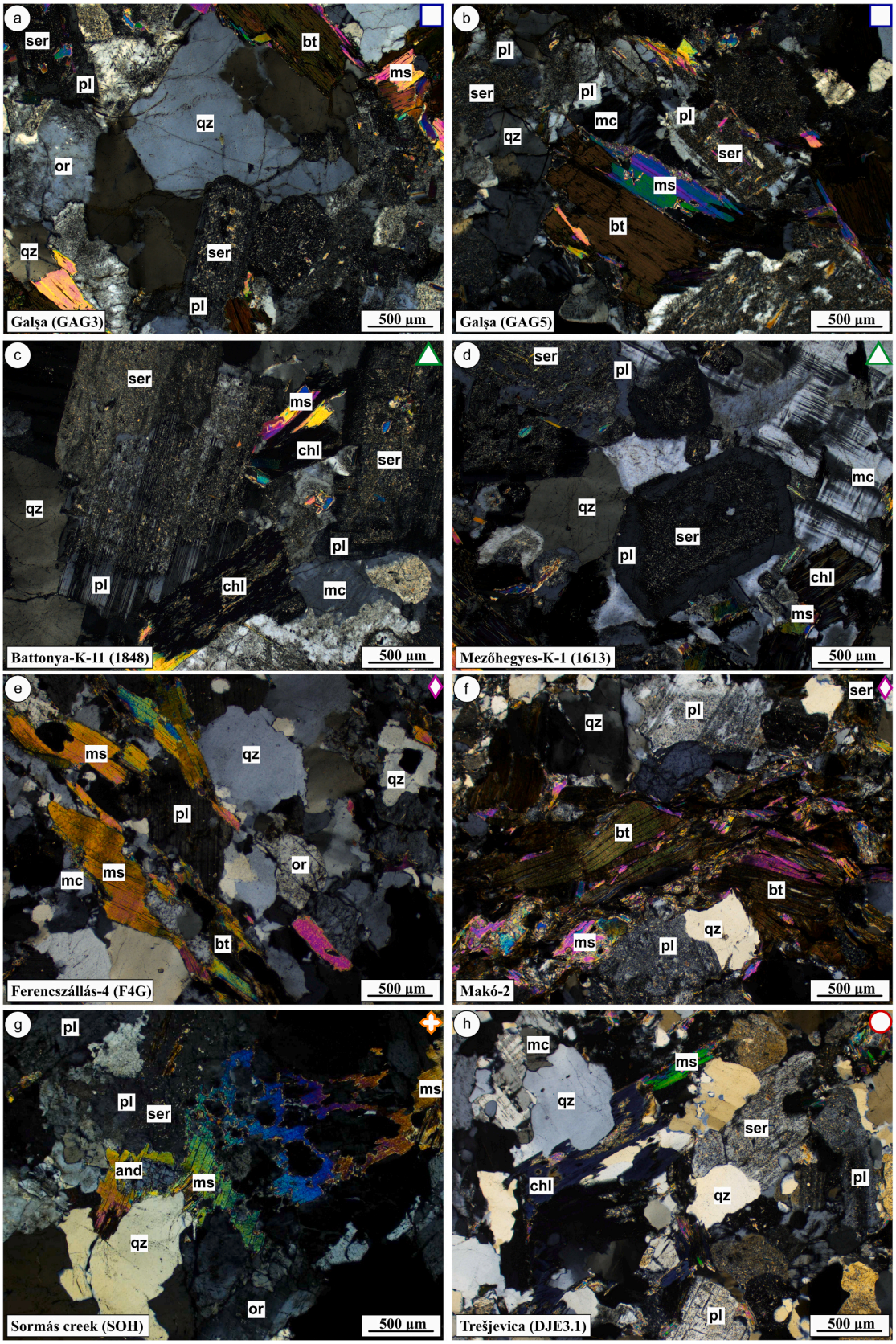


Fig. 2. Representative photomicrographs (crossed polars) of S-type granitoids from the five study areas in the Tisza Mega-unit, showing the most common textural features and rock-forming minerals (including secondary phases and some accessory minerals). Abbreviations: *and* andalusite, *bt* biotite, *chl* chlorite, *mc* microcline, *ms* muscovite, *or* orthoclase, *pl* plagioclase, *qz* quartz, *ser* sericite.

Table 1
Petrographic summary of the studied S-type granitoids, showing rock-forming minerals (modal proportions, crystal shape, average grain size, and alterations) and the occurrence of accessory minerals. Abbreviations: *Ab* albite, *And* andalusite, *Ap* apatite, *Cb* carbonate, *Chl* chlorite, *Ep* epidote, *Grt* garnet, *Hem* hematite, *Ilm* ilmenite, *Mc* microcline, *Mnz* monazite, *Or* orthoclase, *Rt* rutile, *Ser* sericite, *Ttn* titanite, *Tu* tourmaline, *Xtm* xenotime, *Zrn* zircon.

	Quartz	Plagioclase	K-feldspar	Biotite	Muscovite	A
SW Apuseni Mts *granodiorites, aplites and pegmatites*	31–44 vol% subhed. to anhed. 1–3 mm deformed	39–54 vol% euhed. to subhed. 1–3 mm secondary Ser, Ab, Ep	2–13 vol% subhed. to anhed. Mc, subhed. Or 1–3 mm	3–6 vol% euhed. 0.5–1 mm (deformed)	4–9 vol% euhed. 0.5–1 mm (deformed)	Ap Zrn Mnz Ilm Grt
Battonya–Pusztaföldvár Basement Ridge *monzogranites, granodiorites (tonalites, pegmatites)*	30–48 vol% subhed. to anhed. 1–3 mm deformed	27–58 vol% euhed. to subhed. 1–3 mm secondary Ser, Ab, Ep, Cb, clay minerals	3–22 vol% subhed. to anhed. Mc, subhed. Or 2–3 mm	1–8 vol% euhed. 0.5–1.5 mm secondary Chl (deformed)	1–10 vol% euhed. 0.5–1.5 mm (deformed)	Ap Zrn Mnz Xtm Ttn
Algyő–Ferencszállás Basement High *monzogranitic, and granodioritic orthogneisses (aplites and pegmatites)*	31–55 vol% anhed. 1–3 mm strongly deformed	16–41 vol% subhed. to anhed. 1–3 mm deformed	4–20 vol% subhed. to anhed. Or and Mc 0.5–2 mm deformed	1–14 vol% euhed. 0.5–1 mm secondary Chl, Hem deformed	4–18 vol% euhed. 0.5–2 mm deformed	Grt Ap Zrn Mnz Ttn
Western Mecsek Mts *monzogranites (pegmatites)*	38–51 vol% subhed. to anhed 1–3 mm deformed	22–32 vol% euhed. to subhed. 1–3 mm secondary Ser	20–23 vol% subhed. Or 1–3 mm	2–4 vol% euhed. to subhed. 0.5–1.5 mm (secondary Hem)	3–9 vol% euhed. to subhed. 0.5–2 mm	And Ap Mnz Zrn Grt Ilm Rt Tur
Papuk Mt *monzogranitic orthogneisses*	45–51 vol% anhed. 1–3 mm deformed	31–34 vol% euhed. to subhed. 0.5–2 mm secondary Ser deformed	17–18 vol% subhed. to anhed. Mc subhed. Or 1–2 mm secondary clay minerals	1–3 vol% euhed. 0.5–1 mm secondary Chl	1–2 vol% euhed. to subhed. 0.5–1 mm	Ap Zrn Xtm Ttn

Frost and Frost, 2008). In the SiO_2 vs. A/CNK diagram (Chappell and White, 1974), all studied samples plot in the S-type field (Fig. 3c).

Granitoids of the Algyő–Ferencszállás BH, Papuk Mt., and western Mecsek Mts generally have higher SiO_2 contents (>74 wt%) than those from the SW Apuseni Mts and Battonya–Pusztaföldvár BR (<74 wt%, except for some pegmatites and aplites, Fig. 4). SiO_2 content shows negative correlations with Al_2O_3, Fe_2O_3, MgO, MnO, CaO, Na_2O, TiO_2, P_2O_5, Ba, Sr, Zr, Hf, Th, Y, Co, V, and light rare earth elements (LREE), and positive correlations with K_2O, Rb, and Ta (Fig. 4). Samples from Papuk Mt. show opposite trends for some elements (Fe_2O_3, MgO, K_2O, TiO_2, Zr, Hf, Y, and LREE), thus forming a separate group (Fig. 4). The other four study areas form two additional groups (Fig. 4): SW Apuseni Mts and Battonya–Pusztaföldvár BR granitoids are similar, while Algyő–Ferencszállás BH samples plot near the western Mecsek Mts granitoids for most elements, with a few exceptions such as Rb and Cs.

The studied samples are variably enriched in REE, showing distinct fractionated patterns expressed by La_N/Yb_N (1.3–58.5) relative to chondrite. Total REE values range widely, from 13 to 257 ppm, with pegmatites and aplites generally having lower REE contents than monzogranites, granodiorites, and tonalites. Based on chondrite-normalized REE diagrams (Fig. 5), granitoids can be divided into three major groups. (1) SW Apuseni Mts and Battonya–Pusztaföldvár BR granitoids exhibit enriched light REE (La_N/Sm_N = 2.2–4.5), variably enriched heavy REE patterns (Gd_N/Yb_N = 1.1–6.4), and slight negative Eu anomalies (Eu/Eu* = 0.5–0.8). (2) Algyő–Ferencszállás BH and western Mecsek Mts samples are less enriched in light REE (La_N/Sm_N = 1.9–3.3), show similar heavy REE patterns (Gd_N/Yb_N = 0.8–4.0), and deeper negative Eu anomalies (Eu/Eu* = 0.2–0.6). (3) Papuk Mt. orthogneisses display enriched light REE (La_N/Sm_N = 2.1–2.2), near flat heavy REE patterns (Gd_N/Yb_N = 0.5–2.0), and deep negative Eu anomalies (Eu/Eu* = 0.2). In general, pegmatites and aplites are less enriched in both light and heavy REE than the associated granites, granodiorites or tonalites, showing variable negative Eu anomalies (Eu/Eu* = 0.4–0.8).

In multi-element spider diagrams (Fig. 6), almost all samples show negative anomalies in Ba, Nb, Sr, and Ti, and positive anomalies in Rb, Th, U, and K relative to primitive mantle values. Phosphorus shows negative anomalies in the SW Apuseni Mts, Battonya–Pusztaföldvár BR, and Papuk Mt. samples, and positive anomalies in the Algyő–Ferencszállás BH and western Mecsek Mts samples. Pegmatites and aplites differ from the granites, granodiorites and tonalites, generally showing smaller enrichments or depletions for most elements, including Ba, Th, U, Ti, and Y.

Zircon saturation temperatures (T_{Zr}) for the studied granitoids were calculated following Boehnke et al. (2013; ESM 1). The highest T_{Zr} values are found in Trešnjevica orthogneisses from Papuk Mt. (average 772 °C), slightly lower in Codru granodiorites from the Apuseni Mts (average 755 °C) and Battonya–Pusztaföldvár granitoids (average 740 °C), and lowest in Algyő–Ferencszállás granitoids (average 704 °C) and granitic pebbles from western Mecsek Mts (average 664 °C).

4.4. Zircon U—Pb geochronology

Most of the studied zircon crystals (Supplementary Fig. 5) are euhedral to subhedral, variably resorbed, and 80–350 μm in size. The most common type is isometric or moderately elongated, bipyramidal zircon, slightly or not resorbed (Supplementary Fig. 5a–f). Strongly resorbed stubby crystals are frequent in samples of the Pannonian Basin (Supplementary Fig. 5b–d), while highly elongated crystals (up to 500–600 μm) appear only in the SOH sample from the western Mecsek Mts (Supplementary Fig. 5e). Oscillatory zoning is common and high-intensity cathodoluminescent cores were observed in all samples, particularly abundant in GAG5, 1262–1263, DEH DNy-4, and Deszk-1a (Supplementary Fig. 5a–d). Laser ablation spots were generally placed on zircon mantle domains, avoiding cracks, inclusions, and cathodoluminescent cores where possible; however, due to the small size of many grains, inner domains were occasionally included in the measured volume.

Data with >10% discordance between $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates were excluded (ESM 2). These represent 10–60% of all analyses depending on the sample (Table 2, ESM 2). The remaining concordant

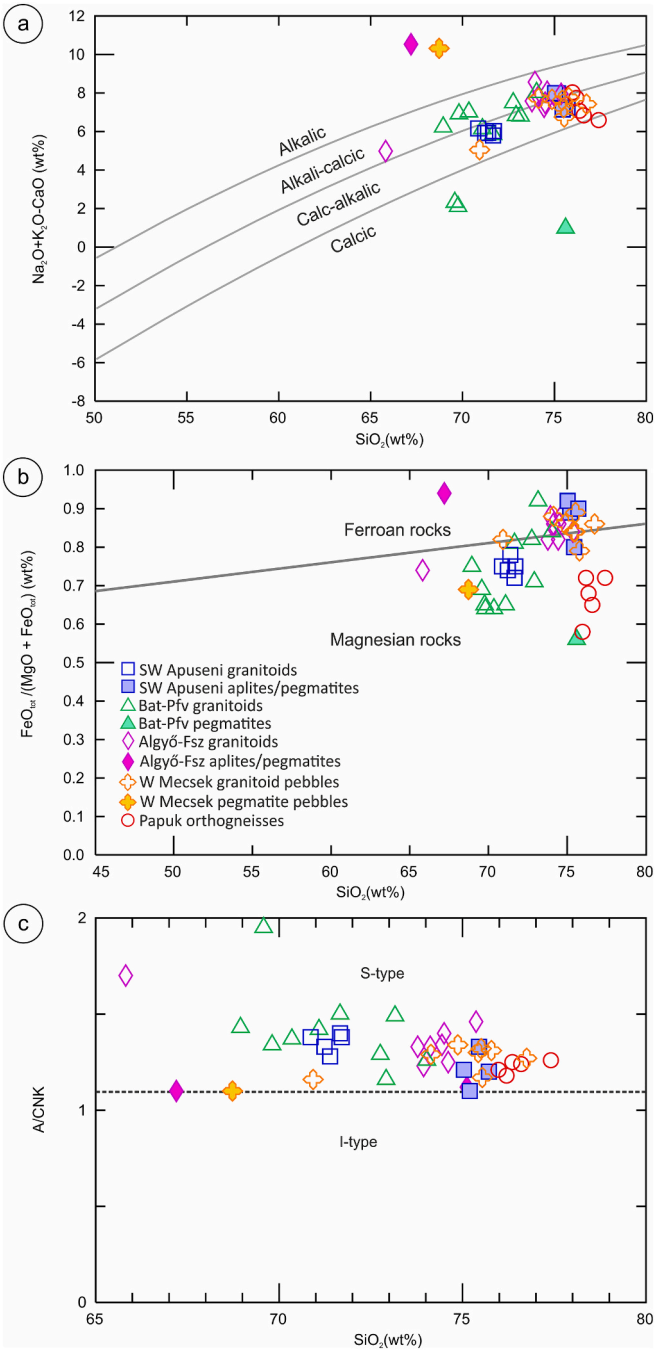


Fig. 3. Bulk-rock major element geochemistry of S-type granitoids from the five study areas in the Tisza Mega-unit shown in commonly used granitoid diagrams. (a) Modified alkali-lime index diagram (MALI; Frost et al., 2001); (b) Fe-number diagram (Frost et al., 2001; Frost and Frost, 2008); (c) SiO_2 vs. A/CNK diagram (Chappell and White, 1974).

$^{206}Pb/^{238}U$ dates show significant age dispersion with variable age distributions, including only minor concordant clusters in some samples (Supplementary Figs. 6–7). These distributions reflect the presence of older, inherited crystals or domains, and may result from mixed analyses of zircon zones with different growth histories, including core and rim domains, as well as the possible effect of Pb loss (selective leaching of daughter isotopes in an open system). The samples gave an average 2 s uncertainty between 1.2 and 4.2%. Th/U ratios average 0.2–0.4 (except DEH DNy-4 with 2.5, caused by some extremely high Th/U values; ESM 2), and calculated eU values (eU = U + 0.235 × Th) show no systematic relation with $^{206}Pb/^{238}U$ dates (Supplementary Fig. 8).

For all samples, the timing of magmatism was calculated using the TuffZirc Age algorithm (Ludwig, 2012), which estimates the youngest coherent group of concordant $^{206}Pb/^{238}U$ dates. The resulting age spectra show variable complexity and generally higher uncertainties in several samples (Table 2). In some cases, broader ranges of concordant dates are present, and additional older or younger concordant clusters can be observed (e.g., GAG5, DEH DNy-4, BATG). Kernel density plots and histograms (Density Plotter; Vermeesch, 2012) illustrate the distribution of dates and facilitate sample comparison (Figs. 7, 8). Age calculation was not possible for Deszk-1a due to the limited number of zircon grains, and the lack of a coherent concordant population.

The oldest, Early Ordovician age (473.1 +4.2 –0.9 Ma) was calculated for the DJE1.1 orthogneiss (Papuk Mt) using 12 coherent data. Despite a few older (possibly inherited) and younger (Pb loss-affected) dates, the zircon crystallization age appears robust at ~473 Ma (Fig. 7), interpreted as possible protolith age of the Trešnjevica orthogneiss. The SOH monzogranite (western Mecsek Mts) is the only Permian granitoid, with a TuffZirc age of 270.6 +1.3 –2.4 Ma from 15 coherent dates; only a minor number older concordant dates were measured (Fig. 7). Devonian–Carboniferous ages were obtained from the Apuseni Mts and Battonya–Pusztaföldvár BR samples, but these are associated with abundant discordant, inherited, or Pb loss-affected dates, and relatively high uncertainties. The most robust Early Carboniferous age (355.9 +4.6 –4.0 Ma) comes from the BATG granodiorite (13 coherent dates), overlapping with sample 1262–1263 (356.1 +6.5 –6.9 Ma), representing the Battonya granitoids (Fig. 8). Similar ~360–350 Ma concordant dates are observed in DEH DNy-4 (Battonya–Pusztaföldvár BR) and GAG5 (Apuseni Mts), but the TuffZirc age algorithm yields significantly younger (303.9 +14.2 –19.0 Ma) and older (397.2 +10.5 –6.0 Ma) ages, respectively (Table 2), reflecting different subsets of concordant analyses (Fig. 8). Due to the presence of multiple age components and higher uncertainties, GAG5 and DEH DNy-4 were not further interpreted. Older concordant age clusters are particularly abundant in the Battonya–Pusztaföldvár BR and the Apuseni Mts (ESM 2). The main populations include Neoproterozoic (predominantly Ediacaran; ~650–530 Ma), Cambrian (~525–490 Ma), and Silurian–Early Devonian (~440–390 Ma) ages, which are most consistently recorded in the eastern Tisza MU (e.g., GAG5, BATG, 1262–1263), but occur sporadically in the western Mecsek Mts and the Papuk Mt.

4.5. K/Ar geochronology

Potassium-argon ages for different grain-size fractions of Deszk-1a range narrowly from 16.40 ± 0.25 Ma to 16.88 ± 0.26 Ma, overlapping within analytical error (Supplementary Table 3). This suggests that the K/Ar system in the orthomagmatic mica of the granitoid was completely or near-completely reset, or primary mica and feldspar have been uniformly replaced by secondary sericite that formed during subsequent hydrothermal activity. The average age of 16.6 ± 0.25 Ma (Early Miocene) is interpreted to reflect a hydrothermal overprint.

For DEH DNy-4, radiometric ages show a linear decrease from 130.31 ± 1.85 Ma to 106.44 ± 1.51 Ma with decreasing grain-size fractions (5–0.5 μm; Supplementary Table 3), indicating two generations of mica: fine-grained mica (illite or sericite) formed during secondary hydrothermal or diagenetic processes, and coarse-grained, partially altered, residual muscovite. Complete separation of primary and secondary micas is impossible, so measured K/Ar ages are mixed and do not record a single well-defined geological event. These data are consistent with a secondary thermal overprint affecting the granitoid not earlier than ~106 Ma.

5. Discussion

Integrated mineralogical, petrological, geochemical, and geochronological data indicate that the studied granitoids record multiple

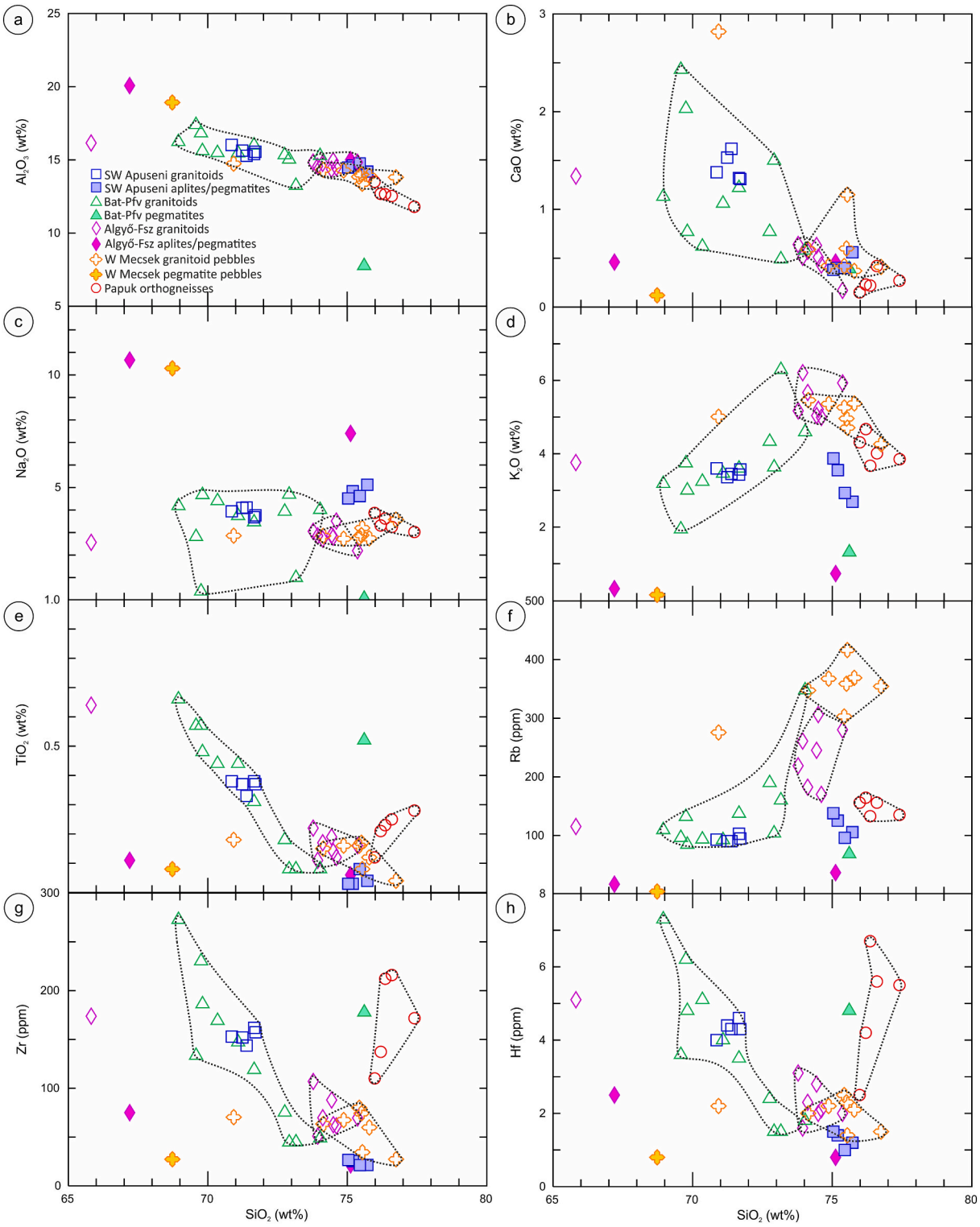


Fig. 4. Bulk-rock major and trace element geochemistry of S-type granitoids from the five study areas in the Tisza Mega-unit shown in characteristic Harker diagrams. Note similarities between SW Apuseni Mts and Battonya–Pusztaföldvár Basement Ridge granitoids, as well as between Algyő–Ferencszállás Basement High and western Mecsek Mts grantioids (marked by black, dashed polygons). Orthogneisses from Papuk Mt. clearly differ from other studied samples.

episodes of Paleozoic magmatism related to both pre-Variscan and Variscan stages in the evolution of the Tisza Mega-unit basement. The results suggest repeated partial melting of continental crust, expressed in Early Ordovician, Late Devonian–Early Carboniferous, and Middle Permian igneous episodes. The primary magmatic signatures were variably modified by Variscan deformation and metamorphism, Alpine tectonothermal overprinting, and later hydrothermal activity, which locally affected mineralogy, textures, and geochemistry, including isotopic systems.

In the following sections, post-magmatic alteration processes are first evaluated to determine their potential impact on the reliability of petrogenetic and geochronological interpretations. This is followed by a

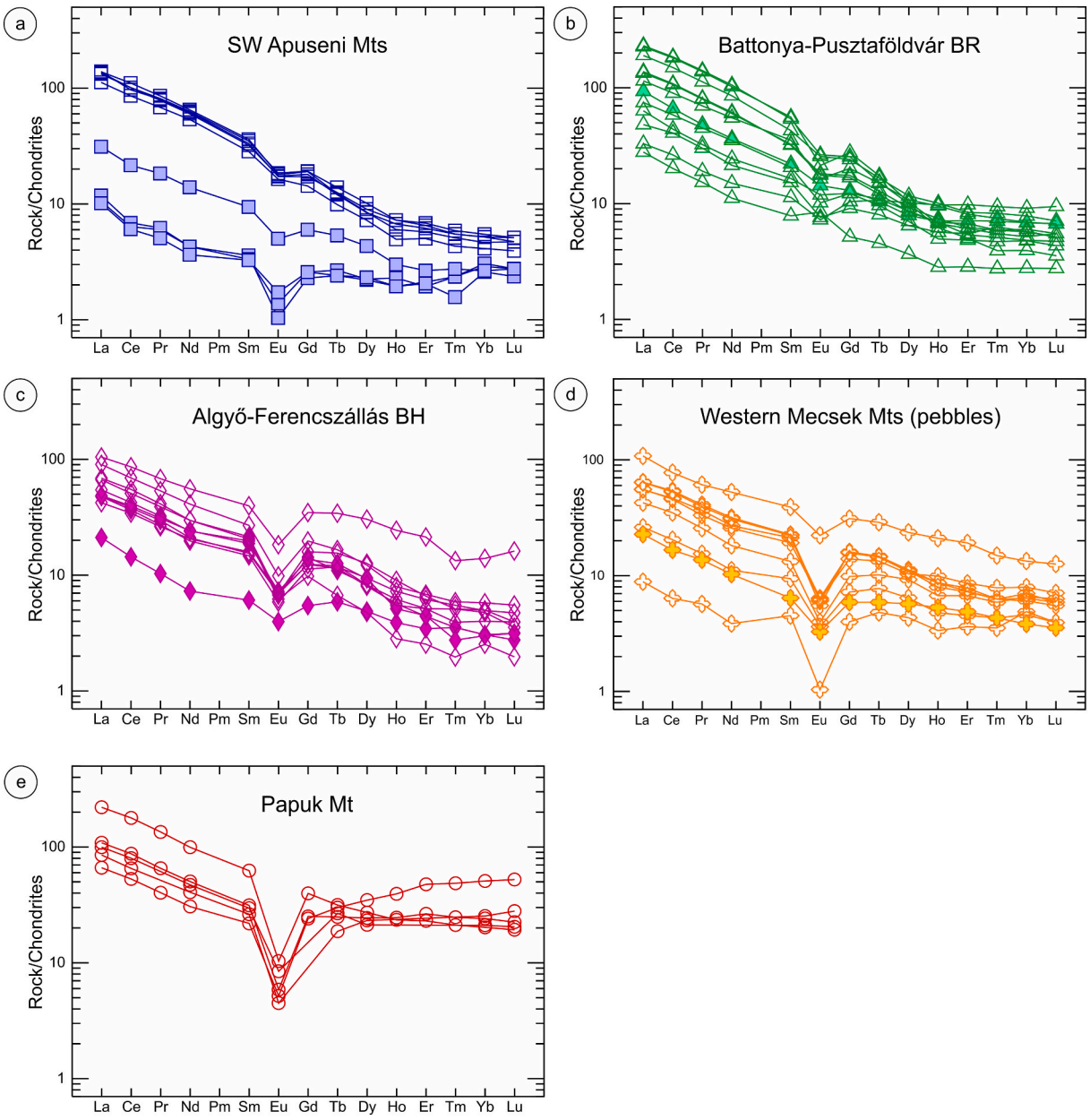


Fig. 5. Chondrite-normalized rare earth element (REE) patterns (Sun and McDonough, 1989) of S-type granitoids from the five study areas in the Tisza Mega-unit. Note similar, parallel REE patterns of SW Apuseni Mts and Battonya–Pusztaföldvár Basement Ridge granitoids (a–b, except for aplites/pegmatites which strongly differ from the monzogranites to tonalites) and similarities between Algyő–Ferencszállás Basement High and western Mecsek Mts granitoids (c–d). Orthogneisses from Papuk Mt. (e) clearly differ from the other studied samples.

discussion of the individual magmatic episodes, integrating the most robust petrological, geochemical, and geochronological constraints with their geodynamic implications. Finally, the relationships among the studied granitoids are evaluated against coeval granitoid suites from the Carpathian–Pannonian region, and the results are interpreted within the broader tectono-magmatic framework of the Central European Variscides.

5.1. *Post-magmatic modification and reliability of geochronological data*

Petrographic observations reveal widespread but variable post-magmatic alteration affecting the studied granitoids (Fig. 2, Supplementary Figs. 1, 3). The most common process is sericitization of plagioclase, typically initiated in crystal cores (Fig. 2, Supplementary Fig. 1a, c, and, d) but locally resulting in complete replacement by fine-grained mica (e.g., Supplementary Fig. 3e). Additional alteration processes include albitization, epidotization, carbonatization, and clay mineral formation (Supplementary Fig. 1a and c–d). These are accompanied by secondary minerals such as chlorite (after biotite), epidote-zoisite/clinozoisite, and tourmaline, which occur variably within the studied granitoids (Fig. 2c–d and h, Supplementary Figs. 1h and b, 4a and g–i), reflecting heterogeneous hydrothermal fluid–rock interaction.

Beyond hydrothermal overprint, the granitoids show variable ductile and brittle deformation related to Variscan and Alpine tectonometamorphic reworking. This is evidenced by recrystallized quartz (Fig. 2e–h, Supplementary Fig. 3), curved mica flakes (Fig. 2e–f, Supplementary Fig. 3c), deformed feldspar twins, anastomosing sericite bands (Supplementary Fig. 3e), and carbonate-filled veins. Structural fabrics range from weak foliation in the Apuseni Mts, Battonya–Pusztaföldvár BR, and western Mecsek Mts to well-developed

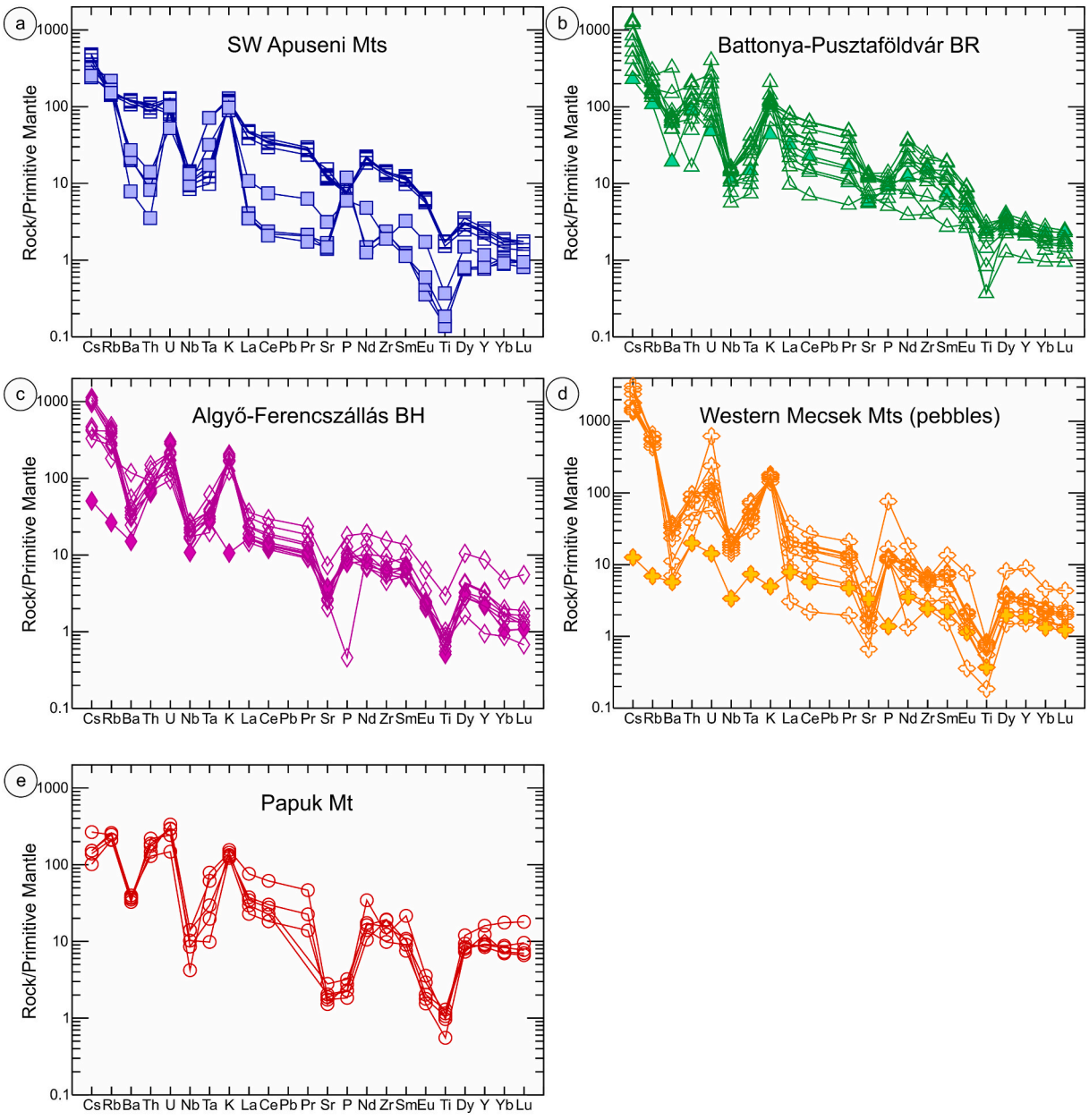


Fig. 6. Primitive mantle-normalized spider diagrams (Sun and McDonough, 1989) of S-type granitoids from the five study areas in the Tisza Mega-unit. Note similar, parallel patterns of SW Apuseni Mts and Battonya–Pusztaföldvár Basement Ridge granitoids (a–b, except for aplites/pegmatites which strongly differ from the monzogranites to tonalites) and similarities in immobile trace element concentrations of Algyő–Ferencszállás Basement High and western Mecsek Mts granitoids (c–d). Orthogneisses from Papuk Mt. (e) clearly differ from the other studied samples.

gneissic S1 schistosity in the Algyő–Ferencszállás and Papuk Mt. areas, locally including mylonitic S—C fabrics. These features indicate progressive deformation and metamorphic overprinting during Alpine tectonometamorphism, superimposed on pre-existing Variscan fabrics.

To evaluate post-magmatic modification and its potential impact on bulk-rock chemistry, the Alteration Index (Ishikawa et al., 1976) vs. Carbonate–Chlorite–Pyrite Index (Large et al., 2001) diagram was used (Fig. 9). Most samples plot within the unaltered to weakly altered igneous fields. A subset, particularly from the Algyő–Ferencszállás BH and western Mecsek Mts, shows a slight shift toward the sericitization trend, indicating limited redistribution of fluid-mobile elements. A few strongly altered samples, together with aplites and pegmatites, were excluded from further consideration.

Post-magmatic processes, including Cretaceous (~106 Ma) to Miocene (~16 Ma) hydrothermal activity, have variably affected the zircon U—Pb system, leading to Pb loss in fractured or metamict grains and variable degrees of discordance (Figs. 7, 8, Supplementary Figs. 5–7, Table 2). As a result, zircon age spectra show variable complexity between samples, reflecting differing preservation of magmatic crystallization ages.

Zircon U—Pb data indicate multiple age clusters in most samples, but only a limited subset of concordant analyses defines coherent populations corresponding to igneous episodes. The most robust constraints are obtained from the Papuk Mt. sample (DJE1.1; ~473 Ma), the Battonya–Pusztaföldvár samples (BATG, 1262–1263; ~360–350 Ma), and the SOH sample from the western Mecsek Mts (~270 Ma), which define three distinct Paleozoic magmatic episodes. In contrast, the GAG5 and DEH DNy-4 samples show mixed age spectra, with abundant inheritance, discordance, and possible Pb loss effects, and therefore provide less precise constraints on crystallization ages.

Table 2
Zircon U—Pb geochronological results of the studied S-type granitoids in the Tisza Mega-unit calculated using the TuffZirc age algorithm (Ludwig, 2012) which selects the youngest coherent group of concordant $^{206}Pb/^{238}U$ dates. For GAG5 and DEH DNy-4, TuffZirc ages were reconsidered and not directly used for further interpretations; these results are shown in italics.

Area	Sample	Concordant[1]/ all spots	Th/U range	TuffZirc age[2,3] (Ma)
SW Apuseni Mts, Galşa	GAG5	42/56	0.0–2.4	*397.20 +10.50 –6.00 (5)*
Battonya–Pusztaföldvár Basement Ridge	BATG	44/57	0.0–1.1	355.90 +4.60 –4.00 (13)
	1262–63	15/21	0.0–1.3	356.10 +6.50 –6.90 (6)
	DEH DNy-4	19/48	0.0–33.8	*303.90 +14.20 –19.00 (7)*
Algyő–Ferencszállás Basement High	Deszk-1a	11/14	0.0–0.8	not calculable
Western Mecsek Mts (pebbles)	SOH	29/37	0.0–0.6	270.60 +1.30 –2.40 (15)
Papuk Mt, Trešnjevica	DJE1.1	26/29	0.1–0.6	473.05 +4.15 –0.85 (12)

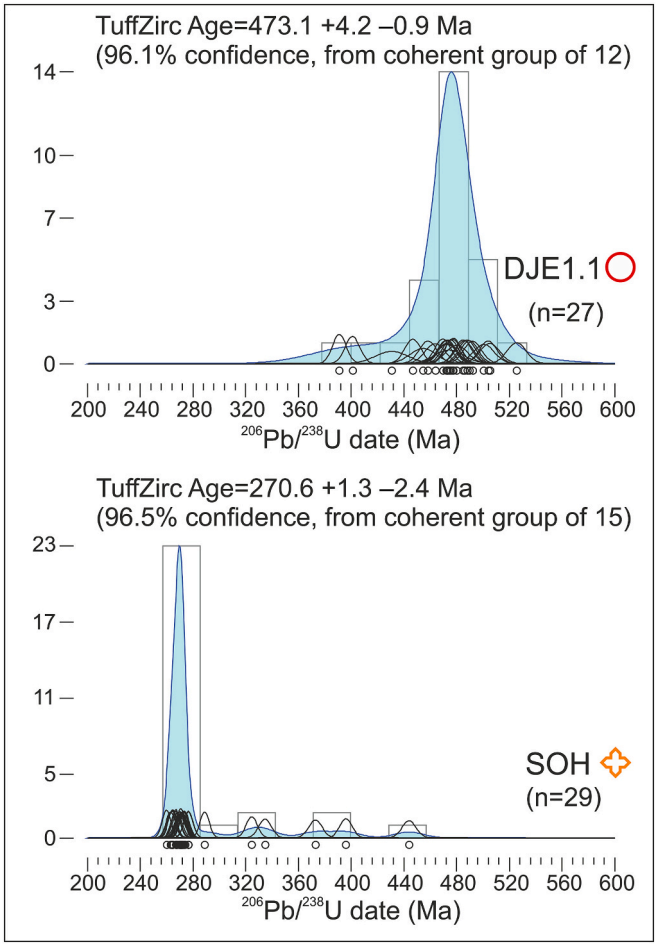


Fig. 7. Zircon U—Pb geochronological results of the DJE1.1 (Papuk Mt) and the SOH (western Mecsek Mts) samples: kernel density plots with individual data as points and bells (2 s uncertainties) and histograms using Density Plotter (Vermeesch, 2012).

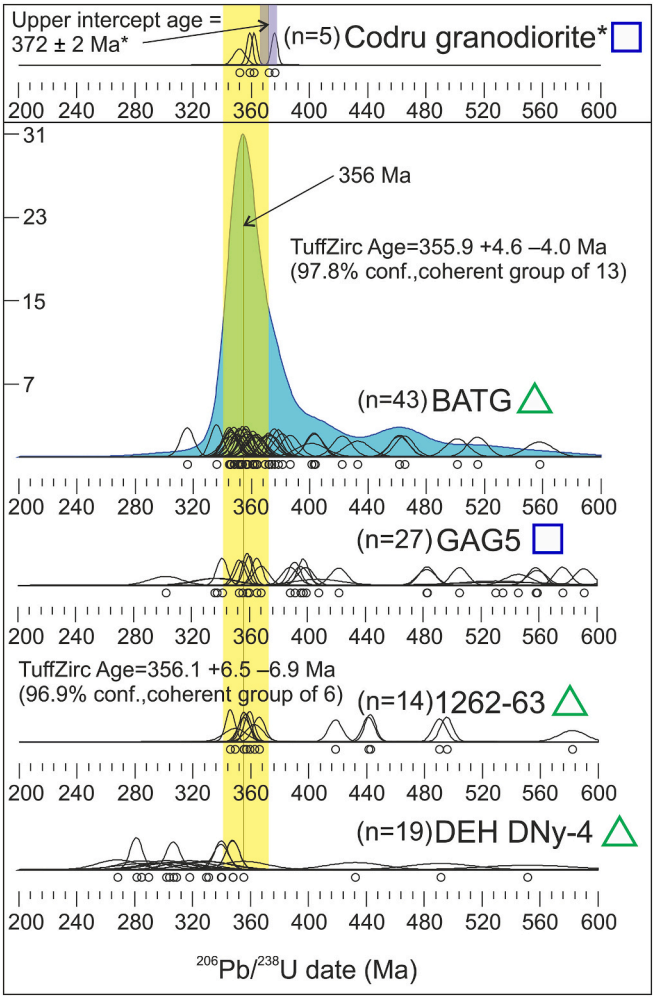


Fig. 8. LA-ICP-MS zircon $^{206}Pb/^{238}U$ dates of GAG5 (SW Apuseni Mts), BATG, DEH DNy-4, and 1262–1263 (Battonya–Pusztaföldvár Basement Ridge) and zircon ID-TIMS $^{206}Pb/^{238}U$ dates and upper intercept age of the Codru granodiorite (* Pană et al., 2002). Only concordant dates are displayed, i.e., those for which the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates differ by less than 10%. Kernel density estimates of the BATG and the individual data as points and bells (2 s uncertainties) were generated using Density Plotter (Vermeesch, 2012). TuffZirc ages of BATG and 1262–1263 were calculated using Isoplot 4.15 (Ludwig, 2012). TuffZirc age and kernel density estimates are not shown where interpreted as inconclusive.

Inherited zircon grains or xenocrystic cores record various age clusters, among which Neoproterozoic (Ediacaran; ~650–530 Ma), Cambrian (~525–490 Ma), and Silurian–Early Devonian (~440–390 Ma) are the most significant, reflecting recycling of older crustal material during magma generation. Crustal inheritance, Pb loss, and later overprinting collectively contribute to the complexity and discordance in zircon age spectra, particularly in samples from the eastern Pannonian Basin and SW Apuseni Mts.

Despite these complexities, most TuffZirc results provide broad constraints on the timing of the three major Paleozoic magmatic episodes. Integration of zircon geochronology with mineralogical, petrographic, and geochemical data supports the petrogenetic interpretations.

5.2. *Paleozoic magmatic evolution and petrogenesis of S-type granitoids*

The studied samples are mineralogically and texturally similar (Fig. 2, Supplementary Figs. 1–2), although variations in heavy mineral assemblages (Supplementary Fig. 4) and bulk-rock geochemistry

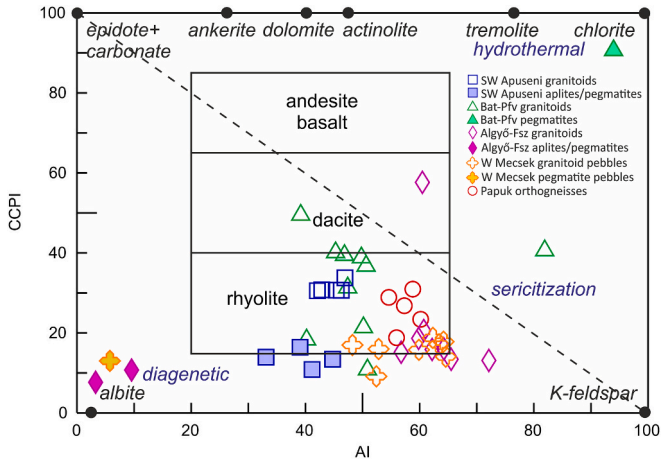


Fig. 9. Alteration Index (Ishikawa et al., 1976) vs. Carbonate–Chlorite–Pyrite Index (Large et al., 2001) diagram (modified after Shanks III and Thurston, 2012; Hübner et al., 2021) showing post-magmatic alterations of the studied S-type granitoids in the Tisza Mega-unit.

(Figs. 3–6) may reflect either source heterogeneity or post-magmatic modification. Muscovite (0.5–2 mm), commonly associated with biotite, together with an accessory assemblage of Al-rich phases (e.g., garnet, andalusite), monazite, zircon (commonly with inherited cores), and F-rich apatite (Fig. 2, Supplementary Figs. 1, 3, 4), is consistent with peraluminous crustal melts (e.g., Chappell and White, 1974, 2001; Clemens and Wall, 1981).

The bulk-rock chemistry indicates an S-type continental crustal affinity. The granitoids are peraluminous and characterized by high Al_2O_3, moderate to high SiO_2, low CaO, and typically high K_2O/Na_2O ratios (Figs. 3–4), together with relatively low zircon saturation temperatures (~660–770 °C). Trace element patterns, including slight to moderate negative Eu anomalies and positive anomalies in Cs, Rb, Th, U, and LREE, as well as negative anomalies in Ba and Sr, are typical of S-type granitoids (Figs. 5–6; Chappell and White, 1974, 2001; Clemens and Wall, 1981). The classification scheme of Chappell and White (1974), together with the presence of inherited zircon populations, further supports this interpretation (Figs. 3c, 7–8, Supplementary Figs. 5–7).

Despite these similarities, zircon U—Pb data indicate three distinct Paleozoic magmatic episodes (Figs. 7–8, Supplementary Figs. 6–7, Table 2). Their interpretation is based on petrographic observations, geochronological constraints, and tectonic discrimination diagrams (Fig. 10; Pearce et al., 1984; Batchelor and Bowden, 1985), integrated within a regional geological context.

An Early Ordovician age (473.1 +4.2 –0.9 Ma) was obtained for the Trešnjevica orthogneiss from Papuk Mt. (Fig. 7), representing one of the oldest granitoid protoliths in the Tisza MU. Its mineralogical and geochemical characteristics are consistent with peraluminous crustal melts, although its genetic classification remains uncertain due to the metamorphic overprint. Tectonic discrimination diagrams yield contrasting results: the R1–R2 diagram (Batchelor and Bowden, 1985; Fig. 10a) suggests a syn-collisional affinity, whereas HFSE-based diagrams (Pearce et al., 1984; Fig. 10b–c) indicate transitional arc-to-within-plate signatures. This discrepancy likely reflects limitations of discrimination diagrams in strongly reworked granitoids. The present gneissic fabric reflects Variscan tectonometamorphism, although a possible earlier Cenerian imprint cannot be excluded based on evidence from adjacent regions (e.g., Slavonian Mts and Western Carpathians; Starijaš Majer et al., 2023; Petrík et al., 2024). A later Alpine overprint, widespread in the Carpathian–Pannonian region (e.g., Western Carpathians, Eastern Alps, Apuseni Mts; Gaab et al., 2006; Yuan et al., 2020; Szemerédi et al., 2023), may have further modified the rock.

Carboniferous zircon crystallization ages were obtained from three

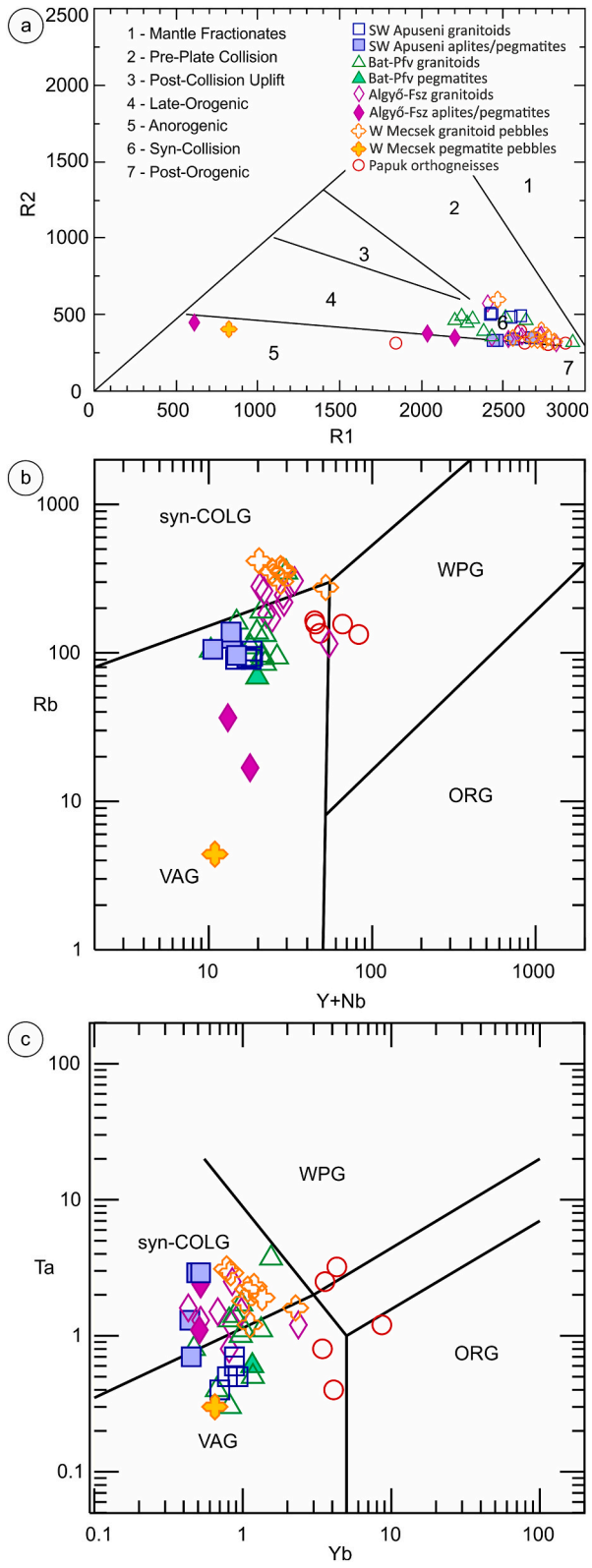


Fig. 10. (a) R1–R2 (Batchelor and Bowden, 1985), (b) Y + Nb vs. Rb, and (c) Yb vs. Ta (Pearce et al., 1984) discrimination diagrams for geotectonic implications of the studied S-type granitoids in the Tisza Mega-unit. Note volcanic-arc or syn-collisional character of the SW Apuseni Mts and Battonya–Pusztaföldvár Basement Ridge granitoids, syn-collisional character of Algyő–Ferencszállás Basement High and western Mecsek Mts granitoids, and scattered Papuk Mt. orthogneisses data suggesting a transition to within-plate magmatism.

samples of the Battonya–Pusztaföldvár BR. Two samples yield consistent Tournaisian ages (BATG: 355.9 +4.6 –4.0 Ma; 1262–1263: 356.1 +6.5 –6.9 Ma), whereas DEH DNy-4 shows a more complex zircon age spectrum with abundant discordant and inherited analyses (Fig. 8, Table 2). This sample also yields a Cretaceous (~106 Ma) mica K/Ar age (Supplementary Table 3), indicating Alpine hydrothermal overprint and possible disturbance of the zircon U—Pb system. Accordingly, the most reliable constraint for Early Carboniferous magmatism in the Battonya–Pusztaföldvár BR is ~360–350 Ma.

The GAG5 sample from the SW Apuseni Mts shows significant petrological and geochemical similarities to the Battonya–Pusztaföldvár granitoids and yields zircon U—Pb dates between ~420 and 340 Ma, defining two main clusters (~420–380 Ma and ~370–340 Ma). The younger population overlaps with the Tournaisian ages from the Battonya–Pusztaföldvár BR (Fig. 8). Published zircon U—Pb data from the Codru granodiorites yielded Late Devonian (~372 Ma; Pană et al., 2002) and Early Carboniferous (~350 Ma; Balintoni et al., 2007) ages, with Pană et al. (2002) identifying two-component mixing and suggesting the upper intercept age of 372 ± 1 Ma as reliable for the crystallization. Although age spectra are locally complex and may reflect open-system behaviour, the overlapping age ranges, together with comparable mineralogical (Fig. 2, Supplementary Figs. 1–2) and geochemical (Figs. 3–6) characteristics, support a correlation between the Codru granodiorites and the Battonya–Pusztaföldvár granitoids. Geodynamically, both groups plot within the syn-collisional field in the R1–R2 diagram (Fig. 10a), whereas HFSE-based diagrams indicate mixed syn-collisional and arc-related affinities (Fig. 10b–c).

In contrast, zircon U—Pb dating of the Algyő–Ferencszállás granitoids was unsuccessful due to the low abundance of zircon in the Deszk-1 drill core (the only sample available in sufficient volume) and the lack of coherent age clusters (Supplementary Fig. 6). Sericite K/Ar dating revealed a Miocene (~16 Ma) hydrothermal event, which may have

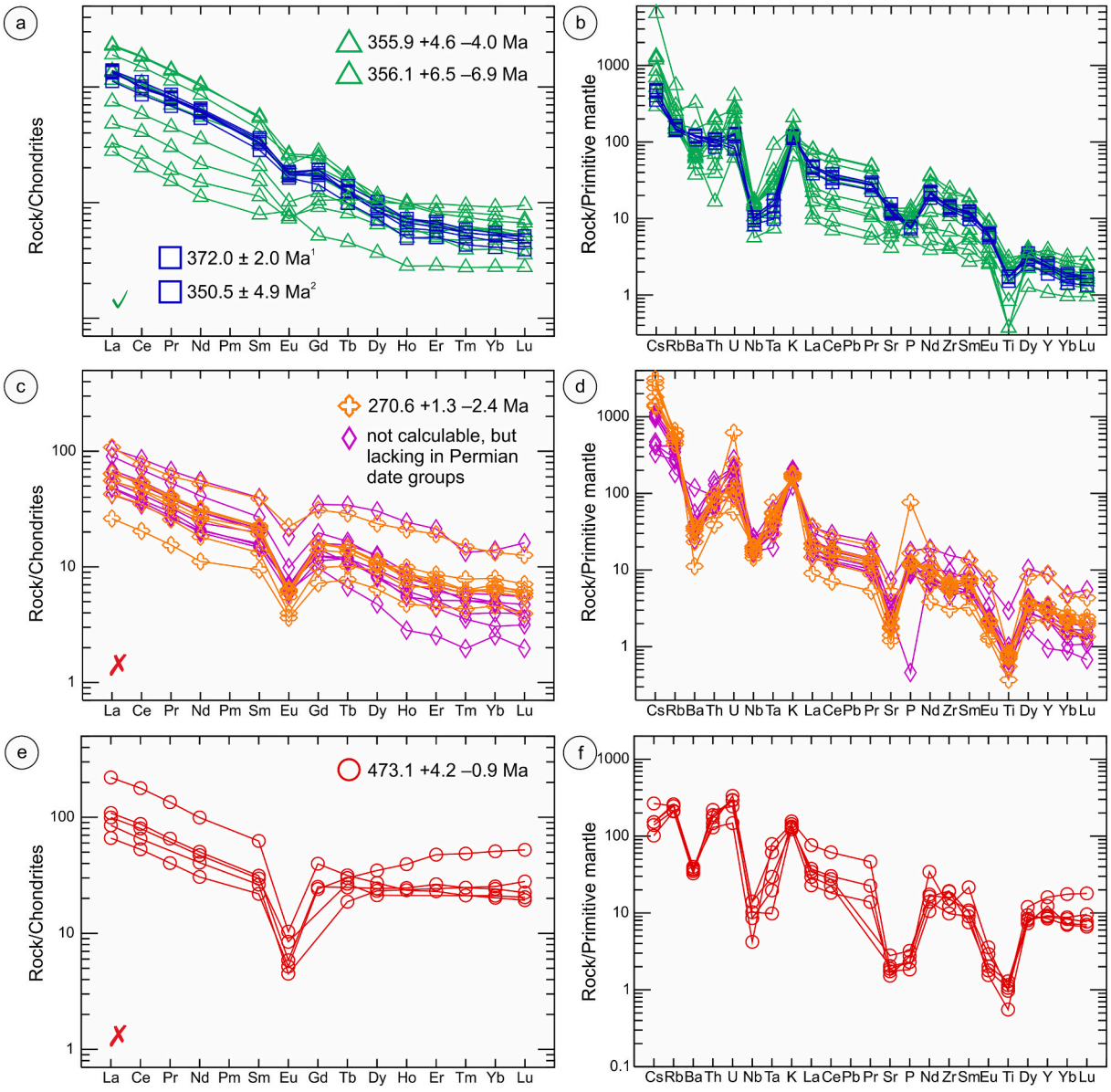


Fig. 11. Bulk-rock trace element geochemistry and zircon U—Pb geochronology of the studied S-type granitoids in the Tisza Mega-unit, suggesting local correlation between the granitoids from the SW Apuseni Mts (Codru granodiorites) and the Battonya–Pusztaföldvár Basement Ridge (Battonya granitoids, a–b). Despite similar bulk-rock geochemistry, geochronology does not support local correlation of the Algyő–Ferencszállás granitoids and monzogranite pebbles from the western Mecsek Mts (c–d), though they may represent similar geodynamics. Orthogneisses from Papuk Mt. (e–f) clearly differ from all other studied rocks. References: [1]Pană et al. (2002); [2]Balintoni et al. (2007).

contributed to the discordant and Pb loss-affected analyses. Nevertheless, discrimination diagrams suggest syn-collisional affinities (Fig. 10), and these rocks show geochemical similarities with monzogranitic pebbles from the western Mecsek Mts (Figs. 3–6).

The youngest zircon crystallization age was obtained from the western Mecsek Mts, where the SOH sample yielded a Middle Permian (Guadalupian) age of 270.6 +1.3 –2.4 Ma. These granitoids show syn-collisional affinities (Fig. 10) and geochemical similarities to the Algyő–Ferencszállás samples. Despite the well-constrained age and the homogeneous mineralogy and geochemistry of these pebbles from Miocene conglomerates, their origin remains uncertain, as no comparable granitoid bodies are currently known from the exposed or drilled basement of the Tisza MU.

5.3. Regional correlations and Paleozoic tectono-magmatic implications

Despite their broadly similar mineralogical compositions and textural features (Fig. 2, Supplementary Figs. 1–2), the Paleozoic granitoids of the Tisza MU have remained difficult to correlate due to the limited availability of robust geochronological and geochemical constraints. The new zircon U—Pb ages and petrological data improve local correlations within the Tisza MU and provide a basis for comparison with coeval granitoid suites in the Carpathian–Pannonian region.

On a local scale, the Battonya–Pusztaföldvár granitoids show strong similarities to the Codru granodiorites of the Apuseni Mts. Overlapping REE and trace element patterns (Fig. 11a–b), apatite-dominated heavy mineral assemblages (Supplementary Fig. 4a–c), and Early Carboniferous zircon U—Pb ages (360–340 Ma; Fig. 8) support a correlation between these granitoid suites. Their occurrence within the same structural unit of the Tisza MU (Békés–Codru Unit/Codru Nappe System, Fig. 1) further suggests that they record a common Late Devonian–Early Carboniferous magmatic event.

Geochemical similarities are observed between the Algyő–Ferencszállás orthogneisses and monzogranitic pebbles from the western Mecsek Mts (Fig. 11c–d). However, differences in modal compositions (Supplementary Fig. 2), accessory mineral assemblages (Supplementary Fig. 4), and available geochronological constraints (Table 2, Supplementary Fig. 6) argue against their local correlation. The Papuk Mt. orthogneisses, in contrast, are distinguished by their significantly older Early Ordovician age and contrasting geochemical characteristics (Figs. 3–6, 9, and 11).

On a regional scale, the Trešnjevica orthogneiss is comparable with felsic metaigneous rocks from several basement units in the Carpathian–Pannonian region. Similar Late Cambrian to Middle Ordovician zircon ages have been reported from the Apuseni Mts (~495–477 Ma; Balintoni et al., 2010; Szemerédi et al., 2025) and orthogneiss complexes of the Western Carpathians, including the Tatric and Veporic Units (~480–440 Ma, Fig. 12a–b; Méres and Hovorka, 1992, Gaab et al., 2006; Petrík et al., 2006; Putiš et al., 2008, 2009). Although direct correlations remain uncertain due to limited geochemical data, these occurrences suggest that Early Ordovician felsic magmatism was widespread across basement units later incorporated into the Alpine–Carpathian orogenic system.

Granitoids from the Apuseni Mts and the Battonya–Pusztaföldvár BR, correlated on a local scale (Fig. 11a–b), are also comparable to Early Carboniferous (362–342 Ma) S-type granitoids of the Western Carpathians (Tatric Unit; Broska et al., 2022; Broska and Svojtka, 2020; Broska and Uher, 2001). Similar ages and geochemical characteristics (Fig. 12c–d, Supplementary Fig. 9) suggest a broader occurrence of Early Carboniferous S-type magmatism in the Carpathian–Pannonian region.

Middle Permian (~270 Ma) monzogranitic pebbles from the western Mecsek Mts were compared with Permian igneous rocks from several basement units of the region. These include anorogenic A-type granitoids of the Highiş igneous complex (SW Apuseni Mts, Dacia MU; ~268–263 Ma; Pană et al., 2002; Szemerédi et al., 2021), post-collisional S-type granitoids of the Western Carpathians (Gemeric and Veporic Units; ~277–246 Ma, recently refined to ~265–264 Ma; Broska and Uher, 2001; Kubiš and Broska, 2010; Villaseñor et al., 2021), and orthogneisses with protolith ages of ~272–268 Ma in the Eastern Alps (Yuan et al., 2020). Despite similar crystallization ages, the Highiş granitoids show distinct REE and other immobile trace element patterns compared to the studied pebbles (Supplementary Fig. 9g–h). More subtle geochemical differences are also observed relative to the Eastern Alpine orthogneisses (Fig. 12g–h), whereas the closest similarities are recorded with Permian post-collisional S-type granitoids of the Western Carpathians (Fig. 12e–f). These observations suggest that the studied pebbles are most consistent with Middle Permian post-collisional crustal magmatism.

Overall, these results highlight strong similarities between the Paleozoic basement units of the Tisza MU and the Western Carpathians, expressed by several comparable magmatic episodes. Early Ordovician (~480–440 Ma) orthogneisses are interpreted as products of collision-related to post-orogenic processes (this study; Méres and Hovorka, 1992; Gaab et al., 2006; Petrík et al., 2006; Putiš et al., 2008, 2009; Balintoni et al., 2010). Late Devonian–Early Carboniferous (~370–340 Ma) S-type granitoids (this study; Broska and Uher, 2001; Pană et al., 2002; Balintoni et al., 2007; Broska and Svojtka, 2020; Broska et al., 2022) are accompanied by coeval Carboniferous I-type granitoid magmatism (e.g., Broska et al., 2013; Broska and Uher, 2001; Gerdes, 2006; Király and Koroknai, 2004), associated with Variscan subduction and collision. Middle Permian (~270–260 Ma) silicic magmatism includes both rift-related A-type (Broska and Uher, 2001; Ondrejka et al., 2021; Szemerédi et al., 2021; Villaseñor et al., 2021) and post-collisional S-type granitoids (this study; Broska and Uher, 2001; Kubiš and Broska, 2010; Villaseñor et al., 2021). These are commonly associated with felsic volcanic and volcaniclastic rocks (Szemerédi et al., 2020, 2023).

To place the results within the geodynamic framework of the Central European Variscides, the Tisza MU basement is compared with the Western Carpathians and the Bohemian Massif, two key reference domains of the Variscan crust. Recent syntheses (Janoušek et al., 2026) suggest that these domains represent contrasting segments of this system. As discussed above, the Tisza MU and Western Carpathians share correlatable Variscan igneous suites. These similarities provide a basis for interpreting the Variscan tectono-magmatic evolution of the Tisza MU in a regional context. Pre-Variscan crustal evolution is considered next to complete the Paleozoic geodynamic framework.

The oldest record of pre-Variscan crustal evolution is provided by inherited zircon crystals spanning Neoarchean to Cambrian ages, with a dominant Neoproterozoic (Ediacaran, ~650–530 Ma) population that is also common in the Western Carpathians (e.g., Putiš et al., 2008; Soejono et al., 2024; Vozárová et al., 2010). These age populations correspond to magmatic and metamorphic events associated with a Cadomian continental arc-related setting along the northern Gondwanan margin. Paleogeographic reconstructions by Soejono et al. (2024), based on zircon U—Pb ages and Hf isotopic data, suggest that the Western Carpathians formed along a passive margin of northern Gondwana during the Cambrian. This margin subsequently underwent significant Early Paleozoic reworking, including multiphase rifting and subduction-related events between ~530 and 460 Ma, accompanied by magmatism and tectono-thermal overprinting (e.g., Balintoni et al., 2010; Putiš et al., 2008, 2009; Vozárová et al., 2010). Although the exact paleoposition of the Tisza MU remains uncertain, the observed similarities may indicate broadly comparable Early Paleozoic crustal evolution between the two domains. Among these processes, the Early Ordovician magmatism recorded by the Papuk Mt. orthogneisses plays a key role and reflects magmatic activity along the northern margin of Gondwana during the Cenerian orogenic cycle (Zurbriggen, 2017). Given its Early Ordovician (~473 Ma) age and geochemistry, the Papuk Mt. orthogneisses are interpreted as related to syn-collisional to post-orogenic processes (Fig. 13a), consistent with comparable units in the Western Carpathians (e.g., Gaab et al., 2006; Méres and Hovorka, 1992; Petrík et al., 2006, 2024; Putiš et al., 2008, 2009).

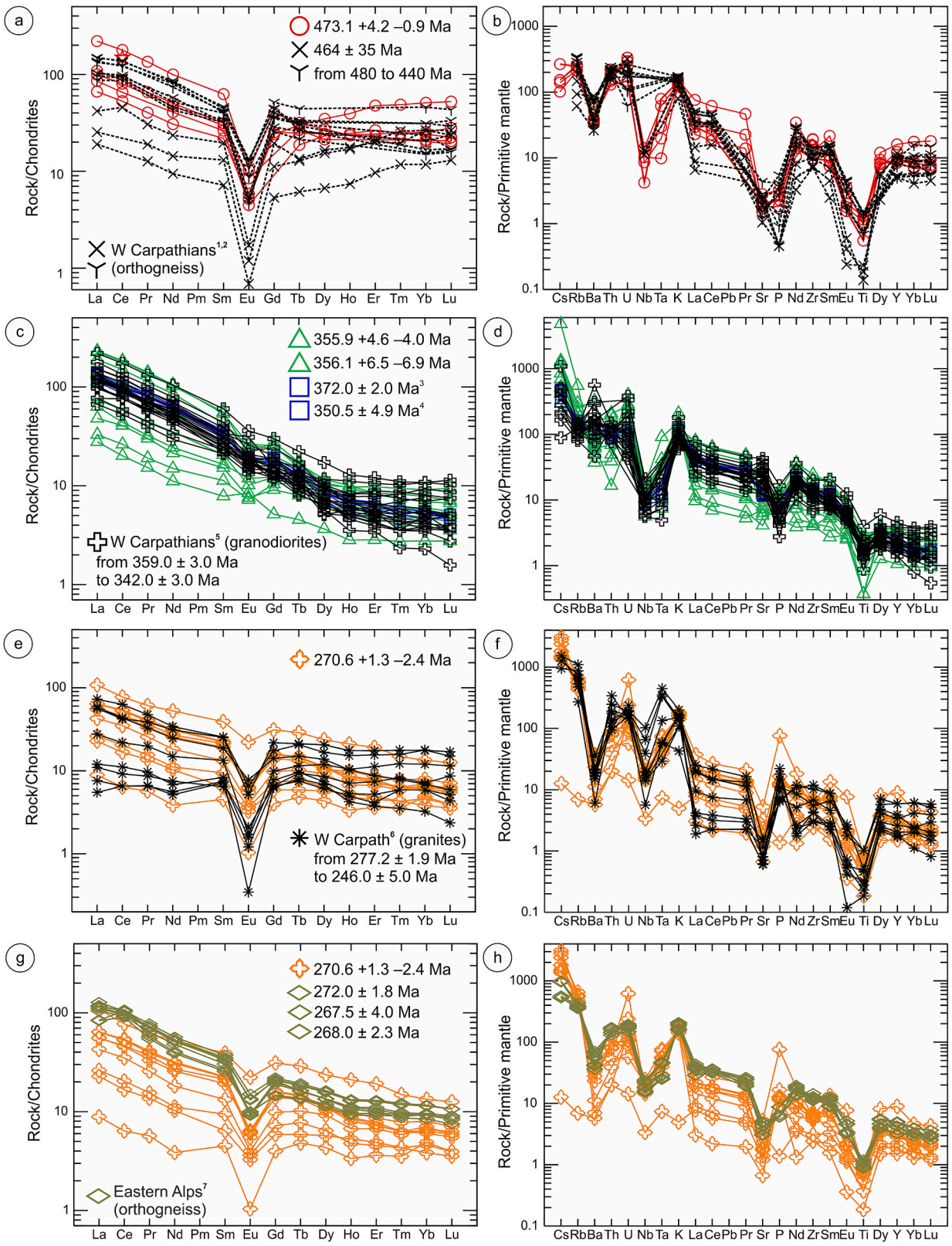


Fig. 12. Potential local to regional correlations of the studied S-type granitoids in the Tisza Mega-unit based on bulk-rock trace element geochemistry and zircon/monazite U—Pb geochronology. Note analogous Ordovician orthogneisses (a–b), Early Carboniferous S-type granitoids (c–d), and Middle Permian (specialized) S-type granites (e–f) in the Western Carpathian units (Tatric, Veporic, and Gemeric Units), suggesting feasible regional correlations. References: [1]Gaab et al. (2006); [2]Putiš et al. (2008); [3]Pană et al. (2002); [4]Balintoni et al. (2007); [5]Broska et al. (2022); [6]Villaseñor et al. (2021); [7]Yuan et al. (2020).

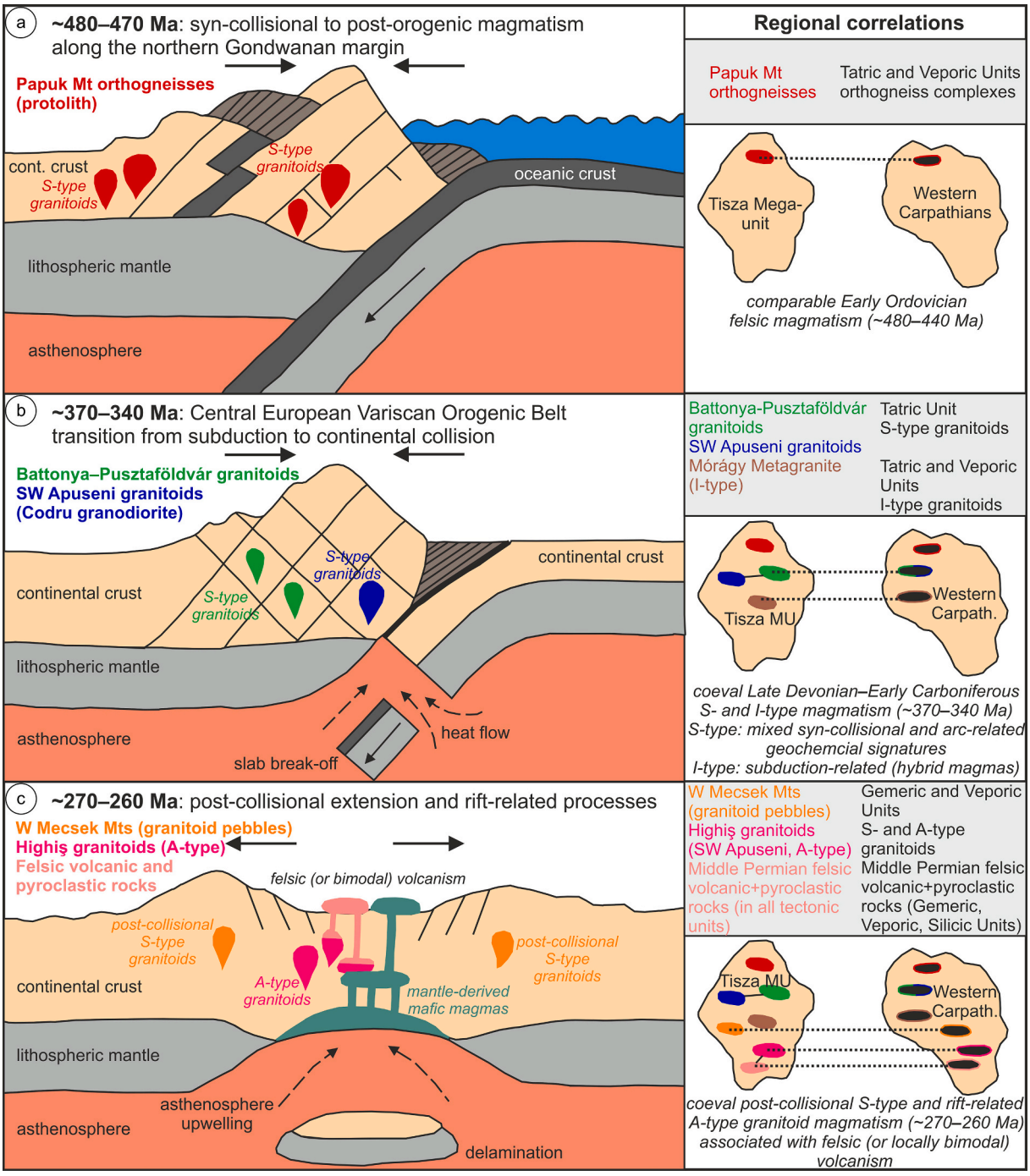


Fig. 13. Schematic geodynamic evolution of the studied S-type granitoids in the Tisza Mega-unit, illustrating: (a) Early Ordovician (~480–470 Ma) syn-collisional to post-orogenic magmatism along the northern margin of Gondwana, represented by the Papuk Mt. orthogneisses; (b) Late Devonian–Early Carboniferous (~370–340 Ma) magmatism related to the transition from Variscan subduction to continental collision, with possible slab break-off, represented by the Battonya–Pusztaföldvár and SW Apuseni Mts granitoids; and (c) Middle Permian (~270–260 Ma) post-collisional S-type magmatism, represented by the western Mecsek Mts granitoid pebbles, and coeval to slightly younger rift-related A-type magmatism and associated felsic volcanic and volcaniclastic activity along the southern margin of Europe, adjacent to the northern margin of the Paleo-Tethys Ocean. The studied rocks were compared with analogous formations in the Western Carpathians, and potential correlations are displayed in the schematic cartoons. Brown, hatched units represent different sedimentary successions, and the oceanic crust symbol also denotes ophiolitic remnants of former oceanic basins in panel (a). Colour codes of the granitoids are consistent with those used throughout the figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Late Devonian–Early Carboniferous (370–340 Ma) granitoids of the Apuseni Mts and the Battonya–Pusztaföldvár BR, characterized by mixed syn-collisional and arc-related geochemical signatures, are associated with the Variscan orogeny and are comparable to coeval S-type granitoids of the Western Carpathians (Broska and Uher, 2001; Broska and Svojtka, 2020; Broska et al., 2022). Broska et al. (2022) interpreted these granitoids as reflecting slab break-off during the transition from Variscan subduction to continental collision. Given the strong petrological, geochemical, and geochronological similarities (Fig. 12), the Tisza MU granitoids likely record a similar geodynamic setting (Fig. 13b). In this context, these magmatic events likely reflect the final stages of Rheic Ocean closure and the convergence of

Gondwana and Laurussia, leading to the accretion of Gondwana-derived crustal fragments within the European Variscan belt (e.g., Gawęda et al., 2016; Kroner and Romer, 2013).

The Variscan collision was followed by post-collisional extension and rift-related processes. Based on their Middle Permian (~270 Ma) age and geochemical characteristics, granitoid pebbles from the western Mecsek Mts are interpreted as products of a Variscan post-collisional setting (Fig. 13c) and represent crustal sources comparable to coeval S-type granitoids of the Western Carpathians (Broska and Uher, 2001; Kubiš and Broska, 2010; Villaseñor et al., 2021). Slightly younger or coeval (~270–260 Ma) A-type granitoid magmatism and associated volcanic activity, documented in both the Tisza MU and the Western Carpathians (Ondrejka et al., 2021; Szemerédi et al., 2020, 2021, 2023; Villaseñor et al., 2021), indicate a rift-related tectonic regime (Fig. 13c). Together, these observations support a broadly shared Late Paleozoic magmatic evolution of these two crustal domains along the southern margin of Europe, adjacent to the northern margin of the Paleo-Tethys Ocean (e.g., Stampfli and Kozur, 2006).

6. Conclusions

(1) S-type granitoids in the pre-Alpine basement of the Tisza Mega-unit record repeated Paleozoic crustal melting and define three main magmatic episodes: Early Ordovician (~473 Ma), Late Devonian–Early Carboniferous (~370–340 Ma), and Middle Permian (~270 Ma). Early Ordovician orthogneisses in the Papuk Mt. reflect syn-collisional to post-orogenic processes along the northern Gondwanan margin. Late Devonian–Early Carboniferous granitoids from the Battonya–Pusztaföldvár Basement Ridge and the SW Apuseni Mts exhibit mixed arc-related and syn-collisional signatures, consistent with the Variscan subduction-to-collision transition and possible slab break-off. Middle Permian monzogranitic pebbles from the western Mecsek Mts represent post-collisional crustal magmatism, coeval with rift-related A-type granitoids and associated volcanic and volcaniclastic rocks. Orthogneisses from the Algyő–Ferencszállás area may record Variscan crustal melting but remain geochronologically unconstrained.

(2) Strong local correlations are supported between the SW Apuseni Mts and Battonya–Pusztaföldvár granitoids based on integrated petrographic, geochemical, and geochronological evidence. On a regional scale, the Tisza Mega-unit shows clear affinities to the Western Carpathians, where comparable Early Ordovician, Early Carboniferous, and Middle Permian magmatic episodes indicate a broadly shared Paleozoic evolution along the northern margin of Gondwana and later within the Variscan Orogenic Belt. These similarities point to repeated crustal reworking and partial melting within adjacent crustal domains of the Central European Variscides.

(3) This study highlights the importance of integrated mineralogical, petrological, geochemical, and zircon geochronological approaches for resolving complex, multiply reworked granitoid systems. Such a combined dataset allows discrimination between primary magmatic features and overprinting processes related to Variscan and Alpine tectonometamorphism, as well as subsequent hydrothermal alteration, thereby improving the reconstruction of Paleozoic tectono-magmatic evolution and providing a robust framework for local- to regional-scale correlations within the Carpathian–Pannonian region and the broader Central European Variscan orogenic system.

Declaration of generative AI use

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) for language editing and improvement of readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the manuscript.

CRediT authorship contribution statement

Máté Szemerédi: Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **István Dunkl:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Dóra Georgina Miklós:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Réka Lukács:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marija Horvat:** Writing – review & editing, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Krisztina Sebe:** Writing – review & editing, Investigation, Conceptualization. **Árpád Máthé:** Writing – review & editing, Investigation. **Zoltán Kovács:** Writing – review & editing, Resources, Methodology, Investigation. **Zoltán Máthé:** Writing – review & editing, Investigation. **Zsolt Benkó:** Writing – review & editing, Validation, Resources, Investigation, Formal analysis, Data curation. **János Szepesi:** Writing – review & editing, Validation, Resources, Investigation, Formal analysis, Data curation. **Szabolcs Harangi:** Writing – review & editing, Resources. **Elemér Pál-Molnár:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lithos.2026.108770.

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