Introductions and aims

Paleozoic igneous formations occur in various parts of the Tisza Mega-unit, including outcrops in the Apuseni, the Mecsek, and the Papuk Mts as well as basement areas in the eastern Pannonian Basin (e.g., Battonya–Pusztaföldvár Basement Ridge, Algyő–Ferencszállás Basement High). Regarding the magmatic rocks, the major aims of this project were (1) to understand the formation of the Permian felsic plutonic, volcanic, and volcanosedimentary rocks in the Tisza Mega-unit exploring their feasible plutonic–volcanic connection and (2) to understand the petrogenesis of Variscan S-type granitoids in the Tisza Mega-unit and to connect their representatives in the basement of SE Hungary to the analogous formations in the Apuseni Mts. During the early stage of this project, combined petrographic, whole-rock geochemical, and zircon U–Pb geochronological investigations revealed that in the studied Permian rift-related magmatic system, mafic–intermediate plutonic rocks (as part of the Highiş igneous complex SW Apuseni Mts) and lavas (western Apuseni Mts) are closely associated with the targeted granites and felsic volcanic and volcanosedimentary rocks, respectively. Therefore, various Permian mafic–intermediate formations from the Apuseni Mts were also involved in our research. Moreover, the study areas of the Variscan S-type granitoids were extended by the Papuk Mts, where orthogneisses with a mineralogical composition similar to that of the granitoids in the eastern part of the Tisza Mega-unit occur, as well as by the also similar two-mica granitoid pebbles collected in the Western Mecsek Mts (as part of the Miocene Szászvár Formation). Besides the two major magmatic events, (1) a Middle Permian (~270–260 Ma) rift-related magmatism and (2) an Early Carboniferous S-type granite magmatism (~360–340 Ma), locally (and sometimes accidentally) Early Ordovician meta-igneous rocks were also revealed. The petrology, geochronology, and geotectonic interpretations of the studied igneous formations as well as their significance in the local to regional correlations are summarized below, in the *Results* section of this report.

Traditionally, the pre-Cenozoic basement of the eastern Pannonian Basin belongs to the Codru Nappe System (Békés–Codru Unit) of the Tisza Mega-unit. Alternatively, crystalline basement parts of the Algyő High were included into the Biharia Nappe System, i.e. into the Dacia Mega-unit. An important aspect of the Apuseni Mts is, however, the presence of a Variscan greenschist shear zone between the Codru and Biharia Nappe Systems with Alpine overprint, named as Highiș–Biharia Shear Zone, which was previously referred to as the Upper Silurian to Lower Carboniferous Păiușeni assemblage including metaconglomerates and metasandstones. Interestingly, this Palaeozoic series was tentatively correlated with the metaconglomerate core sections in the Szeged–Ásotthalom basement area (Algyő High and its surroundings). This ongoing controversy about the origin, paleogeographic situation, and tectonic position of the Păiușeni assemblage also indicates that the evolution of the south-eastern part of the Tisza Mega-unit is still not fully understood. Genetic relationships of the Păiușeni Series are rather poorly understood and contradictory interpretations are known in the literature. Consequently, further investigations could be fruitful to unravel the questions regarding its metasedimentary or sheared metamagmatic origin. The importance of identification of the possible Alpine shearing zone in this area, with regard to fluid pathways in the basement, cannot be overemphasized. Additionally, the basement rocks of the Biharia Nappe System comprise several dolomite and calcite marble sequences or lenses which suffered deformation and metamorphic overprint during the Alpine orogeny. New Sr, O, and C-isotope data in combination with considerations from the lithological sequences indicate, at least partly, Middle to Late Triassic deposition of precursor carbonate sediments of the marbles from the Biharia Nappe System. In the Algyő High (Dorozsma area) a few-tens-of-meter-thick marble zone also occurs belonging to a shear zone. Furthermore, Lower and Middle Triassic rocks were explored at the uplifted basement highs (Algyő, Battonya) which are thought to be a

continuation of the Codru Unit. In the SE part of the basement of the Pannonian Basin, shallow marine Triassic dolomites (Szeged Dolomite Formation) were extensively investigated during the last years at the host institution. This research on the Szeged Dolomite revealed that, in addition to multistage dolomitization, metamorphogenic (and/or magmatic) hydrothermal fluids played an important role in the evolution of the porosity and that these fluids were probably channeled along the Upper Cretaceous subhorizontal overthrust zones. As a continuation of this research, sampling, and examination of lithotypes of the Bulz and Sohodol Formation from the Apuseni Mts yield a good chance for a correlation study. Complex investigations obtain relevant information on provenance, paleoclimate and tectonometamorphic evolution. The new data serve as a key regarding correlation between the different Permo-Triassic sites of the SE part of the Tisza Mega-unit.

Materials and Methods

Samples (sampling campaigns, drill cores)
Three sampling campaigns were conducted in the Apuseni Mts, targeting the Highiş granites and the Codru granodiorites (SW Apuseni Mts, 2020); the gabbros, diorites, and associated subvolcanic rocks in the Highiş massif (SW Apuseni Mts, 2021); and the Permian basalts and andesites in the western Apuseni Mts (2021). In addition to the original research plan, Variscan orthogneisses were also collected in the Papuk Mts (2021) as well as two-mica granitoid pebbles from the Miocene conglomerate in the Western Mecsek Mts (2023). Regarding the Middle Triassic dolomites, an intense sampling campaign was performed in the Apuseni Mts including Bulz and Sohodol Formations (2022). Samples representing theAlgyő–Ferencszállás Basement High were provided by the drill core depository of the MOL Plc (2022), and some additional core samples and separates derive from the Mecsekérc Ltd (2023). A significant proportion of the samples were collected during previous campaigns (including Paiuşeni Complex, and middle Triassic dolomites of Galşa and Măderat) or derive from the collections of the host institute (e.g. core samples from the Dorozsma High, and Kelebia area). Further details regarding origin and collection of the samples are available in the related papers, see *Results*.

Petrography (thin sections, SEM)
Petrographic analyses were performed at the host institute (polarizing microscopy) and at the Department of Petrology and Geochemistry, Eötvös Loránd University as well as the HUN-REN Centre for Energy Research (scanning electron microscopy). Altogether 188 pieces of thin sections were studied among which 57 represent Permian felsic volcanic rocks, 15 represent Permian A-type granites and felsic dykes, 48 represent Permian mafic–intermediate plutonic and volcanic rocks, 61 represent Variscan S-type granitoids, and 7 represent Ordovician metagranitoids and orthogneisses.

X-ray powder diffractometry
Determination of the bulk mineralogical composition and characterization of the separated <2 μm grain size fraction of the representative samples was made by X-ray powder diffractometry (XRPD) at the host institute. The selected samples were measured by a Rigaku Ultima IV X-ray diffractometer using Bragg-Brentano geometry. Random powder mounts were made using ~0.04 g rock powder on a Si single crystal sample holder to determine the bulk mineralogical composition. The qualitative and semiquantitative evaluation of the XRPD spectra was performed using the Rigaku PDXL 1.8 software (ICDD database, PDF2010) and estimated based on the reference intensity ratio method, respectively. Grain size separation for clay fraction (<2 μm) analysis was achieved by repeated ultrasonic deflocculation and gravitational settling using Stokes' law. Highly oriented XRPD slides with 3mg/cm^2 density were prepared

by repeated sedimentation of the separated fraction on a standard glass sample holder. Both air-dried and ethylene glycol-solvated preparations were scanned, and subsequently, the mounts were treated at 350 and 550°C and measured immediately after storage in a desiccator. For the determination of illite and chlorite "Crystallinity Index" and calculation of crystallite size, a triplicate scan of the same slide was run. The determination of "crystallinity" was made using the Crystallinity Index Standards (CIS) and the Kübler and Árkai Indices were calculated after the international recommendations. Additionally, the illite crystallite size was determined by a routine single peak method (on the 001 reflection of the K-white mica) using the Scherrer equation embedded in the PDXL 1.8 software. For differentiation between K-, Na-, and Ca-rich white micas, the XRPD (00,10) basal reflections around 2Å were checked using highly the oriented slides. For a better resolution and precise determination of the position of the 00,10 K-white mica peaks, triplicate analyzes were performed. Additional details of instrumental conditions and analytical quality are available in the related papers, see *Results*.

Electron microprobe analysis
The composition of tourmaline grains from the Covăsinţ section was established with a JEOL JXA-8600 electron microprobe, upgraded by SAMX control, in wavelength-dispersive mode (WDX) at the Institute of Exploration Geosciences of the University of Miskolc, Hungary.
An operating voltage of 20 kV and a probe current of 20 nA were used. The following standards were used: quartz (Si USNM R17701), ilmenite (Ti and Fe USMN 96189), corundum (Al USNM 657S), MnS_2 (Mn synthetic), olivine (Mg USNM 111312/444), Cr-augite (Ca USNM 143965), anorthoclase (Na USNM 133868), orthoclase (K MAC 14024), and LiF (F synthetic). PAP correction was used for concentration calculations of the WDX analyzes.

Mössbauer spectroscopy
For a high quality characterization of four selected Fe-rich phyllosilicate separates (<2μm grain size) from the Paiuşeni Complex, Mössbauer spectroscopy measurements were run at the Institute of Chemistry of the Eötvös Loránd University, Budapest.

Whole-rock geochemistry
Whole-rock major and trace element geochemical analyses were performed at the Bureau Veritas Mineral Laboratories (AcmeLabs, Vancouver, Canada) using ICP-MS and ICP-ES methods. Altogether 96 new whole-rock geochemical analyses were carried out among which 8 represent Permian A-type granites and felsic dykes, 35 represent Permian mafic–intermediate plutonic and volcanic rocks, 50 represent Variscan S-type granitoids, and 3 represent Ordovician orthogneisses. Additionally, a total of 24 samples representing the Paiuşeni Complex and the Triassic siliciclastics were analyzed in the mentioned laboratory.

Zircon U–Pb geochronology
Zircon crystals were separated at Department of Petrology and Geochemistry, Eötvös Loránd University and U–Pb dating occurred at the GÖochron Laboratories, Georg-August University, Göttingen using LA–SF–ICP–MS. Altogether 25 samples were dated among which 14 represent Permian felsic volcanic rocks, 3 represent Permian A-type granites, 2 represent Permian diorites, 4 represent Variscan S-type granitoids, and 2 represent Ordovician metagranitoids and orthogneisses. Additional zircon separation and U–Pb dating from the drill cores of the Algyő–Ferencszállás Basement High (3 samples) and from the granitoid pebbles, Western Mecsek Mts (2 samples) are in progress.

K–Ar geochronology

The geochronology of K–Ar isotopes was performed on selected samples, rich in K, at the Geochronology Laboratory of the Institute for Nuclear Research, Debrecen, Hungary. For mica-rich samples, whole rock and separated size fractions were also measured. Both the <2 μm and <1 μm size fractions were separated from the aqueous suspension after ultrasonic disaggregation. Details of the analytical processes and quality control are described in the related papers, see *Results*.

Heavy mineral analyses
Heavy mineral separation occurred at the Department of Petrology and Geochemistry, Eötvös Loránd University as well as at the Archeometry Laboratory, National Archeological Institute of the Hungarian National Museum, while analyses (targeting 9 samples altogether) are being performed by the latter institute.

Results

1. Permian felsic volcanism in the Tisza Mega-unit: petrology, geochronology, and correlations
Permian felsic volcanic rocks are widespread in the Tisza Mega-unit, including southern Transdanubia (Western Mecsek Mts, northern foreland of the Villány Mts, Máriakéménd–Báta area), the eastern Pannonian Basin (Kelebia area, Battonya–Pusztaföldvár Basement Ridge), and the western–central Apuseni Mts (Codru-Moma, Bihor, and Highiş Mts). The studied samples of southern Transdanubia, the Kelebia area, and the Apuseni Mts are dominantly crystal-rich, rhyodacitic–dacitic pyroclastic rocks (non-welded to strongly welded lapilli tuffs); lavas (northern foreland of the Villány Mts) and subvolcanic rocks (northern foreland of the Villány Mts, Highiş Mts) are subordinate. On the other hand, the Battonya–Pusztaföldvár Basement Ridge is represented by crystal-poor, rhyolitic pyroclastic rocks (welded lapilli tuffs, rheoignimbrites, lava-like ash tuffs) and volcanogenic sedimentary rocks. In general, the studied rocks were affected by various types and degrees of post-magmatic alterations including hydrothermal sericitization (majority of them), carbonatization and albitization of feldspar, and mylonitization under greenschist to subgreenschist facies (Kelebia area, SW Apuseni Mts), the effect of which has been considered during the interpretation of the primary magmas; and post-magmatic textures and secondary phases (e.g., illite) provided precious information about the conditions and the age of the Alpine (~98–80 Ma) deformation and metamorphism. Numerous whole-rock major and trace element analyses and zircon U–Pb dating suggested that all the studied felsic volcanic rocks belong to the same, relatively short-lived, anorgenic, rift-related felsic volcanism in the Middle Permian (~271–259 Ma) and regionally show correlation with the analogous formations in the Western Carpathians (Gemeric and Silicic Units). In a local to subregional scale, correlations are suggested between the petrographically unique, garnet-bearing felsic pyroclastic rocks of the northern foreland of the Villány Mts (Villány–Bihor Unit) and the Codru-Moma Mts (Codru Nappe System) that contradicts to the traditional, Alpine evolution-based subdivision of the mega-unit. Moreover, the common occurrence of low-grade metamorphic pyroclastics in the Kelebia area (Békés–Codru Unit, according to the traditional subdivision) suggests the correlation of the latter with the Biharia Nappe System where similar formations also occur.
These results were published in ***Central European Geology***, JCR: Q3 (Battonya–Pusztaföldvár Basement Ridge) and in ***Lithos***, JCR: Q1 (Apuseni Mts, eastern Pannonian Basin, southern Transdanubia).

2.1. Permian A-type granites: regional correlations and feasible plutonic–volcanic connections in the Tisza Mega-unit

Permian A-type syenogranites accompanied by subvolcanic microgranites and crosscut by aplite veins occur in the Highiş massif, SW Apuseni Mts as part of the anorogenic, bimodal Highiş igneous complex that consist of gabbros, diorites to alkali-feldspar granites (Bonin and Tatu 2016). As previous zircon U–Pb dating (Pană et al. 2002) of the Jernova porphyritic microgranite yielded similar age (~265 Ma) to that of the studied Middle Permian, rift-related felsic volcanic rocks (~271–259 Ma), further petrological and geochemical investigations as well as zircon U–Pb dating were carried out on the Highiş granites, focusing on the possibility of plutonic–volcanic connections and the regional correlation of the A-type granites. The studied samples of the Highiş granites have peraluminous, subalkaline, alkali-calcic or calc-alkali, and ferroan character, and their trace element compositions refer to the partial melting of the continental crust in an extensional setting (continental rifting in the Paleo-Tethyan realm). Zircon U–Pb dating of the medium-grained syenogranites yielded main zircon crystallization ages between 268 and 263 Ma that fairly overlap with the previous results (Pană et al. 2002) and the recently obtained age of the Permian felsic volcanism in the Tisza Mega-unit (e.g., Szemerédi et al. 2020). Moreover, the Highiş granites also show very similar (practically indistinguishable) trace element compositions with the studied Permian felsic volcanic rocks in the Tisza Mega-unit suggesting that they are most possibly in a plutonic–volcanic connection with the latter. Further connections were presumed among the gabbros and diorites of the Highiş igneous complex and the mafic–intermediate lavas (basalts to andesites) in the western Apuseni Mts (Codru-Moma Mts, Nicolae et al. 2014) that initiated the sampling, petrographic and geochemical investigations of the latter. In a regional scale, the Highiş granites and the most possibly associated felsic volcanic rocks proved to be significantly younger (~270–260 Ma) than the similar episodes in the stable Europe (~300–290 Ma), however, showed correlations with the analogous formations in the Western Carpathians (felsic volcanic rocks in the Gemeric and Silicic Units and A-type granites in the Veporic Unit and the Pieniny Klippen Belt).
These results were published in ***Geologica Carpathica***, JCR: Q2.
References:

Bonin, B., Tatu, M., 2016. Cl-rich hydrous mafic mineral assemblages in the Highiş massif, Apuseni Mountains, Romania. Mineral. Petrol. 110, 447–469.

Nicolae, I., Seghedi, I., Bobos¸, I., Azevedo, M.R., Ribeiro, S., Tatu, M., 2014. Permian volcanic rocks from the Apuseni Mountains (Romania): geochemistry and tectonic constrains. Chem. Erde 74, 125–137.

Pană, D.I., Heaman, L.M., Creaser, R.A., Erdmer, P., 2002. Pre-alpine crust in the Apuseni Mountains, Romania: insights from Sm-Nd and U-Pb data.

Szemerédi, M., Lukács, R., Varga, A., Dunkl, I., Józsa, S., Tatu, M., Pál-Molnár, E., Szepesi, J., Guillong, M., Szakmány, Gy, Harangi, Sz, 2020. Permian felsic volcanic rocks in the Pannonian Basin (Hungary): new petrographic, geochemical and geochronological results. Int. J. Earth Sci. 109, 101–125.

2.2. Permian A-type granites: examination of metasomatic processes of the boron-rich open greisen system in the Highiş granitoids

The objective of this investigation is to reveal the main metasomatic effects and paragenetic sequences of related mineralizations in the Highiş granitoids, SW Apuseni Mountains. In a natural outcrop, more than 30 samples were collected from granitoids, felsic veins, and country rocks. We carried out a detailed mineralogical and petrological characterization of carefully selected samples using X-ray powder diffractometry, electron microprobe analysis, and microscopic methods together with K–Ar ages of whole rocks and K-bearing minerals. Several characteristic features of albitization, sericitization, tourmalinization, epidotization, and hematitization were recognized in the studied samples. Crystallization of quartz, K-feldspar, and magnetite represents the first stage during the magmatic-hydrothermal transition. The

mineral assemblage of albite, sericite, schorl, and quartz originates from the early and main stages of greisenization. While the subsequent mineral assemblages, which predominantly include dravite, specular hematite, and epidote, are closely related to the late vein-depositing stage. We propose that the study area could belong to a boron-rich open greisen system in the apical portion of the A-type Highiş granitoids of Guadalupian age. In the contact aureole, spotted schists with presence of porphyroblastic biotite and cordierite occur. The observed mineralogical assemblages together with the petrographic features show that the thermal mineral assemblages were overprinted by greisenization. Furthermore, exogreisen deposits developed in both pelitic and mafic rocks in the study area. Based on a new hypothesis, the previously published Permian crystallization ages (between ~272 Ma and ~259 Ma) could be homogenized and/or partially rejuvenated during the hydrothermal mineralization processes due to uraniferous vein minerals. Additionally, the studied system related to the Highiş granitoids suffered a Cretaceous thermal overprint (between ~100 Ma and ~96 Ma). The results may help to understand the evolution of highly evolved granite intrusions worldwide and improve our knowledge of the effect of hydrothermal mineralization processes on the emplacement ages.
These results were published in ***Minerals***, JCR: Q2.

3. Permian mafic–intermediate rocks in the Tisza Mega-unit and their connection with the Permian felsic magmatism
In the Highiş massif (SW Apuseni Mts) gabbros, diorites and mafic–intermediate dykes (microgabbros and microdiorites) occur, being associated with the Highiş granites (Bonin and Tatu 2016) as part of the Middle Permian (268–263 Ma) anorogenic, rift-related bimodal magmatism. The detailed petrographic observations of gabbros and microgabbros revealed at least two main phases of post-magmatic alterations (that were basically not detectable in the case of the granitoids), including (1) an early metasomatic affect, by fluid exsolution after emplacement and during cooling, that resulted in the alteration of primary clinopyroxene to amphibole and (2) Alpine deformation and low-grade metamorphism that resulted in a secondary mineral assemblage of sericite, albite, epidote, and chlorite. Therefore, the petrogenetic interpretation of the mafic–intermediate rocks were conducted on relatively immobile trace elements (HFSEs, e.g., Ti, Zr, Y) that supported the within-plate (anorogenic) origin of these rocks. Very similar, but less fractionated trace element patterns of the studied (micro)gabbros and (micro)diorites further supported that they are cogenetic with the Highiş granites, and the zircon U–Pb dating of the Cladova diorites yielded ~265 Ma that overlaps well with the age of the A-type granite magmatism (268–263 Ma). Furthermore, basalts and andesites were collected in the Codru-Moma Mts (following the sampling strategy of Nicolae et al. 2014) and observed in the light of potential volcanic–plutonic connections with the Highiş gabbros and diorites. These mafic–intermediate lavas were also affected by the Alpine tectonic events that resulted in a secondary assemblage of sericite and chlorite, replacing plagioclase and mafic minerals, respectively. Their rare earth and other immobile element patterns are very similar to those of the Highiş gabbros and diorites suggesting further feasible plutonic–volcanic connections in a Middle Permian complex, cogenetic magmatic system.
These results (in prep) will be submitted to ***Geologica Carpathica***, JCR: Q2.
References:
Bonin, B., Tatu, M., 2016. Cl-rich hydrous mafic mineral assemblages in the Highiș massif, Apuseni Mountains, Romania. Mineral. Petrol. 110, 447–469.
Nicolae, I., Seghedi, I., Bobos¸, I., Azevedo, M.R., Ribeiro, S., Tatu, M., 2014. Permian volcanic rocks from the Apuseni Mountains (Romania): geochemistry and tectonic constrains. Chem. Erde 74, 125–137.

4. Variscan S-type granitoids in the Tisza Mega-unit: petrology, geochronology, and correlations

Varican S-type granitoids occur in various parts of the Tisza Mega-unit including the western Apuseni Mts (Codru Nappe System), the Battonya–Pusztaföldvár Basement Ridge and the Algyő–Ferencszállás Basement High in the eastern Pannonian Basin, as well as pebbles in the Miocene conglomerate (Szászvár Fomation) in the Western Mecsek Mts. Despite the petrographic similarity of the abovementioned formations, all of which are leucocratic, medium- to coarse-grained, two-mica granodiorites or monzogranites that often have deformed, weakly to strongly oriented (even gneissic) texture, they have never been compared to each other on detailed petrographic, whole-rock geochemical or zircon U–Pb geochronological basis. Petrographic (e.g., lack of mafic enclaves, primary muscovite, accessory monazite, occasionally garnet or andalusite) and geochemical features (e.g., high Al_2O_3, SiO_2, K_2O, and Rb contents, low CaO and Sr contents, peraluminous character, weak to moderate negative Eu anomaly) of all the studied granitoids suggest that they represent continental crustal melts in a Variscan syn-collisional setting (~356–343 Ma based on the zircon U–Pb dating of granitoids from the SW Apuseni Mts and the Battonya–Pusztaföldvár Basement Ridge) and they were affected by post-magmatic alterations (e.g., sericitization, chloritization) and Alpine deformation (and metamorphism) in various ways and degrees. Despite the general similarity, some unique petrographic features (e.g., plagioclase textures, presence of andalusite), the concentrations of several major and trace elements, and chondrite-normalized rare earth element patterns discriminate two unequivocal groups of the studied S-type granitoids. Granodiorites of the SW Apuseni Mts (Codru Nappe System) show strong correlation with the monzogranites and granodiorites of the Battonya–Pusztaföldvár Basement Ridge (Békés–Codru Unit) which most probably belong to the same Variscan magmatic episode. On the other hand, the samples of the Algyő–Ferencszállás Basement High (Biharia Nappe System or Villány–Bihor Unit according to the most recent tectonic interpretations) differ from the latter (e.g., in their higher SiO_2, K_2O, and Rb contents, distinct REE patterns, deeper negative Eu anomaly), but fairly match with the two-mica granite pebbles in the Miocene conglomerate of the Western Mecsek Mts the origin of which has been enigmatic so far. The latter might suggest that a basement block of similar assemblages with the Algyő–Ferencszállás Basement High was quickly (and probably completely) eroded south from the Mecsek Mts during the Miocene. For correlational studies further zircon U–Pb dating are in progress and, as a new (and barely used) correlational tool, heavy mineral analyses are carried out on the samples of all the studied areas. These results (in prep) will be submitted to ***International Journal of Earth Sciences***, JCR: Q1.

5. Ordovician orthogneisses and metagranitoids in the Tisza Mega-unit: petrology and geochronology

Orthogneisses were collected in Djedovica quarry, Papuk Mts to compare them to the petrographically similar Variscan S-type granitoids in the Tisza Mega-unit (western Apuseni Mts, Battonya–Pusztaföldvár Basement Ridge, Algyő–Ferencszállás Basement High, Western Mecsek Mts). Despite the similar mineralogical composition (quartz, plagioclase, K-feldspar, biotite, and muscovite) and the oriented (gneissic) texture, the samples of the Papuk Mts showed significant geochemical differences (e.g., higher SiO_2 and HFSE contents and a strong negative Eu anomaly) with the Variscan two-mica granitoids in the other areas of the Tisza Mega-unit, and they form a well-visibly distinct group. However, according to the mineralogy and geochemical composition, the Djedovica samples are most possibly syn-collisional, as well. Preliminary zircon dating yielded an Early Ordovician (~480 Ma) age for the granite magmatism, while metamorphism might have occurred during Variscan times. Interestingly, from the Bihor Mts (Biharia Nappe System) a strongly deformed metagranitoid sample (collected during a previous sampling campaign which focused on the Permian felsic

pyroclastic rocks) yielded very similar age (~478 Ma) that shows the presence of not only Permian and the widespread Early Carboniferous, but also Ordovician granitoids in the basement of the Tisza Mega-unit even if the latter are relatively sporadic (Bihor and Papuk Mts).
The results of the metagranitoids, Bihor Mts (in prep) will be submitted to ***Carpathian Journal of Earth and Environmental Sciences***, JCR: Q3, while those of the Djedovica orthogneisses to ***International Journal of Earth Sciences***, JCR: Q1.

6. Mineralogical and petrographic characterization of the Permo-Triassic noncarbonate cover succession in the Kelebia basement area (Szeged Basin, S Hungary): consequences regarding Alpine evolution of the SE Pannonian Basin.
This research focuses on understanding of the major effects of diagenetic to metamorphic overprint on the mineralogy and micropetrographic features of three Permo-Triassic lithologies (Permian siliciclastics and ignimbrites, as well as Triassic sandstones) located in the pre-Cenozoic basement, Codru Nappe System (Szeged Basin, Hungary). Mineralogical and petrological data suggest that the Permo-Triassic noncarbonate cover succession in the Kelebia basement area suffered a high anchizonal to epizonal metamorphic alteration after their deposition. Additionally, several deformation features were recognized in the studied samples, showing a weakly to moderately developed disjunctive foliation in the Permian rocks. The occurrence of deformation lamellae in quartz overgrowth cement together with quartz veinlets and fluid inclusion plains in Lower Triassic quartz arenite clasts indicates that the time of ductile and brittle deformation and contemporaneous fluid migration was before the Early Miocene partial surface exposure. Most likely, Cretaceous orogenic events favored the prograde reaction series of phyllosilicates (~300°C temperature for the peak metamorphism), instead of the depth of burial. We propose that the "Turonian" phase (Early–Late Cretaceous nappe stacking) resulted in the prograde greenschist facies metamorphism in the study area. Furthermore, the Permo-Triassic cover succession of the Codru Nappe System was also affected by shearing episodes along the contact zone between the Tisza and Dacia megaunits.
These results were published in ***Geofluids***, JCR: Q3; an additional related paper dealing with petrography and deformation characteristics of the quartz arenites was published in ***Földtani Közlöny***, JCR: Q4).

7. New petrographic observations on the basement rocks of Dorozsma High (SE Hungary): insights into metamorphic and structural evolution of a dolomarble cataclasite zone.
The Dorozsma High structurally comprises metamorphic basement blocks with different P-T-d histories. The contact along with the blocks is an intensively deformed, few-meter thick dolomarble zone. Mg-chlorite and phlogopite occur along with dolomite, which documents migrational dynamic recrystallization, suggesting a low-to-medium temperature (350°C−420°C) metamorphism and deformation. Calcite protomylonites and marble mylonites developed within the lithology due to an intensive ductile deformation which associated with migrating hydrothermal fluids during the Cretaceous. Later in the Miocene, the extensional tectonics resulted in multistage brittle deformation of the studied rock assemblages. This deformation event produced cataclasites and breccias containing substantial amount of silicate clasts, which were probably derived from the surrounding metamorphic blocks. The breccias and cataclasites are mostly cemented by dolomite + quartz + calcite. The pore-filling dolomite and calcite host cogenetic, aqueous and petroleum-bearing fluid inclusions, recording hydrocarbon emplacement. Besides them, solid bitumen with flow textures and framboidal pyrite also occur in the pore spaces of the samples. These observations are further supported by oil-producing intervals of the wells coincide with this dolomarble zone (in prep, it will be

submitted to ***Geoenergy Science and Engineering,*** formerly known as Journal of Petroleum Science and Engineering, with a 2022 IF of 4.4, JCR: Q1).

8. Mineralogical, petrographic and geochronological examinations of the Paiuşeni Complex (Highiş Mountains, SW Apuseni Mountains).
The lower part of the Biharia nappe system were affected by repeated shearing events manifested in the formation of deformed rocks including phyllonites known as Paiuşeni Complex. In the frame of the present research project, representative samples from the Şiria Fortress and Covăsinţ SE sections were investigated. Characteristic features were documented regarding both major rock suites of the complex, i.e. foliated felsic and metabasic rocks, as a result of a detailed micropetrographic analysis. Both sedimentary and magmatic precursor lithologies were identified. Furthermore, textural evidences of deformational processes and pervasive metasomatism were documented. A detailed XRPD-based mineralogical study yielding the first calibrated illite crystallinity data from the complex was performed. The Esquevin index values demonstrate a rather wide range of composition of illite-mica independently from the locations and rock types. Calibrated Kübler indices together with the calculated main apparent crystallite size values show that crystallization of the illite-mica and chlorite of the clay fraction occurred under epizonal to transitional anchi/epizonal conditions. In order to specify the type of the iron-bearing constituents of these layer silicate-rich rocks, e.g. degree of the celadonite substitution in the K-white mica and type of chlorite, Mössbauer spectroscopy was used as an effective and independent analytical method. Additionally, a detailed whole rock major and trace element geochemical analysis was accomplished in order to recognize the types of the precursor lithologies and the fingerprint of the fluid-controlled alteration effects, including metasomatism. Geochronological data measured on clay-sized illite-rich concentrates from the foliated felsic rocks show middle Cretaceous K–Ar ages (in prep, it will be submitted to ***International Journal of Earth Sciences;*** JCR: Q1).

9. Mineralogical, petrographic and geochronological examinations of the Cladova Formation (Highiş Mountains, SW Apuseni Mountains).
In the northern part of the Highiș Mountains, black-colored contact metamorphosed rocks occur along the boundaries of intrusive Permian granitoid bodies (Cladova Formation). According to the different authors, the entire contact metamorphic series is interpreted to be formed from either a basaltic or sedimentary precursor. On the basis of our new XRPD observations, the massive hornfels samples are composed of albitic plagioclase, biotite (probably close to the phlogopite endmember), white mica, hematite, and quartz. In pelitic hornfels, locally showing relic sedimentary lamination, albitic plagioclase, white mica, quartz, chlorite, cordierite, hematite, and biotite are the detected minerals. According to the micropetrographic observations, the albite-biotite hornfels is fine-grained
and massive with a granoblastic texture. It consists of albite and biotite as major minerals with disseminated opaque grains (most likely hematite), which are also common and locally limonitized. Tourmaline occurs in nests or forms dark clots that show a close textural relationship with plagioclase, quartz, biotite, epidote, and hematite. Another type of the studied hornfels is a dark gray to black rock, showing a spotted porphyroblastic texture with cordierite porphyroblasts. Additionally, foliation and primary bedding, a clear indication of sedimentary origin, were documented. Geochronological investigations, performed on phlogopite-rich concentrate separated from a hornfels sample, yielded middle Cretaceous K–Ar ages.
The results were published in ***Minerals***, JCR: Q2.

10. Petrographic and stratigraphic examinations of Anisian dolomites (Bulz and Sohodol Dolomite Formations) from the Codru nappe system, Apuseni Mountains.

Following the research plan, characteristic lithologies of the Anisian dolomite succession of the Codru nappe system were sampled and investigated from the Galşa section and the Măderat quarry (Highiş Mountains; Bulz Dolomite Formation of the Finiş Nappe), from a single outcrop of the Valea cea Mică ("Little Valley") section (Codru-Moma Mountains; Bulz Dolomite Formation of the Dieva Nappe), and from the road cut S of Sohodol village (Pădurea Craiului Mountains; Sohodol Dolomite Formation of the Finiş Nappe). According to the field petrographic observations, the Sohodol Dolomite comprises thick-bedded, coarse-grained, more or less brecciated gray dolomite, while the Bulz Dolomite is characterized by thin-bedded, dark gray–black dolomite. The first documentation of the microfacies and some microfossils from this shallow marine carbonate sediment is linked to the present research. Fine- to coarse-crystalline dolomites are predominant, and both fabric-destructive and partially fabric-retentive dolomite textures were documented. In the case of the fabric-retentive dolomites, some of the original textural elements, including microbial boundstone texture and fenestral pores, can be observed. In order to clarify the diagenetic history of the studied carbonate bodies, stable isotopic composition of the calcite and dolomite cement phases from the well-developed fracture porosity and the matrix dolomite was determined. As far as the micropaleontological results are concerned, from some samples of the Galşa section representing fabric-retentive dolomite, a well preserved Dasycladacean green algae assemblage was identified. The microfossils of the Bulz Dolomite Formation from Măderat are predominated by foraminifers indicating a backreef lagoon depositional environment. A detailed comparison of the studied Anisian dolomites of the Apuseni Mountains, including depositional environment and diagenetic history as well, with those from the different parts of the Tisza Mega-unit (Mecsek and Villány area and Szeged Basin) is in progress.
Publications of the results are in preparation as follows:
1) The results of the petrographic analysis and micropaleontological observations will be submitted separately to ***Central European Geology;*** JCR: Q4;
2) The results of the micropetrographic and stable isotope analysis of the material of the carbonate vein system with tectonic interpretation will be submitted to ***Journal of Structural Geology;*** JCR: Q1;
3) The detailed correlation of the Anisian dolomites from the different parts of the Tisza Mega-unit with special regard to the correlation and the diagenetic processes will be submitted to ***Marine and Petroleum Geology***; JCR: Q1.

Cooperative partners

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Publication list

Jákri, B., Szemerédi, M., Dunkl, I., Kovács, Z., Pál-Molnár, E. (2023): Variszkuszi, S-típusú granitoidok a Codru-takarórendszerben (Erdélyi-khg.): a Galsai pluton kőzettani-geokémiai vizsgálata és korrelációja a Tiszai-főegységben, conference abstract, ***13th Assembly of Petrology and Geochemistry***, Szekszárd, p. 7.

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Scientific dissemination

During the project several TV, radio, and press interviews and reports occurred for scientific dissemination purposes providing information to a much broader and more general audience than the narrowest scientific society. Some of the latter (all available online) are listed below.

Délmagyar: https://www.delmagyar.hu/helyi-kozelet/2022/12/nemzetkozi-kutatas-kereteben-vizsgaljak-a-del-alfold-melyen-talalhato-vulkanokat-az-szte-geologusai

Kossuth Rádió: https://drive.google.com/file/d/1pj8oU7zWq2vvr1D802GdQlIS8m0IUfyt/view?usp=sharing

National Geographic: https://ng.24.hu/termeszet/2023/02/24/tobb-millio-eve-kihult-vulkanok-a-del-alfold-sik-felszine-alatt/

Szeged TV, Kvantum: https://www.youtube.com/watch?v=a0aFdv4YzMs

University of Szeged: https://u-szeged.hu/sztevulkankutatas?objectParentFolderId=19396