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Smolenice, Slovakia, June 7–10th, 2023

Edited by Igor Broska, Friedrich Finger and Jiří Žák

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Cover photo:
Cross-cutting pegmatite veins within the Variscan Bratislava granite massif indicate two principal directions of late-stage magma emplacement (Malé Karpaty, Zuckermandel). Photo J. Madarás.

Content

Forword

The Earth Science Institute of the Slovak Academy of Sciences was asked to prepare the 5th Bohemian Massif meeting which follows the previous successful meetings organized by Austrian, Czech, and German researchers of Bohemian Massif in the Šumava/Böhmerwald in 2014 and 2016, in Presseck in 2018, and in Freistadt in 2021.

The aim of this traditional Bohemian Massif meetings is to bring together geoscientists to discuss the latest data from the research of classical Variscan terrains such as the Bohemian Massif and data from adjacent areas in order to obtain new ideas for correlation research.

Timing and evolution of the Variscan orogeny in adjacent areas to the Bohemian Massif are still not clear and intensively discussed for a long time. The role of the Rheic Ocean in the formation of the Variscan orogen and arc granites is without dispute. However, another possibility still cannot be excluded of evolution connected with northward subduction of Paleotethys beneath Galatian terrain which was opened by separation from the northern Gondwana margin.

The research of fragments of crystalline basements in the present Western Carpathians is permanent challenge to understand the evolution of this part of very long Variscan belt which is spread over recent Northern America, Europe and Asia. Many new datings, bulk rock analyses, and structural data gathered from the Western Carpathians and the Eastern Alps are subject for correlation research towards better understanding the Variscan structures in Central Europe. We feel that the symposia became a good base for initiation of a correlation program either via UNESCO network or some other cooperation scheme like Danube region.

After talks during five sessions of the symposia the excursions to the Malé Karpaty Variscan crystalline basement was organised to present the local Variscan evolution from the Lower Paleozoic to Carboniferous and followed products of the Permian rift-related regime. The second excursion organised to the Tríbeč Variscan basement presents the intensively Alpine overprinted Variscan granites forming a granite duplex.

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Rare metal A-type granites in Arabian Nubian Shield: Implications for origin and concentration of rare metals

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Neoproterozoic rare metal bearing A-type granitic rocks are sporadically exposed in the Arabian Nubian Shield (ANS). They commonly occur in post-collision and intraplate tectonic settings. Their source and petrogenesis can provide insights into post-collisional magmatic processes, composition and evolution of continental crust. The ANS rare-metal granites have gained a lot of attention because of their economic importance as sources of Nb, Ta, U, Zr, Th and rare-earth elements (e.g., Moghazi et al. 2015; Abdelfadil et al. 2022). Despite numerous studies and widespread ANS outcrops, their origin and geotectonic evolution and their related rare metal mineralization remain controversial. Genesis of A-type granite is a matter of debate; different models have been introduced to describe its origin. The first description for the generation of alkaline granite is from mantle-derived magmas (Litvinovsky et al. 2011). However, the significant role of crustal-derived material is still valid.

The Sikait–Abu Rusheid gneissose granite, as a case study, displays high SiO_2 and alkali and low CaO wt.%, TiO_2, FeO_t, and MgO contents. They are exhibiting ferroan, peraluminous feature (A/CNK <1.3–1.7). Moreover, they show strong negative Ba, P, Eu and Ti anomalies low Nb/Ta, K/Rb and Zr/Hf, high Y/Nb ratios and their REE patterns are characterized by distinct tetrad effects. They were crystallized under relatively low pressures (3.9–5.2 kbar) and low to moderate temperature (670–800 °C) from strongly oxidized magmas (log fO2= −19.69 to –20.50) at shallower crustal levels.

High-K peraluminous A-type gneissose granites from Abu Rusheid–Sikait area formed in post-collisional settings, have been assumed as being generated by melting of crustal source rocks via decompression following delamination of the lithospheric root.

Although numerous studies have shown that rare-metal granites were formed between 630 and 590 Ma, the majority of the rare-metal granites in ANS lack specific age dates. Accurate age dating of highly evolved rare metal granite in the ANS is often hindered by extreme hydrothermal overprints, which may disturb widely used radiometric systems such as Rb-Sr, K-Ar and Ar-Ar. In addition, zircon is commonly displaying high U contents because of metamictization. The EPMA U–Th–Pb dating on monazite in some locations (Abu Rusheid, Um Samra, Muweilha) yields a precise dating for some rare metal granites in the Arabian Nubian Shield (Abdelfadil et al. 2022). The obtained ages range between c. 640 to c. 590 Ma consistent with the recent geochronological studies of rare metal granites (U-Pb monazite dating of Abu Dabbab; Lehmann et al., 2020) and indicates that the post-collisional stage began after ~640 Ma in the north of the ANS.

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Variscan magmatism in the Western Carpathians with linkage to slab-breakoff? Implication from age data and mineralogy

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Recently summarised isotopic ages obtained from large spectrum of granitic rocks in the Western Carpathians points to time span 365–332 Ma (Kohút and Larionov 2021). New set of age data (SHRIMP, LA ICP MS and monazite U–Th–Pb) show probably narrower time span of Variscan granites formation in the Western Carpathians, typically Na rich calk- alkaline suites in sense Bonin et al. (2020), and moreover, there is an indication of their possible episodic formation. Episodic events clearly demonstrate age granite data indicated by the youngest West-Carpathians Visean granodiorites (347–342 Ma) from the Malá Fatra which heated the previously emplaced Tournaisian tonalite in age of 353 Ma – here in situ U–Pb zircon dating recorded an age of 353 Ma for zircon cores, but for rims an age of 342 Ma, which corresponded to the age of adjacent granodiorites (Broska & Svojtka 2020). Th/U ratio from older zircon cores shows a magmatic value of 1.0, whereas 0.2 identified in zircon rims most likely represents thermal imprint by fluids.

The granodiorites from the Malá Fatra crystalline basement with S-type affinity are quite homogenized or show features of melt mixing, which is evidenced by preserved of the relic plagioclase cores with basicity up to An 56 included in the plagioclases with typical intermediate basicity, quartz ocelli, and textural transitional between tonalitic and granodioritic rocks. Moreover, the presence of antiperthite records a higher temperature conditions during genesis than those that are usually shown in the Western Carpathian granitic massifs.

The data overall indicate a formation of granites from hot melt formed in deep lower crustal conditions. The deep levels of partial melting were in stability field of garnet in disequilibrium of plagioclase what reflects high Sr/Y and La/Yb ratios. Such “adakitic” *s.l.* signature is typical also for the Nízke Tatry granite suites. In general, increased temperature detected in granite formation assume high HREE residues and origin at reduced water contents (Ribeiro et al. 2016; Zellmer et al. 2012). The data indicate effects of slab break-off.

Slab break-off during subduction is an important factor in triggering of granite formation because it opened for long time way for large heat and fluid flow from the asthenosphere (Davis and von Blanckenburg 1995). It could have happened after the collision of lithospheric blocks during the Devonian period. Slab break-off had been accompanied by exhumation, crust melting and forming of diatexites during decompression within the high-grade metamorphic complexes (Janák & Lupták 1997). Diatexite dated in the area of Martinské Hole of the Malá Fatra shows age of 362±4 Ma (ICP MS dating, Broska et al. 2022) and in the Nízke Tatry age of 360.4±4 Ma (SHRIMP, Maraszewska et al. 2022). In this sense the main granitic masses were emplaced as (post)-collisional granites (Broska et al. 2022).

The new still unpublished data indicate main granite formation from the Devonian / Carboniferous boundary to lower / middle Visean stage. SHRIMP zircon ages obtained from the Malé Karpaty and Tribeč Mts along with published age of diorite from the High Tatra Mts, probably belong to the oldest granite pulses in age of ca 359 Ma. The early granitic phases occurred after massive plagioclase crystallisation and unique stability transfer from allanite - titanomagnetite accessory assemblage to monazite giving to granodiorites more pronounced S-type character by decrease of water activity. Collectively, I/S transition granite typology found in Western Carpathian magmatism is very widespread and manifest increased input of crustal material to the granite melts derived from anatexis of mixed mantle and lower crustal material. The most of age determinations in the Western Carpathians recently oscillated around 355–352 Ma which was recognised from the Modra Massif in the Malé Karpaty, Suchý, Žiar, Malá Fatra, Nízke Tatry, Vysoké Tatry Mts. The Visean pulse ca 347–342 m.y. seems to be the youngest and except of forming “granotonalite” resulted in leucogranites in sense of Castro (2013). In this view granite massifs in the Western Carpathians represent mostly composite plutons formed in several magmatic pulses.

To summarize presented data, the principal formation of large calc-alkaline granitic rocks in the Western Carpathians occurred probably mainly in the time range 362–342 Ma with peaks estimated on ca (1) 358–359 m.y, which is a phase with less developed tonalite-granodiorite suites, (2) 355–353 m.y, which is the time of culmination of granite origin,and (3) 347–342 m.y, which is an era formation of the granotonalites and leucogranites, probably with some metallogenetic aspects. The episodic granite formation is possibly connected with more pronounced episodic rising of asthenosphere as a main source of heat for melting of lower crust.

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Exhumation of the High Tatra Mountains and implications for the Western Carpathians (Slovakia)

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The High Tatra Mountains (HTM) in northern Slovakia represent an anomalous uplifted portion of basement in the Western Carpathians and offer an excellent opportunity to study arcuate orogenesis, deep crust exhumation, and the transition between thin-skinned shortening and basement-involved transcurrent deformation as the HTM is comprised of large granitic basement domain, offering insights into the ages and timescales of their magmatic evolution.

This study investigates the exhumation history of the HTM along the sub-Tatra fault east of Gerlachovský štít (Velická Dolina and Zelené Pleso region). New apatite and zircon U–Pb LA-ICP-MS track the Variscan magmatic evolution of the HTM, whereas hile apatite and zircon (U–Th)/He ages from granitoids, collected at different elevations, were analyzed to track the Cenozoic exhumation.

Samples with paired apatite and zircon U–Pb ages indicate rapid cooling following crystallization. For example, the oldest zircon U–Pb data from along the sub-Tatra fault in the easternmost part of the range yields an age of 361±5 Ma (Zsat 768 °C) and an apatite U–Pb age of 337±2 Ma (n=65, Tc 375–600 °C). The oldest zircon in a sample from the base of Lomnický štít is 355±5 Ma (Zsat 764 °C), and its apatite is 353.5±2.2 Ma (n=52).

Zircon (U–Th)/He ages are scattered with respect to elevation and spatial distribution, ranging from 47.8±5.6 Ma to 15.5±1.9 Ma. The (U–Th)/He apatite ages show apparent cooling from 28.2±4.9 Ma to 9.6±0.6 Ma, with younger ages at higher elevations. The apparent average exhumation rates derived from the age-elevation profile in the Velická Dolina region are inconsistent with a proposed rapid early Miocene exhumation pulse. Instead, an exhumation rate of 0.042 mm/yr from five apatite samples in this profile is estimated. We determined an estimated burial depth in two regions using the synthetic grain, multi-thermochronometric HeFTy inverse model. The Velická Dolina region achieved maximum burial at 8.25–6.4 km depth from ca. 35 Ma to 20 Ma, whereas those closer to Lomnický štít achieved a maximum burial from 7.5–5.2 km at ca. 40 Ma to 35 Ma. These results may have been influenced by lineaments that divide individually exhumed blocks in the High Tatra Mountains.

Overall, the results provide insight into quantifying and postulating exhumation patterns of overburden experienced during Paleogene accumulation from the middle Eocene through to rapid cooling during early and middle-Miocene tectonic unroofing. Final exhumation may have been induced by sinistral releasing bend uplift as recently as 10 Ma as evidenced by spatial trends in ages and by young ZHe aliquots in a region determined to show strike-slip stepover faulting.

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Unravelling the nappe stacking in the Eastern Mediterranean: The role of Permian detrital zircons

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The nappe pile of Crete consists of two different parts, which are separated by the Pindos suture. The lower part belongs to the External Hellenides. The upper part, referred to as Uppermost Unit, is commonly attributed to the Internal Hellenides. To shed light on the age and provenance of the Uppermost Unit, we determined the U-Pb age of detrital zircons of metasediments of the Preveli, Vatos, Greenschist and the ACC nappe, which are main constituents of the Uppermost Unit.

The Precambrian detrital zircons of all investigated metasediments display a typical Minoan-type age spectrum, with Edicacaran, Tonian-Stenian and Paleoproterozoic to Archean zircons, but with a Mesoproterozoic age gap (apart from Stenian). These zircons are characteristic for the NE margion of Gondwana.

The depositional age of the *Preveli metaconglomerate* is constrained to the early/middle Permian based on the U–Pb age of the youngest detrital zircon (308±6 Ma) and the middle to late Permian age of the Preveli marble (Bonneau & Lys 1978). Components of high-grade metamorphic rocks and large amounts of latest Devonian and Carboniferous detrital zircons suggest the Preveli metaconglomerate to be Variscan molasse.

Based on the youngest detrital zircon of the *Vatos quartzite* (291±6 Ma), the maximum deposition age (MDA) is middle Permian and thus significantly older than the Jurassic/Early Cretaceous MDA of the Vatos beds as constrained by fauna. For this reason, the quartzite should be part of a large olistolith within the Vatos beds, which is probably derived from the Preveli Unit.

The *Greenschist Unit* and the *ACC,* on the other hand, include late Permian and Mesozoic zircons, which extend until Jurassic and Cretaceous times. For this reason, their MDA is Jurassic or younger. The Triassic detrital zircon ages fit well with the age of felsic volcanic rocks of the Preveli Unit, which could have acted as source area. The late Permian zircons are particularly important, as these are entirely lacking in the External Hellenides, in the Pelagonian and in the Cyclades/Menderes domain. Late Permian rift-related igeneous rocks, on the other hand, are widely distributed in the Black Sea area (Istanbul Zone), the Strandja Massif and in the Romanian and Western Carpathians. These areas are also affected by late Cretaceous arc-type magmatism, which is well documented in the Pontides, Istanbul Zone, Strandja Massif, Sredna Gora, Southern Carpathians and the Apuseni Mountains (Banatitic Magmatic and Metallogenetic Belt). As late Cretaceous (Campanian) arc-type granitoids are also characteristic rocks of the ACC, the latter rocks should have been derived from these northern domains. The Istanbul Zone is free from Devonian and Carboniferous magmatism, and the detrital zircon age spectrum reflects an Amazonian affinity. For this reason this unit can be excluded as source area. The Strandja Zone, on the other hand, is well suited as source area. It includes late Permian and late Cretaceous igneous rocks and is partly affected by late Jurassic deformation and metamorphism (Okay & Nikishin 2015). Possible equivalents of the Uppermost Unit of Crete, previously situated in the Strandja Zone, might have been scraped off and shifted towards Crete by the southwestward movement of the Anatolian block. This movement is related to counterclockwise block rotation and dextral strike-slip along the North Anatolian Fault Zone (NAFZ) since Eocene times.

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The oriental versus the occidental Variscides and the role of the respective Cenerian and Cadomian precursor orogens

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The terminology "oriental and occidental Variscides" is introduced here and builds on the classic Galatia–Armorica terrane model of Von Raumer et al. (2013). It also includes, however, some significant modifications:

1) We tentatively define the Saxothuringian, the Tepla–Barrandian and the eastern Moldanubian Zone (Schwarzwald, Vosges, Bohemian Massif) as "occidental Variscides". We interpret these units as Africa-derived crust that was originally situated close to the Sahara metacraton due to the fact that relatively little Tonian/Stenian zircon detritus is found in comparison to Palaeoproterozoic zircons. Similar interpretations have been presented by Linnemann et al. (2004), Franke et al. (2017), Siegesmund et al. (2021) or Žák et al. (2023), but note that Von Raumer et al. (2013) assigned most of the Bohemian Massif to the Ligerian/Galatian terrane (i.e., the oriental Variscides, see below) and considered only the Saxothuringian Zone as Africa-derived.

2) We propose that the oriental Variscides comprise nearly all pre-the-Devonian intra-Alpine units as well as parts of the Massif Central and Iberia (Ligeria according to Von Raumer et al. 2013). The most diagnostic feature of the oriental Variscides seems to be the relative abundance of Tonian/Stenian detrital zircons. For instance, the frequency ratio of Tonian/Stenian (800–1200 Ma) to Palaeoproterozoic (1.6–2.5 Ga) detrital zircons is typically <0.3 in the Bohemian Massif but commonly >0.3, and often >1, in the Alps (see data compilation in Finger & Riegler 2023). These remnant Tonian/Stenian zircons are most likely derived from the Arabian–Nubian Shield (Dörr et al. 2015; Haas et al. 2020; Meinhold et al. 2021), which implies that the oriental Variscides had their ancestry in this region (therefore the term "oriental").

3) The oriental and the occidental Variscides underwent a significantly different tectonic evolution during the Early Palaeozoic and were probably part of two completely different precursor orogens, the Cadomian (CADO) and the Cenerian (CENO). We define the CADO, remnants of which can be studied throughout the occidental Variscides, as an Ediacaran–Cambrian Andean-type Gondwana coastal orogen ahead of the Sahara metacraton. Subduction activities in the CADO ceased in the early Cambrian and were replaced by an extensional setting, which resulted in the formation of an hyperextended passive margin (Žák et al. 2023).

The CENO, represented by rocks from the oriental Variscides, can be interpreted as a Gondwana coastal orogen ahead of the Arabian–Nubian Shield. It was akin to Alaskan-type and records subduction processes from the Ediacaran to the Ordovician (Zurbriggen 2015; Starijaš Mayer et al. 2023) perhaps intermittently even until the Devonian (Neubauer et al. 2022).

It is a highly puzzling question why the two proto-European peri-Gondwana orogens CENO and CADO had such different characteristics and tectonic evolutions despite their probable proximity in the Avalonian–Cadomian belt (Nance et al. 2008; Žák et al. 2023). A possible explanation is that they were at nearly right-angles to each other (Finger & Riegler 2023), as a consequence of the concave coastal embayment between NW and NE Gondwana (Fig. 1).

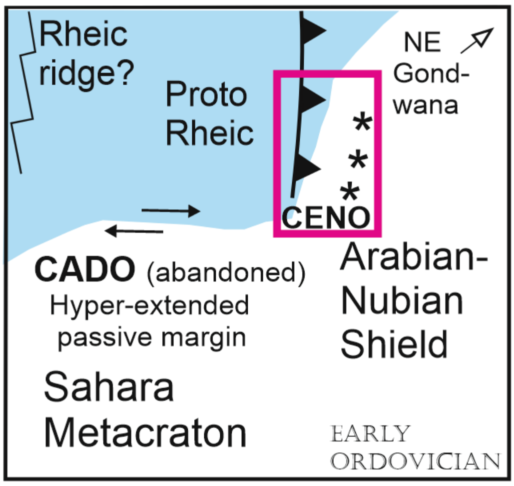

Fig. 1. Palaeogeographic sketch illustrating the inferred positions of the Cenerian (CENO) and Cadomian orogens (CADO) within north Gondwana during the early Ordovician. Modified after Stampfli et al. (2013) and using ideas of Žák et al. (2023). Stars highlight extension (back-arc rifting) inboard on the CENO (Nievoll et al. 2022).

In this interpretation, it can be envisaged that, as subduction came to an end in the CADO, the proto-Rheic oceanic crust continued to be subducted in the CENO. This resulted in subduction-accretion processes in the frontal parts of the CENO and a dextral transform regime in the CADO realm as the proto-Rheic oceanic plate moved east (Fig. 1).

Like Von Raumer et al. (2013), we postulate that after a major rifting event in the Devonian (opening of the Palaeotethys), the oriental and the occidental proto-Variscan units detached as terranes from main Gondwana and were subsequently juxtaposed via dextral strike-slip processes in the Carboniferous. Important parts of this major, hithertoo underrated, suture zone between oriental and occidental Variscides are now hidden under the northern front of the Alps (Finger & Riegler 2022).

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Magnetic fabric and emplacement of the Weinsberg Composite Pluton

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The late-orogenic granitoids of the Moldanubian Batholith (Moldanubian Zone; Bohemian Massif) carry an unique evidence of post-collisional crustal exhumation, commonly associated with decompression melting, mixing and mingling of individual magma pulses and differentiation.

The Weinsberg Type Granitoids (WTG) have the geochemical signature demonstrating the substantial role of partial melting of volcanosedimentary sequences, magmatic fractionation and assimilation of host xenoliths.

The textures of the Weinsberg Type Granitoids are characterised by straight crystal size distribution (CSD) consistent with in-situ crystallization and gentle crystal/melt separation, forming abundant K-feldspar phenocryst-rich domains (KPDs).

The KPDs were formed either by the redistribution of K-feldspar phenocrysts (crystal accumulation) in a suspension during magma flow in the vertical direction and/or by a minor amount of interstitial melt extraction followed by melt escape from highly crystallized mush.

On the basis of a detailed structural and AMS analysis we offer a new scenario of the Weinsberg Composite Pluton reflecting a polyphase emplacement of individual pulses of granitoids under the changes of regional stress conditions between ca. 330 to 305 Ma.

This time-span includes a crucial events in the Variscan late-orogenic episode from regional N–S compression (ca. 335 to 325 Ma) followed by regional extension in WSW–ENE direction (ca. 325 to 305 Ma).

Variscan and pre-Variscan metamorphism in the Eastern Alps: Petrology and geochronology

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The pre-Alpine basement in the Eastern Alps and Carpathians are derived from the north-eastern Gondwana margin. Although these Variscan fragments are incorporated nowadays within the Alpine nappe pile of the Eastern Alps, not all of them were affected severely by Alpine metamorphism (Neubauer et al. 2022). Besides the nearly unmetamorphosed Carnic Alps, Gurktal Mountains, Graz Paleozoic and the Noric–Tirolic Nappe comprising early Paleozoic passive margin sediments, higher grade rocks and igneous suites of Variscan and Pre-Variscan origin are well known to occur within the Austroalpine in: (i) the Silvretta-Seckau Complex, (ii) Speik Complex, (iii) Kaintaleck Complex (Greywacke Zone), (iv) Waldbach Complex, (v) Bundschuh Complex, (vi) Gailtal/Nötsch and Defereggen Complexes.

Garnet bearing gneisses and schists define the Seckau crystalline basement into which Devonian and Cambrian granitoids intruded. The basement enclosing the Devonian granitoids exhibits garnet bearing gneisses with distinct two- phase garnet growth.

Within the Speik Complex eclogites associated with harzburgites and dunites are found around Hochgrössen (Faryad et al. 2002) and Kraubath, Styria. Geothermobarometric results indicate temperatures of around 700 °C and 2.0 GPa. Some of the eclogites contain fresh omphacite and garnet with cores either as inclusion poor idiomorphic crystal or as inclusion rich domain surrounded by an inclusion poor rim. An Ar/Ar hornblende age (Hochgrössen) gave 397 Ma (Faryad et al. 2002).

The Kaintaleck Complex occurs as dismembered lens-shaped bodies of several kilometers length within the Eastern Greywacke Zone. Two phase garnet growth, Zr-in-rutile thermometry and phengite barometry indicate a first metamorphic phase at ca. 680 °C and 0.8 GPa, followed by pressure increase and cooling reaching eclogite facies conditions at ca. 550 °C and 1.7 GPa. Chemical Th–U–Pb monazite dating of garnet-mica-schists revealed Variscan metamorphism at ~360 Ma, U/Pb zircon ages from a garnet-amphibolite yield a Lower Devonian age of protolith formation of ~410 Ma

The Gailtal Complex comprises staurolite and staurolite+garnet micaschists. Temperatures around 600 °C and pressures of ca. 0.7 to 0.8 GPa are indicated by Grt–Bt–Plg and Grt–Sta equilibria. Mica-rich samples gave a chemical U–Th–Pb date of ~318 Ma and a quartz–feldspar rich sample gave a Triassic age of ~220 Ma.

The source and PTt data from the different intra-Alpine Variscan metamorphic complexes document the opening and closure of (short) lived oceans/ocean basins related to the break-up of northern Gondwana and its collision with Laurussia during (1) Lower Devonian, (2) Upper Devonian, and (3) Early Carboniferous times.

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Early, subduction-related plutonism in the Central European Variscan Belt: Correlation between Bohemian Massif and Central Western Carpathians

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Complex interplay between oceanic subduction, crustal relamination, and continental collision made the Mid-Devonian–Visean the most exciting period in the geological history of the Central European Variscides. As a consequence, two conspicuous plutonic associations formed that can be traced along much of the orogen's entire northern realm up to the Bohemian Massif (Finger et al., 1997; Žák et al., 2014): (1) calc-alkaline (CA) plutons, a vestige of an Andean-type continental margin (Schulmann et al. 2009) and (2) Mg–K-rich plutons, formed from crustally contaminated lithospheric mantle (Holub 1997; Janoušek et al. 2020). Their continuation further to the Western Carpathians remains unclear, though.

In the Teplá–Barrandian domain of the Bohemian Massif (BM), the **older (***c.* 390–365 Ma) **arc** magmatism produced primitive, K-poor CA gabbros–trondhjemites intruding high-grade metabasites of the *Mariánské Lázně Complex* (ε^{386}_{Nd}=+5.8 to +2.3). Within this interval fall also mainly granodioritic, normal-K CA *Čistá* (ε^{370}_{Nd}=+4.3 to +0.4) (Deiller et al. 2021) and *Štěnovice* (Žák et al. 2011) plutons. Within the *roof of the Central Bohemian Plutonic Complex* (CBPC), tholeiitic protoliths to the felsic orthogneisses show variable Nd isotopic signatures (ε^{386}_{Nd}=+3.2 to –4.1) (Košler et al. 1993; Košler & Farrow 1994). Finally, the qtz dioritic–tonalitic, CA *Lišov pyroxene granulites* are remnants of an ~360 Ma igneous arc (ε^{360}_{Nd}=+2.8 to –5.2) (Janoušek et al. 2006).

The **younger** (354–335 Ma) **arc** activity shifted eastwards. In the CBPC, ~354 Ma normal-K CA Amp gabbros and quartz diorites–trondhjemites of the *Sázava suite* show CHUR-like Sr–Nd isotopic compositions (Janoušek et al. 2000, 2004). The ~346 high-K CA *Blatná suite* (Dörr & Zulauf 2010; Janoušek et al. 2010), besides prevailing (Amp–) Bt granodiorites (ε^{346}_{Nd}=–3.2 to –6.3), features monzonitic rocks, produced from slightly enriched mantle (ε^{346}_{Nd} ~ –3). The *Older Suite of the Nasavrky Plutonic Complex* consists of normal-K CA (Amp gabbros–qtz diorites) to high-K CA (tonalites–granites) intrusions. This activity was newly dated at 347–340 Ma by laser-ablation ICP-MS, confirming the ~340 Ma Pb–Pb age of Schulmann et al. (2005). Compositionally equivalent high-K CA tonalites–granodiorites in the *Polička Unit* were dated at ~350 and ~346 Ma (Vondrovic et al. 2011). Finally, the *Staré Město Belt* decorating the Saxothuringian–Brunovistulian contact is dominated by the syn-tectonic 344–341 Ma old Amp–Bt tonalites (Jastrzębski et al. 2018).

Correlation of granite suites from the Bohemian Massif and the Western Carpathians complicates the fragmentary occurrence of Variscan blocks within Alpine edifice of the latter. The Variscan granitic rocks are known from the Tatric, Veporic and Gemeric units – i.e. the Central Western Carpathians (CWC). While Tatric and Veporic units shared the pre-Alpine history, Gemeric Unit was stacked onto Veporic Unit during Cretaceous from a different position.

The Famennian–Visean subduction- and collision-related plutonism is known only in the *Tatric* and *Veporic units*. The **older arc magmatism** (*c.* 374–359 Ma) produced primitive, K-poor CA gabbros–diorites, forming small intrusions within the Devonian low-grade volcano-sedimentary *Pernek Group* (ε^{370}_{Nd}=+9.4 to +8.0) (Ivan et al. 2007; Putiš et al. 2009) and/or small (decametric to 1 km) dioritic bodies enclosed within the younger granitic rocks (ε^{360}_{Nd}=+2.1 to +0.7) (Kohút et al. 1999; Magna et al. 2010; Kohút 2014). The first "immature" granitic rocks and/or diatexites (*c.* 367–361 Ma) were coeval with the older arc gabbro–diorite magmatism, and form mainly the apical, unhomogenized parts of plutons. They are variable, with normal- to high-K CA character and ε^{365}_{Nd} of +0.5 to –2.3, reflecting source in a vertically zoned lower crust (Poller et al. 2000; Gaweda et al. 2016; Kohút & Larionov 2021).

The **younger arc-related CWC granitoids** (*c.* 359–352 Ma) can be divided to (1) (Amp)–Bt tonalites–granodiorites of the ACG & KCG character (*sensu* Barbarin, 1999) (ε^{355}_{Nd}= +1.3 to –2.4) coming from lower crustal source supplemented from the SCLM, and (2) biotite granodiorites–granites (CPG-like; ε^{355}_{Nd}=–1.2 to –3.1) produced from the lower/middle crust (Kohút et al. 1999; Magna et al. 2010; Poller et al. 2000; Gaweda et al. 2016; Broska et al. 2013, 2022; Kohút & Larionov 2021). Slab break-off played an important role in the genesis of these granitic suites since the formation of diatexites at the Devonian/Carboniferous boundary (Broska et al. 2022).

The **(post)-collisional CWC granitoids** (*c.* 350–340 Ma) represented mainly by peraluminous Mu–Bt granodiorites–granites (MPG affinity; $\varepsilon^{345}_{Nd} = -2.3$ to -4.7), had a likely source in variegated lower/middle crust containing felsic orthogneisses and metasediments (Kohút et al. 1999; Magna et al. 2010; Poller et al. 2000; Kohút & Nabelek 2008; Gaweda et al. 2016; Kohút & Larionov 2021).

Taken together, the Mid-Devonian to Visean subduction-related CA magmatic activity of the BM and CWC was comparable in terms of timing, composition and likely sources. The principal difference consists in the occurrence of (ultra-) potassic magmatic rocks; while their abundance and spatial–temporal association with HP–HT felsic granulites are characteristic of the Moldanubian Zone in the BM, they are conspicuously lacking in the CWC. Bohemian oceanic subduction was terminated by deep subduction and relamination of the attenuated felsic continental crust (yielding the HP–HT granulites) and contaminated lithospheric mantle produced Mg–K-rich magmas with a curious mixed crustal–mantle signature (Schulmann et al. 2014; Janoušek et al. 2020 and references therein). In the CWC, the early oceanic slab break-off and ensuing asthenospheric upwelling enhanced the granite formation (Broska et al. 2022) but apparently prevented the continental crust to be dragged into the subduction zone.

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The Paleozoic meta-basic rocks from the Tatric Unit of the Western Carpathians: Current controversies

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The Western Carpathians are the northernmost, E–W trending branch of the Alpine belt, linked to the Eastern Alps in the west and to the Eastern Carpathians in the east. The correlation of the Variscan and pre-Variscan basement rocks of the Western Carpathians with the pre-Mesozoic basement areas of the European Variscides and Alpine orogenic belts is still uncertain due to a lack of precise age and compositional data of the metamorphic units. The pre-Mesozoic basement of the Tatric Unit was studied with respect to its lithological, structural, metamorphic and age characteristics. The available data proves that the basement of the Tatric Unit is made of two different rock complexes – the older ***Lower Étage*** (Cambrian to Silurian) showing high-grade metamorphic evolution, and the ***Upper Étage*** (Upper Silurian to Devonian) presenting low-grade metamorphism and younger stage of development (Kohút et al. 2022).

The Lower Étage (***LE***) is composed by a banded amphibolite complex (AC) with remnants of retrogressed eclogites and metaultramafites, tonalitic gneisses, sheared Cambrian-Ordovician felsic magmatites – now orthogneisses, and these metaigneous rocks are intercalated with metamorphosed psammites/pelites (gneisses) with rare carbonatic (calc-silicates) lenses, and scarce black schists. The metamorphic conditions of this complex are usually characterized by 650–800 MPa and 600–780 °C, sometimes with characteristic widespread migmatization/granitization, while P–T reached up to 1.7 GPa and 700–750 °C in the HP eclogite remnants. The Upper Étage (***UE***) is the Upper Silurian – Devonian in age, and typically comprises volcano-sedimentary sequences composed of meta-greywackes, phyllites, metabasites (epidote-actinolite amphibolites), black shales, lenses of calc-silicates, Fe+Pb–Zn Lahn-Dill mineralization, and scarce apatite-rich rocks. Their low-grade metamorphism reached a greenschist facies only (below 350 MPa and 650 °C), and weak intrusive migmatitic zones are merely observed.

Since the amphibolitic rocks are present in both above mentioned étages (principal structural and lithological levels) of the Tatric Unit crystalline basement, we focus on their mineralogical, geochemical and isotopic differences in order to better understand their genesis and geotectonic evolution. Generally, on the basis of field and petrographic evidence the LE amphibolites can be divided into garnet-free and garnet-bearing assemblages. Garnet-free amphibolites are dominant petrographic type, and consist mainly of: amphibole (Mg-hornblende, and locally actinolite as later phase); less frequent plagioclase ($An_{10–40}$); and minor phases: pyroxene (clinopyroxene), quartz, rutile, ilmenite, epidote, zoisite±chlorite. Garnet amphibolite and eclogite are less frequent than garnet-free amphibolites, and are present within the boudins (lenses) in banded amphibolites. Their mineral assemblage consists of: amphibole again as a major phase (Mg-hornblende, pargasite, and actinolite); garnet forming porphyroblasts with abundant inclusions in the cores (mainly: amphibole, zoisite, rutile, phengitic white mica, quartz, and ±epidote, ±chlorite), the garnets correspond to almandine (25–60 mol. %) with significant grossular (22–29 mol. %) and pyrope (11–30 mol. %); clinopyroxene occurs as glomeroblastic and vermicular grains, symplectitic intergrown with plagioclase indicate breakdown of the "primary" omphacite with initial jadeite content of 23–40 mol. %; sporadic orthopyroxene in the clinopyroxene+plagioclase symplectitic domains; plagioclase various basicity ($An_{10–50}$); minor phases: quartz, rutile, ilmenite, titanite, epidote, white mica, zoisite±chlorite. However, the UE amphibolitic rocks on the basis of petrography and field indications can be tentatively divided into the greenschists and low-grade amphibolites. Greenschists are light green massive or foliated rocks composed mainly of actinolite, albitic plagioclase, prehnite or clinozoisite, ±epidote; minor phases are represented by accessory carbonate, titanite and pyrite. Low-grade amphibolites consist of: blue-green amphibole (mostly Mg-hornblende or tschermakite, ±pargasite) and albitic plagioclase. Actinolite is locally preserved in the form of relic cores in some amphibole porphyroblasts. Small relics of prehnite or clinozoisite and epidote are also sporadically preserved. Disseminated small grains of magnetite or pyrite rimmed by magnetite are common.

Whole rock (WR) geochemistry suggests that chemical composition of the LE amphibolites corresponds mainly to the composition of common basalts in the TAS diagram although part of the low-silica (SiO_2 ≤45 wt.%) can be analogue to "picro-basalts" and a few samples with SiO_2 ≥52 wt.% fall in the basaltic andesite field. Most of the UE amphibolitic rocks fall into the field of basalts to "picro-basalts". Results of Winchester & Floyd (1977) discrimination indicate that majority of the studied LE & UE meta-basic rocks forms analogues of common basalts ±basaltic andesites somewhat with sub-alkaline character, and only a small part of the UE amphibolitic rocks fall within the alkali basalts. Similar picture shows classification according Pearce (1996). However, based on a comprehensive evaluation, part of the UE meta-basic rocks samples can be marked as meta-gabbros+meta-dolerites. Generally flat C1 chondrite-normalized REE patterns of the LE amphibolites with slight LREE enrichment show extensive variability in total content of the REE (ΣREE= 22–150 ppm), and can be determined as the N-MORB products. On the other hand, the flat C1 chondrite-normalized REE patterns of the UE amphibolitic rocks with either slight LREE enrichment or depletion (ΣREE=27–97 ppm) represent analogues of the N-MORB or E-MORB/OIB basaltic rocks. Geotectonic interpretation of available WR data from the studied LE and UE meta-basic rocks is partly controversial mainly due to inter-laboratory bias, used method of the trace element analysis and/or different stages of metamorphosis ±fluids alteration. Various multi-element discrimination diagrams (Wood, 1980) provide ambiguous results when the LE amphibolites compositions fall into either the IAT and CAB or N-MORB fields. On the other hand, the UE amphibolitic rocks fall either into the CAB and N-MORB fields or within the CAB and WPT/E-MORB basic rocks. Comparable equivocal results were obtained by applying discriminations according to Pearce & Can (1973), Pearce & Norry (1979), Meschede (1986) or Cabanis & Thieblemont (1988). Noteworthy, Vermeesch (2006) reconsideration of various above mention discriminations and/or new recommendation favour mainly MORB and IAB tectonic environment for the LE amphibolites, whereas origin of the UE amphibolitic rocks can be seen in the OIB (WPB) and MORB setting. According to Hollocher *et al*. (2012), genesis of the studied LE and UE meta-basic rocks reflects mostly paleo-environment of the BABB with affinity part of the UE samples to the OIB and part of the LE samples to the CAB. Interpretation of the available Sr and Nd isotopic data can shed light to the Tatric Unit amphibolitic rocks and/or the LE & UE dilemma. The LE meta-basic rocks protolith was N-MORB or CAB basaltic magma produced in the arc or back-arc geodynamic setting with possible slight crustal material contamination showing by $I_{Sr(500)}$=0.7052–0.7088, $\varepsilon Nd_{(500)}$=+2.6 ~ +7.2 and model ages $T_{(DM2st)}$=1.0–0.6 Ga (Poller & Kohút unpublished data). Most of the meta-gabbroic–basaltic rocks, from the UE, have chemical compositions typical of the N-MORB, and partly the E-MORB (OIB) characteristic. The source of the UE meta-ophiolites, connected with opening of the oceanic basin along the rifted continental margins, was in the depleted mantle (DM) with $\varepsilon Nd_{(370)}$=+8.0 ~ +9.4 (Ivan et al. 2007). However, their recalculated Nd model ages $T_{(DM2st)}$=0.43–0.32 Ga can indicate their primitive–juvenile mantle character.

General feature of the LE is its ductile shear deformation and concomitant HT/MP metamorphism with widespread partial anatexis during the Devonian/Carboniferous subduction/collision processes. Though, the UE is still preserving its “layered/stratified” volcanic-sedimentary character with brittle deformation and rather narrow contact aureole at the boundaries with intruded Carboniferous granitic rocks. Kohút et al. (2022) assume that the LE has its origins in the Rheic Ocean, while the UE was deposited in a different the Rheno-Hercynian basin. The Variscan amalgamation of the Tatric Unit basement was a consequence of subduction of the Rheic Ocean under Galatian Superterrane, and final collision with marginal Rheno-Hercynian zone.

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Durbachites – source of uranium for the deposits in the eastern Moldanubian Zone

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The Moldanubian Zone of the Variscan Bohemian Massif hosts significant hydrothermal U-deposits associated with shear zones in the high-grade metamorphic basement. The formation of hydrothermal U-deposits in the entire European Variscan belt is assumed to be related to the fluid-driven alteration of Late-Carboniferous peraluminous granites (Cuney 2009). However, within the Moldanubian Zone, there is a lack of evidence of genetic and/or spatial link of vein-type U-mineralization to U fertile leucogranites

The unusual trace element chemistry of the low-T hydrothermal vein-type deposits (high Zr, Nb, Ti, ∑REE) and their close spatial association with HFSE- and U–Th REE-rich durbachite intrusions in the Moldanubian Zone of the Bohemian Massif most likely point towards their mutual genetic relation. The massive mobilization of U together with HFSE and REE in durbachites is well-documented by EMP imaging (Fig. 1) and analyses of their main U-bearing phases – pristine magmatic Uraninite, Thorite, Zircon, Allanite and rare Monazite. (Kubeš et al. 2021, 2022). We propose that radiation damage of major refractory minerals likely enhanced permeability due to their volume expansion, which facilitated fluid-mineral interaction and thus promoted HFSE and REE leaching from their source. Accordingly, enhanced HFSE mobility in circulating hydrothermal fluids is reflected by presence of Zr–Th–U–Si phase that typically fills abundant microfractures intimately surrounding metamict zircon (Fig. 1). Thus, the extreme HFSE and REE mobilization linked to the extensive dissolution of major U-bearing phases in durbachites provide the most likely explanation for the unusual chemistry of Moldanubian U-deposits. Taking into account a much larger original extent of the highly alkaline (ultra)potassic intrusions, the original U content of this intrusion was estimated on minimum 28 mil t of U.

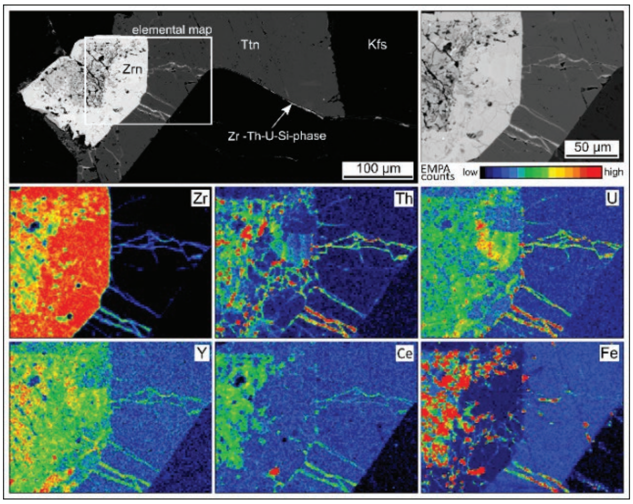

Fig. 1. BSE image and EMP maps showing massive fluid-driven HFSE mobilization from altered zircon. Zrn=zircon, Ttn=titanite, Kfs=K-feldspar

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Accessory U–Th–REE minerals in leucogranite in Nízke Tatry Mts., Western Carpathians: The story of melts, fluids and ores

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Small leucogranite body was found in ridge areas of Low Tatra Mts., (Tatric Unit, Western Carpathians) between Zámostská hoľa and Ďurková hills (Zámostská hoľa leucogranite"; abbreviated hereandafter to ZHlG). ZHlG is emplaced within hybrid, postcollisional Ďumbier–Prašivá biotite tonalite- granodiorites types forming Low Tatra pluton (LTP). The ZHlG exhibits microtexture typical for syn-deformational disruption of already solidified portions of magma by late residual magmas, evidenced by brittle deformation – and polymodal grain size, reminding "two-phase" granites (cf. Štemprok et al. 2008). It consists of (1) euhedral phenocryst of zoned plagioclase ($An_{20–6}$), K-feldspar (Kfs), chlorite (Chl) and quartz (Qz), overflown by (2) fine-grained Kfs–Qz–Pl (An<10)+Ms matrix and (3) "pegmatitic" Ms and Qz locally replacing Kfs. Geochemical data show strongly peraluminous (ASI 1.23) and alkali-rich ($Na_2O+K_2O=8$) character with low Fe,Mg,Ti and extremedepletion in P (<0.1 wt%). It shows REE pattern with enrichment HREE trend from Gd to Lu. Accessory mineral assemblage in ZHlG is hosted by phenocrysts or it is interstitial between phenocrysts and matrix, and includes zircon (Zrn), xenotime-Y(Xtm), monazite-(Ce) (Mnz), allanite-Ce (Aln) each exhibiting range of microtextures, zonation in chemical composition.

Zrn occurs as clusters of crystals <10–100 µm size. Concentric, fine oscillatory zonation, is typical for magmatic Zrn but only in crystals, which despite boundaries resorption retained bipiramidal with prismatic outline (Zrn1). Towards rims, the zonation is often locally truncated or blurred, implying alteration. Nevertheless, most of the crystals are unzoned or weakly patchy zoned (Zrn2), and strongly resorbed implying dissolution and recrystallisation. U and Y-rich thorite forms inclusions overgrowths especially in Zrn2. Zrn1 crystals are extensively fractured and disrupted, implying metamictisation, but also brittle deformation; subordinate microporosity especially in Zrn2 occurs.

Zrn shows very low Zr/Hf ratio 14–23 due to elevated HfO_2 (1.9–3.2 wt%) and is high but variable in trace elements, which are variously intercorrelated and related to several substitution mechanisms. Zrn1 is elevated in P_2O_5 (≤1.19 wt%), Y_2O_3 (≤3.93 wt%) HREE (ΣGd–Lu_2O_3 ≤3.0 wt%) and UO_2 (≤1.9 wt%) but depleted in ThO_2 (≤0.15 wt%) resulting in extremely low Th/U ratio (0.0–0.4). Zrn2 shows variable compositional trends, but in general is lower in U, P, Y+HREE. Both Zrn types contain also As_2O_5 (up to 0.5 wt%) and halogens (Cl≤0.19 wt% in Zrn2 and F≤0.15 in Zrn1). The analytical totals 91–98 wt% implies high hydratation and metamictization. Overall, Zrn chemistry resembles late-magmatic or altered zircons from strongly evolved granites (Perez-Soba et al. 2007; Breiter et al. 2014) or from pegmatites (Mahdy 2021). High U and low Th/U are typical for S-type granites, but high Y+HREE in excess to P – for A-type granite suites (Breiter et al. 2014). Nevertheless, unzoned and irregular Zrn is low in trace elements and higher in Hf resembling hydrothermal or totally recrystallised Zrn (Hoskin 2005).

Xtm is omnipresent as euhedral to anhedral inter- or overgrowths on Zrn. Concentric oscillatory zonation is rarely preserved in euhedral crystals (Xtm1) and most of grains are unzoned or patchy and strongly irregular (Xtm2). Xtm shows wide range of concentrations of UO_2 (0.2–3.2 wt%) and ThO_2 (<0.1–1.2 wt%); in Xtm1 U content is usually <1 wt%, whereas in Xtm2 U is <1 wt%. Y/Ho (27–58), Y/Dy (12–20), Gd/Yb (0.2–1.1) ratios are higher in Xtm2 then Xtm1 and indicates increase of fluid activity during growth (Forster 1998; Breiter et al. 2009). Xtm2 contains As_2O_5 up to 2.3 wt%. The diversity of Xtm morphology and chemistry suggests growth in magmatic and subsolidus conditions, and at least part of Xtm2 was formed by zircon recrystallisation.

Mnz only sporadically coexists with Zrn and forms subhedral, but strongly embayed grains up to 100 µm size, with regular, sector zoning in cores (Mnz1) typical for igneous origin. The rims of Mnz, sometimes transgressive into cores, are irregular, sutured and distinctively brighter under BSE (Mnz2). Mnz1 is high in ThO_2 (≤9.5wt%) and UO_2 ≤1.0 wt%, incorporated cheralite-type substitution; coexisting Mnz2 shows increase of huttonite component, and near total removal of U. Y_2O_3 in Mnz ranges from 0.9 to 3.2 wt%, and corresponds to temperatures 900–750 °C in Mnz1 and 350–650 °C in Mnz2. Both Mnz1 and Mnz2 are unusually high in F (0.4–0.85 wt%), what is ambiguitous, considaring overall morphology and composition similar to early-crystallised Mnz in the S-type granites (Broska & Petrík 2008).

Aln occurs in fissures of Pl and Kfs, pointing to late, syndeformative crystallisation via reaction of aluminosilicates and REE in melt/fluid. High Al_2O_3 (17.7–20.5 wt%), MnO (≤2.3 wt%), Y_2O_3 ≤1.5 wt%, low ThO_2 and UO_2 (<0.15 wt%) and moderate ΣREE_2O_3 (<22 wt%) are attributes of late-stage Aln in peraluminous granites, whereas ratios of La/Nd (1.37–0.7) and La/Sm (2.4–6.6) is typical for Aln from pegmatites (Giere & Sorensen 2004).

Ap in ZHlg is very rare. very small <20 µm rounded inclusions in Kfs or Pl, and is almost free in trace elements. Kfs and Pl are enriched in P_2O_5 (≤0.3 wt%) and contains exsolved tiny fluorapatite inclusions typical for fractionated granites (Broska & Petrík 2008). In this sense textural context and composition suggest secondary nature of Ap via fluid liberation of P from feldspars.

The accessory mineral assemblage in ZHlG records magmatic and hydrothermal evolution and along with rock composition and petrography indicate presence of highly differentiated melt and reactive fluids. The late-stage granitic melts performs evolved geochemical character as high-silica, high peraluminousity, enrichement in alkalis and "voltatiles" or "fluids" such as H_2O, F, Cl ,or CO_3^{2-} facilitating transport of "incompatible" elements, including U, Y and HREE (Webster et al. 2004). In the evolved melt, Mnz is early phase, wheareas Zrn may accommodate large amounts of trace elements (Perez-Soba & Villaseca 2007; Mahdy 2021). Its crystallisation is suppressed to late-magmatic stages (Broska & Petrík 2008; Ayers et al. 2012).

Localised releasment of alkaline, fluid-rich dominated reactive melts, possibly immiscible from peraluminous melt (Thomas et al. 2006) caused alteration and U+Y+HREE depletion of previously crystallised zircon and monazite (Harlov & Hetherington 2010; Chen & Zhou 2017). Reactive volatiles scavanged P from P-rich feldspars, which contributed to prolongation of Xtm crystallization from melt- to fluid-dominated enviorment in expanse of Zrn, what is specific for fluorine. The mobilised LREE reacted with albitised feldspars forming allanite. Elevated As content in Xtm and Zrn points to arsenate-rich, oxidising enviroment (Ondrejka et al. 2007) and there is probably a potential link between ZHlG and mineralization in nearby Sb–Au–As–Pb ore system of Magurka. The ore-forming fluids linked with highest-temperature, presumably magmatic ore association contained significant portion of NaCl and CO_2 contributing to alteration.

This data demonstrates the Zrn composition in ZHlG and its association with Xtm reminds pegmatite setting or rare-metal (Li–Nb–Ta), however such magmatic system absent in LTP and Tatric Unit at all. The unusual accessory assemblage in ZHlG reflects local formation of highly differentiated fluid rich melts in final stages of LTP differentiation.

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Rare earth geochemistry and the progressive development of lanthanide tetrad effect in monazites and xenotimes during hydrothermal evolution: A case study from the Prakovce–Zimná Voda REE–U–Au vein

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A hydrothermal quartz vein with REE–U–Au mineralization in the Zimná Voda, Prakovce (Gemeric Unit, Western Carpathians, Slovakia) is associated with contact metamorphism between Permian granites and host phyllites and metaquartzites. It contains unique REE minerals of the monazite and xenotime groups. Monazite-(Ce), monazite-(Nd), monazite-(Sm), and monazite-(Gd), along with xenotime-(Y) to Gd-dominant xenotime ["xenotime-(Gd)"] show heterogeneous compositions and reflect a strong fractionation trend from La–Nd to Sm–Dy with Gd~Sm>Nd>Ce>La (MREE>LREE) and equally negligible Ho–Lu (HREE)+Y abundances. Although different REE^{3+} are the dominant cations in the corresponding monazite members, their chondrite-normalized REE patterns exhibit the conspicuous maxima at Sm and Gd. However, the patterns of Nd-, Sm-, and Gd-dominant monazite are partly distinct from monazite-(Ce), which shows a less clear maximum at Sm, but more enriched in La and Ce and conspicuously depleted in HREE. There are also distinct differences in the shape of the first tetrad (La–Ce–Pr–Nd) which shows a downward concave W-type curvature, progressively developing from monazite-(Ce) to monazite-(Gd) with average t1=0.63, (Mnz-Ce) to t1=8.64 (Mnz-Gd).

The chondrite-normalized REE pattern of xenotime I shows a different REE distribution compared to xenotime II. It has the most extensive M-type tetrad effect on t3 and t4 tetrads with average t3= –4.74 and t4= –8.44. The Gd-rich xenotime II has a significant upward convex MREE pattern with a maximum in Gd and a less-distinct M-type tetrad effect signature compared to xenotime I.

This study demonstrated the gradual remobilization–fractionation of REE in aqueous media and continuous evolution of the W-type tetrad effect from REE patterns without tetrad effect to the well developed W-type tetrad effect during the crystallization of monazite toward Ce→Nd→Sm→Gd species. Similarly, the evolution from the REE patterns with well-developed M-type tetrad effect to the patterns with less pronounced or no M-type tetrad effect is documented during xenotime crystallization toward Y→Gd species. This clearly indicates that the W-type tetrad effect gradually develops during progressive precipitation from aqueous media and associated processes, and thus the pattern changes to the late and low-T hydrothermal stage (more W-shaped). The primary monazite-(Ce) and xenotime-(Y) were partially replaced by Gd–(MREE)-rich minerals during the interaction with F-rich fluids. Middle REE usually do not comprise any mineral endmembers (with exceptions) and are considered to be regularly present at low concentrations when compared to their LREE or HREE counterparts. This study shows that low-T hydrothermal alteration and replacement reactions of MREE-selective, but nominally REE-free minerals, e.g. uraninite, brannerite, and fluorapatite, can produce an enhanced MREE signature in chemically closed systems.

Allanite–monazite stabilities vs. P–T paths of granitic and metamorphic rocks

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Stabilities of allanite and monazite based on experiments and thermodynamic calculations (Janots et al. 2008; Spear 2010) showed that the boundary Mnz/Aln has (1) positive slope, (2) monazite is on the high temperature side, and (3) position of boundary critically depends on CaO and REE contents. The boundary is significantly shifted to higher T with increasing CaO and LREE expanding the allanite field. It is suggested that various configurations of this boundary and P–T paths experienced by ascending magmas and/or solid rocks can explain the variety of textural relations observed between allanite and monazite. These include: allanite enclosed by monazite, monazite enclosed by allanite, monazite replaced by allanite–apatite coronas, and monazite replacing allanite. Individual cases for P saturated rocks are discussed below for two schematic Mnz/Aln stablity boundaries – for high CaO and low CaO. The stability boundaries in all Figures are taken from Spear (2010).

Case I: Allanite as a single LREE mineral in Ca-rich (I-type) tonalites. In this case allanite as a high temperature mineral crystallises with plagioclase in the Aln stability field of the high T boundary calculated for high-Ca system (4.34 % CaO; Fig. 1). This allanite never converts to monazite although undergoes various low-T alterations and/or oxidation.

Case IIa: Monazite as a single LREE phase crystallises in the monazite stability field of lower T stability boundary for Ca-poor rocks.

Two P–T paths are shown in Fig. 2: a more rapid ascent to shallower level keeping higher T and not crossing the boundary: monazite remains stable (solid line). A less steep ascent at deeper level followed by isobaring cooling crosses the Mnz/Aln boundary. Monazite breaks down to Aln/Ap coronas (dashed line).

Case IIb: Early monazite is replaced by allanite in high CaO tonalite at high-T stability boundary (Fig. 3). In this case the replacing allanite does not form coronas because monazite does not break down.

Case III: In a high LREE, low CaO granodiorite melt inlusions with early allanite are enclosed by high-T magmatic monazite. The replacement is interpreted by shift of the boundary to lower T due to Ca fractionation to plagioclase (Fig. 4): Allanite finds itself in the Mnz stability field (Broska et al. 2000) and is replaced by monazite.

Alternatively, this mineral change may be explained by the P–T path crossing the high-T boundary during rapid nearly isothermal ascent (Fig. 5).

Case IV: A new monazite crystallises at low-T due to P–T path crossing the low-T boundary in a low CaO rock (Fig. 6). If there is an earlier monazite with brekadown

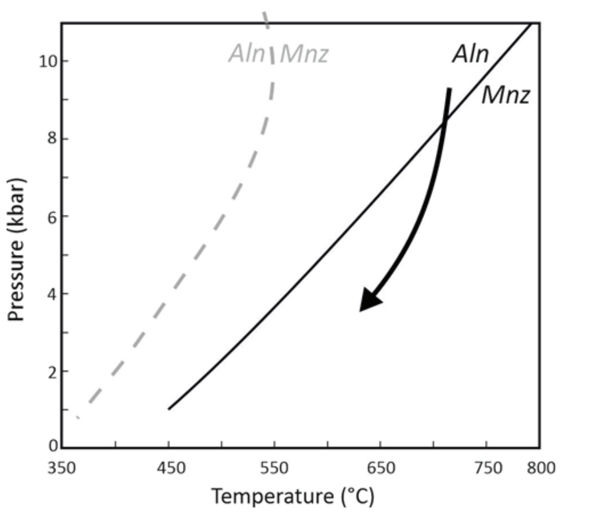

Fig. 1. Single Aln crystallises in Ca- and LREE-rich rocks (I-type granitoids)

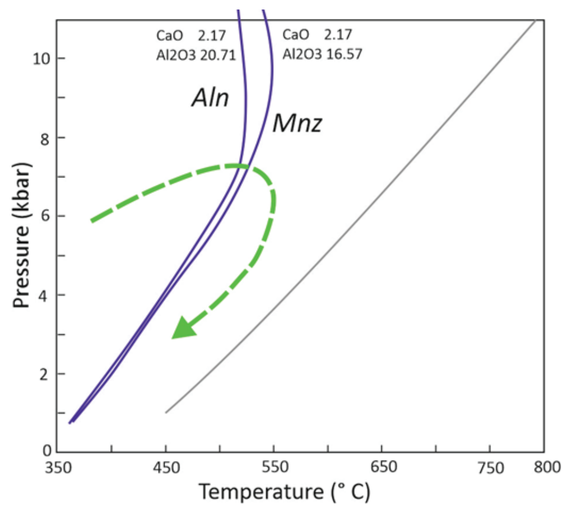

Fig. 2. Single Mnz crytallises in low-CaO rocks. Breakdown coronas either form or do not form depending on the slope of the P–T path.

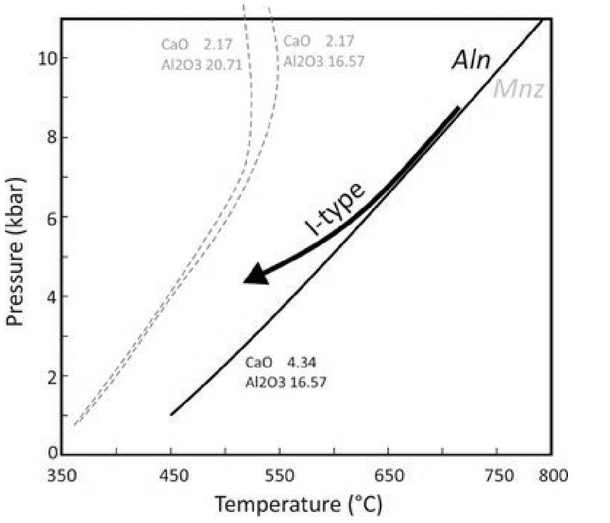

Fig. 3. Slow cooling crosses the boundary and monazite is overgrown by later allanite.

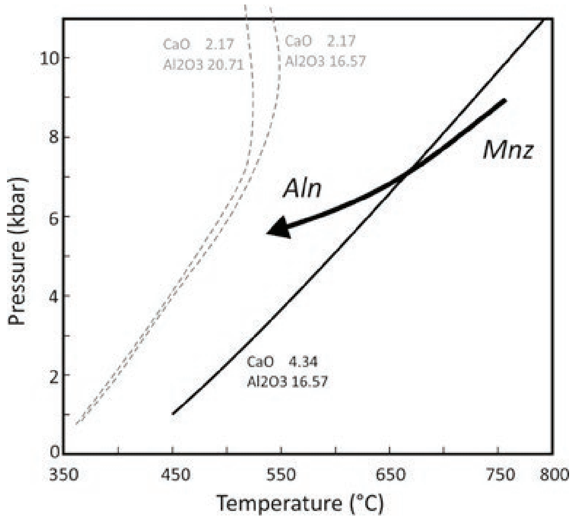

Fig. 5. Alternatively, Mnz replaces Aln by decrease of pressure.

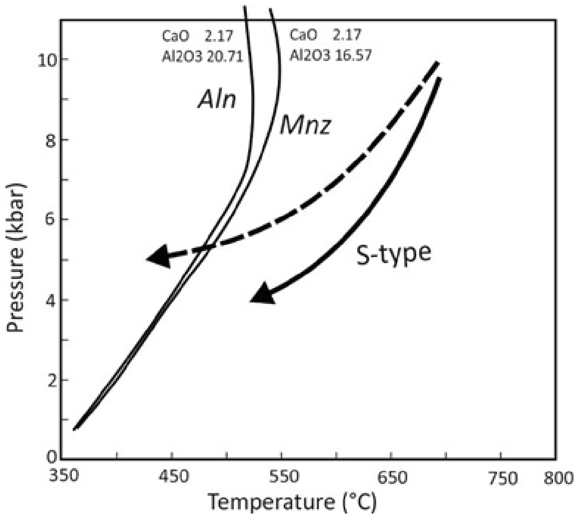

Fig. 4. Shift of Mnz/Aln boundary due to drop of CaO explains replacement of Aln by Mnz.

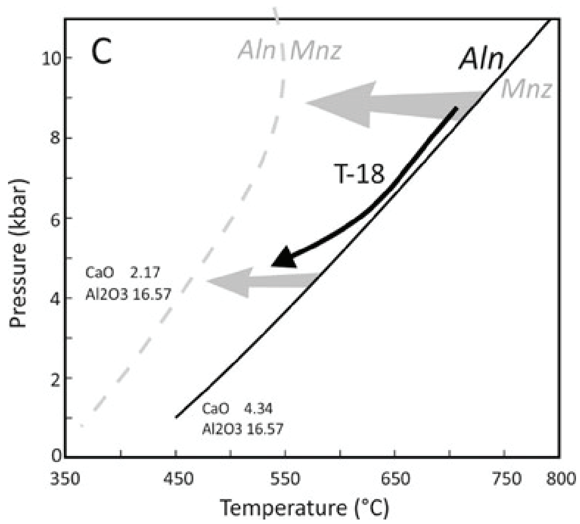

Fig. 6. Alpine P–T paths crosses the low-T boundary enabling formation of satellite Mnz.

corona the new monazite may form satellite grains the earlier monazite remaining intact (Finger et al. 2016). The situation is typically observed in Alpine reworked low-Ca rocks.

Conclusions

All the observed monazite−allanite relations in granitic and metapelitic rocks can be explained by combination of Mnz/Aln stability boundary positions mostly determined by CaO and LREE concentrations, and variable regressive P–T paths experienced by the rocks. Contrasting P–T paths of LREE minerals can be used to support tectonic evolution (Broska et al. 2023).

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Zircon ages and geochemistry of metamafic complexes from the Variscan suture zones of the West-Carpathian basement: Indicators of northern Gondwana breakup and collision events

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The already realized studies of metamafic rocks (e.g., Bajaník et al. 1984; Spišiak et al. 1985; Hovorka et al. 1988, 1997; Radvanec 1994; Faryad 1996; Putiš et al. 1997, 2018; Ivan et al. 1996; Németh 2005; Janák et al. 1996, 2007, 2020; Burda et al. 2021; further references are in the text) might indicate diachronous Variscan suture zones in the West-Carpathian basement. Here, we provide new age and geochemical constraints on the selected sutured crust-mantle sections using the SIMS and LA-ICP-MS U–Pb zircon dating (in Beijing 2012–2019) and the XRF, ICP-MS, and Rb–Sr and Sm–Nd isotopic analysis (in Vancouver and Prague, respectively).

(1) The tectonic juxtaposition „suture“ zone between the Upper and Middle Variscan units is defined by the **Layered amphibolite complex** (LAC; Putiš 1992, or Leptyno-amphibolite complex by Hovorka & Méres 1993; Fauré et al. 1979) in the Tatric and Veporic basement. The host rock is a Ky–Grt gneiss with the predominant concordia zircon ages of **607±10 Ma** and **558±7 Ma** (oscillatory zoned zircon with Th/U=0.26–1.38 from inferred magmatic sources) supplemented by the scarce concordia ages of **538±9 Ma** or **534±7 Ma** (zircon outer mosaic spots with Th/U=0.11–0.14 of inferred metamorphic overprint), constraining the remnants of a gneissic Cadomian basement (Putiš et al. 2008). The lenses of massive metamafic rocks with largely variable Nd isotopic compositions ($\varepsilon Nd_{(500)}$=+7.7 to 0.0, $TDM_{(2st)}$ 0.58–1.18 Ga; but mostly +4.0 to +0.7, $TDM_{(2st)}$ 0.87-1.13 Ga), including rare mafic eclogites (with a protolith age of **478±3 Ma**) and peridotites, occur in the lower part of the Ky–Grt gneiss complex, while 200–300 m thick horizon of inferred gabbro intrusions differentiated into melagabbro, diorite to tonalite layers ($\varepsilon Nd_{(480)}$=+10.1 to +5.5, $TDM_{(2st)}$ 0.37–0.73 Ga) occurs in the upper part and on the top of this gneiss complex. The magmatic compositional layering of the LAC was dated in an interval of ~**503–480 Ma** in the Tatric and Veporic basement, or ~**480–450 Ma** in the Tatric Branisko Mts. (Putiš et al. 2009). Magmatic oscillatory zoned zircons of the dark gabbro-dioritic and pale tonalitic layers of the LAC have Th/U 0.22–0.45 and provide the same ages within the analytical error. The lower massive metamafic rocks are enriched in TiO_2 (1–3 wt.%) and HFSE (av. 14 ppm Nb; av. La_N=56.12, av. La_N/Yb_N=4.93) and classified as WPT and calc-alkaline VAB. The layered metamafic rocks with 0.17–2.7 wt.% TiO_2 are enriched in LILE, depleted in HFSE (av. 2 ppm Nb; av. La_N=51.23, av. La_N/Yb_N=3.34) and classified as calc-alkaline to tholeiitic VAB. The composition of the LAC indicates an arc-back-arc type magmatism. The lower $\varepsilon Nd_{(t)}$ values of the basal metamafics may reflect derivation from the subcontinental lithospheric mantle. In contrast, the layered amphibolites with higher $\varepsilon Nd_{(t)}$ values indicate their formation by melting of rather juvenile mantle sources. The northward subduction and metamorphic overprint of the LAC is registered in zircon mosaic outer zones (Th/U 0.12–0.15) that yield ages of ~**405–385 Ma**. A similar monazite U–Pb age of ca **380 Ma** was found from the Tatra Mts. (Moussallam et al. 2012). The post-collision extension and exhumation melting of the LAC was accessed from dioritic to leucotonalitic layers and veins at **370–360 Ma**.

The LAC is tectonically overlain by a few km thick succession of paragneisses with rare calc-silicate rocks, amphibolites and orthogneisses of the **Upper Unit** *Jarabá Complex*. The granitic protoliths of orthogneisses were dated in the interval from **515** to **440 Ma** (Putiš et al. 2008), testifying the melting of Cadomian continental margin fragments during the inferred long-lasting Cambrian–Ordovician subduction beneath the northern Gondwana margin magmatic arcs. The host paragneiss contains detrital zircons with predominated Neoproterozoic concordia ages between **572 and 552 Ma**, and fewer **630–610 Ma**, in the Tatric (Strážovské vrchy, Malá Fatra, Nízke Tatry Mts., incl. Klinisko) and Veporic (eastern Nízke Tatry and Vepor Mts.) basement indicating deposition of sedimentary protoliths close to Ediacaran magmatic arc. The Middle Proterozoic sources are rare, but the Early Proterozoic to Archean ages between **2.0** and **3.4 Ga** were detected. Similar zircon ages in the LAC underlying **Middle Unit** *Hron Complex* micaschists (Závadka nad Hronom, Veporic basement) may suggest a Cadomian/West African provenance (after Linnemann et al. 2008). These successions might have reached the maximum formation age in earliest Devonian, before they underwent the inferred Early Variscan tectono-metamorphic overprint at ca **380–360 Ma**, followed by melting within two diachronous arcs: (1) at ca **360–350 Ma** related to the LAC subduction; and (2) at ca **350–340 Ma** which might be related to the Paleotethys and/or the Rheic subductions (e.g., Broska et al. 2022).

(2) The North Gemeric Devonian **Rakovec–Klátov Complex** and closely related Carboniferous successions (Radvanec & Németh 2018; Vozárová et al. 2021) define another suture zone (Németh 2002) separating the **Lower Variscan Unit** of South Gemeric Late Cambrian–Silurian Gelnica Group (Vozárová et al. 1998, 2010) from the Upper and Middle units. This zone was developed by the rifting of the South Gemeric type basement on the Gondwana side. The early rifting stage stratiform sulfidic mineralization, bound to trachyte-basalt outflows on the seafloor (Radvanec et al. 2017, 2019, 2022), was followed by the formation of the Early Devonian Rakovec–Klátov Complex. The **Rakovec Group** *Sykavka Formation* composed of basalts, dolerites, gabbro-porphyrites and gabbros ($\varepsilon Nd_{(400)}$=+8.2 to +3.7, $TDM_{(2st)}$ 0.46–0.81 Ga; av. La_N=85.53, av. La_N/Yb_N=5.49) has composition of mostly WPT and less E-MORB. In contrast, the **Klátov Group** massive to layered gabbros, plagiogranites ($\varepsilon Nd_{(400)}$=+9.8 to +5.4, $TDM_{(2st)}$ 0.34–0.68 Ga; av. La_N=21.51, av. La_N/Yb_N=1.24) are mostly N-MORB magmas associated with peridotites. A separated part of this group is represented by calc-alkaline diorites to tonalites (av. La_N=97.89, av. La_N/Yb_N=5.77) and silica-poor gneissic metaclastic rocks derived from a destructed intermediate magmatic and less siliciclastic sources, tentatively called the *Ružín Formation*. The *Zlatník Formation* N-MORB type basalts, dolerites, gabbros and ultramafic rocks (Ivan & Méres 2012) may belong to the Klátov Group (av. La_N=23.50, av. La_N/Yb_N=1.43). The magmatic ages of the Rakovec Group *Sykavka Formation* were dated on a porphyric metagabbro from the Šajby locality at ~**405 Ma**, whereas a metagabbro from Poráč Valley, Slovinky mine yields an age of ~**395 Ma**. However, the infolded slices of the intermediate and acidic metavolcanics of the *Nálepkovo Formation* (Gelnica Group?) were dated at **476, 471, and 468 Ma**. Six metagabbro samples of the Klátov Group (Dobšiná, Rudňany, Košická Belá and Vyšný Klátov) provided magmatic ages of **410–383 Ma**, and a metaplagiogranite boulder from Late Carboniferous conglomerates at Závadka **398 Ma**. The *Zlatník Formation* metagabbro was dated on zircon at ca **410 Ma**, while on titanite at **388±4 Ma** with the outer metamorphic zone of **340 Ma** (Hnilčík, Zimná Valley). The latter titanite age is consistent with the metamorphic zircon age of a porphyric metagabbro of **350±5 Ma** from the *Sykavka Formation* (below Ostrá Hill). These dates indicate a subduction event (Radvanec 1999; Faryad et al. 2020) and the closure of the Rakovec–Klátov Basin after ca **375 Ma**.

(3) The Late Devonian (dated dolerite at **371±4 Ma**; Putiš et al. 2009) **ophiolitic Pernek Complex** (Ivan et al. 2001) occurs on the Upper Unit. It consists of deepwater silicitic Mn-rich sediments and black shales, N-MORB-type basalts, dolerites and gabbros ($\varepsilon Nd_{(370)}$=+10.4 to +8.0, $TDM_{(2st)}$ 0.27–0.43 Ga; av. La_N=16.32, av. La_N/Yb_N=1.09). This BAB closed at ~**365–355 Ma** and the thrust plane of metaophiolites over the marginal Lower to Middle Devonian metasediments is crosscut by tonalite apophyses of **352–343 Ma** (Putiš et al. 2004) generated within a Mississippian magmatic arc.

Data interpretation: (1) The transformation timing of the Gondwana margin late Cadomian gneissic basement to a Prototethyan Late Cambrian–Silurian continental arc-immature back-arc is constrained by the LAC magmatic ages from the inferred Panthalassa supra-subduction zone. (2) The Early Devonian (405–385 Ma) northward LAC subduction resulted in its suturing between the being metamorphosed Late Cambrian–Silurian inferred forearc Upper and passive margin Middle units, thus connecting a distant Cadomian terrane Galatian microplate and the Gondwana (Putiš et al. 2009). (3) The slab break-off and post-collision extension exhumation partial melting of the LAC was dated at ca 370–360 Ma, followed by older granites emplacement in an older magmatic arc. However, the migmatitization and the granite formation in the gneissic Upper Unit in the Tatric basement was continuing during the second period of melting at ca 350–340 Ma (Suchý, Strážovské vrchy Mts., new data) or in Tatra Mts. (Janák et al. 2022), possibly indicating a newer(?) magmatic arc, which might have been related to the Paleotethys and/or Rheic subduction. (4) The closing of the pre-Variscan basin system and the northward slab pull could have triggered a tension in the being rifted Gondwana margin (with the Gelnica Group) and finally the opening of the Paleotethyan Rakovec–Klátov Basin in the Early Devonian. (5) A 370–340 Ma closure of the Rakovec–Klátov Basin by the northward oceanic crust subduction resulted in the accretion of the Lower Unit Gelnica Complex to the ocean rift-derived and sutured Rakovec–Klátov Complex. We relate the Mississippian Črmeľ Formation (Vozárová et al. 2021), north of this suture, to supra-subduction forearc environment (M. Grecula 1998). (6) The Late Devonian Pernek BAB may have been opened by roll-back of the LAC-bearing subducted slab in combination with the southward Rheic oceanic subduction beneath the Galatian microplate (Putiš et al. 2009), resembling the Brévenne BAB in the French Massif Central (Fauré et al. 2005). (7) The Pernek Complex was welded with the Upper Unit during the Late Variscan southvergent collision and thrusting of the exhumed Upper Unit and the hanging wall LAC (amphibole ^{40}Ar–^{39}Ar age of 356±6 Ma; Dallmeyer et al. 1996) over the Middle Unit, while the Rakovec–Klátov Complex might have overthrust the Gelnica Complex at ca 350–330 Ma (Grecula et al. 2009).

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Permo–Carboniferous magmatism in the Tisza Mega-unit (Pannonian Basin and Apuseni Mts.): Petrology, zircon U–Pb dating and regional correlations

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In the Tisza Mega-unit, the products of several Late Palaeozoic magmatic episodes are exposed to the surface in Apuseni and Mecsek Mountains or were drilled by hydrocarbon and uranium ore exploration works in the eastern Pannonian Basin and southern Transdanubia during the second half of the 20th century. First descriptions and interpretations of these rocks were associated with the previous industrial reports that provided obsolete and/or incomplete information. Therefore, many of the available formations were reexamined during the previous years in modern petrological views, including bulk-rock major and trace element geochemistry and zircon U–Pb geochronology. In general, these rocks were affected by various postmagmatic alterations (e.g., shearing, low-grade metamorphism, hydrothermal overprint, Na/Ka metasomatism), therefore, their bulk-rock compositions should be treated by care, relying mostly on immobile trace elements (HFSEs, REEs). In the following, the major outcomes and the regional significance of our investigations are summarized.

S-type granitoids (variously deformed granodiorites and leucogranites, metagranitoids and orthogneisses sometimes cut through by aplites/pegmatites) were studied from several parts of the Tisza Mega-unit such as the basement highs in the eastern Pannonian Basin (Algyő–Ferencszállás and Battonya–Pusztaföldvár areas, the so-called Battonya granitoids), outcrops in the western Apuseni Mts. (Codru granitoids) and the Papuk Mt. (Djedovica Quarry). All of them consist of quartz, plagioclase, K-feldspar, biotite, and muscovite as well as apatite, monazite, and zircon as accessory components and have subalkaline, peraluminous, alkali-calcic or calc-alkalic, and magnesian character. Regarding their REE and other immobile element distributions, the samples of the Battonya–Pusztaföldvár area are highly similar to the Codru granitoids, whereas granitoids of the Algyő–Ferencszállás (AF) area and orthogneisses from the Djedovica Quarry (Papuk Mt.) differ from them. Despite the typical S-type mineralogy of the studied rocks, which should refer to their continental crustal source, only the samples of the AF area show syn-collisional derivation (e.g., in the Yb vs. Ta and the Yb+Ta vs. Rb diagrams). The apparent arc-origin character of the Battonya and the Codru granitoids might be the result of a slab break-off, also supported by relatively high Sr/Y and La/Yb ratios, just as for the analogous formations in the Western Carpathians (Broska et al. 2021). Zircon dating of the Battonya granitoids suggests that the magmatism occurred during the Early Carboniferous (~356 Ma), and correlations are very likely between the Battonya and the Codru granitoids, while the granitoids of the AF area and the Papuk Mt. most probably represent distinct sources in the Variscan orogeny. At regional scale, all the studied S-type granitoids show close similarity to those of the Western Carpathians (Broska et al. 2021).

Variously altered Permian magmatic rocks were studied from a broad area of the Tisza Mega-unit including southern Transdanubia (dacitic/rhyodacitic pyroclastites, lavas, and dykes), the eastern Pannonian Basin (rhyolitic pyroclastites), and the Apuseni Mts. (dacitic/rhyodacitic pyroclastites, basalts, andesites as well as granitoids, diorites, gabbros and associated subvolcanic rocks). Zircon dating, coherent REE and other immobile trace element distributions suggested that all the studied plutonic and volcanic rocks could represent the same large-volume, Middle Permian (~271–259 Ma) magmatic system associated with continental rifting in the Palaeo-Tethyan realm. At regional scale, they show close similarity to the A-type granitoids and felsic volcanic rocks in the Western Carpathians (Gemeric, Veporic, and Silicic Units, e.g., Vozárová et al. 2009; Ondrejka et al. 2018, 2021).

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Influence of the stratigraphy and the shape of the seamounts on formation of mélanges in subduction zones: Insights from analog modeling

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Seamount subduction is one of the most dynamic processes at active plate margins leading to significant upper plate deformation, submarine slumping, and tectonic erosion (Ruh, Sallarès et al. 2016). Deformation processes occurring in regions of active plate convergence can be studied by (1) field work and study of deformation patters in previously accreted (paleo-) accretionary wedge exposed on the Earth's surface, (2) geological numerical modeling, (3) analogue modeling studying deformation structures (Angiboust, Menant et al. 2022). Experimental models focusing on seamount subduction, considered seamounts as a solid and coherent bodies (Dominguez, Lallemand et al. 1998). Recent research shows, that seamounts are often surrounded by large accumulations of loose blocks (Clarke, Vannucchi et al. 2018). The presence of loose blocks could play significant role in the subduction processes and deformation of accretionary prism and formation of tectonic mélanges. Seamounts are commonly disintegrated and mixed with the upper-plate, mostly arc-derived material to form mélanges, yet the details of the mixing mechanisms as well as whether these mélanges form at the surface as sedimentary (by slumping) or within the accretionary wedge as tectonic (by shearing and fragmentation) remains unclear.

These different mélange-forming processes may be suitably reproduced and studied through analog modeling allowing the direct observation of large-scale deformation processes in laboratory. In this work, twelve simple scaled sandbox experiments were performed, where the main goal is to understand the formation of mélanges during subduction of seamounts with three modeled variables (1) the angle of the slab dip (2) the presence/absence of surrounding loose blocks (3) shape of the seamounts. We also examined how the loose blocks were incorporated into accretionary wedges to form the dismembered Ocean Plate Stratigraphy (OPS), also referred to as the OPS mélange.

In contrast to published experiments, which consider entirely coherent seamounts made of gypsum, our experiments simulated subduction of seamounts, volcanic ridges and oceanic plateau composed of solid seamount(s) made of gypsum and surrounding loose blocks, also made of gypsum. This alternative setup may match closely the thick talus deposits around seamounts or even extensive accumulations of volcanic blocks in moat basins. Twelve different experiments were performed in this study:

The first four experiment revealed that subduction of a single seamount results in increasing the critical taper, resulting in the formation of a "plateau" atop the accretionary wedge, increased topography, and massive slumping of the previously accreted wedge and volcanic material over the trenchward side of the seamount. This process produced layers of sedimentary mélanges. With increased angle of slab dip, more material has been offscraped from the landward side of the seamount and deposited in the area behind the seamount while part of the blocks was incorporated into the accretionary prism.

The next four the experiments represented successive seamount chains that were incorporated into accretionary prism, resulting in more complex seamount–wedge interactions. The first subducted seamount thickened the wedge and generated a zone of extensive slumping at the surface, the eroded material was later reincorporated into the trench. Subsequently, subduction of the second seamount produced layers of tectonic mélanges that were strongly sheared and detached from the seamount.

The last four the experiments correspond to subduction of the oceanic plateau. The experiments represent initial stage of oceanic rise subduction. The incorporation of massive topographic elevation into accretionary prism. The oceanic plateau is underplated to the base of accretionary prism causing increase in critical taper, increased topography, and mass slumping on the surface of the accretionary prism forming sedimentary mélanges. The loose blocks surrounding plateau are deposited seaward and incorporated into accretionary prism along the shear zones, forming tectonic mélanges.

In conclusion, the results of experiments showed that both sedimentary and tectonic mélanges may form during seamount subduction, preferentially from domains composed of loose blocks made of gypsum representing volcanic blocks surrounding the seamount (talus or moat basin). The former type of mélanges forms at the wedge surface by sliding and mixing of loose blocks with sandy matrix, whereas the latter type of mélanges is controlled by intense shear deformation and overpressure state in front of the seamount along seamount/wedge interface. Some of these processes are greatly exemplified by the basalt-bearing mélanges in the Blovice accretionary wedge, Bohemian Massif.

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A brief insight to geological history of Ethiopia

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Ethiopia provides an unique record of geological evolution of the Earth´s crust from Precambrian to Recent. Among the most significant events have been studied include the East-African orogeny (ca. 770 to 550 Ma) and evolution of the Main Ethiopian Rift (from ca. 42 Ma to recent).

The Precambrian basement rocks in Ethiopia differ in deformation style, degree of metamorphism, and lithological pattern, from low- to high-grade units. The tectonometamorphic evolution could be summarized into four phases:

(1) The late Tonian to late Cryogenian formation of volcanic arc(s) dated at ca. 770 Ma;

(2) The crustal accretion related with intense migmatization and HT–MP metamorphism (T: 700–850 °C and P: 0.7–0.9 GPa) at depths of ~25–35 km dated at ca. 720 and 715 Ma;

(3) The late Cryogenian to early Ediacaran episode (ca. 650 to 620 Ma) of continental collision was associated with main collisional episode between East Gondwana and the consolidated Congo–Tanzanian–Saharan craton of the West Gondwana;

(4) Ediacaran–Cambrian Pan-African episode (ca. 630–500 Ma) linked with the late-orogenic exhumation, post-orogenic magmatism and localized activity along the regional strike-slip shear zones.

The Main Ethiopian Rift is an active intra-continental rift bearing magma-dominated extension between the African (Nubian), the Somalian, and the Arabian lithospheric plates. The current extension rate between the African and Somalian Plates in the southern Main Ethiopian Rift is 5.2±0.9 mm/yr in ~E–W orientation.

The Main Ethiopian Rift (MER) reflects a characteristic evolution of continental rifting from early plateau basalt lava flows (pre-rift stage), followed by forming of fault-dominated rift morphology in the early stages of the continental extension (early-rift stage) toward the magma-dominated extension (late-rift stage).

The origin of rift-related faults and escarpments commenced during the Miocene, accompanied by basalts, felsic volcanic, and volcaniclastic rocks varying from transitional to alkaline. These volcanic eruptions were followed by a period of drastically low volcanism.

Subsequently, the products of Pleistocene to Holocene late-rift bimodal volcanic activity (from ca. 7 Ma to Recent) ensued along with volcaniclastic rocks and rhyolites along with the strongly welded rhyolitic ignimbrites and other pyroclastic deposits. The late-rift volcanic activity is dominated by the sequence of acid volcaniclastic deposits, alkali basalt to trachyte lava flows, and pyroclastic cones.

EDX Analyses of U-rich microminerals both for geochronology and hydrogeology – examples from recent studies in Austria

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Due to the radioactive decay of uranium, U-rich microminerals like uraninite, uranothorite or coffinite can be used to determine the age of geological processes. Under certain conditions, uranium is highly water-soluble – therefore the investigation of U-rich microminerals is also of interest to hydrogeology.

Within the last years, the Geological Survey in Vienna (since 1. 1. 2023 GeoSphere Austria) was involved in some projects investigating uranium-bearing microminerals by means of scanning electron microscopy – both for hydrogeological and economical geology.

In several Austrian regions, there appears groundwater with a uranium concentration over the national threshold value for drinking water, which is 15 µg/L (Berka et al. 2014 and Schubert et al. 2018). The high uranium concentrations in groundwater appears mostly within the orthogneisses of Alpine regions and in the dry Neogene basins in the East (eastern Molasse Basin, Vienna Basin and western margin of the Pannonian Basin). Within the DaFNE-project "uranium in groundwater", for the first time the mineralogy of aquifers was scanned by means of electron microscopy on the micro- and submicrometre scale (Humer et al. 2019).

From 2016 to 2017 in the MRI-project "micro uranium minerals" the U–Th–Pb-analysis by electron microscope was improved and U-rich microminerals from the central Tauern window were dated chemically (Finger et al. 2017). Between 2018 and 2023 in the MRI-project DaMM ("dating of mineralisation processes by means of innovative micromineral analysis") such minerals were systematically used for the age dating of samples from Austrian ore deposits both in the Alps and in the Bohemian Massif. Furthermore, in both projects the influence of the U-rich microminerals to groundwater was taken under consideration.

Concerning hydrogeology, it came out that in the crystalline regions a high uranium content in groundwater was always associated with abundant U-rich microminerals. This is not the case in the Neogene basins in the east of Austria. Here other sources should be taken under consideration (concentration of uranium by evaporation and redox reactions, uranium from phosphate fertiliser). It is also remarkable, that U-rich granites and orthogneisses are normally associated with high radon concentration in the groundwater whereas in the basins in the East the radon content is very low.

The type, quantity and distribution of uranium mineralisation (uraninite, thorite, coffinite, brannerite, etc.) in rocks are important in our studies, as well as the U–Th–Pb content of the investigated minerals. Extremely helpful for this was and is the development of new EDX detectors with larger and more sensitive detector areas and better counting statistics, but also the development of better electron microscopes with regard to beam and current stability as well as current yield (Waitzinger 2018). Nowadays, this allows not only the qualitative but also the quantitative analysis of micrometre and even submicrometre sized minerals after successful detection of uranium-bearing minerals.

For instance, with this methodology and comparative measurements using the microprobe, it has been shown that uraninite, xenotime and brannerite were formed in the Hüttenberg siderite deposit about 80 Ma ago (Waitzinger 2020). In the region of the Tauern window, uraninites with Permian and Variscan and thorites with Alpine formation age (Tauern crystallization), all enclosed in metamict zircons, were found in the Ahorn gneiss. In the surroundings of the Reichenspitze, uraninites were discovered in a molybdenum-bearing aplite gneiss, which were also built during the Variscan orogeny as well as in the periode of Tauern crystallisation.

Graphite mineralisations in the Bohemian Massif contain uraninites, which were formed during the Cadomian as well as the Variscan orogeny.

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Depositional ages, tectonic setting, and paleogeographic significance of Neoproterozoic to Lower Paleozoic metasedimentary successions in Bulgaria

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Large portions of Variscan and Alpine orogenic belts in Europe contain variably reworked crustal fragments that originated in the Neoproterozoic to Cambrian Avalonian–Cadomian belt of northern Gondwana. Whereas the classic areas underlain by Cadomian basement such as the Armorican Massif, Iberia, and Bohemian Massif have long been studied and their pre-Variscan tectonosedimentary history has been well constrained, much less information is available for comparable units now exposed within the Alpine orogens. As an intriguing example, extensive Ediacaran and Lower Paleozoic volcano-sedimentary complexes occur in Bulgaria and adjacent parts of Serbia, surprisingly only weakly overprinted by Alpine deformation, but mostly of unknown provenance and poorly constrained age.

We analyzed U–Pb detrital zircon ages from several pre-Darriwillian low-grade units (Lakavitsa, Berkovitsa, Bilo, Diabase–Phyllitoid Complex, Sredna Gora, Stara Planina, and Vlasina complexes) but also from the overlying Darriwillian Grohoten and Famennian–Frasnian Katina formations. The age spectra and the maximum depositional ages of the pre-Darriwillian units suggest deposition in an accretionary wedge/forearc basin setting, or in an incipient rift superposed on the Cadomian forearc/arc region, from the latest Ediacaran to late Cambrian. The basins were sourced mostly from a magmatic arc with a limited input of cratonic detritus. In contrast, samples from the overlying formations indicate a sustained delivery of the cratonic detritus, perhaps first into passive-margin basins of the 'Gondwana super-fan' system and then into a Variscan foreland basin.

In order to estimate their provenance and paleoposition, we statistically compare the detrital zircon ages in these units and similar terranes from the Eastern Alps to Iran with igneous and metamorphic U–Pb zircon ages from North African source areas. The comparison is done through multi-dimensional scaling (MDS) to examine the degree of inter-sample similarity. This information is then transferred to a tentative paleogeographic map showing position of each terrane with respect to its most likely source region. As a result, we define a 'westerly' terrane assemblage (including the Vlasina complex), characterized by Mesoproterozoic ages and sourced from the West African craton and the Trans-Saharan belt and an 'easterly' assemblage formed next to the Saharan Metacraton and the Arabian–Nubian shield (the remaining units).

Moreover, the statistical analysis shows that the sampled units exhibit age spectra well compatible with the Cadomian terranes, whereas they differ significantly from those reported from Avalonian-type Moesia microplate attached to the southeastern margin of Baltica. Hence, the detrital zircon ages may help to locate the Rheic suture, left behind the Rheic Ocean that opened between Avalonia and Gondwana in the late Cambrian to early Ordovician and was consumed during the Variscan plate convergence. It cannot be excluded, however, that the easterly Cadomian terranes may have remained attached to Gondwana during the entire Early Paleozoic and thus the Rheic suture did not reach that far east and terminated at an intraoceanic transform plate boundary.

Zircon U–Pb–Hf isotope systematics of southern Black Forest gneiss units (Germany): Implications for the Pre-Variscan evolution of Central Europe

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Presently, little is known about depositional ages, geological settings, and provenance of (meta)sedimentary rocks constituting the southern part of the Black Forest Gneiss Complex, preventing detailed reconstructions of the Cadomian to Variscan geodynamic evolution in Central Europe and beyond. Here, we present the first systematic U–Pb–Hf isotope data of detrital zircon grains combined with geochemical data of metasedimentary rocks from the Murgtal, Todtmoos, and Wiese-Wehra gneiss units, preserving different stages of the pre-, syn- and post-Cadomian evolution. Protoliths of Murgtal metagreywackes were deposited during the Ediacarian at <550 Ma and sourced from the Avalonian-Cadomian Belt (550–700 Ma; ~70%) and Sahara Metacraton (760–1045 Ma, 1850–2250 Ma, 2720–3230 Ma; ~30 %). In contrast, metasedimentary rocks of the Wiese-Wehra and Todtmoos gneiss units reveal late Devonian depositional ages at <370 Ma, but in different geotectonic settings. Data from Wiese–Wehra metagreywackes provide evidence for the existence of pre-Cadomian oceanic crust formed at 610 Ma (εHf_t = +5 to +8), accreted to the Avalonian-Cadomian Belt at ca. 540 Ma, and successively reworked during peri-Gondwana rifting between 490 and 430 Ma (εHf_t = +1 to +6). Finally, these rocks became part of an early Variscan arc-back arc system with juvenile input at 370 Ma (εHf_t = 0 to +10). Todtmoos metaarkoses mainly reflect subduction-related magmatism at 490–420 Ma (~88 %), and at 380 Ma (~10 %) in an evolved continental arc setting (εHf_t = −2 to −8), and only rare evidence for Cadomian arc magmatism at 560–700 Ma (εHf_t = −10 to +3; ~2 %). Zircon grains of some samples additionally reveal metamorphic overprint at 347–340 Ma. In combination, new and existing data from the Black Forest and other basement units throughout Europe provide evidence for the amalgamation of pre-Cadomian juvenile terranes along the northern margin of Gondwana until 540 Ma, followed by a complex rift history, accompanied by subduction between 500 and 400 Ma. They further point to the existence of an extensive oceanic arc-back arc system, which has been located south of the Armorican terrane assemblage at 380–365 Ma, and underwent northward directed subduction-accretion until 345 Ma.

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