

Review article

Petrochemical correlation of Eifelian–Visean magmatic rocks of the Bohemian Massif and the Central Western Carpathians: Two contrasting Variscan crustal segments

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Abstract: The nature and timing of Mid-Devonian–Visean plutonic activity in the Variscan Bohemian Massif (BM) and the Central Western Carpathians (CWC) differed profoundly. In the BM, most of this period was marked by vigorous arc-related magmatism that ceased only at ~340 Ma by the collision and the ensuing slab break-off. The oceanic subduction passed to deep continental underthrusting, and relamination of felsic metagneous material of Saxothuringian origin, soon thereafter transformed into (U)HP–HT granulites. The Visean activity in the BM was characterized by an emplacement of voluminous (ultra-)potassic plutons and countless dykes of matching chemistry, but practically no syn- to early post-collisional S-type granitoids. In the BM, the bulk of S-type magmas was produced in Serpukhovievian or younger. In the CWC, the evolution started later but was considerably faster; the classic magmatic arc seems not to be preserved here. Subduction, evidenced by Frasnian back-arc mafic magmatism and anatexis, was terminated by collision and early (Late Devonian) slab break-off. The attendant heat pulse produced dioritic rocks, and then a Tournaisian late-collisional flare-up of the I- and immature (biotite-bearing) S-type granitoids. The mature (muscovite-bearing) Visean S-type granites were already post-collisional. In the CWC, the (ultra-)potassic magmatic rocks are conspicuously missing, as are the (U)HP–HT granulites. This reflects a too early slab break-off and/or inappropriate composition of the downgoing continental slab. The contrasting Mid-Devonian to Visean magmatic histories clearly reflect distinct paleogeographic positions of the BM vs. CWC crustal segments, probably along the two unconnected sutures in the widely separated branches of the Variscan orogenic collage.

Keywords: granitoids, Variscan, U–Pb geochronology, whole-rock geochemistry, Sr–Nd isotopes, paleogeography

Introduction

Variscan Orogeny in Europe was accompanied by voluminous and diverse magmatism, reflecting the spatial and temporal evolution of changing magma sources (both crustal and in the mantle), P – T – fO_2 conditions of melting and, ultimately, a complex interplay among variable differentiation processes at distinct crustal levels. In terms of geodynamic setting, petrologically and geochemically contrasting magmas were produced throughout the orogen's evolution from oceanic subduction (active continental margin), through oceanic closure (continental collision) and slab break-off to post-collisional and post-orogenic/rifting stages (Finger et al. 1997; Timmerman 2008; Moyen et al. 2025).

As has been shown previously, an analogous typology and temporal evolution of magmatic suites (from Late Devonian oceanic subduction to c. 340 Ma collision, and Visean granitic

flare-up) can be followed from the Vosges Mts. in eastern France as far as to the Bohemian Massif (Fig. 1a), the easternmost largely undisturbed outcrop of the Variscan basement in Central Europe (Finger et al. 1997; Trubač et al. 2020; Schulmann et al. 2022; Moyen et al. 2025).

The continuation further east and south-west has been obscured by the Alpine Orogeny that fragmented the Variscan basement. In particular, in the Central Western Carpathians (Slovakia – Fig. 1b), the Devonian–Mississippian granitoid bodies are embedded in the Cretaceous Paleo-Alpine structures (Broska & Uher 2001; Kohút & Larionov 2021). This makes it difficult to trace any relationships among them.

The first whole-rock geochemistry-based correlation of Variscan granitic magmatic associations from the Bohemian Massif (BM) and Central Western Carpathians (CWC) was attempted some 50 years ago (Cambel et al. 1980; Klomínský et al. 1981). The main difference noted at that time was the lack of (ultra-)potassic magmatic lithologies in the Central Western Carpathians, ubiquitous in the Bohemian Massif ('durbachite suite'). Furthermore, in view of these authors, the West Carpathian granitoids generally had higher Na_2O/K_2O

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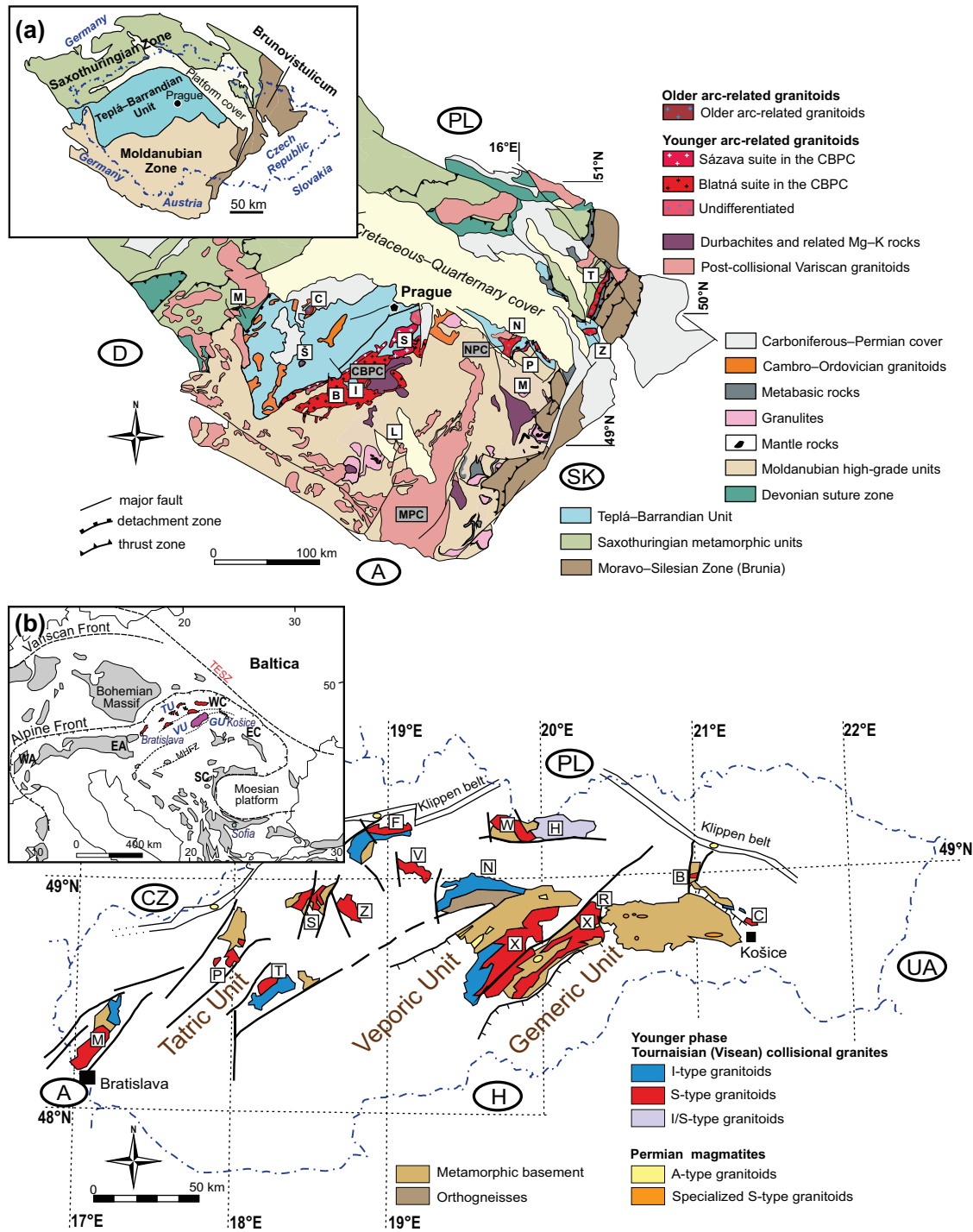


Fig. 1. Geological sketches of the studied regions, BM and CWC. **(a)** Bohemian Massif. *Inset:* Major lithotectonic zones of the Bohemian Massif. *Main map:* Simplified geological map of the Bohemian Massif showing geological units and distribution of major Variscan plutonic bodies (modified after Schulmann et al. 2014). Granitoid bodies plotted in the diagrams: Older (Devonian) phase: M – Mariánské Lázně Complex (MLC), C – Čistá, Š – Štěnovice, I – Islet Zone orthogneisses, L – Lišov mafic LP granulites; Younger (Tournaisian–Visean) phase: S – Sázava, B – Blatná, N – Nasavrky, P – Polička, Z – Zábřeh, M – Moldanubian (Kotlasy), T – Staré Město Belt. CBPC – Central Bohemian Plutonic Complex, NPC – Nasavrky Plutonic Complex, MPC – Moldanubian Plutonic Complex. **(b)** Central Western Carpathians. *Inset:* Distribution of pre-Alpine basement in the central-eastern Europe (modified from Kounov et al. 2012). WC – Western Carpathians, EC – Eastern Carpathians, SC – Southern Carpathians, EA – Eastern Alps, WA – Western Alps, TESZ – Trans-European Suture Zone (Tornquist Zone), MHFZ – Main Hungarian Fault Zone, TU – Tatric Unit, GU – Gemeric Unit, VU – Veporic Unit. *Main map:* Variscan segments with exposed granite backbones in the Central Western Carpathians (adapted acc. Broska & Uher 2001). Granitoid bodies plotted in the diagrams: M – Malé Karpaty Mts., P – Považský Inovec Mts., T – Tribeč Mts., S – Strážov Hills, Z – Žiar Mts., F – Malá Fatra Mts., V – Veľká Fatra Mts., W – Západné Tatry Mts., H – Vysoké Tatry Mts., N – Nízke Tatry Mts., B – Branisko Mts., X – Slovak Ore Mts., C – Čierna Hora Mts., R – Rochovce.

ratios and more leucocratic character than their Bohemian counterparts. The main problem that the early correlations were facing, however, was the scarcity of precise trace-element and isotopic data, as well as of reliable age information.

Meanwhile, since 1980's, we have witnessed rapid advancement of statistical and analytical techniques which call for revisiting this correlation issue. In particular, ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and TIMS (Thermal Ionization Mass Spectrometry) techniques keep bringing a flood of precise and time-efficient trace-element analyses, *in situ* geochronological and radiogenic isotopic data (Johnson et al. 2013; Janoušek & Moyen 2020). Therefore, resuming work on the correlation between the Czech and Slovak Variscan magmatic suites has long been overdue.

Here, we compile a large body of available petrological, whole-rock geochemical, geochronological, and Sr–Nd isotopic information on contrasting plutonic associations from the central parts of the Bohemian Massif (Teplá–Barrandian and Moldanubian units) and the so-called ‘core mountains’ of the Central Western Carpathians. We have focussed onto arguably the most exciting Mid-Devonian to early Carboniferous (Tournaisian–Viséan) evolution, encompassing the oceanic subduction, through continental collision to early post-collisional orogenic stages. This scope was chosen carefully as the evolution of the mentioned parts of the BM and the CWC was indeed comparable till *c.* 330 Ma but then diverged conspicuously. Moreover, such a focus has allowed us to keep the geochemical database, including the number of individual magmatic bodies and, consequently, geosetting and petrology chapters of this text (and reference number) at a manageable size. The post-Viséan magmatism in both BM and CWC would, undoubtedly, constitute sufficient material for a specialised contribution of a size comparable to the current one.

Our aim here is to portray the common features, as well as to underline important differences, among magmatic suites of both regions, in terms of their timing, petrology, whole-rock geochemical and Sr–Nd isotopic composition and prospective genesis. This, in turn, should allow drawing geodynamic and paleogeographic consequences for Central European segment of the Variscan Belt.

Geological setting

Variscan Orogeny in Central–Western Europe

The Variscan Orogeny in Central–Western Europe was driven by Late Devonian–Carboniferous convergence of Gondwana and Baltica (and numerous microcontinents sandwiched in between), closure of intervening oceanic domains, collision and amalgamation of various microcontinental blocks (Franke 2000; Edel et al. 2018; Schulmann et al. 2022; Murphy et al. 2025). The largest and best-preserved tracts of the Variscan Orogen in Europe can be found in Iberia, Armorican Massif, French Massif Central, Vosges, Schwarzwald, Sardinia–

Corsica and Bohemian Massif (Schulmann et al. 2022). In addition, small fragments of the Variscan orogenic crust are included within the Mesozoic Alpine collisional belt (von Raumer et al. 2013; Neubauer et al. 2022).

Bohemian Massif (BM)

In the Bohemian Massif, the characteristic succession of principal lithotectonic domains differing in age, lithology and metamorphic grade has been interpreted as spanning from Andean-type subduction (Palivcová 1984; Schulmann et al. 2009; Žák et al. 2014) (Fig. 1a). If going from NW to SE, these are: (1) the Saxothuringian domain with Cadomian basement and Paleozoic metasedimentary/metaigneous cover (representing the lower plate) (Linnemann et al. 2025), (2) the variably metamorphosed Ediacaran accretionary wedge and unmetamorphosed Lower Paleozoic sequences of the Teplá–Barrandian Unit (Hajná et al. 2018; Žák et al. 2025), (3) the mid- and lower crustal rocks of the Moldanubian Domain, the high-grade ‘orogenic root’ of the Variscan Orogen, including (U) HP–HT metamorphic complexes and various mantle-derived lithologies (Schulmann et al. 2009; Faryad 2011; Lardeaux et al. 2014), and (4) the Moravo–Silesian Zone (or Brunia), with the Brunovistulicum representing the Cadomian arc-related (meta-)granitoids and metasediments in the basement of metamorphic nappes of the Ediacaran–early Paleozoic protoliths and the Devonian–Carboniferous (volcano-)sedimentary complexes (Hanžl et al. 2025).

In geodynamic terms, the south-east-dipping (present-day coordinates) Andean-type subduction beneath Teplá–Barrandian Unit (Schulmann et al. 2009; Žák et al. 2014) led to the closure of the intervening ocean, deep underplating of the (mostly felsic metaigneous) continental crust, contamination and metasomatic modification of the local lithospheric mantle and relamination of this originally Saxothuringian crust to the overriding Moldanubian plate (Janoušek & Holub 2007; Schulmann et al. 2014; Nahodilová et al. 2020; Janoušek et al. 2025a).

Central Western Carpathians (CWC)

The Variscan basement of the CWC consists of two principal structural and lithological étages (Kohút et al. 2022). The Lower Étage (Cambrian to Silurian in age) is composed of a leptynite–amphibolite complex (LAC) with remnants of retrogressed eclogites and metaultramafites, tonalitic gneisses and sheared Cambrian–Ordovician felsic magmatites (now orthogneisses). All these rocks are intercalated with metapsammites to metapelites with rare carbonate (calc-silicate) lenses, and scarce black shales. The metamorphic conditions of this complex were commonly estimated at 650–800 MPa and 600–780 °C (e.g., Krist et al. 1992; Janák & Lupták 1997) sometimes with characteristic widespread migmatization/granitization. In contrast, *P–T* conditions reached up to 1.2–2.5 GPa and 700–750 °C in the eclogite remnants (e.g., Janák et al. 1996, 2009; Faryad et al. 2005).

The Upper Étage is formed by characteristic Upper Silurian–Devonian volcano–sedimentary sequences composed of metagraywackes, phyllites, metabasites (epidote–actinolite amphibolites), black shales, calc-silicate lenses, Fe+Pb–Zn Lahn-Dill-type mineralization, and scarce apatite-rich rocks. The low-grade metamorphism reached a greenschist facies only (below 350 MPa and 550 °C), and weak intrusive migmatitic zones are merely observed (e.g., Krist et al. 1992; Ivan et al. 2001; Méres 2005).

However, Putiš et al. (2024), in their new concept, have distinguished post-Cadomian (~550–500 Ma) and Prototethyan subduction–accretion (Cenerian; ~500–400 Ma) forearc-arc/incipient back-arc complexes from Paleotethyan rift-related complexes (~400–360 Ma). All were thought to be located on the northern Gondwana margin (Galatian Terrane), close to the Cadomian Ediacaran magmatic arc and far away from the Saharan Metacraton. Interestingly, their south-vergent early Variscan structure (~400–360 Ma) of the Western Carpathians basement included, from top to bottom, and north to south: (1) *The Upper Unit*, composed of higher grade metamorphic rocks of the Jarabá Complex (~Cambrian–Silurian/lowest Devonian) with the Layered Amphibolite–Gneiss Complex (LAGC, upper Cambrian–Ordovician) on the footwall, (2) *The Middle Unit* micaschists–gneisses of the Hron Complex (Cambrian–Lower Ordovician?) and (3) *The Lower Unit*, formed by an accreted Gemic Zone (late Cambrian–Ordovician). The Upper Unit represents a northern Gondwana active continental margin (the Galatian Terrane in Putiš et al. 2009), while the Middle Unit presumably formed a passive Gondwana margin. The Lower Unit – the Gelnica Complex of the Gemicum – was characterized as an active Gondwana margin again (Putiš et al. 2024).

In the CWC, Frasnian–Visean subduction- and collision-related plutonism is known only in the *Tatric and Veporic units* (e.g., Kohút et al. 2009; Burda et al. 2011; Broska et al. 2013, 2022; Kohút & Larionov 2021; Catlos et al. 2022 and references therein). The *Tatric Unit* is c. 8 km thick nappe composed of Variscan basement, Mesozoic sedimentary cover (e.g., Plašienka 2018 and references therein) and terminated by upper Cretaceous Gosau Group, like in the entire Alpine realm (Wagreich & Faupl 1994) (Fig. 1b). Granite massifs in the *Tatric Unit* occur in cores of the Miocene horsts, the ‘core mountains’ formed during the Cenozoic tectonic evolution (i.e., the Malé Karpaty, Považský Inovec, Tribeč, Strážov Hills, Žiar, Malá Fatra, Veľká Fatra, Západné and Vysoké Tatry, Nízke Tatry and Branisko Mts). In contrast, Veporic granitic rocks, subjected to Alpine amphibolite-facies metamorphism, form a large-scale dome (Janák et al. 2001).

In both the *Tatric* and *Veporic* units, each of the massifs contains various proportions of S- and I-type granitic rocks (Cambel & Petrik 1982; Cambel & Viliňovič 1987; Broska & Uher 2001). Their typology is based on the whole-rock geochemistry and mineral characteristics. In particular, the presence/absence of monazite became an important discrimination criterion, as did apatite and biotite compositions (Broska et al. 2004).

The early Variscan oceanic subduction produced mainly mafic and intermediate plutonites in the CWC. The production of the early Variscan granitoids was originally interpreted as related to the northward subduction of Paleotethys (Broska et al. 2013), perhaps under a ribbon continent that drifted off Gondwana in early Paleozoic times (Stampfli & Borel 2002). In view of the new paleogeographic models, more feasible seems a NW-ward subduction of Balkan–Carpathian oceanic segment, like in the Eastern Alps (e.g., Neubauer et al. 2022).

Following the Devonian subduction and collision, the Mississippian period was characterised by the production of large volumes of granitic melts. The Tournaisian granite flare-up at c. 350 Ma (Kohút & Larionov 2021; Catlos et al. 2022) was explained as a consequence of slab break-off (Davies & von Blanckenburg 1995) by Broska et al. (2022). This slab break-off was accompanied by Famennian crustal exhumation and attendant decompression melting, producing voluminous diatexites (Broska et al. 2022; Maraszewska et al. 2022; Kohút et al. 2026). Some post-collisional granites have ‘adakite-like’ (high Sr/Y and La/Yb) signature indicating formation in deep crust, within the garnet stability field, without the residual plagioclase. Late high-*T* granodiorites–tonalites reflect asthenospheric rise terminated by the Permian rifting. The principal evidence for the presence of a hot magmatic system includes the occurrence of high Ti-quartz with later exsolved rutile needles, antiperthite and calcic (An>50) plagioclase cores (Kurylo & Broska 2025).

Review of regional distribution, age, petrology and classification of the Mid-Devonian–Visean magmatic suites from Bohemian Massif and Central Western Carpathians

The following text provides a brief outline of Mid-Devonian to Visean magmatic activity in the Bohemian Massif and Central Western Carpathians. It is based on our own data, as well as extensive literature search and previous reviews on character and geodynamic context of the Variscan magmatism from the Bohemian Massif (e.g., Klomínský et al. 2010; Žák et al. 2014), and the Western Carpathians (Petrik et al. 1994, 2001).

Older phase (Mid- to Late Devonian)

Bohemian Massif

In the BM, the oldest magmatism connected with the **Andean-type subduction** of the Saxothuringian Ocean (Schulmann et al. 2009) produced geochemically primitive clinopyroxene–amphibole gabbros to trondhjemites that intruded high-grade metabasites of the *Mariánské Lázně Complex* (MLC) c. 385 Myr ago (Deiller et al. 2021) (Fig. 2). Near-contemporaneous were amphibole–biotite granodiorites to granites of the c. 390–365 Ma *Čistá* and of the 375±2 Ma *Štěnovice* plutons (Žák et al. 2011a; Deiller et al. 2021).

Further east, within the so-called Metamorphic Islet Zone (roof of the Mississippian Central Bohemian Plutonic Complex; CBPC), the protoliths of the felsic (tonalitic–granodioritic) (amphibole–) biotite orthogneisses were dated at 380–365 Ma (Košler et al. 1993; Tomek et al. 2015). Finally, the protoliths of the quartz dioritic–tonalitic Lišov low-pressure (pyroxene-bearing) granulites formed at a mid-crustal (*c.* 5 kbar) level of a ~360 Ma igneous arc (Janoušek et al. 2006).

Central Western Carpathians

The **older arc-related magmatism** in the CWC (*c.* 380–361 Ma) yielded mainly basaltic lava flows, primitive amphibole±clinopyroxene gabbro intrusions and dolerite dykes within the Devonian low-grade volcano-sedimentary Pernek Group of the *Malé Karpaty Mts.* (Ivan et al. 2001) dated at 371±4 Ma (Putiš et al. 2009) and/or small gabbroic body with an age of 373±2 Ma (Kohút unpublished data) enclosed within the younger granitic rocks in the *Branisko Mts.* Besides these (ultra-)basic to intermediate rocks were produced the first, ‘immature’ granitic rocks and/or diatexites (*c.* 367–361 Ma). They were melted from the apical, unhomogenized parts of plutons, probably during an ‘initial collisional stage’ (Poller et al. 2000; Gawęda et al. 2016; Kohút & Larionov 2021).

However, relatively soon after the beginning of continental collision, the **slab break-off** resulted in influx of hot asthenospheric mantle melt, intrusions of gabbro–diorites and diorites before 361–357 Ma, triggering the formation of diatexites and leading to the Tournaisian granite flare-up (Broska et al. 2022; Maraszewska et al. 2022; Spišiak et al. 2024).

Younger phase (Tournaisian–Visean)

Bohemian Massif

In the Bohemian Massif, the Tournaisian–Visean **subduction-related magmatic activity** (*c.* 359–335 Ma) migrated eastwards, forming the so-called Peri-Moldanubian Arc, decorating the Teplá–Barrandian–Moldanubian boundary (Janoušek et al. 2025b).

In the *Central Bohemian Plutonic Complex*, the oldest were *c.* 354 Ma (amphibole–) biotite gabbros, quartz diorites, tonalites and trondhjemitites of the Sázava suite (Holub et al. 1997a; Janoušek et al. 2004a). Besides prevailing crustally-derived (amphibole–) biotite granodiorites, the ~346 Ma Blatná suite features monzonitic rocks, produced from slightly enriched mantle (Dörr & Zulauf 2010; Janoušek et al. 2010).

The oldest (347–341 Ma: Soejono et al. in review, Gondwana Research), arc-related Nasavrky suite of the *Nasavrky Plutonic Complex* (NPC) consists mainly of amphibole–biotite tonalites to granodiorites, associated with large bodies of amphibole-rich gabbros to quartz diorites (Táborská 1997; Hroudá et al. 1999). The younger, mostly granodioritic Skuteč suite of the NPC has been newly dated at 337±2 Ma (Soejono et al. in review).

Compositionally equivalent amphibole–biotite tonalites–granodiorites with minor associated mafic bodies occur also further east, in the Polička Unit. These plutons were dated at ~353 Ma (*Miřetín*) and ~350–346 Ma (*Budislav*) (Vondrovic et al. 2011; Janoušek et al. 2025b). A rare example of dismembered quartz dioritic–tonalitic arc fragments incorporated into the nearby parts of the Moldanubian Domain represents the ~352 Ma *Kotlasy* intrusion (Janoušek et al. 2025b).

Continuing NE into Moravia, arc-related amphibole-bearing tonalites form the contemporaneous (~353 Ma) *Zábřeh Pluton* (Buriánek et al. 2003; Vondrovic 2015; Janoušek et al. 2025b). Finally, the N–S trending, syn-tectonic *Staré Město Belt* rimming the Saxothuringian–Brunovistulian contact is dominated by the metamorphosed (in part anatectic), syn-tectonic *c.* 344–339 Ma amphibole–biotite tonalites (Parry et al. 1997; Jastrzębski et al. 2018; Śliwiński et al. 2025).

In the CBPC, the truly metasediment-derived Tournaisian–Visean **anatectic (S-type) granites** are extremely rare. The two-mica, often cordierite-bearing granodiorites of the so-called Maršovice suite (Holub et al. 1997b; Janoušek et al. 2000b) likely originated by anatexis of paragneisses in the CBPC roof. They were dated at 345.5±0.6 Ma by conventional U–Pb zircon dating (Dörr & Zulauf 2010). The (muscovite–)biotite Říčany granite in the NE CBPC with abundant potassic mafic microgranular enclaves (MME) intruded at *c.* 337 Ma (Trubač et al. 2017).

Characteristic of the Moldanubian Zone are (ultra-)potassic plutons (Kfs-phyric durbachite suite and minor two-pyroxene syenitoids) (Holub 1997; Janoušek et al. 2019, 2020), which are accompanied by countless lamprophyre and lamproite dykes (Holub 1997; Janoušek & Holub 2007; Žák et al. 2014; Krmíček et al. 2020). The Moldanubian (ultra-)potassic magmatism has been dated between *c.* 339 and 335 Ma (Janoušek & Svojtka 2021; Schaltegger et al. 2021 and references therein).

Central Western Carpathians

According to Kohút et al. (2026), the Tournaisian **late-collisional CWC granitoids** (*c.* 357–345 Ma) can be divided into (1) (amphibole–)biotite tonalites–granodiorites of the ACG (Amphibole-bearing Calc-alkaline Granitoids) and KCG (K-rich Calc-alkaline Granitoids) character (*sensu* Barbarin 1999) coming from metaigneous lower crustal sources supplemented by mafic melts derived from the subcontinental lithospheric mantle, and (2) biotite granodiorites–granites (resembling Cordierite-bearing Peraluminous Granitoids, CPG) with minor proportion of muscovite leucogranites and two-mica granites (Muscovite-bearing Peraluminous Granitoids, MPG), produced from the metasedimentary lower/middle crust (Poller et al. 2000; Magna et al. 2010; Burda et al. 2011; Broska et al. 2013, 2022, 2024; Gawęda et al. 2014, 2016; Kohút & Larionov 2021; Petrik et al. 2024; Kohút et al. 2026).

Nevertheless, the heat from the underplated mantle-derived mafic magma not only interacted with the orogenic lower crust, but also softened the middle and upper crust. This led to intense partial melting, migmatization and anatectic granitoid

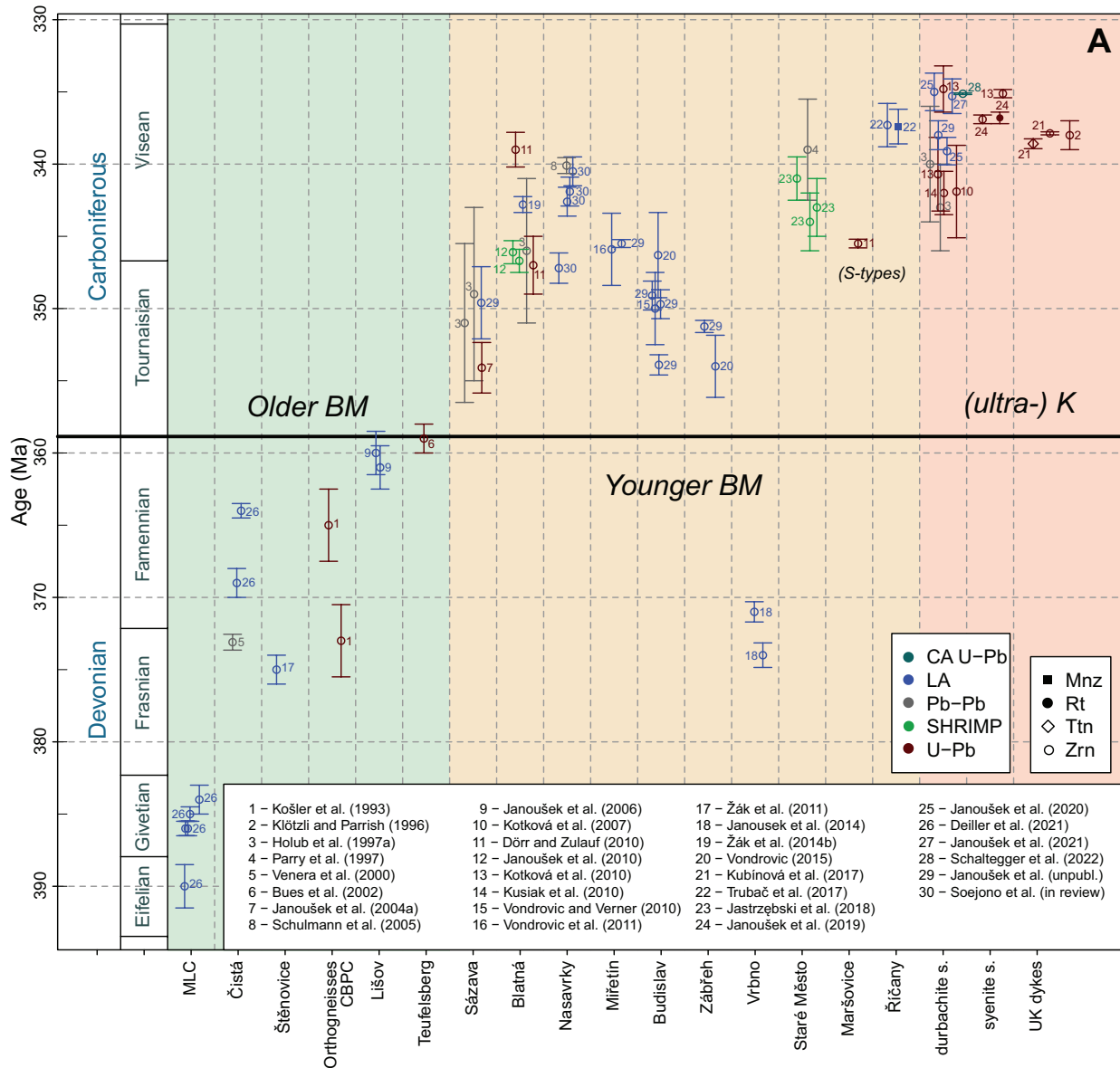


Fig. 2. Overview of U–Pb geochronology: (A) Bohemian Massif; (B) Central Western Carpathians. CA – chemical Abrasion, LA – Laser Ablation ICP MS, SHRIMP – Sensitive High-Resolution Ion Microprobe, SIMS – Secondary-Ion Mass Spectrometry, UK – ultrapotassic. For data sources, see [Electronic Supplement S1](#).

production. Oblique collision with dominant transpression created space in the crust for pluton emplacement.

The magmatic rocks contain only scarce MME, as the mafic magma was presumably largely digested by the granitic one during their high-*T* interactions (Broska & Petřík 2011; Kurylo & Broska 2025).

The Viséan (post)-collisional CWC granitoids (*c.* 345–332 Ma), represented mainly by peraluminous muscovite–biotite granodiorites–granites without any MME (having affinity to muscovite-bearing peraluminous granitoids, MPG), had a likely source in variegated lower/middle crust built by felsic orthogneisses and metasediments (Poller et al. 2000; Magna et al. 2010; Gawęda et al. 2016; Kohút & Larionov 2021; Broska et al. 2022; Catlos et al. 2022). The only exception represents

the Kriváň tonalite–granodiorite in Malá Fatra Mts. (Broska & Svojtka 2020). Granitic magmatism of this period reflected an important switch from convergent to divergent regime. The reduced density of the crustal rocks triggered gravitational instability, causing the collapse of the collisionally thickened orogen and related crustal thinning. The ensuing decompression melting occurred during rapid uplift and exhumation of the Variscan basement (Kohút et al. 2026).

Major-element whole-rock geochemistry

In order to compare the evolving whole-rock geochemical signatures of the Eifelian–Viséan granitoids of the BM and CWC, we have assembled all the relatively modern (younger

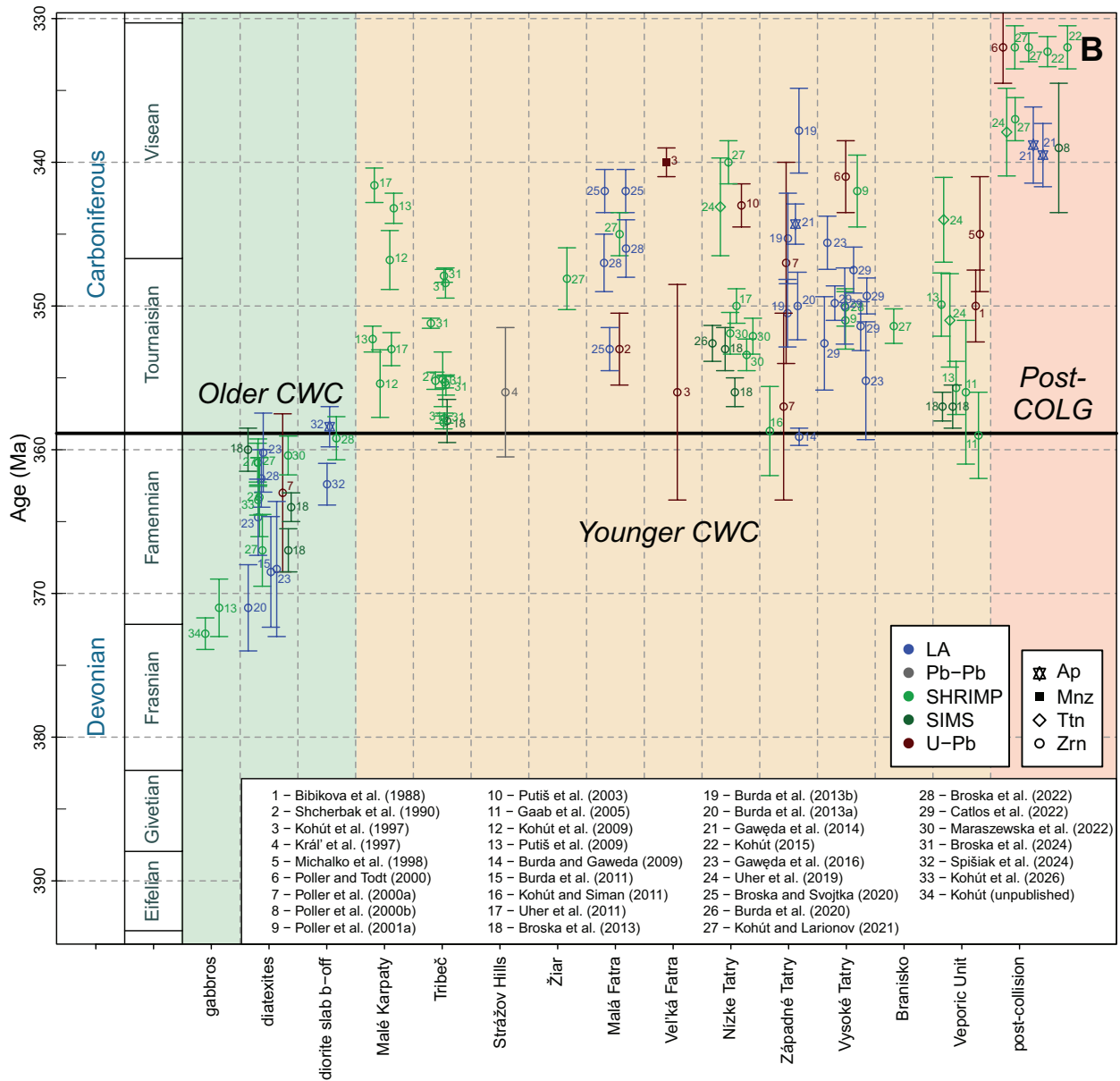


Fig. 2. (continued)

than *c.* 30 years) major-/trace-element, and Sr–Nd isotopic data (see [Electronic Supplement S2](#) for the literature sources).

Selected diagrams illustrating the major-element-based classification of the combined dataset are presented, respectively, in two facing plates, [Fig. 3A](#) (Bohemian Massif) and [B](#) (Central Western Carpathians). Individual subalkaline associations were discriminated using the standard AFM diagram of [Irvine & Baragar \(1971\)](#) ([Fig. 3a](#)) and the SiO₂–K₂O diagram of [Peccerillo & Taylor \(1976\)](#) ([Fig. 3b](#)). The characteristic mineral assemblage can be judged on the basis of the CAF (Ca–1.67×P, Al–Na–K, Fet+Mg in mol.%) projection ([White 1990](#)) ([Fig. 3c](#)). Special attention was paid to millications-based multielement plots of [Debon & Le Fort \(1988\)](#). Shown are the P–Q ‘nomenclature’ diagram (plagioclase

proportion among feldspars vs. quartz) ([Fig. 3d](#)), the B–A ‘characteristic minerals’ diagram (maficity vs. peraluminosity) ([Fig. 3e](#)) and the K/(Na+K) vs. B diagram ([Fig. 3f](#)).

The **Older BM** samples are exclusively calc-alkaline and low-K (most of the MLC) to normal-K (Štěnovice, Čistá, Lišov, part of the CBPC orthogneisses) character. Only some of the most felsic CBPC orthogneisses ([Košler 1993](#)) fall into high-K field ([Fig. 3Ab](#)). In terms of the SiO₂ distribution, the dataset is nearly bimodal; intermediate compositions with ~60 wt.% are mostly missing. Most common are metaluminous gabbros, quartz diorites to tonalites ([Fig. 3Ac–e](#)), amphibole–biotite ± clinopyroxene-bearing. The CBPC orthogneisses are granodioritic to (leuco-)granitic and reach peraluminous domain, with aluminosity (*A*) index occasionally exceeding 50.

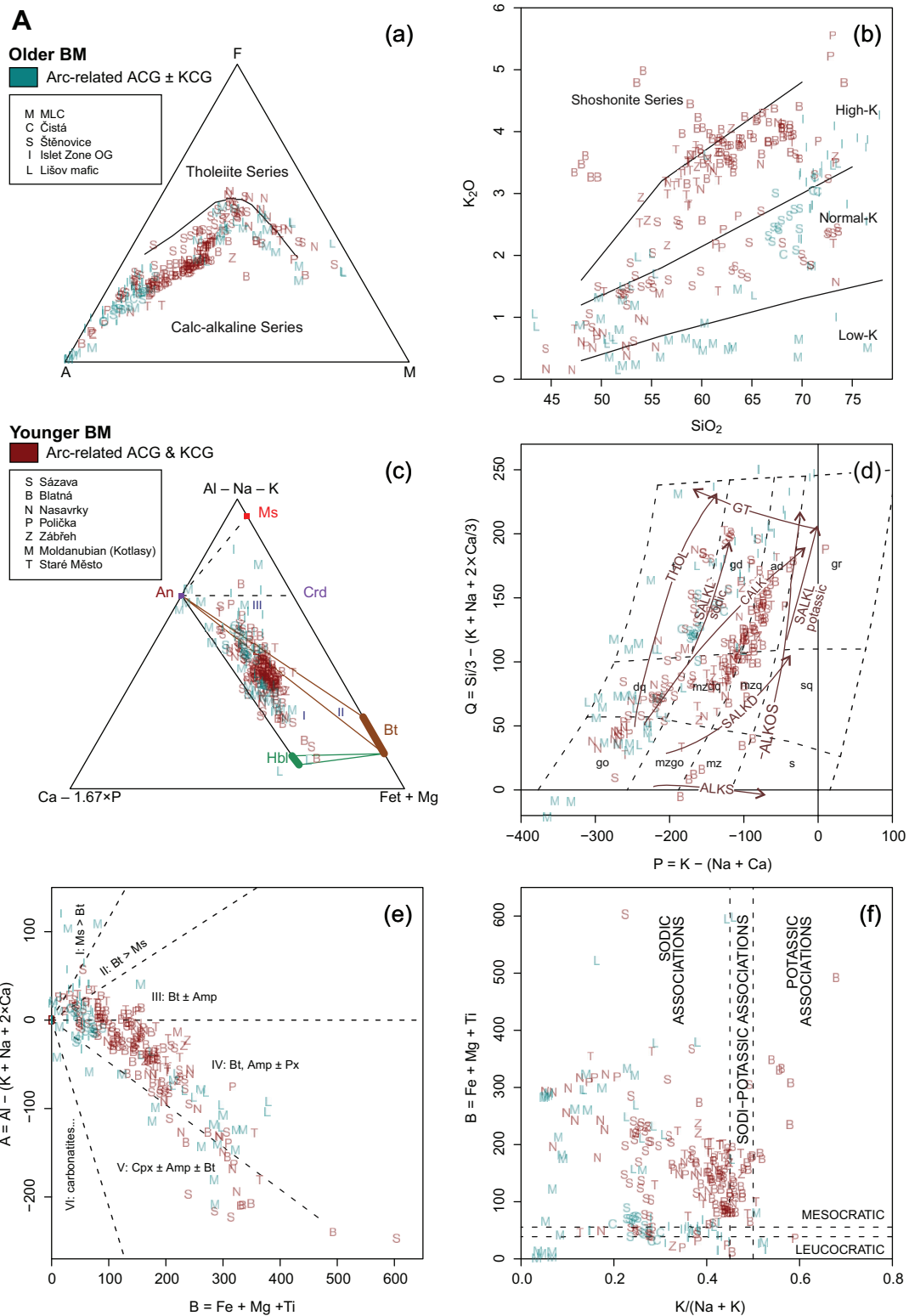


Fig. 3. Whole-rock geochemical classification: **(A)** Bohemian Massif; **(B)** Central Western Carpathians. a – AFM (Na₂O+K₂O, FeO, MgO in wt.%) diagram to distinguish calc-alkaline and tholeiitic magmatic series (Irvine & Baragar 1971); b – SiO₂–K₂O (wt.%) plot (Peccerillo & Taylor 1976); c – CAF (Ca–1.67×P, Al–Na–K, Fet+Mg in mol.%) projection showing characteristic mineral assemblages (White 1990). Assorted millications-based multielement plots of Debon & Le Fort (1988); d – P–Q (plagioclase proportion among feldspars vs. quartz) ‘nomenclature’ diagram. The reference trends show common subtypes of cafemic and aluminocafemic associations: THOL, tholeiitic; CALK, calc-alkaline; SALKD, SALKL, dark- and light-coloured subalkaline (i.e. monzonitic); ALKS, dark-coloured alkaline saturated; ALKOS, light-coloured alkaline oversaturated; GT, granitic–trondhjemitic; e – B–A (maficity vs. peraluminosity) ‘characteristic minerals’ diagram. f – K/(Na+K)–B diagram. For data sources, see Electronic Supplement S2.

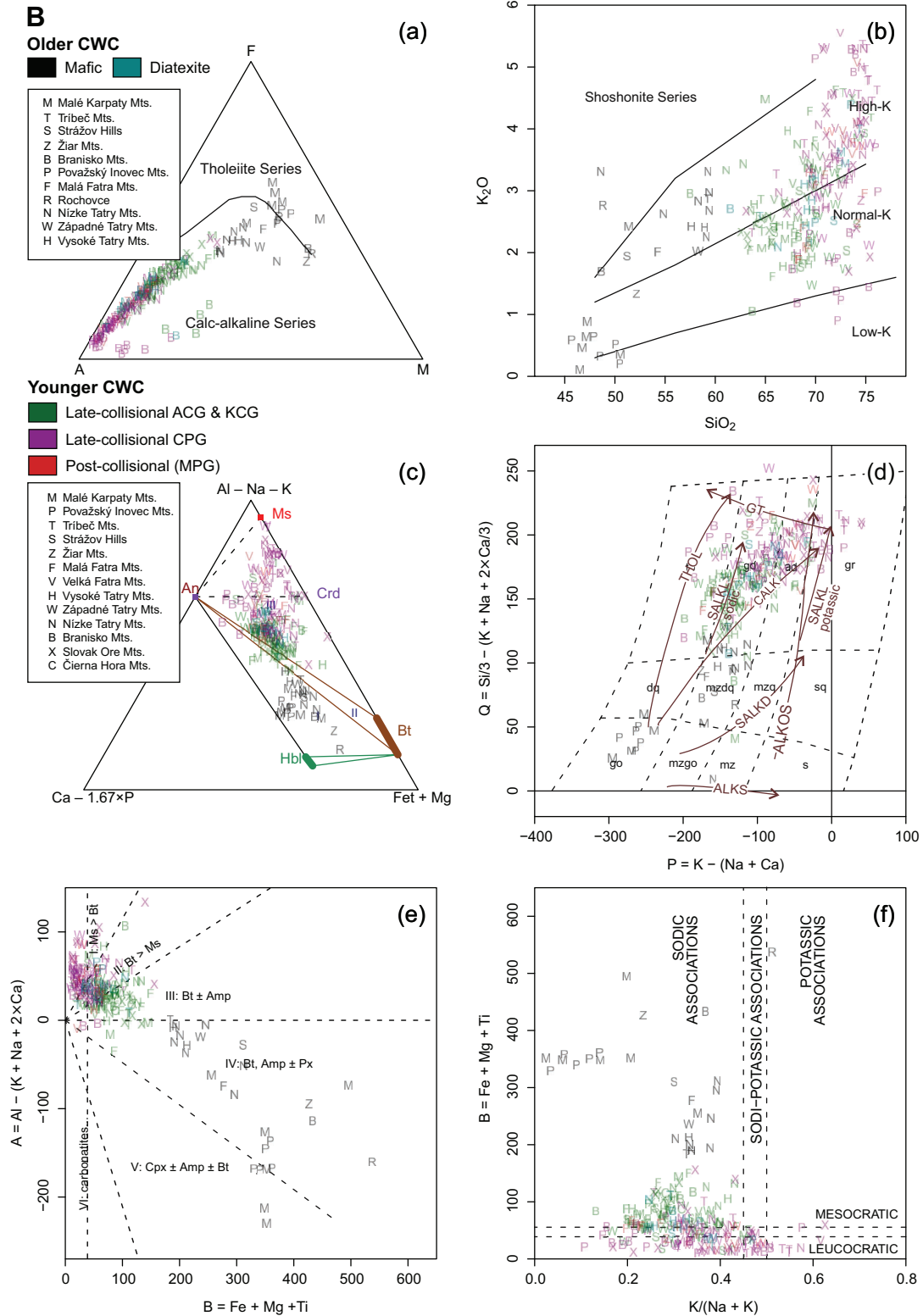


Fig. 3. (continued)

All mesocratic rocks are sodic, and the $K/(Na+K)$ ratio increases solely in the most felsic terms (Fig. 3Af). Altogether, the trends observed in the P–Q plot correspond to the tholeiitic (THOL; Mariánské Lázně), light-coloured subalkaline sodic

(SALKL sodic) or calc-alkaline (CALK) associations of Debon & Le Fort (1988) (Fig. 3Ad).

The Younger BM rocks are much more variable. Again, they are calc-alkaline (Fig. 3Aa), normal-K (Sázava suite – CBPC,

mafic rocks and tonalitic Nasavrky suite – NPC) to high-K (Blatná suite – CBPC, granodioritic Skuteč suite – NPC, Miretín and Budislav plutons of the Polička Unit, Zábřeh, Staré Město Belt) (Fig. 3Ab). The only shoshonitic compositions represent the clinopyroxene-bearing biotite–amphibole monzonitic rocks (monzogabbros to quartz monzodiorites) associated with the Blatná suite. The intermediate, (amphibole–)biotite granodioritic compositions strongly prevail over monzonitic mafic rocks, forming two subalkaline associations (SALKD and SALKL potassic) *sensu* Debon & Le Fort (1988) (Fig. 3Ac–d). The only exceptions are the Sázava and the Nasavrky suites, where amphibole–biotite quartz diorites–(leuco-)tonalites are much more abundant and are associated with the amphibole-rich gabbros (calc-alkaline association *sensu* Debon & Le Fort (1988) (Fig. 3Ad). In accord with their modal composition, most of the mafic–intermediate samples are metaluminous, and only the most felsic granodiorites–granites straddle the boundary of the peraluminous domain (Fig. 3Ae). Again, the Sázava and Nasavrky suites are strongly sodic, with $K/(Na+K)$ typically below 0.3 (ACG). The intermediate terms in the other plutons are typically richer in K (KCG), some passing to the sodic–potassic associations, and the Blatná monzonitic rocks are exclusively potassic (Fig. 3Af).

The **Older CWC** samples are mostly normal- to high-K (nebulites/diatexites and diorites); only gabbroic rocks straddle the boundary of the low-K field (Fig. 3Ba–b). Their silica contents are variable – the gabbroic ones are exclusively basic ($SiO_2=45–51$ wt.%), dioritic rocks are typically intermediate (51–59 wt.%), nebulites and diatexites with elevated SiO_2 (68–74 wt.%) represent acid igneous rocks (Fig. 3Bb). The gabbros and diorites are mostly metaluminous, rich in amphibole–biotite±clinopyroxene, while diatexites with muscovite–biotite±cordierite are peraluminous rocks (Fig. 3Bc–e) having locally leucocratic character with aluminosity (*A*) index occasionally lower than 50. All gabbros–diorites are common mesocratic and sodic rocks, whereas some diatexites/nebulites with low maficity ($B\leq 50$) and partly elevated potassic index ($K/(Na+K)\geq 0.45$) fall within the field of leucocratic and sodi-potassic association (Fig. 3Bf). The overall trend for the Older Western Carpathian samples observed in the P–Q plot corresponds to the light-coloured subalkaline sodic (SALKL sodic) or calc-alkaline (CALK) associations *sensu* Debon & Le Fort (1988) (see Fig. 3Bd).

The **Younger CWC** magmatites are generally less variable than older ones, showing systematically normal-K and high-K calc-alkaline character (Fig. 3Ba–b). In terms of the SiO_2 distribution (62–76 wt.%) they represent evolved, intermediate and acid igneous rocks. In accord with their mineral associations, in which biotite slightly predominates over muscovite and scarce cordierite (and/or, locally, garnet), they belong to common peraluminous granitoids; rare are subaluminous members with minor amphibole (Fig. 3Bc–e). About half of the dataset for this group belongs to the common mesocratic and sodic associations. Of course, with increased degrees of fractionation, reflected by the elevated potassic index

($K/(Na+K)\geq 0.5$) and decreased maficity ($B\leq 50$), some of the samples fall within the leucocratic and potassic associations (Fig. 3Bf). Anyway, general trend in the P–Q plot suggests again light-coloured subalkaline sodic (SALKL sodic) or calc-alkaline (CALK) associations (Fig. 3Bd).

Simple comparison of panels A and B of Fig. 3 reveals that there are several features that distinguish the Mid-Devonian to Viséan magmatic suites of the CWC from those of the BM. Even though some proportions may reflect statistically biased sampling, the most striking characteristics of the CWC magmatism seem: (1) relative scarcity of samples with intermediate silica contents (Fig. 3b,d); (2) mostly restricted K_2O contents, largely without extreme (both K-poor and K-rich) compositions (Fig. 3b), that is demonstrated by lack of monzonitic and syenitic rocks (belonging to the SALKD, SALKL potassic and ALKOS associations of Debon & Le Fort 1988) (Fig. 3d); (3) scarcity of mafic, metaluminous, amphibole-bearing lithologies (Fig. 3c,e), (4) abundance of felsic, peraluminous, muscovite- or cordierite-bearing granites (Fig. 3b,e).

Trace-element whole-rock geochemistry

In order to compare the distributions of trace elements, whose concentrations differ by several orders of magnitude, we have employed conventional Normal Mid-Ocean Ridge Basalts (NMORB)-normalized multielement (Sun & McDonough 1989) and chondrite-normalized REE (Palme & O'Neill 2014) spiderplots (Fig. 4A and B).

The NMORB-normalized patterns for the **Older BM** samples (Fig. 4Aa) are characterized by strong enrichment in hydrous fluid-mobile large-ion lithophile elements (LILE) over the conservative high-field strength elements (HFSE). In detail, the picture is more complex, though. Some of the LILE in fact fluctuate broadly, most notably Cs, Rb, Th and U. Conspicuous are positive anomalies for Pb, K and Sr, as well as negative ones for Nb, P and Ti. The analyses vary strongly in total REE abundances, but typical is the relatively high degree of LREE/HREE fractionation; Eu anomalies are typically missing or are poorly developed (Fig. 4Ab).

The NMORB- and chondrite-normalised spiderplots for the **Younger BM** magmatites (Fig. 4Ac–d) do not differ much neither in the total ranges of the normalized trace-element contents (see the yellow field denoting the variation of the Older BM samples taken from Fig. 4Aa–b), nor in the overall shapes (the relative degree of the LILE/HFSE and LREE/HREE enrichment). Both the Younger and Older BM magmatites feature deep negative anomalies for Nb, P, Zr and Ti. The former group displays on average elevated total trace-element contents (most importantly alkalis, Th, U and Pb), as well as deeper negative Eu anomalies in the chondrite-normalized REE plots (Fig. 4Ad).

In the NMORB-normalized spiderplot (Fig. 4Ba), the **Older CWC** samples show enrichment in the LILE (Cs, Rb, Ba, K, Pb) and depletion in the HFSE (Nb, P, Zr, Ti). The chondrite-normalized REE spiderplots differ significantly between the mafic (gabbro–diorite suite) rocks on the one hand, and

nebulites with diatexites on the other. Rather flat patterns for the mafic suite vary between the NMORB- and EMORB-like, while diatexites have more or less uniform patterns with moderate–strong degrees of LREE over HREE enrichment and shallow negative Eu anomalies (Fig. 4Bb).

The **Younger CWC** samples display comparable NMORB-normalized patterns (Fig. 4Bc) with locally less pronounced enrichment in the LILE and stronger depletion in the HFSE (e.g., Nb and Ti). The REE patterns are again mostly uniform, with moderate–strong LREE/HREE enrichment, and moderate negative Eu anomalies (Fig. 4Bd). However, the total REE contents are often significantly lower than in the Older CWC suite.

Geotectonic diagrams

The major- and trace-element geotectonic diagrams are shown in Fig. 5A, B. These include the multicationic R_1 – R_2 projection (de La Roche et al. 1980), which according to Batchelor & Bowden (1985) can aid petrogenetic interpretation of the magmatic suites (Fig. 5a). In this projection, the common petrogenetic processes such as partial melting, fractional crystallization, crystal accumulation, or binary mixing result in linear trends obeying the lever rule. Besides that, the R_1 – R_2 diagram, modified by Batchelor & Bowden (1985), serves well to distinguish some particular geotectonic settings, such as pre-plate collision (=Andean-type arc), post-collision uplift (=Caledonian-type of Pitcher 1983) or late-orogenic associations. The convergent (including various arc-related environments) and divergent tectonic settings can be distinguished using the Nb_N – Th_N binary plot (Saccani 2015) (Fig. 5b) or ternary plot $La/10$ – $Y/15$ – $Nb/8$ (Cabanis & Lecolle 1989) (Fig. 5c). The Nb/Yb ('mantle/melting-derived variance') vs. Th/Yb ('crustal input proxy') projection (Pearce 2008) (Fig. 5d) is useful to differentiate the pristine canonical mantle-derived melts from those that were significantly contaminated by crustal materials (in the mantle wedge for magmatic arcs or generally, during magma ascent) or pure crustal melts. Finally, we show two of many diagrams discriminating arc, arc-failure (oceanic closure-related slab-breakoff; Davies & von Blanckenburg 1995) and anorogenic (A-type) magmatic suites (Whalen & Hildebrand 2019) (Fig. 5e–f).

The **Older BM** granitoids fall mainly into the pre-collisional field of the R_1 – R_2 plot (Fig. 5Aa), whereby their main trend could have formed by fractional crystallization of an amphibole–biotite assemblage, with relatively calcic plagioclase and magnetite. Some of the basic samples, forming a trend oblique to the main trend just described, likely experienced accumulation of variable combinations of the same minerals. The inferred continental arc-related environment is in line with the outcome of assorted trace-element plots (Fig. 5Ab–d). It is noteworthy that in the Nb/Yb – Th/Yb diagram (Fig. 5Ad), some of the most primitive MLC basic rocks project close to the EMORB end-member, and others form a linear array towards clearly continental arc-derived com-

positions. Only a few of the Older BM samples passed the rigorous criteria of Whalen & Hildebrand (2019) that eliminate S-types, cumulate mafic arc-related samples, and felsic slab failure samples, and so could be plotted in Fig. 5Ae–f. These can be interpreted as a classic arc-related association.

The **Younger BM** granitoids – apart from the pre-collisional Sázava and Nasavrky suites – plot mostly into the post-collision uplift field of the R_1 – R_2 diagram (Fig. 5Aa). In the trace-element plots (Fig. 5Ab–d), the Younger BM data points are practically indistinguishable from the Older BM ones. The only differences can be observed in the diagrams of Whalen & Hildebrand (2019), where the Younger BM data tend to fall into the slab failure field, except mostly the Sázava suite (Fig. 5Ae–f).

In the R_1 – R_2 plot, the **Older CWC** samples mimic their contrasting modal compositions – while the gabbroids and diorites fall clearly into the pre-collisional field, diatexites reflect their syn-collisional origin (Fig. 5Ba). Interestingly, the continental arc affinity of diatexites and diorites is obvious in Fig. 5Bb–d, while gabbroids plot close to the MORB–OIB array, showing their likely divergent plate (back-arc?) setting. Noteworthy, most of the diorites and diatexites fall into the slab failure field of Whalen & Hildebrand (2019), whereas part of the Považský Inovec Mts. gabbros tend to fall on a boundary with arc (back-arc?) domain (Fig. 5Be–f).

The **Younger CWC** magmatites seem to belong to the calc-alkaline or peraluminous granitic series; generally, they form well-defined group of the collision-related granitoids, which is manifested as a compact girdle 'migrating' from the syn-collisional to the post-collisional fields in the R_1 – R_2 diagram (Fig. 5Ba). According to Whalen & Hildebrand (2019) diagrams, the position of the studied Younger CWC samples favours mostly the slab failure setting (Fig. 5Be–f). In fact, their chemical composition is analogous to typical granitoids originating in the convergent plate settings from polygenic crustal sources (Harris et al. 1986; Pearce 1996), with granite production vanishing in the late- to post-collisional (transpressional and/or extensional) periods (Fig. 5Bb–d).

Sr–Nd isotopes

The **Older BM** samples are characterized by conspicuously primitive initial Sr–Nd isotopic compositions, mostly with strongly radiogenic Nd and unradiogenic Sr (Fig. 6a). This signature is compatible with an origin from variously depleted mantle domains (esp. Mariánské Lázně, Čistá; Deiller et al. 2021). The only negative epsilon Nd values were obtained from intermediate–felsic Lišov LP granulites (Janoušek et al. 2006), and two of the CBPC orthogneisses (Košíler 1993).

On the other hand, in the **Younger BM** dataset, the only analyses with (often strongly) positive ϵ_i^{Nd} values are the amphibole-bearing gabbros and tonalitic Nasavrky suite of the NPC (Fig. 6a). Field, petrological and geochemical evidence from the NPC underlines vigorous interaction between depleted-mantle- ($\epsilon_i^{Nd} \leq +6.8$) and crustally-derived ($\epsilon_i^{Nd} \geq -5.6$) magmas (Soejono et al. in review). The normal-K calc-alkaline

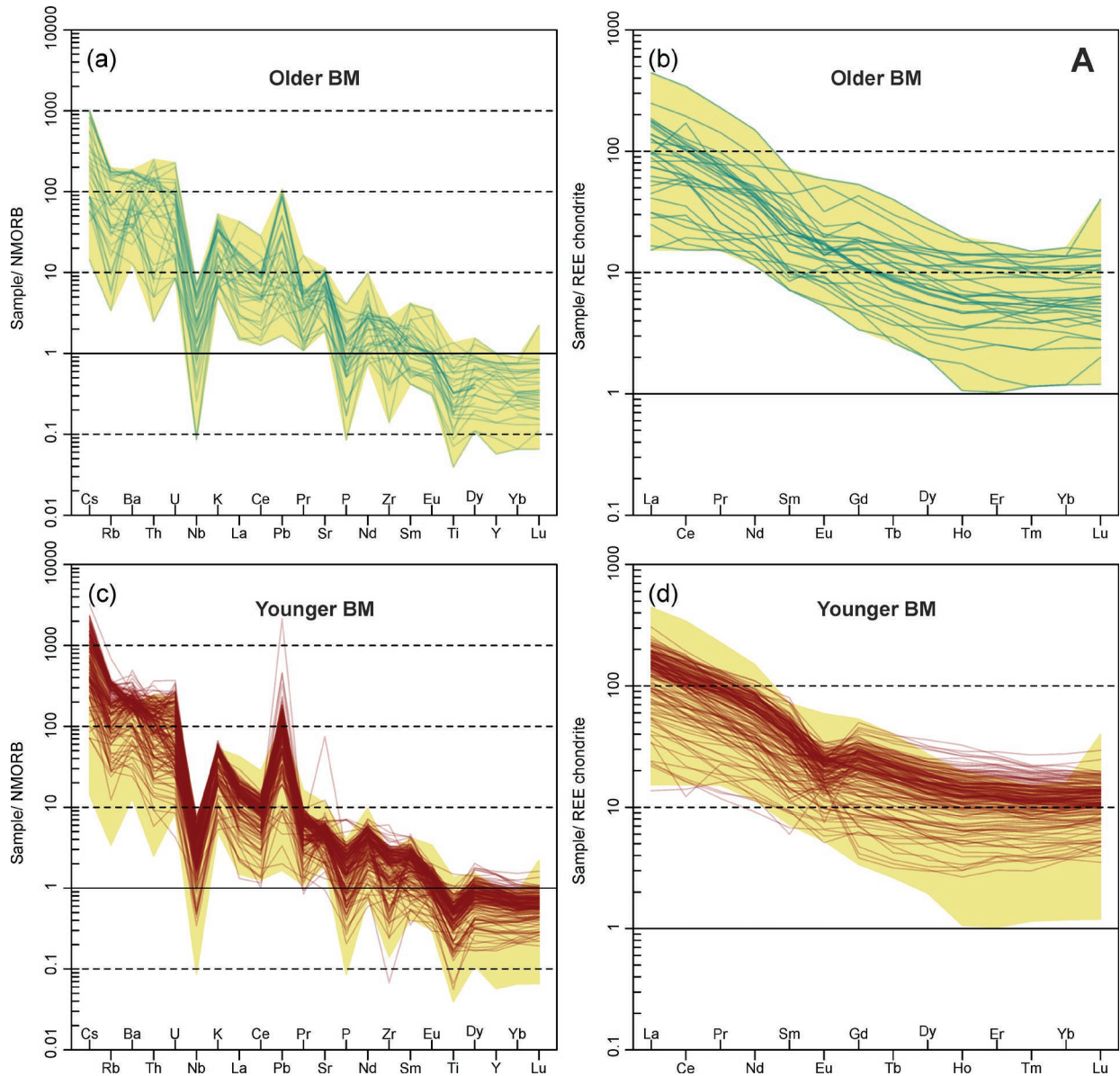


Fig. 4. NMORB- (Sun & McDonough 1989) (a, c) and REE chondrite- (Palme & O'Neill 2014) (b, d) normalized spidergrams for arc-related samples from Bohemian Massif (A) and Central Western Carpathians (B). See Fig. 3A–B for the key to the plotting colours. For data sources, see Electronic Supplement S2.

Sázava suite of the CBPC shows CHUR-like compositions (Janoušek et al. 1995). In contrast, the high-K calc-alkaline Blatná suite of the CBPC displays an extended range of ε_i^{Nd} values from -2.9 to -7.0 (Janoušek et al. 2010). The remaining plutons, i.e., granodioritic Skuteč suite of the NPC, granitoids from the Polička (Měřítn, Budislav) and Zábřeh units share the same, more restricted, ε_i^{Nd} (-2.8 to -4.6) (Janoušek et al. 2025b; Soejono et al. in review). The three analyses published from the Staré Město Belt are practically indistinguishable ε_i^{Nd} (-3.9 to -4.7) (Jastrzębski et al. 2018).

In terms of the Sr–Nd isotopic composition, the **Older CWC** suite has again highly heterogeneous character not only among individual groups (i.e., gabbroids, diorites and diatexites), but also partly within each of them (Fig. 6b).

The gabbroids show primitive, strongly radiogenic Nd and unradiogenic Sr, close to canonical depleted mantle ($\varepsilon_i^{Nd} = +9.0$ to $+7.5$; $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.702\text{--}0.704$), while diorites display much less positive ε_i^{Nd} values ($+2.1$ to $+1.2$) and widely varying initial strontium ratios ($0.704\text{--}0.709$). The diatexites yield more variegated ε_i^{Nd} values ($+2.2$ to -5.3) and significantly more radiogenic initial strontium ratios ($0.705\text{--}0.711$).

By the contrast, the **Younger CWC** samples have Sr–Nd isotopic signatures pointing to a dominance of heterogeneous crustal sources with moderately varied initial ratios ($\varepsilon_i^{Nd} = +2.8$ to -4.2 ; $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.705\text{--}0.708$; Fig. 6b). The granitoids were derived most probably from a vertically zoned lower crust consisting of old acid–intermediate metaigneous, amphibolitic and metasedimentary rocks (Kohút & Nabelek 2008).

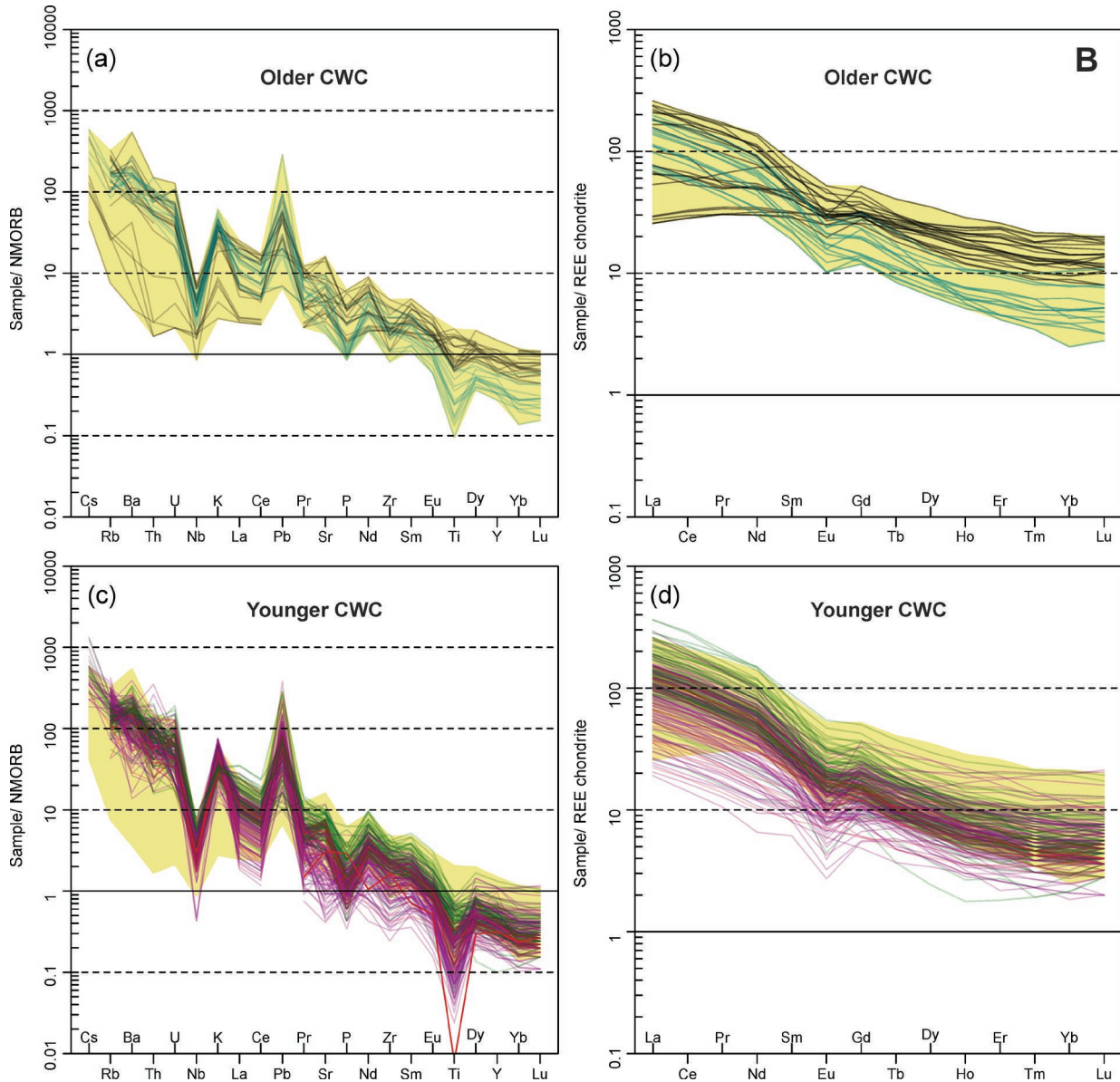


Fig. 4. (continued)

Discussion

Petrogenetic and geodynamic implications

The detailed comparison of variability and spatio-temporal evolution of Mid-Devonian to Visean magmatism in the BM and CWC has demonstrated that it started correspondingly with Andean-type subduction, in Eifelian (BM), or in Frasnian (CWC). Even though, at the first glimpse, several plutonic associations appear comparable in terms of their petrological and geochemical variation, and thus also possibly sources, the evolution of both regions did differ profoundly (Fig. 7).

Bohemian Massif

In the Bohemian Massif, the Andean-type subduction of the Saxothuringian Ocean (Schulmann et al. 2009; Žák et al. 2014) produced the older (Mid- to Late Devonian, c. 390–359 Ma) (meta-)igneous bodies, located mostly within the Teplá–Barrandian Unit, close to the Variscan suture with the westerly Saxothuringian Unit (Holub & Souček 1994; Faryad et al. 2024). Small contemporaneous granitoid intrusions are also known from the central-southern Bohemia (orthoigneisses in the roof of the Central Bohemian Plutonic Complex, Lišov LP mafic granulites). Most of the magmatites are geochemically rather primitive, amphibole-bearing

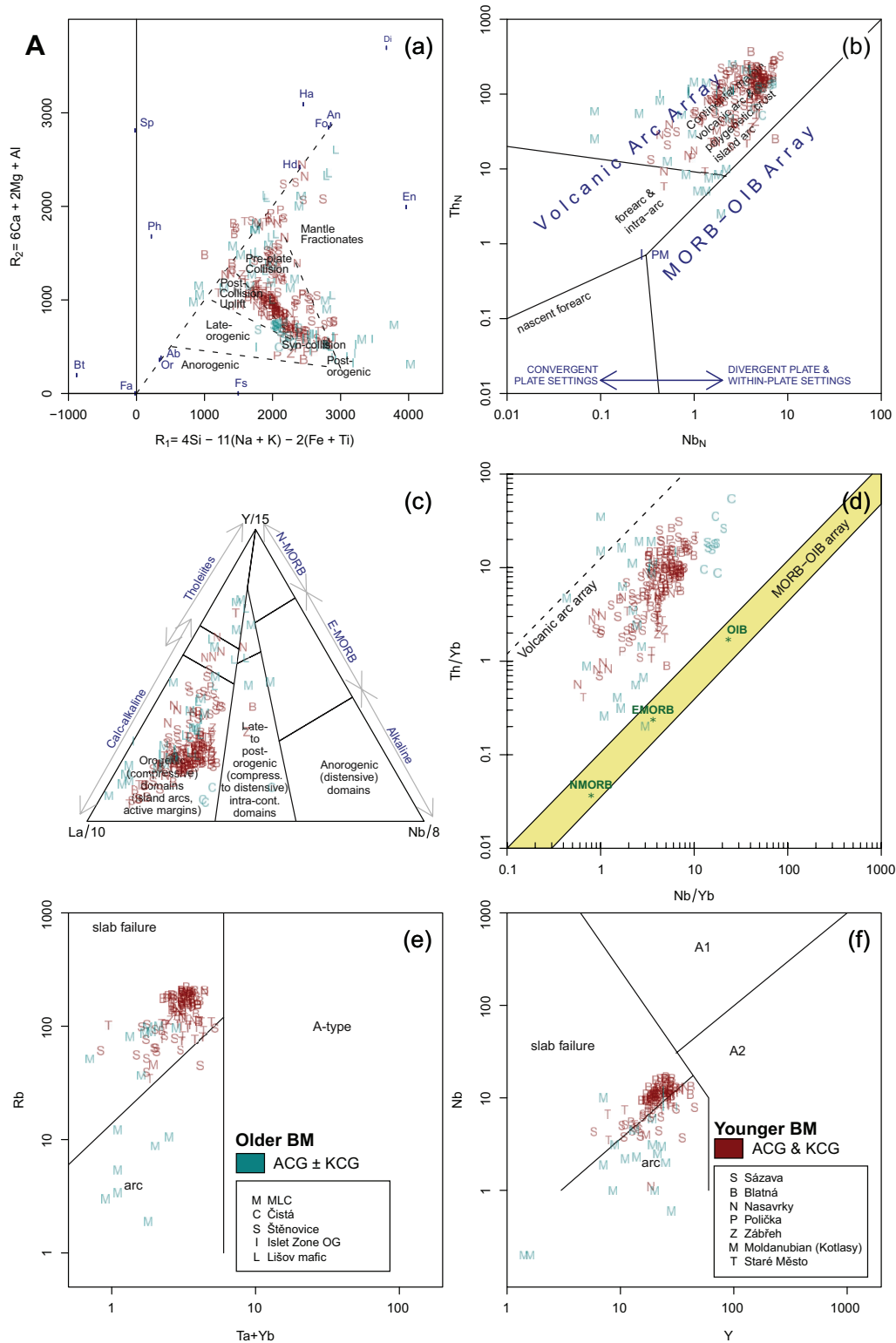


Fig. 5. Geotectonic diagrams: **(A)** Bohemian Massif; **(B)** Central Western Carpathians. a – Multicationic R_1 - R_2 plot (de La Roche et al. 1980) with geotectonic boundaries of Batchelor & Bowden (1985) and ideal mineral compositions of Le Maitre (1982); b – Binary plot Nb_N - Th_N (Saccani 2015) based on NMORB-normalized values of Sun & McDonough (1989); c – Ternary plot $La/10$ - $Y/15$ - $Nb/8$ (Cabanis & Lecolle 1989); d – Binary plot Nb/Yb - Th/Yb (Pearce 2008); e, f – Diagrams discriminating arc, arc-failure and anorogenic (A-type) magmatic suites (Whalen & Hildebrand 2019) modified from Pearce et al. (1984); $Ta+Yb$ vs. Rb and Y vs. Nb . Note that only analyses with ASI (alumina saturation index) <1.1 and $SiO_2=55-70$ wt.% were plotted, as suggested in the original paper. This eliminates S-types, cumulate mafic arc-related samples, and felsic slab failure-related samples. For data sources, see Electronic Supplement S2.

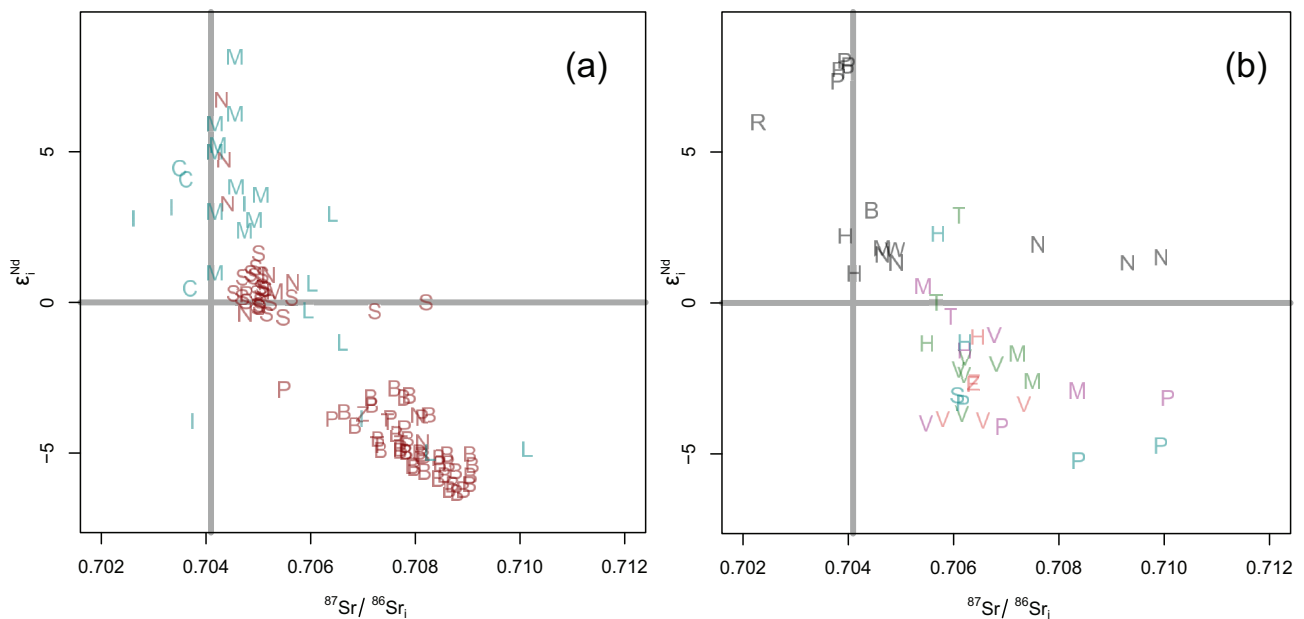


Fig. 6. Initial Sr–Nd isotopic compositions: **(a)** Bohemian Massif; **(b)** Central Western Carpathians. See Fig. 5A–B for plotting legends. For data sources, see [Electronic Supplement S2](#).

The Tournaisian–Visean magmatic activity (*c.* 359–335 Ma) migrated eastwards, forming much more voluminous plutonic complexes: CBPC and NPC, as well as a string of smaller plutons that run further east and then turn north (Miřetín, Budislav, Zábřeh, and Staré Město). All these form collectively the Peri-Moldanubian Arc (Janoušek et al. 2025b).

Two of the oldest, low- to normal-K magmatic suites therein, the Sázava (~354–350 Ma; CBPC) and the Nasavrky (~347–341 Ma; NPC), are petrologically and geochemically very similar to those of the older (Devonian) magmatic phase described above. The similarity includes not only the analogous whole-rock major- and trace-element geochemical signatures (Figs. 3A, 4A) but also, importantly, the positive (in case of the Nasavrky suite often strongly positive) whole-rock ϵ_i^{Nd} values (Fig. 6a). The field and petrological evidence confirm an important role for magma mixing with mafic magmas, derived from strongly heterogeneous mantle, ranging from canonical depleted to CHUR-like (Janoušek et al. 2004a; Soejono et al. in review). This magmatic phase was likely still connected to the ongoing oceanic subduction, and the individual plutons intruded in overall transpressional setting, as has been documented in the Sázava Pluton (Žák et al. 2005a,b; Soejono et al. in review).

The remaining members of the Peri-Moldanubian Arc (including the Blatná suite in the CBPC and the Skuteč suite in the NPC) are mostly metaluminous, high-K; the monzonitic rocks associated with the former suite are even shoshonitic. This magmatic phase was dominated by amphibole–biotite granodiorites (KCG *sensu* Barbarin 1999), characterized by moderately negative whole-rock ϵ_i^{Nd} values (Fig. 6a). Parental magmas have originated mostly from Cadomian graywackes; in some plutons these felsic magmas interacted with mafic,

slightly enriched mantle-derived monzonitic melts (Janoušek et al. 2000a). The whole-rock geochemical signatures, including the NMORB-normalized multielement patterns (Fig. 4Aa) and geotectonic plots (Fig. 5A) point to a waning subduction geotectonic setting, followed by early collision accompanied by the slab failure (Whalen & Hildebrand 2019). Such a scenario is confirmed by structural data (Žák et al. 2014); for instance, the syn-tectonic Blatná Pluton contains two types of fabrics, one recording transpression still ongoing along its contact with the Teplá–Barrandian Unit, and normal movements marking the incipient exhumation of the Moldanubian orogenic root (Žák et al. 2012).

A characteristic feature of the Variscan orogenic root in Bohemian Massif, Schwarzwald, Vosges, Alps and Corsica is the Visean (**ultra**-)potassic magmatism (Holub 1997; von Raumer et al. 2014). In the orogenic root of the BM (Moldanubian Zone), abundant Mg-rich, (ultra-)potassic plutons are closely spatially and temporally associated with HP–HT (garnet- and kyanite-bearing) felsic granulite massifs (Janoušek et al. 2004b; Janoušek & Holub 2007). Parental magmas to ultrapotassic rock types originated from a strongly enriched/crustally contaminated lithospheric mantle and interacted with the Moldanubian crust and leucogranitic magmas derived therefrom (Holub 1997; Krmíček et al. 2016; Janoušek et al. 2022, 2025a).

Central Western Carpathians

The existing whole-rock Sr–Nd isotopic data for Devonian metabasic rocks from the Malé Karpaty and Považský Inovec Mts. (Fig. 5B, Fig. 6b) are characterized mainly by strongly positive ϵ_i^{Nd} values akin to canonical depleted mantle,

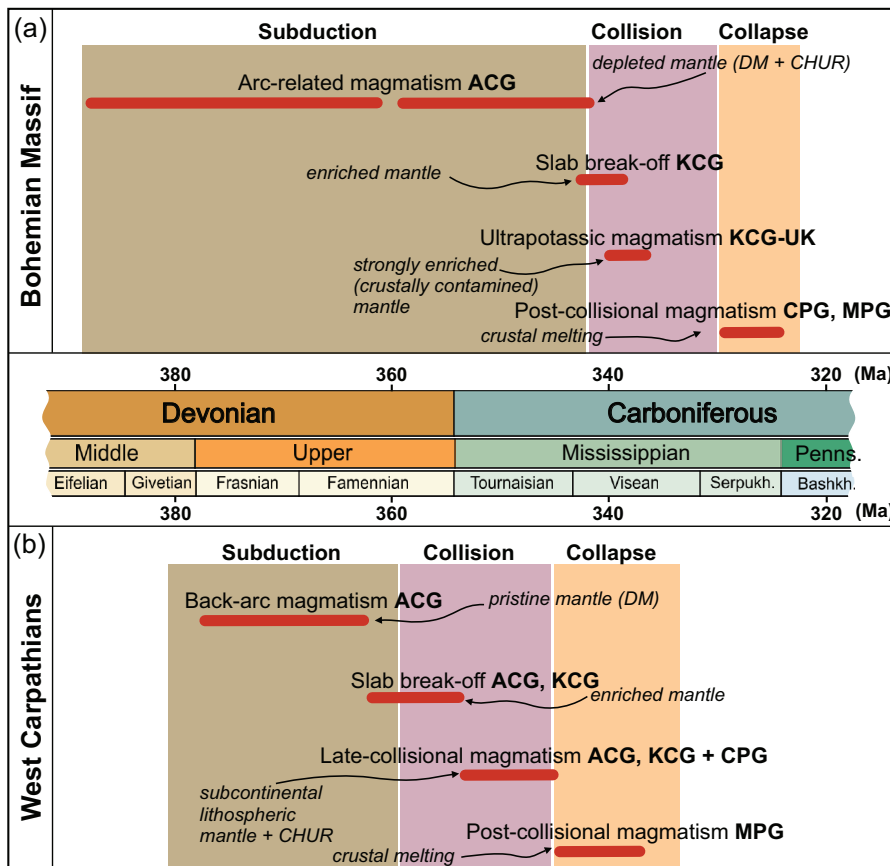


Fig. 7. Comparison of temporal evolution of Mid-Devonian to Mississippian magmatism in the Bohemian Massif (a) and Central Western Carpathians (b). The terminology for granite suites follows that of Barbarin (1999) and Moyen et al. (2025): ACG – Amphibole-bearing Calc-alkaline Granitoids, KCG – K-rich Calc-alkaline Granitoids, KCG-UK – Ultrapotassic Calc-alkaline Granitoids, CPG – Cordierite-bearing Peraluminous Granitoids, MPG – Muscovite-bearing Peraluminous Granitoids.

translating to low Nd crustal residence ages of *c.* 0.42–0.36 Ga, i.e. close to their emplacement. This clearly argues for their pristine depleted-mantle origin, which is more characteristic of back-arc rather than incipient magmatic arc tectonic settings (Ivan et al. 2007; Kohút unpublished data). The initial oceanic subduction in the CWC realm could have been expected somewhat earlier (during the Early Devonian?). Back-arc basin, filled by the recycled Neoproterozoic to Ordovician siliciclastics from the northern Gondwanan Cadomian arc (Kohút et al. 2022), was subsequently subducted or obducted during the Late Devonian initial collision.

Interestingly, the early CWC granitoid rocks – diatexites and nebulites – only slightly post-dated formation of the gabbroic rocks that often represent their host rocks (Fig. 2b). Anyway, presented data favour the notion that an initial record of oceanic subduction is missing in the CWC, as are truly arc-derived plutons. Instead, mafic rocks from the Malé Karpaty and Považský Inovec Mts., along with diatexites from the Malé Karpaty, Považský Inovec, Vysoké Tatry and Branisko Mts., apparently record a back-arc setting (*c.* 380–361 Ma) (Putiš et al. 2009).

However, the mafic magmas in the CWC – parental to the late-Famennian dioritic rocks – were connected already with the slab break-off (Broska et al. 2022; Spišiak et al. 2024), whereby masses of mantle melt having an origin mostly in the subcontinental lithospheric mantle (SCLM) invaded

the middle crust in the latest Devonian times (361–357 Ma). This principal event separated the older (Devonian) compressional granite evolution from the younger (Carboniferous) transpressional granite-forming period.

The Tournaisian witnessed, in terms of the volume, the most important Variscan granite production phase in the CWC (*c.* 357–345 Ma). This flare-up was a syn- to late-collisional process, since the transpression forces facilitated the emplacement of granitic plutons in the middle crust. Granitic rocks of this phase can be found in all ‘core mountains’ of the Tatric Unit, where they form mostly normally zoned granitic or composite plutons. Similar features are shown by the large granite dome in the Veporic Unit.

Interestingly, the Veporic metamorphic complexes are formed by Gondwana-sourced recycled siliciclastics containing mélange of paragneisses, metabasalts (eclogites), ultrabasic rocks, Ordovician orthogneisses and metagranites (Janák et al. 2007; Petrik et al. 2024; Soejono et al. 2024), interpreted as a Cambrian–Ordovician complex (according Zurbriggen 2017). These complexes were metamorphosed (HP) and rearranged during Variscan subduction, and they were intruded by voluminous Variscan granitoid plutons.

In general, this magmatic phase produced both (1) (usually hybrid) biotite±amphibole tonalites–granodiorites (ACG and KCG), coming from the metaigneous lower crustal sources and supplemented by mafic melts derived from the SCLM,

and (2) biotite granodiorites–granites (CPG-like), coming from the felsic metaigneous and/or graywacke-rich lower/middle crust (e.g., Poller et al. 2000; Magna et al. 2010; Burda et al. 2011; Broska et al. 2013, 2022, 2024; Gawęda et al. 2014, 2016; Kohút & Larionov 2021; Petřík et al. 2024).

The Visean granitic rocks apparently formed from hotter magmas intruding the upper crust. From a structural point of view, the tectonic stress field in the crust was probably extensional, indicating a switch from convergent to divergent regime. Rapid uplift and exhumation of the still hot Variscan basement resulted in decompression melting. Post-collisional S-type two-mica granites (MPG) were produced (c. 345–332 Ma) mainly from reworked mature continental crustal material.

Dichotomy of Variscan magmatism in the Bohemian Massif vs. Central Western Carpathians and its likely geodynamic causes

The above summary illustrates that the Variscan Mid-Devonian to Visean (> 331 Ma) magmatism in the Bohemian Massif reflected relatively long-lived arc system, cessation of the eastward subduction and, finally, the early collision accompanied by slab break-off. As a consequence, all the granitoids contain significant mantle components, even though the crustal growth became in part cryptic (Couzinié et al. 2016; Janoušek et al. 2025a); the anatexis of mature meta-sediments and production of purely S-type suites (CPG, MPG) was rather exceptional within this timespan.

The late syn- (compressional) to post-collisional (extensional, related to the orogen's collapse) magmatic suites intruded only later, mostly as a part of the Moldanubian Plutonic Complex in the core of the Moldanubian Unit. Its earliest I- and I/S-type Weinsberg granitoids were dated at c. 331–323 Ma (Gerdes 2001; Gerdes et al. 2003; Finger et al. 2022; Hájek et al. 2023). Two-mica granites (MPG) of the Eisgarn 'family', generated via decompression melting and widespread migmatitization, arrived only at 328–325 Ma (Gerdes et al. 2003; Žák et al. 2011b) And, finally, the post-orogenic magmatism (related to transtensional movements) in the Bohemian Massif continued well into late Carboniferous, or even early Permian times (Gerdes et al. 2003; Laurent et al. 2014; Žák et al. 2014; Finger et al. 2022).

In contrast, the evidence for truly arc-derived magmatic rocks in the CWC is ambiguous; instead, we seem to have recorded solely a back-arc setting so far (Ivan et al. 2001, 2007). Furthermore, the Variscan Orogeny in the CWC was apparently rather short-lived. Within the relevant timeframe (Mid-Devonian to Visean), the evolution progressed rapidly from northward or north-westward (in the present-day coordinates) subduction through the closure of the intervening oceanic domain, continental collision and ensuing slab break-off, to syn- and, finally, the post-collisional magmatism.

Another main difference comes in Visean. While the orogenic root in the BM is characterized by an abundance of c. 339–335 Ma (ultra-)potassic plutons and dykes, intimately

associated with the felsic (U)HP–HT granulites, both rock types are lacking in the CWC. This conspicuous dichotomy, already noted by Cambel et al. (1980), had to reflect first-order differences in the nature, the composition and pre-Variscan geological heritage of the plates involved as well as the mechanism of their collision.

The current models assume that in the Bohemian Massif, the oceanic subduction passed into deep underplating/relamination of the Saxothuringian felsic crust, i.e. the Gondwanan margin attenuated in course of the Ordovician–Silurian rifting (Janoušek et al. 2004b; Schulmann et al. 2014; Kusbach et al. 2015). Soon thereafter, at c. 340–335 Ma, the contaminated lithospheric mantle produced Mg–K-rich magmas with a curious mixed crustal–mantle signature (Janoušek et al. 2025a and references therein). Moreover, the deeply subducted felsic metaigneous crust of the Saxothuringian origin was in part relaminated to the base of the overriding Moldanubian plate, and in part returned through the subduction channel into the Saxothuringian domain (Janoušek et al. 2004b; Schulmann et al. 2014; Maierová et al. 2018, 2021). In both cases they were converted to the (U)HP–HT granulites that form variably sized massifs in the Moldanubian and Saxothuringian units (O'Brien & Rötzler 2003; Janoušek et al. 2004b).

In the CWC, the early (latest Devonian) oceanic slab break-off and ensuing asthenospheric upwelling provided heat needed for triggering the early Carboniferous granitic flare-up (Broska et al. 2022). Presumably, the slab window also prevented the downgoing continental plate from reaching the mantle depths and contaminating the lithospheric mantle. Alternatively, the continental plate involved in the collision had inappropriate composition in terms of its petrochemistry and/or mechanical properties. In either case, this hindered the generation of Mg–K-rich mafic rocks (known as appinites, vaugnerites or durbachites) in the CWC that are common in the more westerly parts of the European Variscan Orogen, from Iberia to the Bohemian Massif (Moyen et al. 2025).

Unfortunately, unlike in the BM, it is not possible to restore the complete orogenic zoning in the CWC. The entire CWC is a fragment of the Variscan orogenic crust in which only part of the magmatic record has been preserved. Missing clear suture–fore-arc–arc–back-arc sequence, together with significant post-Variscan rotation and displacement, does not allow us to deduce the possible subduction polarity which, therefore, remains an unresolved issue.

Location of the Bohemian Massif and Central Western Carpathians in the Variscan belt – the magmatic record perspective

Our comparison shows roughly overlapping timescales for the Variscan magmatism in the BM and CWC; however, the geochemical signatures indicate fundamental differences in the inferred petrogenesis and tectonic significance. For such a reconstruction, it should be taken into account that the entire Western Carpathian area, including the crystalline basement,

was during the Miocene laterally extruded eastward from the Alpine head-on collision to its current position within the Alpine–Carpathian–Pannonian crust (ALCAPA megaunit) (Ratschbacher et al. 1991; Csontos 1995). Moreover, the Carpathian part experienced a 50° counter-clockwise rotation (Márton et al. 2016). This means that the Variscan granites of the Western Carpathians originated much further west, and it is thus assumed that their formation took place in a remote Variscan segment, different from where the Bohemian Massif is presently located.

Our comparison shows that the Variscan magmatic inventories in the BM and CWC differ significantly, as did the timing and tectonic context of magmatism (Fig. 7). The contrasting magmatic histories clearly reflect distinct paleogeographic positions of the BM vs. CWC crustal segments in the Variscan orogenic collage. Specifically, the BM and its granitoids represent a complete section of the orogen's interior, currently situated at the northeastern extremity of the Variscan collisional system (Edel et al. 2018; Schulmann et al. 2022; Martínez Catalán et al. 2024). Its formation was primarily driven by long-lasting Andean-type subduction followed by, in the framework of the entire Variscan belt, relatively early continental collision and orogenic collapse. A similar association of subduction-related granitoids can be traced further west in several parts of Variscides, most notably Vosges (Finger et al. 1997; Schulmann et al. 2022; Moyen et al. 2025), characterized, *inter alia*, by the spatial–temporal association of *c.* 340–335 Ma (ultra-)potassic igneous rocks and HP–HT granulites (Janoušek & Holub 2007; Lardeaux et al. 2014; von Raumer et al. 2014; Hora et al. 2021; Janoušek et al. 2025a).

In contrast, the tectonic position of CWC within a large-scale Variscan orogenic structure is much less certain. The CWC collage comprises fragmented and displaced crustal slices apparently derived from different orogenic sections than the BM. In the Mid-Devonian to early Carboniferous times, this crustal domain underwent a transition from back-arc thinning to crustal thickening, culminating in slab break-off and massive syn- to post-collisional crustal melting.

From this follows, that the timing and duration of individual magmatic stages differed in these two regions. The collisional cycle in the CWC, documented by granitic magmatism, started somewhat later than in the BM, but evolved considerably faster (Fig. 7). The Variscan magmatic evolution of the CWC spanned 50 Myr (*c.* 380–330 Ma), compared to 65 Myr (*c.* 390–325 Ma) in the BM.

Unfortunately, the paleogeographic position of the Western Carpathians in the frame of Variscan belt is poorly constrained. It is one of the pieces of disrupted Variscan belt that was detached and relocated within the Tethyan oceanic system to its current Alpine–Carpathian position (von Raumer et al. 2013; Plašienka 2018; Neubauer et al. 2022). The provenance analysis of the pre-Variscan metasedimentary basement suggests that the Lower Paleozoic sequences of the CWC were supplied by detritus from cratonic sources in the Saharan or East African parts of northern Gondwana (Kohút et al. 2022; Soejono et al. 2024). Furthermore, beyond this recognized

provenance, it also indicates an early Paleozoic proximity of the CWC to the French Massif Central and Iberian Massif Autochthon (Soejono et al. 2024).

It is broadly accepted that the Variscan orogenic collage was formed by the closure of multiple oceanic domains separating subsequently amalgamated continental fragments (Matte 1986; Franke et al. 2017; Martínez Catalán et al. 2024; Murphy et al. 2025). In our case, the question is whether the CWC represents a distant along-strike continuation of the identical suture as the BM, or whether it formed on contact between other crustal blocks, in a completely different branch of the Variscan orogenic system. Differences in the timing, nature, and tectonic setting of the magmatic records rather indicate that the BM and CWC belonged to separate and unconnected oceanic/continental boundaries.

Traditional paleogeographic reconstruction of the basement fragments in the Alpine belt by von Raumer et al. (2013) proposed their Mid-Devonian location within the identical active margin to the east of the BM. This concept has been further refined by several models, which assumed that intra-Alpine units (including the CWC) were part of a separate continental realm, the Paleo-Adria according to Franke et al. (2017) and Neubauer et al. (2022) or Galatia–Ligeria according to Finger and Riegler (2025). Our correlation revealed contrasting Variscan magmatic records in the BM and CWC, suggesting their separate locations within the collision belt, and thus supporting the second group of models.

These pre-Variscan relationships (Soejono et al. 2024) can potentially hint also at the proximity of the Massif Central and/or Iberia during the Variscan collision. However, the magmatic records in these regions do not correspond to those in the CWC. The Variscan magmatism in both the French Massif Central and Iberian Massif exhibited geodynamically distinct characteristics and was systematically younger at most stages, from continental collision to final collapse (e.g., Moyen et al. 2025 and references therein). Theoretically, the Variscan crustal fragments, separated and scattered in the Alpine–Carpathian architecture during the Mesozoic–Cenozoic times, could also be linked to the external subduction system of the Paleo-Tethys Ocean. They could have been derived from a specific, currently missing part of the Variscan system. This putative orogenic domain, located approximately in the region of the present-day western Mediterranean, could have had its own, specific magmatic evolution, and thus did not necessarily need to correspond exactly to any other known parts of the Variscan belt.

Conclusions

The compilation and critical evaluation of the age, petrology and whole-rock geochemistry (including Sr–Nd isotopes) of Mid-Devonian to Mississippian magmatic rocks from the Variscan Bohemian Massif (BM) and ‘core mountains’ in Central Western Carpathians (CWC) has yielded the following conclusions:

- Magmatic evolution in both regions started by Devonian oceanic subduction (in Eifelian: BM, or in Frasnian: CWC). However, the Variscan magmatic inventories in the BM and CWC differ significantly, as did the timing and tectonic context of magmatism.
- While the BM continental-arc magmatism was generated in course of a relatively long-lived (at least *c.* 390–350 Ma) subduction of the Saxothuringian Ocean beneath the Teplá–Barrandian/Moldanubian domains, genuine arc-derived magmatic rocks are missing in the CWC.
- In Tournaisian, the Bohemian magmatism migrated eastwards, forming the Peri-Moldanubian Arc. The evolution of this enormous structure was terminated by the Viséan (~340 Ma) continental collision and slab break-off.
- The oceanic subduction in the BM passed to deep subduction/relamination of the mainly felsic Saxothuringian continental crust (ultimately transformed to felsic HP–HT granulites). Soon thereafter, the crustally contaminated lithospheric mantle produced (ultra-)potassic magmas that formed large plutons and countless dykes with a hybrid crustal–mantle signature penetrating the Moldanubian orogenic root.
- The Mid-Devonian (*c.* 380–361 Ma) gabbros–diorites and diatexites in the CWC were likely generated in a back-arc setting of a hitherto enigmatic arc system. The subduction in the CWC was short-lived, and ended in the latest Devonian by collision, attendant slab break-off and asthenospheric upwelling.
- The early (~360 Ma) oceanic slab break-off and asthenospheric upwelling enhanced granitoid formation in the CWC. The Tournaisian (357–345 Ma), mostly syn- to late-collisional I- and immature S-type (biotite-only) granitoids, gave way to the Viséan post-collisional, two-mica S-type granites of mature metasedimentary parentage. Consequently, CWC contains vast volumes of the Tournaisian–Viséan S-type granites, which are nearly missing in the BM.
- The early slab break-off in the CWC prevented the continental crust to be dragged into the subduction zone, and to contaminate/metasomatize the local mantle. As a consequence, Viséan (ultra-)potassic plutonic and dyke rocks, so abundant in the BM, Vosges, Schwarzwald, Alps and on Corsica, have no known counterpart in the CWC. Also, the felsic HP–HT granulites, similarly characteristic of the Moldanubian Zone in the western–central Europe, are conspicuously missing.
- The timing and duration of individual magmatic stages differed in both studied regions. The collisional cycle in the CWC, documented by granitic magmatism, started somewhat later than in the BM, but evolved considerably faster. The pre- to post-collisional Variscan magmatic evolution of the CWC spanned 50 My (*c.* 380–330 Ma), compared to 65 Myr (*c.* 390–325 Ma) in the BM.
- The contrasting magmatic histories clearly reflect distinct paleogeographic positions of the BM vs. CWC crustal segments, probably along the two unconnected sutures in the different branches of the Variscan orogenic collage.

The BM forms a complete vestige of the orogen's interior, located at the northeastern tip of the collisional system. In contrast, the CWC is a fragmented and displaced crustal section derived from a specific, so far unidentified part of the Variscan belt.

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