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FACULTY OF SCIENCE

DEPARTMENT OF GEOLOGICAL SCIENCES

Mantle-derived potassic-ultrapotassic magmatism of the Bohemian Massif (Moldanubian Zone)

Recherche to the Doctoral Thesis

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Brno 2021

Content

1. Introduction

Mantle-derived potassic to ultrapotassic magmatism is a typical feature of many collisional orogens such as the European Variscides (Janoušek and Holub, 2007; Soder and Romer, 2018; von Raumer et al., 2014) and the Alpine-Himalayan belt (Ersoy and Palmer, 2013; Prelević et al., 2012; Zhao et al., 2009). The emplacement of (ultra)potassic magmas is characteristically related to stages of post-collisional extension leading to partial melting of metasomatically enriched lithospheric mantle domains (Foley, 1992; Prelević et al., 2012). The main metasomatic agent is usually represented by fluids/melts derived from deeply subducted continental material of sedimentary or metaigneous origin (Conticelli and Peccerillo, 1992). Partial melts derived from subducted crustal material are highly fertile components and typically control the trace element budget and isotopic fingerprints of hybrid ultrapotassic melts (Altherr et al., 2004; Conticelli et al., 2009). Accordingly, ultrapotassic magmas are usually characterized by high K_2O and MgO contents, elevated K_2O/Na_2O ratios, conspicuous trace element enrichment, and continental crust-like isotopic signatures (Foley et al., 2013). Therefore, highly alkaline ultrapotassic magmatism, typically related to post-collision extensional settings, represent magmatic proxy to trace lithospheric processes and thus allow to study effects of crustal recycling in subduction zones.

The Moldanubian Zone of the Bohemian Massif, the high-grade Variscan orogenic root in Central Europe, hosts diverse types of ultrapotassic rocks (Janoušek et al., 2019, 2020; Krmíček et al., 2016; Kubínová et al., 2017) and hence provide a unique insight into geodynamic and magmatic evolution of deeper parts of the Variscan Orogen during subduction-related events. Since ultrapotassic magmatic activity typically accompanies high and ultra-high pressure (HP/UHP) metamorphism (Janoušek and Holub, 2007) within deeper levels of subduction zones. The deep Variscan subduction of crustal lithologies is recorded by a close spatial association of HP felsic granulites with garnet-bearing ultrabasic rocks (Medaris et al., 2005) along with the presence of UHP phases preserved in host granulites (Kotková et al., 2011, 2014; Perraki and Faryad, 2014).

Although K-Mg-rich magmatism of the Bohemian Massif has previously attracted the attention of many authors (e.g. Holub, 1997; Janoušek et al., 2019, 2020; Kotková et al., 2010; Leichmann et al., 2007), there currently remain several unsolved aspects regarding the exact origin and nature of enriched mantle source of ultrapotassic magmas, which will be along with petrological and geochemical characteristics of these rocks summarized within this work.

2. Geological background

The Bohemian Massif, the most extensive exposure of the eastern part of the Variscan orogenic belt within Europe (Fig. 1), represents tectonic collage formed due to the Paleozoic convergence of Gondwana and Laurussia during the closure of the Rheic Ocean, eventually leading to the assembly of Pangaea (Franke, 2000; Schulmann et al., 2009). The internal orogenic domain mostly consists of medium- to high-grade metamorphic rocks extensively intruded by numerous granitoid plutons (Žák et al., 2014). The tectonic evolution of the eastern part of the Bohemian Massif included the late Variscan thrusting of the internal orogenic domain over the Cadomian Brunia microplate (Babuška and Plomerová, 2013).

The Moldanubian Zone is traditionally subdivided into three principal tectonostratigraphic units differing in lithological assemblages and metamorphic conditions: the Monotonous, Varied and Gföhl units (e.g. Lardeaux et al., 2014). Mid-crustal, amphibolite-facies Monotonous and Varied units, generally termed Drosendorf unit, are formed predominantly by monotonous, partly migmatitic, cordierite-bearing biotite-sillimanite paragneisses along with subordinate orthogneisses and amphibolites. The Varied group typically contains a higher number of intercalations of amphibolites, quartzites, calc-silicate rocks, marbles, orthogneisses, and graphitic schists in contrast to the Monotonous unit. Moreover, tectonic boudins of retrograde eclogites and spinel peridotites have been described at the boundary between these two distinct geological units (Faryad et al., 2015). Neoproterozoic-Early Paleozoic sedimentation ages were determined for protolith of both mid-crustal complexes (Košler et al., 2014). The lower crustal Gföhl unit, structurally emplaced on the top of the Moldanubian sequence, mainly consists of high-grade anatectic orthogneisses and migmatites (Cooke and O´Brien, 2001; Hasalová et al., 2008), and amphibolites accompanied by HP granulites (Tajčmanová et al., 2006). The abundant HP felsic granulites usually enclose spinel and/or garnet-bearing peridotites with numerous pyroxenite and eclogite layers (Medaris et al., 2005, 2006). The magmatic protolith of anatectic Gföhl gneisses shows Cambrian-Devonian ages (Friedl et al., 2004). The juxtaposition of the highest-grade Gföhl unit with mid-crustal assemblages (Monotonous and Varied units) was related to crustal-scale folding (Franěk et al., 2006).

The Variscan metamorphic evolution of the high-grade Moldanubian Zone, peaking at ~340 Ma (O'Brien and Rötzler, 2003), was accompanied by extensive plutonic activity taking place in different geodynamic settings, mostly from Late Devonian to Carboniferous (e.g. Finger et al., 1997; Timmerman, 2008; Žák et al., 2014). These various igneous stages include:

(1) calc-alkaline and high-K calc-alkaline subduction-related suites of the Central Bohemian Plutonic Complex (CBPC) (~373–340 Ma); (2) (ultra)potassic, Mg-rich plutons of the durbachite series, associated with the fast exhumation of the Gföhl unit to mid-crustal assemblages (~340–355 Ma); (3) peraluminous anatectic S-type and high-K, I-type granitoids (~330–326 Ma) followed by (4) small calc-alkaline intrusions with I-type affinity of the Moldanubian Plutonic Complex (~320–300 Ma).

The extensive (ultra)potassic magmatism of the Moldanubian Zone, a characteristic feature of the whole European Variscan belt (von Raumer et al., 2014), is well-documented by widespread occurrence of durbachitic plutons in the Bohemian Massif, together with other volumetrically subordinate members of ultrapotassic magmatism including lamprophyres, vaugnerites, lamproites etc. Lamprophyres and rare vaugnerites (the named used for K-rich rocks in the French Massif Central by Sabatier, 1980) typically form extensive dyke swarms previously described in the western part of the Moldanubian Zone, covering mostly the area of the CBPC (Kubínová et al., 2017). The dykes have composition of spessartite, gabbrodiorite, minette, kersantite, melasyenite and melagranite. On the other hand, peralkaline dykes of lamproitic composition have been previously observed in the eastern termination of the Moldanubian Zone (Krmíček et al., 2016). They are particularly widespread near Raabs in Austria and Třebíč in the Czech Republic and cut across both the Monotonous and Varied units.

Nevertheless, most of the (ultra)potassic plutons in the Moldanubian Zone form two NNE–SSW oriented belts (Fig. 1) (see Janoušek and Holub 2007 for review). The Western Durbachite Belt includes Milevsko (Čertovo břemeno) and Tábor plutons in the CBPC along with Knížecí Stolec pluton and a small occurrence at Fürstenstein (Bavarian Forest) (Finger et al., 2007). The Eastern Durbachite Belt comprises the ultra-K Jihlava and Třebíč plutons with other small bodies in western Moravia, as well as the shoshonitic Rastenberg and Ybbs plutons in Lower Austria (Janoušek et al., 2020; Zeitlhofer et al., 2016).

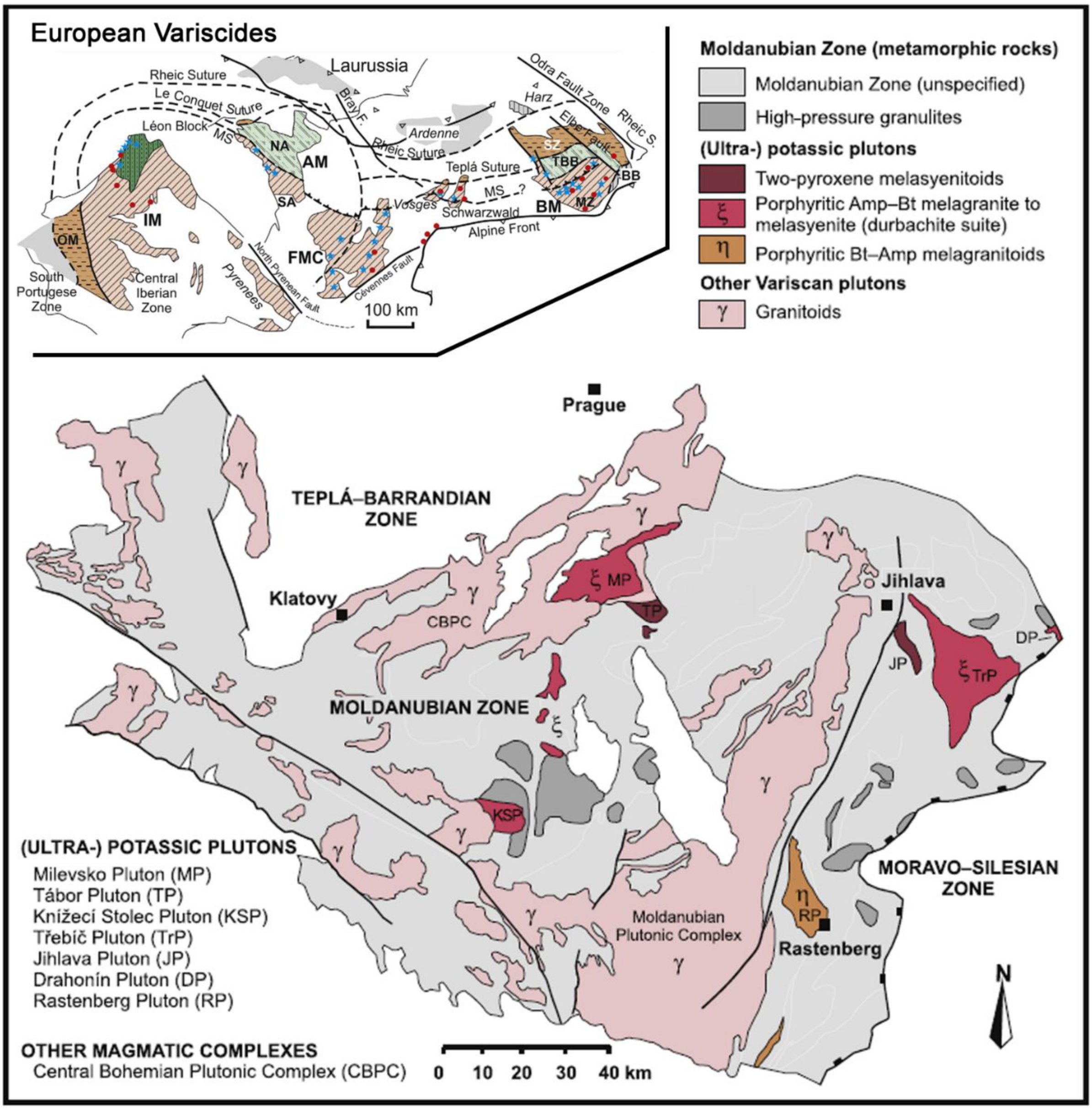


Fig. 1 Position of the Bohemian Massif and Moldanubian Zone in the context of the Variscan orogenic belt in Europe (upper left corner; modified after Kubínová et al., 2017). The red circles represent occurrences of ultrapotassic rocks (von Raumer et al., 2014) and the blue stars indicate distribution of (U)HP lithologies (Faryad and Kachlík, 2013). Variscan basement: BM = Bohemian Massif, FMC = French Massif Central, AM = Armorican Massif, IM = Iberian Massif. Geological sketch of the Moldanubian Zone (lower part; after Janoušek et al., 2019)

2.1. Western Durbachite Belt

Tábor pluton is predominantly built up by biotite-two pyroxene (orthopyroxene usually prevails over clinopyroxene) quartz-poor melasyenite in the central part of this ultrapotassic intrusion, whereas marginal parts are composed of coarse-grained, less mafic biotite-two pyroxene quartz melasyenite to melagranite. Rare enclaves petrographically resembling the central part of the Tábor pluton were commonly observed within marginal facies (Janoušek et al., 2019). Other country-rock xenoliths are rather rare and include among other types calc-silicate rocks and hornfelses. Moreover, numerous aplitic dykes occur in close spatial association with the ultrapotassic body (Holub, 1997). Internal fabrics of the Tábor pluton are solely magmatic and do not show any evidence of crystal-plastic deformation and/or recrystallization. Orientation of magmatic fabrics is subparallel to the pluton contact, decoupled from metamorphic fabrics in the surrounding metamorphic Moldanubian rocks, showing the post-tectonic character of magma emplacement (Žák et al., 2005).

Milevsko pluton, traditionally termed as Čertovo břemeno, forms a subhorizontal, relatively thin tabular body (Dobeš and Pokorný, 1988) with transitional magmatic to solid-state foliation that is contact-parallel to the moderately NW dipping metamorphic foliation in the host Moldanubian migmatitized paragneisses. These fabrics are result of the subvertical shortening due to rapid exhumation of the high-grade metamorphic rocks of the Moldanubian Zone (Žák et al., 2005). Sparsely porphyritic and finer-grained varieties of durbachitic rocks occur frequently in marginal parts of the Milevsko pluton, compared to its central part mainly composed of durbachitic rocks of quartz melasyenite and melagranite composition (Holub, 1997).

2.2. Eastern Durbachite Belt

Třebíč pluton represents the largest durbachitic body in the Bohemian Massif and is characterized by variable petrographic composition (Janoušek et al., 2020). It consists of several textural and mineralogical varieties of coarse-grained, porphyritic biotite and amphibole-biotite melasyenites to melagranites, and contains mafic microgranular enclaves (Holub, 1997). The Třebíč pluton forms relatively thin tabular body (Leichmann et al., 2017) that intruded into partly exhumed high-grade metamorphic assemblages of lower crustal Gföhl unit including HP felsic granulites and anatectic migmatitized orthogneisses. It shows mostly concordant, but locally discordant contacts with these Moldanubian host rocks and dips westward in the eastern and northeastern marginal zone. The ultrapotassic body is regularly rimmed by a discontinuous zone of leucocratic granitoids and/or migmatites, whereas aplitic to pegmatitic dykes commonly crosscut the pluton. Similar to Milevsko pluton, marginal parts of the Třebíč pluton are formed by sparsely porphyritic and finer-grained durbachitic rocks in contrast to central parts of the ultrapotassic body (Holub, 1997). Furthermore, marginal parts of the pluton frequently contain host rock xenoliths of the amphibolite and migmatitic gneiss (Stárková et al., 1993). As revealed geophysical data along with borehole logging, the southern and northwestern part of the Třebíč pluton represent the root zone – magma feeder dyke, whereas the eastern and middle part correspond to a lateral laccolithic extrusion with a thickness of only several hundred meters (Leichmann et al., 2017; Rejl and Sedlák, 1987).

Jihlava pluton is predominantly composed of biotite-two pyroxene melasyenite that was emplaced into already exhumed and mylonitized mid-crustal assemblages of the Monotonous unit, in contrast to the Třebíč pluton. Jihlava pluton shows intrusive contacts with the Moldanubian host rocks mostly represented by partly migmatitic cordierite-biotite paragneisses. The contacts are mostly parallel to the schistosity of the host rocks and dip steeply to the east. Based on geophysical research of Leichmann et al. (2017), it was revealed that Jihlava pluton represent stock-like body showing significant positive gravimetric anomalies in the center of the pluton, caused by presence of abundant gabbroitic rocks. By contrast, positive gravimetric anomaly of the NW part of the pluton was interpreted as a result of steep contacts of the syenite intrusion with maximum depth of 2.5 km (Rejl and Sedlák, 1987). The Jihlava pluton features an internal magmatic foliation, defined by the preferred orientation of K-feldspar phenocrysts, biotite and pyroxene. Magmatic along with host mylonite foliations define a sigmoidal pattern, steeply to moderately dipping to the NE to ESE and widely associated with SSE to SE plunging stretching lineation and right-lateral kinematics (Janoušek et al., 2019).

Rastenberg pluton mainly comprises amphibole-biotite melagranite with and isotropic fabric, irregular texture and phenocrysts of idiomorphic K-feldspar. However, other durbachitic varieties are present as well, for instance amphibole-biotite quartz monzonites, medium-grained quartz monzodiorite and/or K-feldspar-phyric biotite granodiorites (Gerdes et al., 2000). The Rastenberg pluton intruded, with partly discordant contacts, into high-grade metamorphic gneisses of mid-crustal complexes of the Drosendorf unit. As revealed regional distribution of mineral cooling ages (Dallmeyer et al., 1992), the ultrapotassic pluton was emplaced during the exhumation stage of the Variscan Orogeny.

3. Ultrapotassic magmatism

3.1. Timing of magmatic activity

The ultrapotassic magmatic activity in the Moldanubian Zone of the Bohemian Massif has been dated by many studies that revealed relatively coeval intrusion ages of individual ultrapotassic members in a range between ca. 335–338 Ma. For instance, the largest durbachitic pluton in the Czech Republic, the Třebíč pluton, was dated by conventional U–Pb method on zircon (335.127 ± 0.061 Ma; Schaltegger et al., 2021). Similar and/or slightly older igneous ages in a range ca. 336–338 Ma have been also reported for subordinate two-pyroxene syenitoids from the Tábor and Jihlava pluton (Janoušek et al., 2019; Janoušek and Gerdes, 2003) as well as vaugnerite and syenite porphyry from an ultrapotassic dyke swarm exposed in Nihošovice quarry (Kubínová et al., 2017). From this follows that these coeval intrusions reflect the first pulse of (ultra)potassic magmatism in the Variscan Orogenic Belt (Fig. 2) (Soder and Romer, 2018), near-synchronous and shortly following the exhumation of (U)HP crustal complexes (Janoušek and Holub, 2007). As already suggested by Kotková et al. (2010), significantly older ages obtained for some durbachitic members (e.g. Klötzli and Parris, 1996), typically preceding the peak of the Variscan Orogeny (~340 Ma; O'Brien and Rötzler, 2003), were most likely biased by a minor unresolved inheritance.

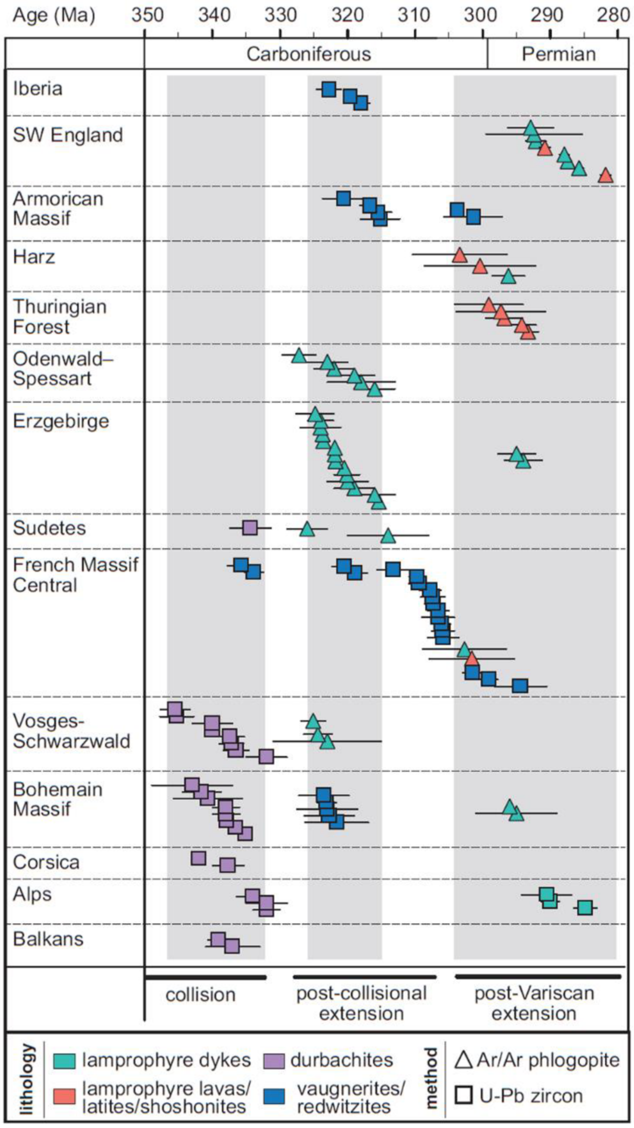


Fig. 2 Compilation of age information on Variscan potassic–ultrapotassic magmatism (adapted after Soder and Romer, 2018)

In general, Variscan K-rich post-collisional magmatism formed during ca. 60 Ma following the peak stage of the Variscan Orogeny, clustering in three major intervals illustrated in Fig. 2. The first pulse of potassic to ultrapotassic magmatism occurred around 340–335 Ma after the exhumation of (U)HP units and mainly include the emplacement of amphibole-biotite quartz-melasyenites to melagranites (durbachites) and subordinate two-pyroxene melasyenites to melagranites, occurring as independent intrusive bodies in Bohemian Massif, Vosges, and Schwarzwald (Holub, 1997; Janoušek et al., 2019, 2020; Kotková et al., 2010; von Raumer et al., 2014; Tabaud et al., 2015). Interestingly, vaugnerites represent the only one ultrapotassic member that is present during all three described magmatic stages (Fig. 2) (Laurent et al., 2017). By contrast, the second and third magmatic pulses occurred during post-collisional and post-orogenic regional extension between 325–315 Ma and 305–280 Ma, mostly including K-rich mafic magmatic rocks such as lamproites, lamprophyres, shoshonites and latites (Soder and Romer, 2018; references therein).

3.2. Petrographic characteristics

The petrographic variability of different types of ultrapotassic rocks from the Bohemian Massif (Moldanubian Zone) has been previously described in detail by many authors (Gerdes et al., 2000; Holub, 1997; Janoušek et al., 2019, 2020; Kotková et al., 2010; Krmíček et al., 2016; Kubínová et al., 2017), and thus only a basic petrographic description is given here.

The igneous rocks of the **durbachite series** petrographically range from melasyenite to quartz melasyenite to melamonzogranite. They are usually coarsely grained with characteristic K-feldspar phenocrysts in a dark medium-grained matrix (Fig. 3a, b). Diverse mafic microgranular enclaves (MME) occur frequently in most durbachitic intrusions (Fig. 3b) (Janoušek et al., 2019, 2020). The K-feldspar phenocrysts typically form tabular crystals reaching up to several cm across. Matrix is usually composed of abundant amphibole, biotite, K-feldspar, plagioclase, and variable amount of quartz depending on a degree of fractionation of host rock. Amphibole is commonly pale green, weakly pleochroic and forms mainly subhedral to nearly euhedral crystals, frequently in association with biotite. It chemically corresponds mainly to actinolite, only exceptionally amphibole of magnesiohornblende-like composition is present as well (Janoušek et al., 2020). Biotite occur as large subhedral flakes showing strong pleochroism (Fig. 3c, d). Chemical composition of abundant biotite corresponds to phlogopite.

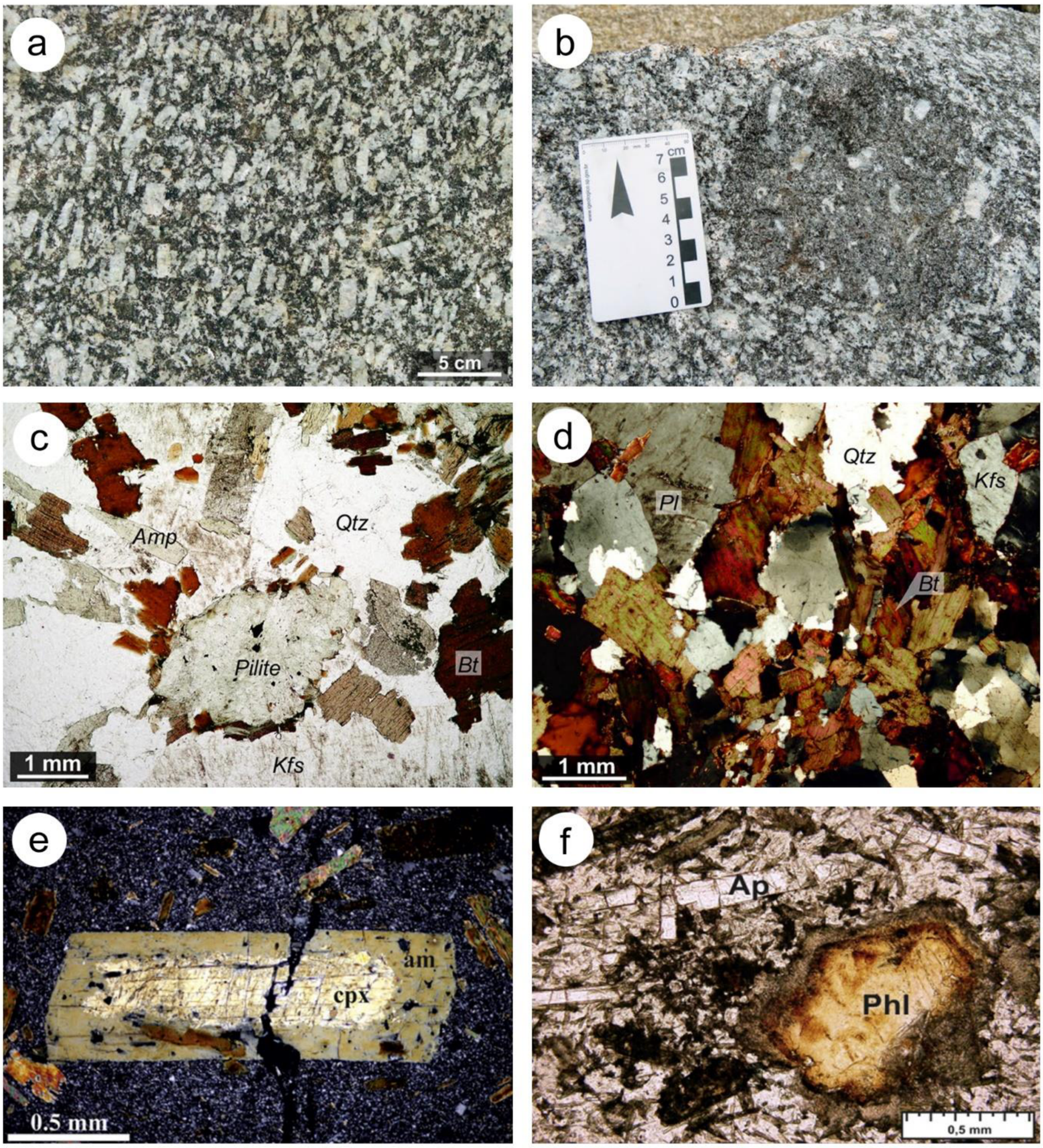


Fig. 3 Common mineral assemblages from ultrapotassic rocks. (**a**) Typical porphyritic texture of amphibole-biotite melagranite showing planar shape-preferred orientation of K-feldspar and plagioclase phenocrysts (**b**) Mafic microgranular enclave enclosed in host amphibole-biotite melagranite (**c**) Pilitic pseudomorphs after olivine composed of Mg-rich actinolite with chromite inclusions (**d**) Close association of phlogopite flakes with abundant quartz crystals along with K-feldspar and plagioclase grains (**e**) Clinopyroxene partially replaced along the rims by secondary amphibole from syenite porphyry (**f**) Phlogopite phenocrysts strongly replaced by K-rich amphibole and abundant apatite prisms in an amphibole–microcline matrix of lamproite. Images and microphotographs of K-Mg-rich rocks of durbachite series (**a–f**), ultrapotassic dykes (**e**), and lamproite series (**f**) are from Janoušek et al. (2020), Kubínová et al. (2017), and Krmíček et al. (2016), respectively

Abundantly occurring strongly perthitic K-feldspar in matrix usually chemically corresponds to microcline or orthoclase. On the other hand, plagioclase is typically present as large, mainly subhedral grains showing only weak continuous zoning. The plagioclase grains are relatively sodic corresponding to oligoclase–andesine.

Clinopyroxene occur exclusively as relics in cores of larger amphibole grains. Chemically it corresponds to ferroan diopside. Orthopyroxene is present only in rare cases, its significant presence is restricted to a small durbachitic body at Písek (Holub, 1997). Common petrographic feature of most durbachitic rocks is the presence of very fine-grained scattered clots – pilitic pseudomorphs (Fig. 3c) that consist of pale-green actinolite conspicuously rimmed by biotite (Janoušek et al., 2020). They are typically interpreted as pseudomorphs after former olivine phenocrysts (Holub, 1974), similar phenomena was described from many potassic lamprophyres (Holub, 1997). It is also noteworthy a close association of quartz with abundant mafic silicates (Fig. 3d) mainly represented by phlogopite and actinolite (minor magnesiohornblende).

The most common accessory phase is short-prismatic fluorapatite (up to 3 vol%) typically associated with mafic silicates such as abundant amphibole and biotite. Other accessory minerals include zircon, titanite, and frequently also allanite and thorite; locally monazite, uraninite and other Th-, U-, and REE-bearing phases of secondary origin such as thorianite, coffinite or bastnäsite (Sulovský, 2001). From opaque minerals are usually present pyrrhotite prevailing over pyrite, arsenopyrite, chalcopyrite, sphalerite and pentlandite. Fe-Ti oxides occur only in a subordinate proportion – ilmenite is rather rare and magnetite absent. Chromite was locally observed enclosed in mafic silicates (Janoušek et al., 2020).

The **ultrapotassic dykes**, corresponding to syenite porphyry and vaugnerite (Kubínová et al., 2017), are mostly characterized by idiomorphic phenocrysts (e.g. clinopyroxene, amphibole, biotite) in a very fine-grained matrix (Fig. 3e) composed of alkali feldspar, quartz, biotite, amphibole, and accessory amounts of apatite, titanite, opaque phases and zircon. Vaugnerite is mainly fine-grained with abundant pseudomorphs of talc after former olivine phenocrysts and clinopyroxene usually replaced by amphibole (Fig. 3e). Similar to vaugnerite, syenite porphyry contains pseudomorphs of talc. It typically consists of phenocrysts of alkali feldspars, clinopyroxene, amphibole, biotite and rarely quartz set in fine-grained to aphanitic matrix within the central part of the porphyry dyke, whereas marginal parts of syenite porphyry at the contact with surrounding rocks are characterized by glassy matrix (Kubínová et al., 2017).

Lamproite series represent the most exotic member of ultrapotassic magmatism in the Bohemian Massif. Lamproites show a characteristic mineralogy with Al-poor phlogopite and/or K-rich amphibole (Mazdab, 2003) as primary mafic OH-bearing minerals. They contain specific accessory minerals with K, Ba, Ti, and Zr, such as priderite and wadeite. Orogenic lamproites from the Bohemian Massif are usually characterized by mineral associations with Fe-rich K-feldspar and K-rich amphiboles (Krmíček et al., 2016). In some cases, phlogopite and clinopyroxene also occur as phenocrysts (Fig. 3f). Two major textural types of lamproitic dykes within the Bohemian Massif have been described (Krmíček et al., 2016): (1) mafic phenocryst-bearing type is related to undifferentiated dykes containing phenocrysts of mafic minerals surrounded and/or enclosed in microcline (2) microcline phenocryst-bearing type is related to differentiated leucolamproites containing microcline phenocrysts surrounded by amphibole and quartz. Lamproites occasionally contains pseudomorphs after olivine that are typically filled by secondary minerals. Accessory minerals usually include titanite, rutile, zircon and apatite (Fig. 3f).

3.3. Whole-rock geochemistry

The above-mentioned members of ultrapotassic magmatism (e.g. durbachites, lamprophyres, lamproites) in the Moldanubian Zone of the Bohemian Massif are characterized by dual mantle–crustal geochemical character (Holub, 1997; Janoušek et al., 2019, 2020; Krmíček et al., 2016; Kubínová et al., 2017). They typically have high concentrations of transitional metals (e.g. Cr, V, Ni), and high Mg# values [molar Mg/(Mg + Fe)] and MgO together with low SiO_2 contents, signalizing a derivation from a mantle-related source. On the other hand, they usually show notably elevated concentration of large ion lithophile elements (LILE; Rb, Cs, Ba, K, Li, Pb), U, Th and conspicuous depletions in high field strength elements (HFSE; Nb, Ta, Ti), pointing to a contribution of crustal continental material (Holub, 1997). Furthermore, various types of ultrapotassic rocks ordinarily exhibit significant enrichment in light rare earth elements (LREE). Therefore, their chondrite-normalized REE patterns are characteristically LREE-enriched with well-marked negative Eu anomalies (Janoušek et al., 2019, 2020). High Rb/Sr, Th/Ta, LILE/HFSE as well as low K/Rb and Rb/Cs ratios are considered as a characteristic fingerprint of the durbachite series (Holub, 1997). Geochemically these plutonic rocks closely resemble some minettes. Interestingly, potassic to ultrapotassic rocks of the durbachite series share mutual chemical affinities with HP Moldanubian granulites (Janoušek and Holub, 2007), as shown in Fig. 4a–c (see *Section 4.3.* for details).

Within the durbachite series, high concentration of K_2O and high K_2O/Na_2O ratios are combined with markedly low CaO and Na_2O. For instance, magmatic rocks of the largest durbachitic pluton in the Czech Republic (Třebíč pluton) are exclusively ultrapotassic (Janoušek et al., 2020), thus having K_2O > 3wt%, MgO > 3 wt% and K_2O/Na_2O > 2, as previously defined by Foley et al. (1987). Because of significantly high K_2O concentrations, durbachites typically have shoshonitic composition (*sensu* Peccerillo and Taylor, 1976). Most durbachitic rocks are metaluminous with increasing molar $Al_2O_3/(CaO + Na_2O + K_2O)$ towards more silica rich and/or strongly contaminated varieties (Holub, 1997). These atypical durbachitic rocks, commonly occurring within marginal parts of ultrapotassic intrusions at the contact with surroundings country rocks, usually have notably low K_2O contents and higher Na_2O and Al_2O_3 concentrations (Holub, 1997). They usually display slightly peraluminous character, notably low trace element contents (Rb, Ba, Th, U), and their Mg# values are lower than those of common magmatic rocks of durbachite series with similar SiO_2 concentrations (Janoušek et al., 2020).

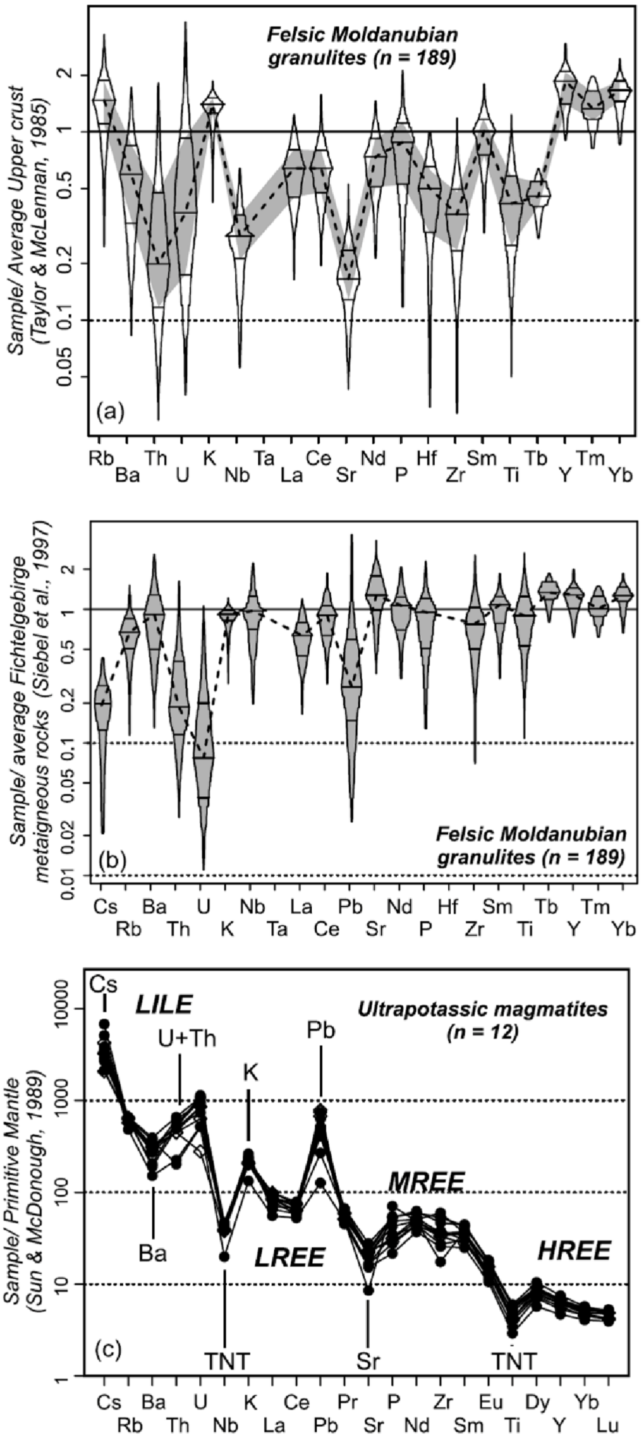


Fig. 4 (**a, b**) Characteristic trace element composition of felsic Moldanubian granulites and (**c**) comparison with common ultrapotassic magmatic rocks of the durbachites series from the Moldanubian Zone of the Bohemian Massif (adapted after Janoušek and Holub, 2007)

Similar to plutonic rocks of durbachite series, highly alkaline dykes described from CBPC typically show ultrapotassic affinity, according to definition of Foley et al. (1987), as demonstrated by elevated $K_2O > 5.8$wt%, $MgO > 3.5$ wt% and $K_2O/Na_2O > 2.2$ (Kubínová et al., 2017). Vaugnerite geochemically corresponds to K-lamprophyre, whereas syenite porphyry has similar composition to silica-rich durbachites. Both ultrapotassic dyke varieties have metaluminous character and usually show a considerable dominance of K_2O content over Na_2O concentrations. Systematic variation between vaugnerite and syenite porphyry is evident in case of transition elements; higher contents of incompatible transition metals (Cr, V) are typical for vaugnerite relative to syenite porphyry. They also share trace element signatures typical for common ultrapotassic rocks of the durbachite series (Kubínová et al., 2017). For instance, ultrapotassic dykes feature LREE-enriched chondrite-normalized pattern with more pronounced negative Eu anomaly for vaugnerite in contrast to syenite porphyry. Most importantly, the primitive mantle-normalized incompatible trace element pattern is characterized by significantly negative HFSE anomalies and strong positive LILE anomalies, indicating a similar mantle source as other ultrapotassic rocks from the Bohemian Massif (see Fig. 4) (Janoušek et al., 2020; Krmíček et al., 2016; Kubínová et al., 2017).

As previously stated, lamproites from the Bohemian Massif represent the most exotic member of potassic–ultrapotassic magmatism and slightly geochemically differ from other plutonic and dyke varieties. On the one hand, they have comparable whole-rock major geochemical composition relative to abundant durbachite plutons, as demonstrated by significant contents of MgO (up to 7.6 wt%) together with low CaO concentrations (Krmíček et al., 2016). On the other hand, due to extremely high K_2O contents (up to 11.3 wt%) and low Al_2O_3 concentrations, lamproites regularly have peralkaline composition, which is typical geochemical signatures of orogenic lamproites and lamprophyres found in the European Variscides (Soder and Romer 2018). Both described textural types of lamproites (*Section 3.2.*) differ in whole-rock geochemistry. The microcline phenocryst-bearing type of leucolamproites shows systematically lower MgO concentrations than the mafic phenocryst-bearing type of lamproites. The lamproites display a broad range in SiO_2, Al_2O_3, and CaO contents or K_2O/Na_2O ratios at a relatively small variation in Mg# values, whereas leucolamproites are characterized by a gradual increase/decrease in major element contents at lower Mg# values (Krmíček et al., 2016).

3.4. Isotope systematics

A characteristic feature of all members of ultrapotassic magmatism in the Bohemian Massif represents highly radiogenic Sr and unradiogenic Nd isotopic composition resembling those of mature continental crust (Fig. 5). The newly obtained data set for ultrapotassic rocks of the Třebíč pluton (Janoušek et al., 2020) and syenitoids from Tábor and Jihlava pluton (Janoušek et al., 2019) demonstrates extreme crust-like radiogenic isotopic signatures (^{87}Sr/^{86}Sr$_{337}$ $\geq$0.7112; εNd$_{337}$ > -6.8) comparable to those of Moldanubian granulites (Fig. 5). Similarly, ultrapotassic rocks of the composite Rastenberg Pluton are characterized by crust-like isotopic composition, suggesting a clear geochemical affinity to K-rich calc-alkaline lamprophyres (e.g. minettes) and lamproites (Gerdes et al., 2000). In accordance with these observations, durbachites and lamprophyres from the Vosges and Schwarzwald (Fig. 1) (Soder and Romer, 2018; Tabaud et al., 2015) show similar isotopic variations as well, presumably indicating comparable mantle source enrichment (*Section 4.3.*). This is further supported by Sr-Nd isotopic constrains for ultrapotassic rocks of the lamproitic series (Fig. 5) from the Bohemian Massif (Krmíček et al., 2016).

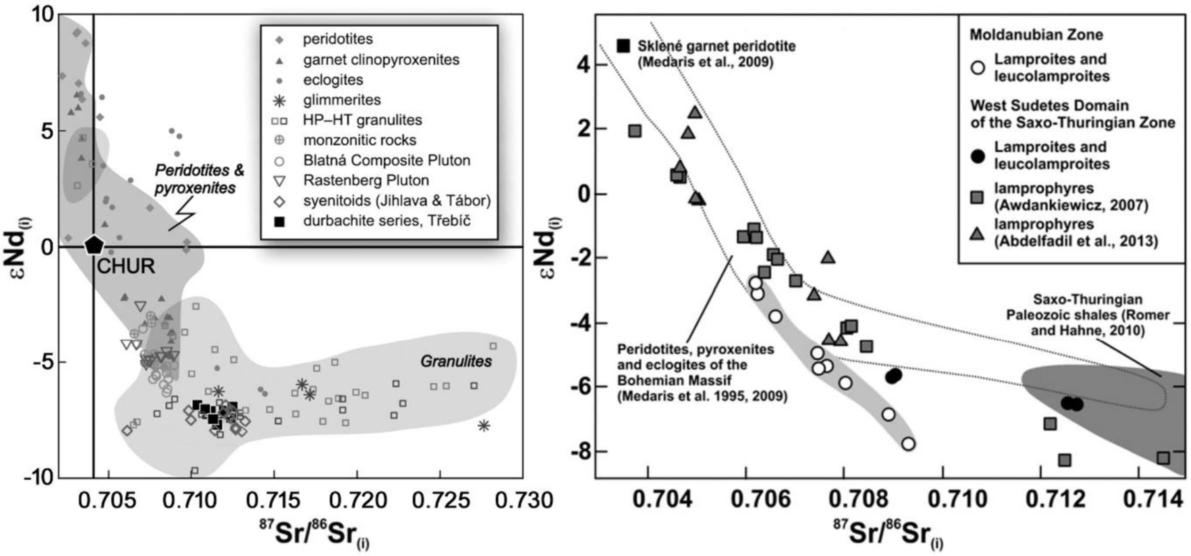


Fig. 5 Initial ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotopic ratios for ultrapotassic rocks of the durbachitic (left part; Janoušek et al., 2020) and lamproitic (right part; Krmíček et al., 2016) series from the Bohemian Massif, with comparison with other mantle-derived, crustal, and hybrid rocks from the Moldanubian and Saxothuringian Zone

4. Deciphering the origin of ultrapotassic magmas

4.1. Petrogenetic enigma of durbachitic rocks

Without any doubt, ultrapotassic rocks of the durbachite series in the Moldanubian Zone of the Bohemian Massif represent one of the most peculiar rock types and thus they have attracted enormous attention during last several decades. Unfortunately, some authors have failed with the task to unravel the origin and petrotectonic evolution of these petrographically and geochemical unusual rocks. Despite the fact that durbachitic rocks were originally thought to have a magmatic origin (Suer, 1893), several hypotheses including various geological processes were proposed, in order to decipher source of these peculiar magmas (see Holub, 1997 for a summary).

Highly alkaline composition of durbachites was previously ascribed to **fluid-driven potassic metasomatism** affecting some metabasite bodies within metamorphic complex composed of high-grade gneisses (Von Eller, 1961; Zoubek et al., 1973). Nevertheless, as previously pinpointed by Holub (1997), such petrogenetic model would require and extreme influx of potassium and incompatible transition metals such as chromium or vanadium into metamorphic rocks and particularly their complete recrystallization. Moreover, such scenario is further precluded by intrusive contacts between durbachites and surrounding rocks, their conspicuous igneous textures and presence of microgranular enclaves.

Model of **gravitational differentiation of a granitic magma** has been applied to durbachitic and associated rocks in the Voges (Fluck, 1980). However, relatively narrow range of Mg# values along with covariations of some trace elements in durbachites strongly argue against this proposed hypothesis (Holub, 1997).

Another possible petrogenetic model of plutonic rocks of durbachite series was proposed by Bubeníček (1968), which included **contamination of original granitic magmas** by the host Moldanubian gneisses with subordinate metabasite bodies, which should have explained melanocratic character of durbachitic rocks in the Třebíč pluton. However, extensive assimilation of these lithologies would not produce such highly alkaline Mg-K-rich magmas.

Model of **recrystallization from a volcanic protolith** was proposed by Vlašímský et al. (1992), who interpreted durbachitic rocks as recrystallization products of alkaline volcanism of a Moldanubian continental rift. Such petrogenetic scenario is ruled out by field observations such as intrusive contacts and contact metamorphism associated with them. Furthermore, durbachite geochemistry contrasts the continental rift settings and crustal source (Holub, 1997).

4.2. Contribution of crustal contamination

In general, ultrapotassic rocks and associated rocks are characterized by conspicuous crustal signatures that are usually reflected by strong enrichments in radiogenic Sr and unradiogenic Nd isotopes with respect to mantle-derived peridotite rocks (Fig. 5) (Altherr et al., 2004; Conticelli et al., 2015; Prelević et al., 2012; Zhao et al., 2009). Importantly, incompatible trace elements are extremely fractionated and show different enrichment in LILE with respect to Sr and other HFSE usually including Nb, Ta, and Ti (Conticelli et al., 2009). These characteristic features resemble closely the distribution of trace elements in mature crustal lithologies (Rudnick and Fountain, 1995). Besides, the strong enrichment in Pb is ordinarily attributed to the recent addition of a continental crustal component (Taylor and McLeannan, 1995). Additionally, high proportions of quartz in many ultrapotassic lithologies (*Section 3.2.*) also strongly argues for assimilation of felsic crustal material during magma ascent (Hegner et al., 1998; Kubínová et al., 2017).

In spite of dual mantle–crustal geochemical character of ultrapotassic rocks, many previous studies have taken all above-mentioned characteristics as the evidence for a significant interaction (crustal hybridization) between primary parental magmas and crustal lithologies during ascent to surface or ascribed such peculiar geochemical character to crustal origin of these highly alkaline magmas (e.g. Vejnar, 1974; Gasperini et al., 2002). However, some authors have brought several arguments against crustal hybridization as a major mechanism producing the crustal-derived geochemical and isotopic signatures of most ultrapotassic rocks worldwide (e.g. Conticelli et al., 1998; Holub, 1997; Gerdes et al., 2000). Firstly, their considerably high Mg# values together with elevated concentrations of incompatible transition metals such as Cr, Ni, and V simply precludes the crustal origin. Secondly, the presence of highly forsteritic olivine on the liquidus indicates a derivation from primitive magmas that originated within peridotitic upper mantle. Thirdly, occurrences of mantle xenoliths in host rocks testify the rapid ascent through the continental crustal blocks. And most importantly, ultrapotassic rocks of lamproitic series displaying the highest MgO contents generally exhibit the strongest enrichments in terms of trace element and isotope composition (Conticelli and Peccerillo, 1992).

In addition, it was previously demonstrated that trace element concentrations of most ultrapotassic rocks are commonly higher than those of average crustal rocks and sediments (e.g. Taylor and McLeannan, 1995; Plank and Langmuir, 1998). Therefore, unreasonably high proportions of crustal assimilants would be required to generate ultrapotassic melts with significant enrichment in most trace elements such as LILE and LREE. From this follows that extreme trace element enrichment makes ultrapotassic rocks nearly entirely insensitive to crustal contamination and rather provide constraints on the source nature of their parental magmas (Conticelli et al., 2009; Zhao et al., 2009).

Accordingly, crust-like isotopic signatures of ultrapotassic magmas could not have been produced solely by continental crustal hybridization. Instead, the involvement of a long-term enriched reservoir was necessary to generate such a highly radiogenic isotopic composition (Gerdes et al., 2000; Tabaud et al., 2015). Furthermore, as already shown for plutonic rocks of the durbachite series in the Bohemian Massif (Janoušek et al., 2020), possible crustal assimilants are isotopically less evolved ($^{87}Sr/^{86}Sr_{337} \leq 0.7102$; $\varepsilon Nd_{337} > -6.5$) than the ultrapotassic primary magma ($^{87}Sr/^{86}Sr_{337} \geq 0.7112$; $\varepsilon Nd_{337} > -7.6$). These observations preclude the contribution of crustal contamination as a major mechanism producing the typical crust-like isotopic composition of these hybrid magmas, indicating only partly limited dilution of source isotopic signatures.

4.3. Insight into petrogenesis of ultrapotassic magmas

It was widely accepted that highly alkaline potassic-ultrapotassic magmatism relates to the melting of heterogeneous lithospheric mantle source contaminated by crustal material (e.g. Avanzinelli et al., 2009; Conticelli et al., 2015; Foley, 1992; Jung et al., 2020; Prelević et al., 2012). Process of crustal contamination of refractory upper mantle usually leads to formation of metasomatically overprinted mantle domains commonly forming vein networks entrapped within wall-rock mantle peridotite (Foley et al., 2013; Sekine and Wyllie, 1982; Yang et al., 2004). These newly formed metasomatic assemblages enclosed in heterogeneous lithospheric mantle are ordinarily composed of hydrous minerals such as particularly phlogopite and/or richterite (e.g. Förster et al., 2020). In order to produce heterogeneous mantle source, these alkali-rich metasomatic agents are envisaged to incorporate a whole spectrum of recycled materials, including for instance terrigenous siliciclastic sediments (Prelević et al., 2008), marly sediments (Avanzinelli et al., 2009) and blueschists (Tommasini et al., 2011).

Indeed, geochemical and isotopic data previously obtained from mantle-derived peridotites and associated pyroxenites (Fig. 5) found in the Moldanubian Zone of the Bohemian Massif (Ackermann et al., 2016; Medaris et al., 2005, 2006; Svojtka et al., 2016) indicate that strongly enriched heterogenous subcontinental lithospheric mantle truly existed beneath the Variscan Orogen. For instance, garnet pyroxenites and subordinate eclogites from the high-grade Gföhl unit typically show strong geochemical evidence for the presence of recycled upper crustal materials and thus they have been interpreted as products of reaction of the wall-rock peridotitic mantle with transient alkaline melts derived from subduction-modified mantle domains enriched in incompatible elements, with the direct involvement of deeply subducted crustal material (Becker, 1996; Svojtka et al., 2016). In accordance with these observations, abundant pyroxenite layers usually showing conspicuous crust-like isotopic signatures (Fig. 5) can possibly account for the enriched mantle source of potassic-ultrapotassic magmas in the Bohemian Massif. Such alternative scenario including melting of heterogenous mantle containing hydrous pyroxenitic veins was previously applied to (ultra)potassic magmatism worldwide (e.g. Foley, 1992; Pilet et al., 2008).

On the other hand, there is mounting evidence that ultrapotassic magmatism closely relates to partial melting of phlogopite-dominated enriched mantle source (e.g. Conticelli et al., 2015; Foley et al., 1992; Prelević et al., 2008; Zhao et al., 2009). Moreover, these observations from natural environments are further supported by results of experimental studies which have successfully produced in laboratory conditions highly alkaline K-rich melts geochemically resembling the most exotic members of (ultra)potassic magmatism such as lamproitic rocks (Förster et al., 2017, 2019). With respect to the results of experimental studies investigating melting of mixed peridotite-phlogopite mantle source (Förster et al., 2017), Janoušek et al. (2020) proposed the petrogenetic model for the largest durbachitic body in the Bohemian Massif (Třebíč pluton), which includes low-degree partial melting of phlogopite-rich "metasomes" enclosed within refractory peridotitic mantle. This petrogenetic model requires re-enrichment of refractory harzburgitic lithospheric mantle by deeply subducted continental crustal material of the Saxothuringian domain, directly and/or through interaction with (U)HP melts/fluids. Accordingly, the deeply subducted crustal component genetically corresponds to HP Moldanubian granulites that most likely represent original metaigneous lithologies of Saxothuringian origin (Janoušek et al., 2004). The causal link between HP granulites and potassic-ultrapotassic rocks of the durbachite series is demonstrated by their close spatial and temporal association (Fig. 1) as well as mutual chemical affinities (Fig. 4a–c) (Janoušek and Holub, 2007).

In addition, there is increasing evidence that Moldanubian granulites have truly reached mantle depths, as evidenced by the spatial association with mantle-derived ultrabasic rocks (Medaris et al., 2005), preservation of UHP phases in granulites (Kotková et al., 2011, 2014; Perraki and Faryad, 2014), and PT estimates of their prograde mineral assemblages (Jedlička et al., 2015). Based on above-mentioned observations, two possible alternatives of enriched mantle source of ultrapotassic magmatism in the Bohemian Massif have been proposed by Janoušek et al. (2020): 1) phlogopite-bearing harzburgitic mantle, and/or 2) phlogopite-veined refractory peridotite. The available geochemical and isotopic data show that durbachitic rocks of the Třebíč pluton have a close affinity to phlogopite-rich rocks collectively termed as glimmerites (Fig. 6) (Janoušek et al. 2020) that were observed within ultrabasic massifs in the Moldanubian Zone of Lower Austria (Becker et al., 1999). These glimmerite veins are interpreted as a product of interaction between wall-rock peridotites and F-rich fluids released during the HP–HT breakdown of phlogopite in the felsic granulites (Becker et al., 1999). The supercritical fluids and/or possibly (U)HP melts derived from deeply subducted metaigneous lithologies (Janoušek et al., 2004), have percolated through overlaying heterogenous subcontinental mantle (Svojtka et al., 2016), which has presumably led to the formation of phlogopite-rich metasomes, either in the form phlogopite harzburgites or glimmerites. In any case, low-degree partial melting of these metasomes would produce potassic-ultrapotassic magmas with composition matching the mantle-derived rocks of durbachite series (Förster et al., 2019).

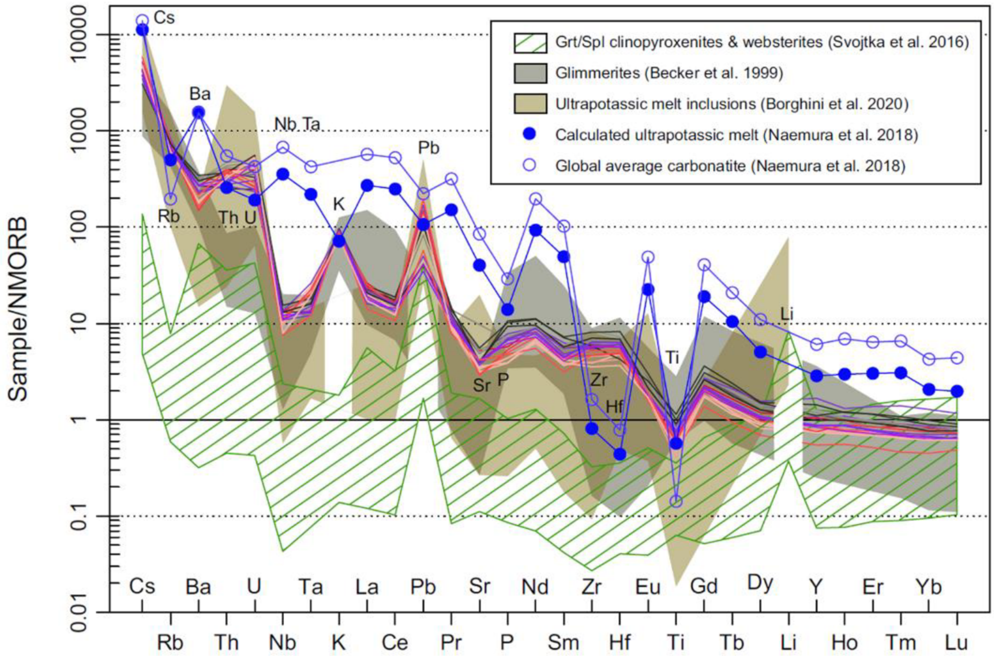
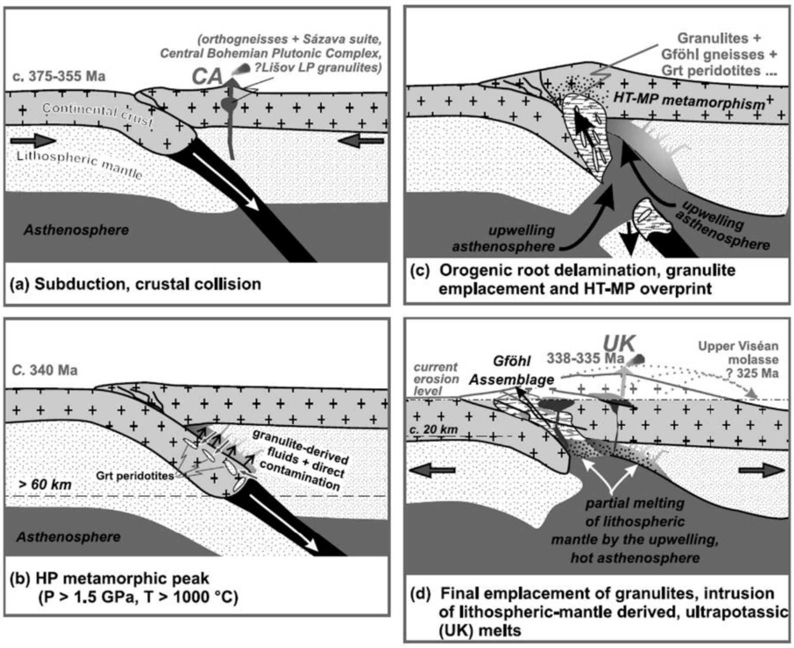


Fig. 6 Spider plot comparing trace element composition of durbachites with their potential parental source (adapted after Janoušek et al., 2020)

4.4. Geodynamic implications

The proposed genetic link between HP Moldanubian granulites, representing likely crustal contaminants of the lithospheric mantle (*Section 4.3.*), and hybrid ultrapotassic magmas shed a light on possible geodynamic settings of the emerging subduction channel between Moldanubian and Saxothuringian domains during the Variscan collision (e.g. Franke, 2000; Matte et al., 1990; Schulmann et al., 2014). Since geodynamic settings of the Variscan subduction zone still remain a matter of debate (Žák et al., 2014).

Taking into account that HP granulites represent a deeply buried Saxothuringian felsic metaigneous material (Janoušek et al., 2004), then short-lived Andean-type subduction (Fig. 7) (Late Devonian–Early Carboniferous) appears to be a most likely geodynamic model (Schulmann et al., 2009). During subduction of Saxothuringian domain underneath the eastern continental Teplá-Barrandian-Moldanubian block, a local lithospheric mantle could have been extensively affected by melts/fluids derived from the down-going slab material (Fig. 7). Such extensive mantle enrichment is likely reflected by formation of metasomatic hydrous mineral assemblages within heterogenous lithospheric mantle (e.g. Ackermann et al., 2016; Becker et al., 1999; Medaris et al., 2006; Svojtka et al., 2016) as well as presence of K-rich melt inclusions trapped in Saxonian eclogites from Granulitgebirge (Borghini et al., 2020), exhibiting trace element signatures typical of common durbachitic rocks (see Fig. 6) (Janoušek et al., 2020).



(a) Subduction, crustal collision

(c) Orogenic root delamination, granulite emplacement and HT-MP overprint

(b) HP metamorphic peak (P > 1.5 GPa, T > 1000 °C)

(d) Final emplacement of granulites, intrusion of lithospheric-mantle derived, ultrapotassic (UK) melts

Fig. 7 Geodynamic model of the Moldanubian Unit in Late Devonian–Carboniferous times (adapted after Janoušek and Holub, 2007)

Available geochronological data obtained from garnet pyroxenites and hybrid glimmerite veins revealed a relatively narrow time interval (~336–338 Ma; Ackerman et al., 2016; Becker et al., 1999) corresponding to the peak stage of the Variscan continental collision (~340 Ma; O'Brien and Rötzler, 2003). Considering timing of lithospheric mantle enrichment during the Variscan subduction, the emplacement ages obtained from ultrapotassic rocks of durbachites series (see *Section 3.1.* for details) (Kotková et al., 2010; Schaltegger et al., 2021), subordinate two-pyroxene syenitoids from the Tábor and Jihlava pluton (Janoušek et al., 2019; Janoušek and Gerdes, 2003) as well as vaugnerite and syenite porphyry from an ultrapotassic dyke swarm (Kubínová et al., 2017), clearly indicate a rapid exhumation of HP-HT assemblages of the Moldanubian domain. The rapid exhumation of deeply buried Variscan orogenic segment in Central Europe, accompanying the ultrapotassic magma emplacement (Leichmann et al., 2007), is further supported by: (1) $^{40}Ar/^{39}Ar$ dating of units overridden by the Gföhl nappes (Dallmeyer et al., 1992); (2) $^{40}Ar/^{39}Ar$ cooling ages of ultrapotassic members from the Saxothuringian Zone, e.g. the Meissen massif (Wenzel et al., 1997); (3) cooling rates given for mantle rocks (Medaris et al., 2005); (4) presence of granulite and durbachite clasts in the Culmian foreland basin (Čopjaková et al., 2005; Kotková et al., 2007).

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