# The causal link between HP–HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif

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JANOUŠEK, V. & HOLUB, F. V. 2007. The causal link between HP–HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif. *Proceedings of the Geologists' Association*, **118**, 75–86. In the Moldanubian Zone of the Bohemian Massif occur Variscan granulites and ultrapotassic magmatites (amphibole-bearing durbachitic suite and two-pyroxene syenitoids) in a close spatial and temporal relationship. The protolith to the most widespread felsic garnet–kyanite–mesoperthite granulites, which equilibrated at $P$>1.5 GPa and $T$ *c.* 1000 °C, was analogous to meta-igneous rocks occurring in the Saxothuringian Zone of the NW Bohemian Massif. For the most basic ultrapotassic rocks, the high contents of Cr and Ni as well as high mg# point to derivation from an olivine-rich source (i.e. a mantle peridotite). On the other hand, elevated concentrations of U, Th, light rare earth elements (LREE) and large ion lithophile elements (LILE), pronounced depletion in Ti, Nb and Ta as well as high $K_2O/Na_2O$ and Rb/Sr ratios apparently contradict the mantle origin. This dual geochemical character and crustal-like isotopic compositions require melting of anomalous lithospheric mantle sources, metasomatized and contaminated by mature crustal material. Both Moldanubian granulites and ultrapotassic rocks show mutually complementary depletions and enrichments in some trace elements (Cs, Rb, Th, U and Pb).

Late Devonian–Early Carboniferous Andean-type subduction is thought to have resulted in continental collision and HP metamorphism of upper crustal, largely meta-igneous lithologies. The subduction of the mature crustal material caused direct contamination and metasomatism in the overlying lithospheric mantle wedge. Shortly after the granulite-facies metamorphic peak (at *c.* 340 Ma) and the slab break off, these metasomatized and contaminated mantle domains were melted by advected heat from the invading asthenosphere, generating ultrapotassic intrusions, closely related to the granulite occurrences in space and time. This tectonic, petrological and geochemical model is outlined.

**Key words:** granulites, whole-rock geochemistry, continental collision, subduction, ultrapotassic magmatism, mantle metasomatism, Variscan belt, durbachites

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## 1. INTRODUCTION

The discovery of ultra-high pressure (UHP) metamorphic rocks with granitic and metasedimentary precursors has opened an exciting prospect that even light, and thus buoyant, upper crustal lithologies can be subducted into mantle depths (Chopin, 1984; 2003; Carswell & Compagnoni, 2003). This represents a major breakthrough in our current understanding of crustal recycling into the Earth's mantle. Not only is there the distinct possibility of direct contamination of the mantle by the subducted crust (Jahn *et al.*, 1999; Peccerillo, 1999), but also the (U)HP metamorphic reactions in the subducted crustal slab may give rise to light rare earth elements- (LREE-) and large ion lithophile elements- (LILE-) rich ultrapotassic fluids that can metasomatize the overlying lithospheric mantle wedge (Schreyer *et al.*, 1987; Massonne, 1992). Regardless of their origin, such anomalous mantle domains may subsequently yield ultrapotassic magmas with rather extreme trace-element and isotopic signatures (e.g. Becker *et al.*, 1999). In rare instances detailed studies of petrology, geochemistry and geochronology reveal the affiliation of the given potassic magmatic suite to a certain subduction episode or even to an actual high-grade crustal unit, responsible for the mantle contamination (e.g. Peccerillo, 1999).

The Bohemian Massif represents the largest preserved fragment of the Variscan crystalline basement in Europe (Fig. 1a). The unique diversity of rock types and complex tectonometamorphic development make its high-grade crystalline core (Moldanubian Zone) a

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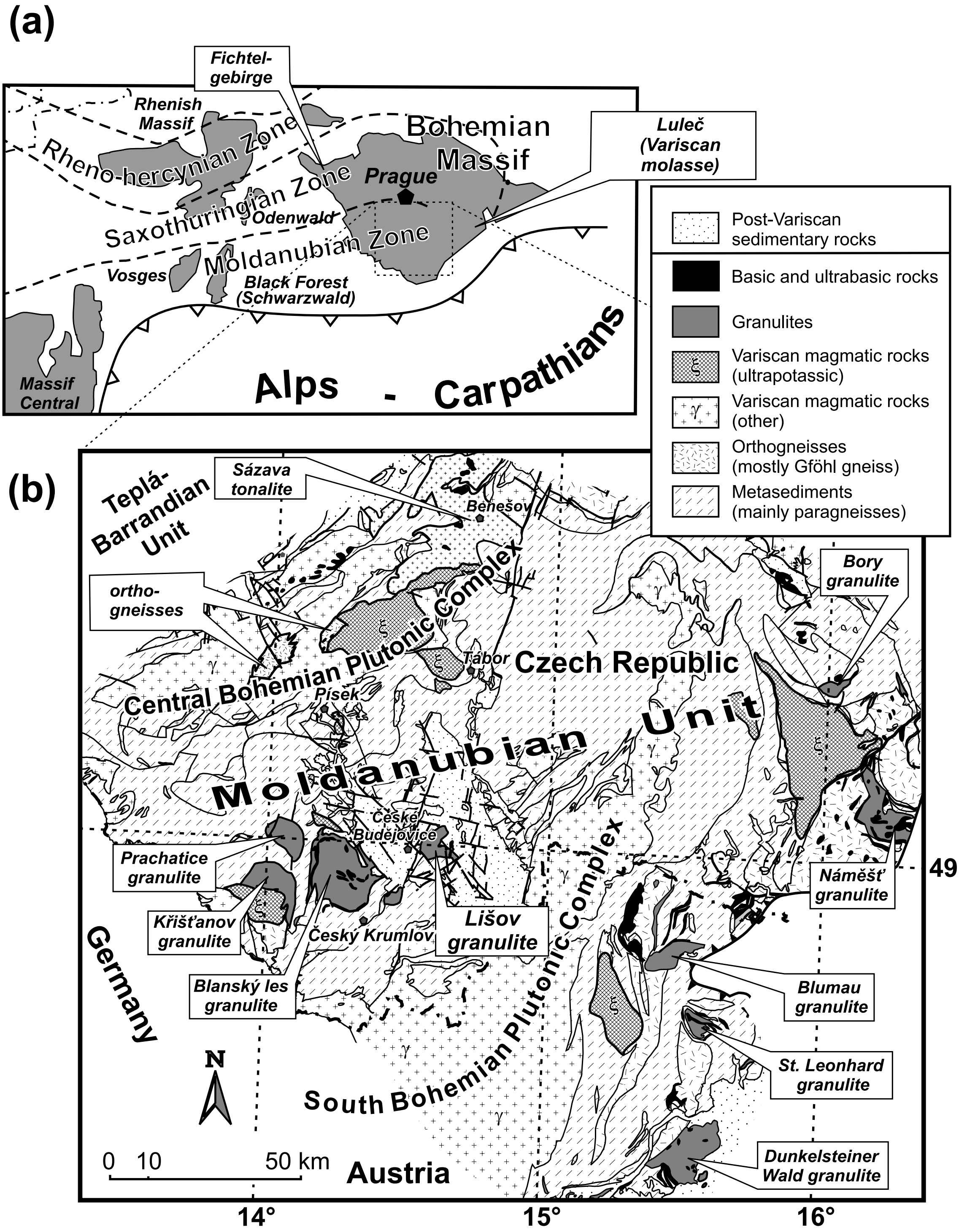


**Fig. 1.** (**a**) Location of the studied area in the context of the Central European Variscides. (**b**) Geological sketch of the Moldanubian Zone in southern Bohemia (modified from the Czech Geological Survey map 1:500 000).

region crucial to our understanding of the Variscan collisional belt. The abundance and diversity of HP–UHP rocks (see Massonne & O'Brien, 2003 for a review) and ultrapotassic magmatites (Holub, 1997; Wenzel *et al.*, 1997; Gerdes *et al.*, 2000) – apparent witnesses of a vigorous mantle–crust interaction – is exceptional.

This paper examines the causes of the conspicuous and unequivocal spatial and temporal link between the *c.* 340 Ma granulite-facies metamorphism and the slightly younger, voluminous ultrapotassic magmatism in the Moldanubian Unit of the Bohemian Massif.

## 2. GEOLOGICAL SETTING

In the southern part of the Bohemian Massif, shared by the Czech Republic and Austria, the Moldanubian Unit consists of several crustal segments with contrasting age and complex polyphase deformational histories, intruded by numerous, mainly post-tectonic granitic masses (Fiala *et al.*, 1995) (Fig. 1a). It has been subdivided into (from structural footwall to top) Monotonous (Ostrong), Variegated (Drosendorf) and Gföhl assemblages (Fiala *et al.*, 1995; Franke, 2000). The **Ostrong Assemblage** is formed by sillimanite–biotite ± cordierite paragneisses and migmatites, enclosing rare intercalations of quartzite and calc-silicate rock as well as small orthogneiss and eclogite bodies. The **Drosendorf Assemblage** is also dominated by paragneisses but the intercalations are more variable and abundant: quartzite, amphibolite, marble, orthogneiss and graphite schist. The contact of both assemblages represents an important tectonic boundary, marked by bodies of Proterozoic orthogneisses (Vrána, 1979). Highest-grade complexes, structurally on the top of the Moldanubian sequence, belong to the **Gföhl Assemblage**.

### The Gföhl Assemblage

*High-pressure granulites*

The lower parts of this unit include mainly anatectic orthogneisses (Gföhl gneiss). The higher are dominated by high-pressure granulites (Fig. 1b), associated with minor bodies of garnet and spinel peridotites, pyroxenites, dunites and eclogites (Fuchs & Matura, 1976; Fiala *et al.*, 1995; O'Brien & Rötzler, 2003).

Felsic meta-igneous granulites ($SiO_2$ >70%) characterized by a high-pressure assemblage of garnet, kyanite, quartz and hypersolvus feldspar (now mesoperthite) form the bulk (>75–80 vol%) of the main granulite massifs. Rutile, zircon, apatite, ilmenite, ± monazite are the common accessories (e.g. Fiala *et al.*, 1987a; O'Brien, 2006). By comparison, mafic-intermediate pyroxene-bearing and sedimentary-derived types are rare.

The Moldanubian granulites are mostly assumed to have attained at least $P$>1.5 GPa, $T$ *c.* 1000 °C (O'Brien & Rötzler, 2003), even though some authors advocate temperatures significantly lower (*c.* 800 °C, Štípská & Powell, 2005). In addition, it seems that some of the granulite types formed at low pressures, never experiencing HP conditions (e.g. the Lišov intermediate-mafic granulites: Janoušek *et al.*, 2006).

*Peridotites and eclogites*

According to Medaris *et al.* (2005), three types of peridotites occur in the Gföhl Assemblage. **Type I** are low P/T spinel and garnet peridotites devoid of garnet pyroxenite and eclogite layers. Their geochemistry corresponds to the oceanic lithosphere and underlying asthenosphere. **Type II** are rare Fe-rich peridotites that probably represent disrupted fragments of a layered mafic–ultramafic complex. More common are **Type III** garnet peridotites associated with garnet pyroxenite and eclogite layers. These layers are presumably cumulates (with trapped liquid) from melts passing through the lithosphere (Medaris *et al.*, 1995; Becker, 1996a). Type III peridotites have a rather variable chemistry, and their derivation is probably from a lithospheric mantle (Becker, 1996b; Medaris *et al.*, 2005).

*Ultrapotassic rocks*

Unusually large volumes of mafic to intermediate, strongly potassic to ultrapotassic (Foley *et al.*, 1987), igneous rocks are present in the Moldanubian Zone, often in a close spatial association with high-pressure granulites and products of their retrogression and anatexis (Fig. 1b). The most prominent group is the **durbachite suite** of syenitoids and granitoids, in which the most mafic, ultrapotassic members correspond to porphyritic amphibole-biotite melasyenite with K-feldspar phenocrysts, identical to the durbachites known from the Black Forest and the Vosges (e.g. Fluck, 1980). These intrusions seem to be arranged into two NNE–SSW-orientated belts (Fig. 2 and numerous plutonic masses too small to be shown). The western one in south Bohemia is conspicuous, spanning from the Čertovo břemeno pluton (*c.* 220 $km^2$) in the area of the Central Bohemian Plutonic Complex to the Knížecí Stolec intrusion (*c.* 90 $km^2$) in the Šumava Mts. On the other hand, the eastern belt in W Moravia and NE Austria is much less well developed, comprising the Třebíč Pluton (*c.* 500 $km^2$) with several small satellite bodies and the Rastenberg Pluton (Fig. 2). The latter is less potassic and more granodioritic than the other rocks of the durbachite suite.

In addition to the durbachitic rocks, less voluminous bodies of ultrapotassic **biotite–two-pyroxene melasyenites to melagranites** rich in K-feldspar but devoid of K-feldspar phenocrysts (Tábor and Jihlava intrusions) occur both in S Bohemia and W Moravia (Fig. 2).

### Geochronology in the Gföhl Assemblage

*Variscan granulite-facies metamorphism*

Arguably the best time constraints for the Variscan granulite-facies metamorphism in the Moldanubian

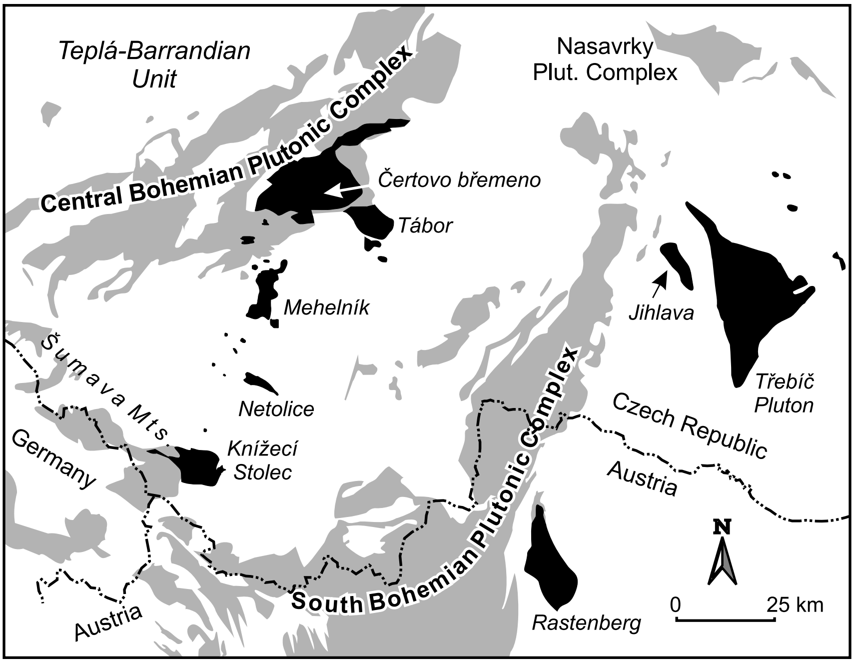


**Fig. 2.** Schematic map showing Variscan granitoid complexes (grey) and distribution of the highly potassic to ultrapotassic plutonic rocks (in black) within the Moldanubian Unit of the Bohemian Massif.

Unit are the U–Pb zircon age from rare K-rich granulites of the Blanský les Massif (Fig. 1b) of 338 ± 1 Ma (Aftalion *et al.*, 1989) and a mean 339.8 ± 2.6 Ma of SHRIMP ages for multifaceted zircon grains in ordinary South Bohemian granulites (Kröner *et al.*, 2000). Numerous other U–Pb zircon and monazite ages clustering around 340 Ma have also been interpreted as reflecting the peak metamorphic crystallization by most of the authors. Apart from those presented in Figure 3, this also concerns U–Pb zircon ages from granulite clasts in the Late Viséan conglomerates (molasse) from Central Moravia (Kotková *et al.*, 2003a).

In contrast, Roberts & Finger (1997) claimed that much of the zircon would have crystallized from partial melts, which would have persisted throughout much of the metamorphic history. Saturation with zircon would only occur on the retrogressive path, with the zircon growth therefore largely post-dating the HP metamorphic climax. Also Prince *et al.* (2000) assumed, based on a Sm–Nd age for garnet cores with prograde zoning (354 ± 6 Ma), that the HP–HT metamorphic peak could have been somewhat older. However, such scenarios would contradict the fact that many of the analysed zircons were enclosed in garnet or antiperthite (former ternary feldspar), the HP–HT metamorphic phases (Aftalion *et al.*, 1989; Kröner *et al.*, 2000). Therefore, the age of the granulite-facies metamorphism is unlikely to differ substantially from 340 Ma.

The high-grade metamorphism in the Gföhl gneiss in Moravia has been pin-pointed to 341 ± 4 Ma and 337 ± 3 Ma (van Breemen *et al.*, 1982). Similarly, the Gföhl gneiss in Austria has been dated at 340 ± 10 Ma and 339.9 ± 0.9 Ma (Friedl *et al.*, 1994; 1998) (Fig. 3).

### *Protolith of the granulites*

The spectrum of inherited ages in zircons from the Moldanubian granulites is characterized by Palaeozoic age maxima at *c.* 360 Ma, 400 Ma and 450–470 Ma (Kröner *et al.*, 2000; Friedl *et al.*, 2004 – see Janoušek *et al.*, 2004b, fig. 2 for a review).

### *Sm–Nd ages from peridotites and eclogites*

The available results of the Sm–Nd mineral isochron dating of the peridotites and associated HP mafic rocks from the Gföhl Assemblage have been summarized by Medaris *et al.* (2005). The garnet peridotites have generally yielded Viséan cooling ages averaging 339 ± 10 Ma and some of the garnet pyroxenite and eclogite layers gave a comparable mean Sm–Nd age of 336 ± 7 Ma. However, several garnet pyroxenite and eclogite samples were dated at *c.* 370 Ma to 377 Ma.

### *Emplacement of ultrapotassic rocks*

The tectonic emplacement of the Gföhl Assemblage to higher crustal levels had to have been finished soon after the peak of the HP metamorphism, because the

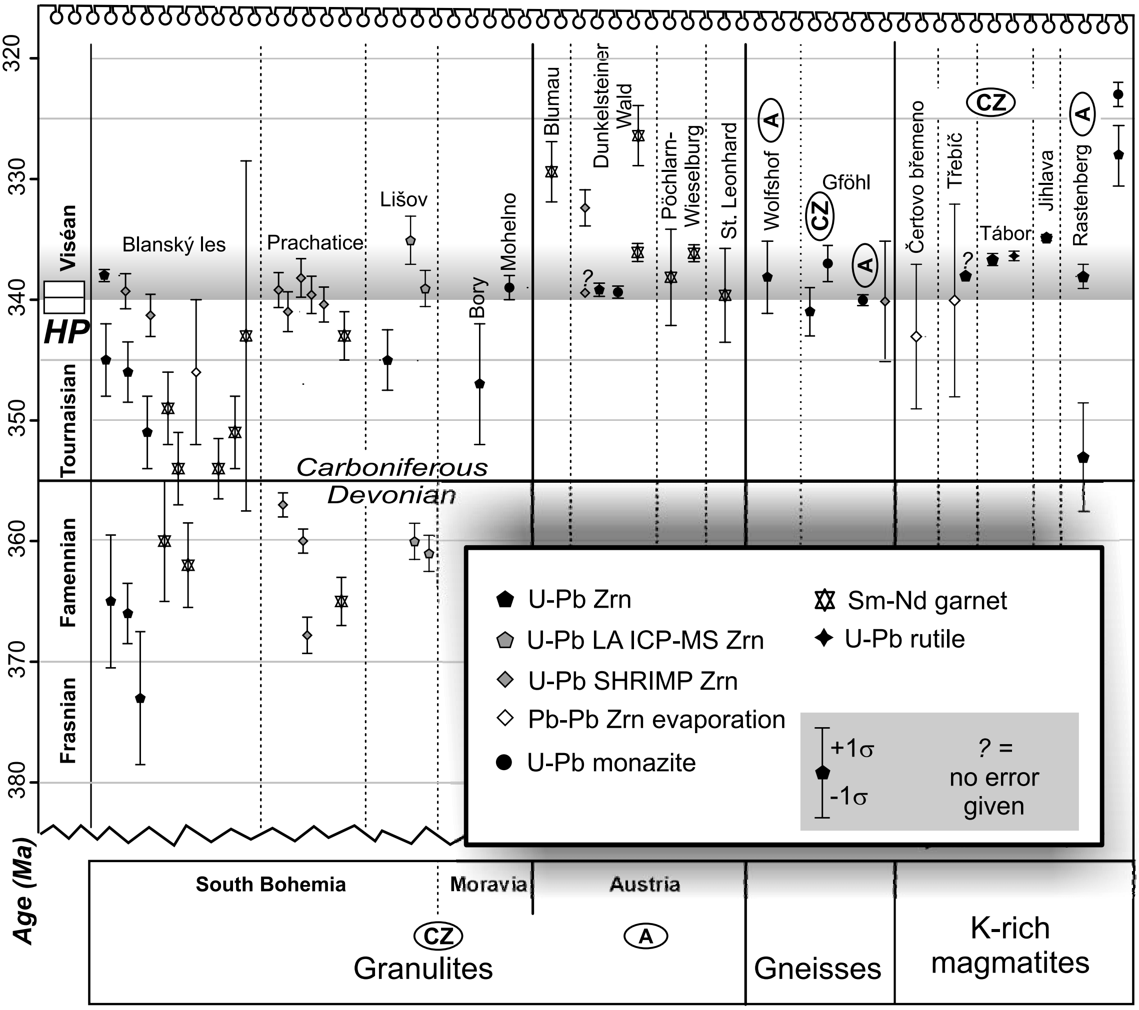


**Fig. 3.** Overview of the Variscan ages in the granulites, orthogneisses and ultrapotassic rocks within the Gföhl Assemblage (see also Fig. 1). **Granulite massifs in Czechia:** *Blanský les Massif* (Aftalion *et al.*, 1989; Wendt *et al.*, 1994; Kröner *et al.*, 2000; Prince *et al.*, 2000), *Prachatice* (Chen *et al.*, 1998; Kröner *et al.*, 2000), *Lišov* (van Breemen *et al.*, 1982; Janoušek *et al.*, 2006), *Bory* (Kröner *et al.*, 1988) and *Mohelno* (van Breemen *et al.*, 1982). **Granulite massifs in Austria:** *Blumau* (Becker, 1997), *Dunkelsteiner Wald* (Schenk & Todt, 1983; Becker, 1997; O'Brien & Kröner, unpublished data mentioned in Kröner *et al.*, 2000; Friedl *et al.*, 2004), *Pöchlarn-Wieselburg* (Becker, 1997), *St Leonhard* (Klötzli *et al.*, 1999). **Orthogneisses:** *Gföhl* (van Breemen *et al.*, 1982; Friedl *et al.*, 1998; 2004), *Wolfshof* (Friedl *et al.*, 1993). **Ultrapotassic rocks:** *Čertovo břemeno* (Holub *et al.*, 1997a), *Třebíč* (Holub *et al.*, 1997a; Kotková *et al.*, 2003a), *Tábor* (Janoušek & Gerdes, 2003), *Jihlava* (Kotková *et al.*, 2003a), *Rastenberg* (Friedl *et al.*, 1992; Klötzli & Parrish, 1996). HP=best age estimate for the granulite-facies metamorphism in southern Bohemia based on SHRIMP data of Kröner *et al.* (2000). Note that the error bars are ±1σ; Zrn=zircon.

syntectonic, K-rich Wolfshof gneiss (with a U–Pb zircon age of 338±6 Ma: Friedl *et al.*, 1993) cuts granulites of the St Leonhard Massif (Fig. 1b) and the Křišťanov granulite Massif is penetrated by the durbachitic Knížecí Stolec intrusion (Holub, 1997).

In Austria, Friedl *et al.* (1992) dated the Rastenberg intrusion by conventional U–Pb method on zircon (328±10 Ma) and monazite (323±2 Ma). Subsequently, Klötzli & Parrish (1996) distinguished two zircon populations of distinct ages, (1) 353±9 Ma (long prismatic crystals) and (2) 338±2 Ma (tabular crystals and overgrowths on the earlier zircon generation).

The ultrapotassic magmatic activity in the Czech Republic has been dated by studies of zircon and rutile to between *c.* 338 Ma and 335 Ma (Janoušek & Gerdes, 2003; Kotková *et al.*, 2003b) (Fig. 3). This age pattern is broadly consistent with the Pb–Pb dating of durbachite clasts in the molasse that has yielded two populations of zircons, cloudy prismatic (*c.* 355–368 Ma) and clear tabular, *c.* 343 Ma old (Kotková *et al.*, 2003a).

## 3. GEOCHEMISTRY

### Felsic Moldanubian granulites

One of the puzzling features of the Gföhl Assemblage is the profusion of large, mostly leucocratic, kyanite- and garnet-bearing HP–HT granulite bodies (Fig. 1b). Some workers concluded that these granulites are nearly isochemically metamorphosed felsic meta-igneous rocks, which have either not undergone HP melting (Fiala *et al.*, 1987a, b; Vellmer, 1992) or, if they have, the partial melt has been essentially retained in the rock volume (Roberts & Finger, 1997; Janoušek *et al.*, 2004b; Tropper *et al.*, 2005), except possibly for rare potassic granulites or gneisses (Becker *et al.*, 1999; Janoušek *et al.*, 2004b). However, others interpret the felsic granulites as restite-depleted, essentially segregated high-pressure magmas (Jakeš, 1997; Kotková & Harley, 1999).

Unlike many HP granulite terrains, the felsic Moldanubian granulites have nearly undepleted LILE contents (Fiala *et al.*, 1987a; Vellmer, 1992) and, except for U, Th, Cs (± in some samples Rb), their whole-rock geochemical signatures were probably preserved despite the HP–HT metamorphism (Janoušek *et al.*, 2004b). Most trace-element contents are comparable to average upper crust (Fig. 4a) and normal felsic igneous rocks (Fig. 4b). The trends of rapidly decreasing Sr, Ba, Eu, LREE and Zr with slightly rising Rb and little change in $SiO_2$ can be explained by fractional crystallization. These are characteristic of evolved granites crystallizing K-feldspar-dominated assemblages with minor zircon, monazite and apatite (Chappell & White, 1992) and seem to have been inherited from the igneous stage. The Zr concentrations are low, as are the LREE contents. Consequently, the zircon (Watson & Harrison, 1983) and monazite (Montel, 1993) saturation temperatures are not too high, resembling normal granitic rocks (*c.* 750° C) and opposing the HP–HT melting model (Janoušek *et al.*, 2004b).

As argued by Janoušek *et al.* (2004b), the composition of felsic Moldanubian granulites matches well with some felsic meta-igneous rocks in the Saxothuringian Zone of the Bohemian Massif, for example orthogneisses and metarhyolites from the Fichtelgebirge (Fig. 1a). The similarities include whole-rock geochemistry (excluding Cs, Th and U) (Fig. 4b), Sr–Nd isotopic compositions as well as protolith ages (Siebel *et al.*, 1997; Wiegand, 1997), falling within the spectrum of inherited ages observed in some of the granulites.

The Moldanubian granulites have high Rb/Cs ratios, demonstrating a conspicuous depletion in Cs, ascribed to the fractionation between K-feldspar and melt or fluid (Hart & Reid, 1991). The remarkable deficit in Cs, U and Th implies their removal in a fluid or a small-scale melt released in response to the high-grade metamorphism (see also Fiala *et al.*, 1987a; Vellmer, 1992; Janoušek *et al.*, 2004b).

### Ultrapotassic magmatites

Durbachites *s.s.* (i.e. the mafic members of the durbachite suite) are highly magnesian (MgO 7–9 wt%, mg# *c.* 70) rocks rich in Cr (450–600 ppm) as well as in U, Th and LILE ($K_2O$ 6–8 wt%, Ba 2000–2750 ppm, Rb 350–400 ppm, Cs 15–25 ppm) with high Rb/Sr, Th/Ta, LILE/HFSE (high field strength elements) as well as low K/Rb and Rb/Cs ratios (Fig. 4c) (Holub, 1997). Geochemically these ultrapotassic plutonic rocks closely resemble some minettes. Also the more acid members, reaching up to 63–66 wt% of silica, are unusually rich in MgO (>3 wt%) and Cr (>200 ppm), if compared to common granitic rock suites. The spatially associated biotite–two-pyroxene melasyenites to melagranites (Tábor and Jihlava intrusions: Fig. 2) are geochemically closely related to the durbachitic rocks. However, the Rastenberg pluton in Lower Austria displays much less extreme composition, more alike shoshonitic than ultrapotassic rocks.

The petrogenesis of (ultra-) potassic plutonic rocks in the European Variscan Belt has been a matter of a passionate debate. This is mainly due to the fact that even the basic, Mg- and K-rich members of these suites have a mixed geochemical character. While their high contents of Cr and Ni as well as high mg# point to derivation from an olivine-rich source (i.e. a mantle peridotite), the elevated concentrations of U, Th, LREE and LILE, a depletion in Ti, Nb and Ta as well as high $K_2O/Na_2O$ and Rb/Sr ratios apparently contradict the mantle origin. Also the Sr–Nd isotopic compositions resemble mature continental crust (Janoušek *et al.*, 1995; Gerdes *et al.*, 2000; Holub & Janoušek, 2003). This led several authors to invoke a partial melting of anomalous (LILE- and LREE-enriched) mantle domains (e.g. Holub, 1997; Wenzel *et al.*, 1997; Becker *et al.*, 1999; Gerdes *et al.*, 2000).

Examination of the spider plots for the Moldanubian felsic granulites (Fig. 4b) and ultrapotassic rocks (Fig. 4c) reveals that they are complementary in many elements. The most striking are the cases of Cs, Rb, Th, U and Pb, which are impoverished in felsic granulites but strongly enriched in the ultrapotassic magmatites. As shown below, this is probably not purely accidental.

## 4. GEOTECTONIC MODEL

### From subduction to continental collision

Any model attempting to explain the evolution of the Gföhl Assemblage needs to take into account the extremely rapid sequence of events from Late Devonian–Early Carboniferous oceanic crust subduction, through crustal thickening and high-pressure

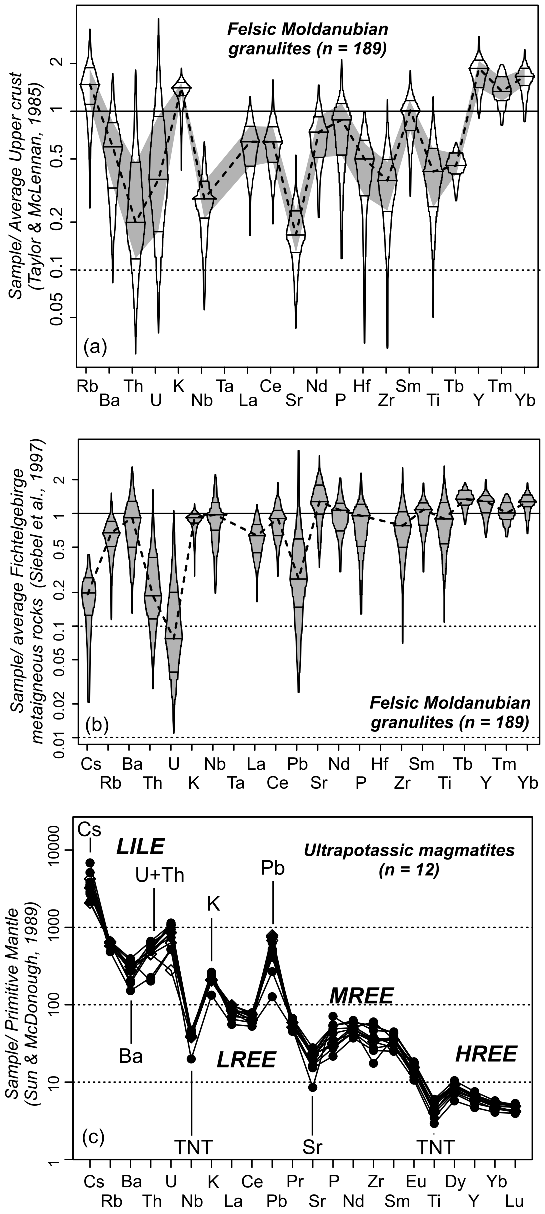


**Fig. 4.** (**a**) Average upper crust normalized (Taylor & McLennan, 1985) 'spider box and percentile plots' for felsic ($SiO_2$ > 70 wt%) Moldanubian granulites. In this new diagram, based on Esty & Banfield (2003), the distribution of each of the normalized trace-element contents is plotted as irregular polygons. Their width at any given height is proportional to the empirical cumulative distribution. As in box plots, the median, 25th and 75th percentiles are marked with horizontal line segments across the box. See Janoušek *et al.* (2004b) for data sources. (**b**) The same dataset normalized by an average of felsic ($SiO_2$ > 70 wt%) meta-igneous rocks from Fichtelgebirge (Siebel *et al.*, 1997 and Wiegand, 1997: Cs). (**c**) Primitive mantle-normalized (Sun & McDonough, 1989) spider plots for the ultrapotassic rocks from the Moldanubian Unit. Based mostly on unpublished data of the present authors and Janoušek *et al.* (2000).

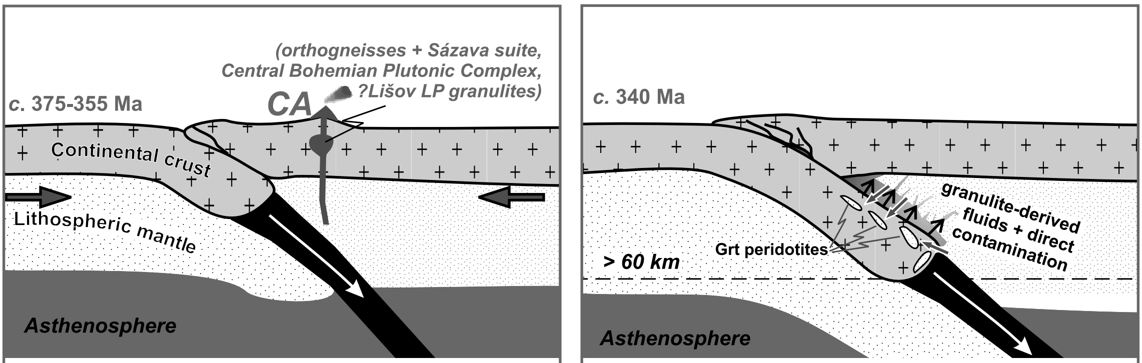
metamorphism (*c.* 340 Ma), tectonic emplacement of the Assemblage soon after and then the intrusion of the ultrapotassic rocks, which took place at relatively high crustal levels (*c.* 338–335 Ma). The authors' preferred scenario is summarized in Figure 5.

A rather short-lived (Late Devonian–Early Carboniferous) Andean-type subduction is supported by the occurrence of the *c.* 355 Ma old medium-K calc-alkaline Sázava suite (Holub *et al.*, 1997b; Janoušek *et al.*, 2004a; Žák *et al.*, 2005) and slightly older (373 ± 5 Ma and 365 ± 5 Ma, U–Pb zircon) orthogneisses in its roof (Košler *et al.*, 1993; Košler & Farrow, 1994). Moreover, the geochemically similar protolith to the LP mafic–intermediate granulites in the Lišov Massif (Fig. 1b) formed *c.* 360 Ma ago (Janoušek *et al.*, 2006).

The configuration of the Late Devonian–Early Carboniferous subduction in the Bohemian Massif is still a matter of debate. Although some workers invoke a bipolar model, also involving subduction of the Moldanubian beneath the Teplá–Barrandian Unit (Franke, 2000; Medaris *et al.*, 2005), most agree that southward subduction of the Saxothuringian crust has taken place. This is in line with the occurrence of the blueschist metamorphic relics known from the NW to N periphery of the Bohemian Massif (e.g. Patočka *et al.*, 1996). In addition, this agrees with the nature and timing of calc-alkaline magmatism in the Central Bohemian and Nasavrky plutonic complexes, which seem to have occurred at a distance appropriate for the presumed subducted slab to have reached the depths of *c.* 110 to 170 km needed for the magmatic arc to form (Tatsumi & Eggins, 1995).

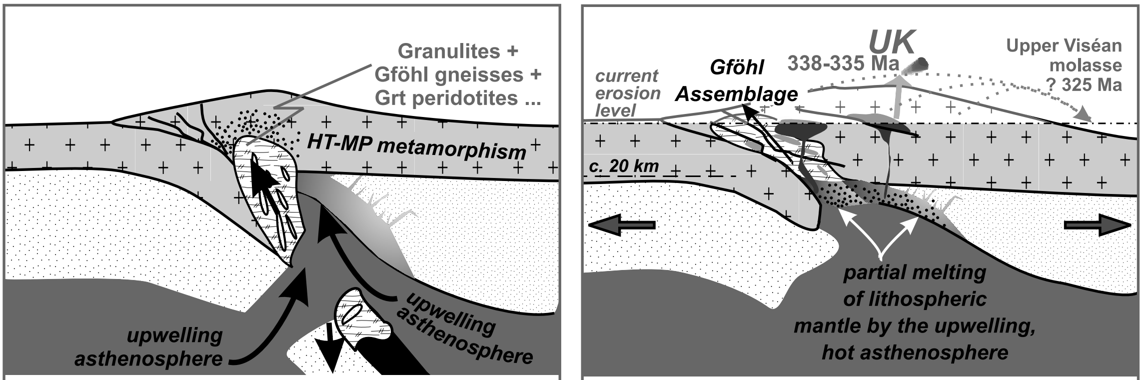
With the ocean closure and onset of collision, the heavy oceanic lithosphere could have dragged mainly felsic meta-igneous crust into the subduction zone. Even though there is no direct evidence so far for burial deeper than *c.* 45 km of the ordinary Moldanubian granulites, some metasedimentary rocks are reported, which have apparently been to depths of 100–120 km (Becker & Altherr, 1992; Kotková *et al.*, 1997; Vrána & Frýda, 2003).

*En route* to deeper levels, the descending continental slab could have trapped enclaves of the lithospheric mantle from the hanging wall (peridotites of Type III: Medaris *et al.*, 2005). Contamination of the overlying lithospheric mantle by the crustal material seems unavoidable (Jahn *et al.*, 1999; Peccerillo, 1999). Upon heating under HP conditions the subducted crust could have melted, or at least released ultrapotassic fluids that metasomatized the mantle wedge. Direct evidence for the presence of small-scale HP melts is provided by rare highly potassic Zr, Hf, Th and U-rich granulites in the Blanský les Massif (Fig. 1b) (Vrána, 1989). In addition, glimmerite veins known from Lower Austria were interpreted as having crystallized from an ultrapotassic fluid released by HP–HT breakdown of F-rich phlogopite in the granulite massifs (Becker *et al.*, 1999).



**(a) Subduction, crustal collision**

**(b) HP metamorphic peak**



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

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

**Fig. 5.** Tentative geotectonic scenario for development of the Moldanubian Unit in Late Devonian–Carboniferous times. See text for discussion. Based on Brueckner & Medaris (2000), Chemenda *et al.* (2000), O'Brien (2000) and Medaris *et al.* (2005). CA, the calc-alkaline magmatism of the listed bodies; in (d), the ultrapotassic melts are the durbachites and related rocks.

## Tectonic emplacement and uplift of the Gföhl Assemblage

The high-grade Viséan metamorphism in the Moldanubian Unit was probably short-lived, as demonstrated by diffusion modelling in garnet from granulites and garnet peridotites (Medaris *et al.*, 2005). Ultimately, the subduction of buoyant felsic crust could not be sustained and mechanical failure occurred (Chemenda *et al.*, 2000). Even though alternative scenarios exist (Henk *et al.*, 2000), a slab break-off model is favoured here (Davies & von Blanckenburg, 1995; Chemenda *et al.*, 2000; Atherton & Ghani, 2002) – one that would trigger overturn of a hot crustal root and rapid exhumation of the Gföhl Assemblage, including granulites, accompanied by mantle peridotites, eclogites and pyroxenites (Brueckner & Medaris, 2000; O'Brien, 2000; Medaris *et al.*, 2005).

Upwelling of the hot asthenosphere following the break off presumably caused partial melting of overlying metasomatized and contaminated lithospheric mantle domains that could have produced ultrapotassic magmas. The direct contamination of the mantle wedge by the subduction-related material is also compatible with the occurrence of *c.* 360 Ma old zircon grains of a distinct morphology in the Rastenberg Massif (Klötzli & Parrish, 1996) and in durbachitic clasts within the Variscan molasse (Kotková *et al.*, 2003a).

The asthenospheric mantle upwelling, together with the emplacement of the hot granulite bodies, could have resulted in advection of surplus heat to the crust. In the geotectonic environment transitional between transpression and extension (Žák *et al.*, 2005), these thermally weakened crustal domains would have been favoured for the final emplacement of the ultrapotassic intrusions. Thus, the remarkable spatial and temporal link between the granulitic rocks and ultrapotassic intrusions could have been two-fold, genetic and structurally predetermined.

At least initially, the exhumation rate of the Gföhl Assemblage was fairly high (several mm $a^{-1}$), as the granulite pebbles already occur in the Upper Viséan (*c.* 325 Ma) molasse in Moravia (Vrána & Novák, 2000; Kotková *et al.*, 2003a; Čopjaková *et al.*, 2005). Rapid uplift and cooling following the HP metamorphic peak at *c.* 340 Ma are also compatible with the many Sm–Nd garnet whole-rock ages (327–340 Ma) from several granulite massifs in Lower Austria (Fig. 3). Furthermore zircons from late cordierite-bearing, low-pressure, probably decompression melt pockets enclosed in the granulites of the Prachatice Massif (Fig. 1b) also provide identical ages of *c.* 340 Ma (Kröner *et al.*, 2000).

## 5. Conclusions

- Variscan HP granulites and ultrapotassic magmatites occur in a close spatial and temporal relationship in the Moldanubian Unit of the Bohemian Massif.
- Ultrapotassic magmatic rocks (durbachitic suite and two-pyroxene syenitoids) were derived from anomalous mantle sources contaminated by mature crustal material.
- Felsic granulites and ultrapotassic intrusions show mutually complementary depletions and enrichments in some trace elements (Cs, Rb, Th, U and Pb).
- The protolith to the most widespread felsic garnet–kyanite granulites was analogous to meta-igneous rocks occurring in the Saxothuringian Zone of the NW Bohemian Massif.
- Late Devonian–Early Carboniferous Andean-type subduction of the Saxothuringian crust most likely resulted in continental collision and HP metamorphism of upper crustal, largely meta-igneous, lithologies. The subduction of the crustal material caused direct contamination and metasomatism in the overlying lithospheric mantle wedge.
- Only shortly after the granulite-facies metamorphic peak (*c.* 340 Ma) and a slab break off, these anomalous mantle domains could have been melted by advected heat from the invading asthenosphere, which was responsible for generating the 338–335 Ma ultrapotassic intrusions, closely related to the granulite occurrences in space and time.

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