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The Saxo-Danubian Granite Belt: magmatic response to post-collisional delamination of mantle lithosphere below the south-western sector of the Bohemian Massif (Variscan orogen)

FRITZ FINGER[1], AXEL GERDES[2], MILOŠ RENÉ[3] and GUDRUN RIEGLER[1]

[1]Fachbereich Materialforschung und Physik, Abteilung Mineralogie, Universität Salzburg, Hellbrunnerstrasse 34, A-5020 Salzburg, Austria; Friedrich.Finger@sbg.ac.at
[2]Institut für Mineralogie, Universität Frankfurt, Senckenberganlage 28, D-60054 Frankfurt a. M., Germany; gerdes@em.uni-frankfurt.de
[3]Academy of Sciences, Institute of Rock Structure and Mechanics, V Holešovičkách 41, CZ-18209 Prague 8, Czech Republic; rene@irsm.cas.cz

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Abstract: On the basis of the synchronicity of geochronological data and the similarity of granite types, it is proposed that the mid-Carboniferous Fichtelgebirge/Erzgebirge Batholith in the Saxothuringian Zone of the central European Variscan Fold Belt and the South Bohemian Batholith in the Moldanubian Zone (including the intervening Oberpfalz and Bavarian Forest granite areas) belong to one coherent and cogenetic, ca. 400 km long plutonic megastructure. Unlike older (syn-collisional) plutonic structures in the Bohemian Massif, this Saxo-Danubian Granite Belt (nov. nom.) has developed discordant to the Devonian/Early Carboniferous collision-related tectonic architecture of the Bohemian Massif. It is argued that the Saxo-Danubian Granite Belt formed in response to a post-collisional detachment of lithospheric mantle below the south-western sector of the Bohemian Massif.

Key words: Variscan orogen, Saxo-Danubian Granite Belt, Bohemian Massif, delamination, granites.

Introduction

Granites are important indicators of thermal and tectonic processes occurring in the lower crust and the upper mantle (Pitcher 1982; Harris et al. 1984; Pearce et al. 1984). By their typology they provide some information on the nature of the source rocks (Chappell & White 1974), although we must be aware of magma modifications that occur, for example, through mixing or assimilation. Moreover, granites can be very precisely dated by geochronological methods. Granitic plutons are thus, in a way, windows through which the deep infrastructure of orogens and their evolution can be viewed.

This short communication covers current research activities at the University of Salzburg, with the aim of exploring the geological information potential stored in the Bohemian Massif granites. As a first step we report here on a newly defined belt of coeval post-collisional granites (Saxo-Danubian Granite Belt — SDGB), that extends over ca. 400 kilometers across the south-western Bohemian Massif. Based on the observed plutonic phenomena, and the given geological background, we argue that the formation of this granite belt was most likely triggered by a process of delamination of mantle lithosphere.

Geological background

The Variscan orogen is a collage of microplates (terranes) that were assembled, between the Devonian and the Carboniferous, along the southern margin of the Old Red Continent (Franke 2000; Friedl et al. 2000; Winchester et al. 2002). The central European section of the Variscan orogen, with the Bohemian Massif as its main exposure (Fig. 1), includes several independent collision zones that represent fold belts active at different times. Northern areas (Rhenohercynian Zone, Northern Phyllite Zone, Mid German Crystalline High) record the final closure of the Rheiic Ocean and the Carboniferous collision of Variscan Europe with the Old Red Continent. In the central part of the Bohemian Massif (Teplá Barrandian block) a ca. 380 Ma old phase of deformation and regional metamorphism is documented, and commonly interpreted in terms of an early Variscan collision between a Saxothuringian and a Bohemian terrane (Zulauf 1997). In the south-eastern part of the Bohemian Massif, a major phase of collisional crustal thickening and high-grade regional metamorphism is recorded at ~340 Ma, and related to the forceful docking of a Moldanubian and a Moravian terrane (Finger & Steyrer 1995; Schulmann et al. 2005). After this "Moravo-Moldanubian" orogenic phase (i.e. at ca. 330 Ma), the Bohemian Massif was more or less established in its present day tectonic configuration, except for some lateral movements along faults (Edel et al. 2003).

During the Carboniferous, numerous granitic plutons intruded all over the Bohemian Massif. These are commonly treated as a single coherent group of "Variscan granites" (Franke 2000), although they are of different ages and types. Elaborating the concept of Finger et al. (1997), it is suggested that they form at least five independent magmatic systems with individual tectonothermal backgrounds (Fig. 1):

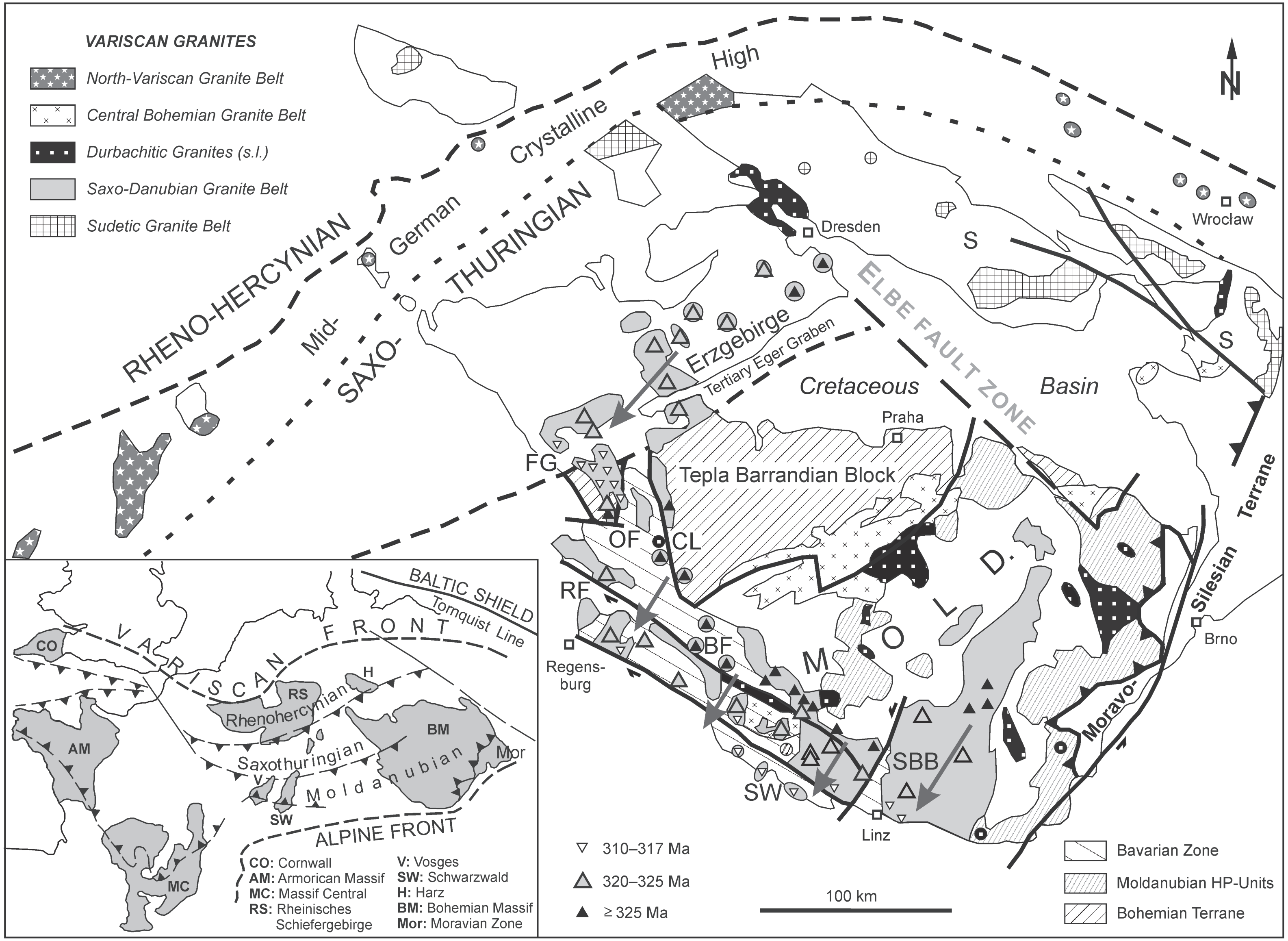

Fig. 1. Sketch map of the Bohemian Massif, mainly after Franke (2000), showing the distribution of Variscan granites and the attempt to group these into plutonic belts of different age and origin. Triangles indicate from which positions in the SDGB reliable intrusion ages have been reported (only modern low-error zircon and monazite ages have been considered). Data sources are given in Table 1. Arrows indicate the proposed growth direction of the SDGB. **BF** — Bavarian Forest, **CL** — Český Les, **FG** — Fichtelgebirge, **OF** — Oberpfalz Forest, **RF** — Regensburg Forest, **SBB** — South Bohemian Batholith, **S** — Sudetes, **SW** — Sauwald. Inset illustrates the position of the Bohemian Massif within the central European Variscides.

1) A "*North Variscan Granite Belt*" with ca. 330 to 350 Ma I-type granite and granodiorite plutons (e.g. Anthes & Reischmann 2001; Zeh et al. 2005; Dörr et al. 2006) extends over almost 500 km along the Mid German Crystalline High eastward into Poland. This belt is commonly interpreted as a magmatic arc that developed above a southward dipping Rhenohercynian subduction zone (Franke 2000; Oncken et al. 2000).

2) A similarly dated (360 to 335 Ma) granite belt, dominated by I-type tonalites and granodiorites, crosses the center of the Bohemian Massif approximately in a NE-SW direction and is termed here the "*Central Bohemian Granite Belt*". It can be followed over ca. 300 km from the Polish Sudetes (Kudowa-Olesnice and Kłodzko-Złoty Stock massifs — Mazur et al. 2007) to the Bavarian Forest (migmatized I-type granitoids near Waldkirchen — Propach 2005), with the Central Bohemian Batholith near Prague (Janoušek et al. 2000) as the major and best studied exposure. The Central Bohemian Batholith includes several generations of granitoids with variable deformation histories (Scheuvens & Zulauf 2000; Bues et al. 2002; Žák et al. 2005). The oldest, Devonian, I-type intrusions, as well as small bodies of I-type orthogneisses in the metamorphic roof of the batholith, dated to ca. 370 Ma (Košler et al. 1993), have been interpreted by Janoušek & Holub (2007) as part of a pre-collisional magmatic arc, that formed in connection with the south-eastward subduction of a Saxothuringian ocean. As opposed to this, Zulauf (1997) and Dörr & Zulauf (2008) argue that all the granitoids (including the mid-Devonian orthogneisses) are post-collisional with reference to the Saxothuringian-Bohemian terrane collision, and intruded in several pulses, when the thickened crust collapsed. Magma generation above a Moravo-Moldanubian subduction system (eastern continuation of the Rheiic suture) has been considered by Finger et al. (2007).

3) 335 to 340 Ma, high-K to shoshonitic (mela)granites, granodiorites and syenites/monzonites, commonly grouped as "*durbachite plutons* (s.l.)", are arranged along two parallel, NNE-SSW trending lines through the Southern Bohemian Massif (Klomínský & Dudek 1978). These "durbachite" intrusions contain components from an enriched mantle source (Janoušek & Holub 2007), and are typically linked to the steeply exhumed HP-HT rocks of the Gföhl Unit (Finger et al. 2007). The magmas obviously used the tectonic uplift channels of the high-pressure rocks for their own ascent. The Mutěnin syenite of the Český Les area (Dörr & Zulauf 2008), the Meissen granitoids near Dresden (Wenzel et al. 1997), and the Niemcza granitoids in the Sudetes (Mazur et al. 2007) correlate to these Moldanubian "durbachites" in age and typology (Fig. 1). All of them intruded on major faults.

4) The south-western sector of the Bohemian Massif (the Bavarian Zone of Finger et al. 2007; Fig. 1) was invaded by numerous, mainly crustally derived, granitic magmas between ca. 330 and 310 Ma, associated with penetrative LP-HT regional metamorphism and anatexis. A granitic complex of batholithic dimensions developed at the eastern end of the Bavarian Zone (South Bohemian Batholith). It will be argued later that these Moldanubian granites form a coherent plutonic belt with the Saxothuringian granites in the western Erzgebirge and Fichtelgebirge (*Saxo-Danubian Granite Belt*).

5) Finally, a belt of comparatively younger granitoids (~315 to 300 Ma) including I-type granodiorites, I/S- and S-type granites (Mazur et al. 2007) occurs in the Sudetic region (*Sudetic Granite Belt* — Fig. 1). This belt extends westward into Germany.

The granite belts 1 to 3 and 5 are not further considered in this paper.

Geochronological data for the Saxo-Danubian Granite Belt

The state of geochronological research in the Erzgebirge is summarized in Förster & Romer (2009). These authors state that most of the granitic plutons of this area were intruded between 325 and 318 Ma (see also Table 1). This is corroborated by recent zircon dating work of Kovaříková et al. (2007), which indicates an intrusion age of 322 to 323 Ma for the large Karlovy Vary/Loket pluton in the Czech part of the Erzgebirge. In the eastern part of the Erzgebirge, some granite bodies show a slightly higher intrusion age of ca. 327 Ma (Table 1, Fig. 1).

Siebel et al. (2003) published age data from the Fichtelgebirge and the Oberpfalz Forest (Table 1). They distinguished between older granites (~325 Ma) and younger granites (~310 to 315 Ma). These data imply that the granitic activity began at the same time as in the Erzgebirge (ca. 325 Ma), but includes another younger magmatic pulse (310 to 315 Ma) not present in the Erzgebirge. The Bor and Babylon granites, which intruded at the south-western termination of the Teplá Barrandian block (Český Les — Fig. 1), are commonly considered to be equivalents of the older granites of the Oberpfalz Forest (Siebel et al. 1999; Siebel et al. 2003). Dörr & Zulauf (2008) presented a monazite age of 331 ± 1 Ma for the Bor granite, which is slightly higher than the ages of the older granites of the Oberpfalz Forest.

A large number of low-error zircon and monazite ages have become available for the Bavarian Zone and the South Bohemian Batholith during recent years (Table 1). The relatively oldest granites (325 to 328 Ma) are present on the northern rim of the Bavarian Zone, and at the northern and eastern rims of the South Bohemian Batholith (Fig. 1). However, the main granitic activity took place between 325 and 320 Ma. Younger granite plutons, dated to 314 to 317 Ma, occur near Linz (Mauthausen and Altenberg granites) and in the Sauwald (Schärding and Peuerbach granite). A minor late pulse of magmatism is also recorded in the South Bohemian Batholith, ~300 Ma (Freistadt granodiorite — Gerdes et al. 2003). Some rhyolites in the Erzgebirge have the same Stephanian age (Förster et al. 2006).

Granite types

Several studies in the Erzgebirge (Förster & Romer 2009, and references therein), the Fichtelgebirge and Oberpfalz Forest (Siebel et al. 2003), the Bavarian Forest (Siebel et al. 2008) and the South Bohemian Batholith (Finger & Clemens 1995; Gerdes et al. 2000) have pointed out that the majority of the

Table 1: Age determinations referred to in this paper.

Erzgebirge	
Karlovy Vary Pluton	322±2 Ma, Zrn, evap., K07
Karlovy Vary Pluton	323±3 Ma, Zrn, evap., K07
Niederbobritzsch Granite	320±6 Ma, Zrn, evap., T97
Schlemma Granite	322±6 Ma, Mnz, ID-T, F98
Ehrenfriedersdorf Granite	324±4 Ma, Urnt, ID-T, R07
Ehrenfriedersdorf Granite	321±2 Ma, Urnt, ID-T, R07
Eibenstock Granite	321±4 Ma, Mnz, ID-T, F98
Pobershau Granite	321±3 Ma, Mnz, ID-T, F98
Markersbach Granite	327±4 Ma, Zrn, L-ICP, H08
Fichtelgebirge, Oberpfalz Forest, Český Les	
Redwitzite Marktredwitz	322±5 Ma, Zrn, evap., S03
Zainhammer Granite	321±1 Ma, Zrn, evap., S03
Marktredwitz G1 Granite	324±4 Ma, Zrn, evap., S03
Leuchtenberg Granite	323±1 Ma, Zrn, evap., S03
Leuchtenberg Granite	324±3 Ma, Zrn, evap., S03
Leuchtenberg Granite	328±1 Ma, Zrn, evap., S03
Liebenstein Granite	315±1 Ma, Zrn, evap., S03
Falkenberg Granite	315±4 Ma, Zrn, evap., S03
Falkenberg Granite	315±2 Ma, Zrn, evap., S03
Flossenbürg Granite	310±3 Ma, Zrn, evap., S03
Steinwald Granite	312±2 Ma, Zrn, evap., S03
Friedenfels Granite	312±4 Ma, Zrn, evap., S03
Mitterteich Granite	310±6 Ma, Zrn, evap., S03
Bor granite	331±1 Ma, Mnz, ID-T, D08
Regensburg Forest	
Stallwang Granodiorite	324±2 Ma, Zrn, evap., S06
Kristallgranit I	315±4 Ma, Mnz, ID-T, P00
Trasching Granite	321±3 Ma, Mnz, ID-T, P00
Two-Mica Granite	323±4 Ma, Mnz, ID-T, S06
Granite Porphyry	323±2 Ma, Zrn, evap., S06
Bavarian Forest	
Gurlarn Granite	311±2 Ma, Mnz, ID-T, P00
Plöckenstein Granite	325±2 Ma, Zrn, evap., B07
Dreisessel Granite	327±2 Ma, Zrn, evap., B07
Steinberg Ganite	328±2 Ma, Zrn, evap., B07
Lalling Granite	322±6 Ma, Zrn, evap., S08
Metten Granit	321±4 Ma, Zrn, evap., S08
Metten Granite	324±5 Ma, Zrn, evap., S08
Sattelpeilnstein Granite	322±3 Ma, Zrn, evap., S08
Miltach Granite	322±4 Ma, Zrn, evap., S08
Arnbruck Granite	325±2 Ma, Zrn, evap., S08
Lusen Granite	325±4 Ma, Zrn, evap., S08
Finsterau Granite I	324±2 Ma, Zrn, evap., S08
Finsterau Granite II	326±2 Ma, Zrn, evap., S08
Haidmühle Granite	321±2 Ma, Zrn, evap., S08
Haidel Granite	323±3 Ma, Zrn, evap., S08
Saldenburg Granite	315±3 Ma, Zrn, evap., C04
Tittling Granite	323±1 Ma, Zrn, evap., C04
Hautzenberg Granite	320±3 Ma, Zrn, ID-T, K08
Patersdorf Granodiorite	325±3 Ma, Zrn, evap., K08
South Bohemian Batholith	
Gebharts Diorite	328±1 Ma, Zrn, ID-T, G03
Eisgarn Granite Aalfang	328±1 Ma, Mnz, ID-T, G03
Sulzberg Granite	326±1 Ma, Mnz, ID-T, G03
Migmagranite Uttendorf	323±1 Ma, Zrn, ID-T, G03
Haibach Granite	316±1 Ma, Zrn, ID-T, G03
Altenberg Granite	315±1 Ma, Mnz, ID-T, G03
Mauthausen Granite	316±1 Ma, Mnz, ID-T, G03
Peuerbach Tonalite	314±4 Ma, Mnz, ID-T, F96
Weinsberg Granite	
Kirchberg	328±1 Ma, Mnz, ID-T, G03
Langschlag	323±4 Ma, Mnz, ID-T, F97
Oberneukirchen	323±1 Ma, Mnz, ID-T, G03
Pregarten	323±1 Ma, Zrn, ID-T, G03
Sarleinsbach	322±4 Ma, Zrn, Shrimp, F03
Sarleinsbach (mafic)	323±1 Ma, Zrn, ID-T, F03

Data sources: Breiter et al. 2007 (B07); Chen & Siebel 2004 (C04); Dörr & Zulauf 2008 (D08); Friedl 1997 (F97); Förster 1998 (F98); Finger et al. 2003 (F03); Gerdes et al. 2003 (G03); Hofmann et al. 2008 (H08); Kovaříková et al. 2007 (K07); Klein et al. 2008 (K08); Propach et al. 2000 (P00); Romer et al. 2007 (R07); Siebel et al. 2003 (S03); Siebel et al. 2006 (S06); Siebel et al. 2008 (S08); Tichomirova 1997 (T97). **Zrn** — Zircon; **Mnz** — Monazite; **Urnt** — Uraninite; **ID-T** — U-Pb dating by isotope dilution-thermal ion mass spectrometry; **L-ICP** — U-Pb dating by Laser ICP mass spectrometry; **evap.** — zircon evaporation age.

granites from these areas are derived through fluid-absent partial melting of lower crustal sources. This mechanism can create large volumes of granite melts, if the source region is of sufficiently high temperature (Clemens & Vielzeuf 1987).

Early, coarse-grained and K-feldspar-phyric granites are particularly characteristic for the entire SDGB (e.g. Fichtelgebirge/Erzgebirge: G1-granite Weißenstadt-Marktleuthen, Karlovy Vary Granite; Oberpfalz Forest and Český Les: Bor, Babylon and Leuchtenberg Granite; Regensburg Forest: Kristallgranit I; South Bohemian Batholith: Schlieren Granite, Weinsberg Granite, Eisgarn Granite). These include two-mica S-type granites as well as a few I-type rocks with hornblende, but most are biotite granites with transitional I/S characteristics. These early, coarse-grained and K-feldspar-phyric granites make up more than half of the granite inventory of the SDGB.

In the Erzgebirge, tin-bearing granites play an important role. Their presence may reflect a local availability of Sn-enriched crustal source rocks (Förster & Romer 2009). Other differences between the Erzgebirge granite terrain and the South Bohemian Batholith appear to be a matter of a different exposure level. Many granitic intrusions in the Erzgebirge are felsic high-level plutons with a high degree of fractionation, while the exposure level of the South Bohemian Batholith is generally deeper and involves considerable amounts of cumulate material (Finger & Clemens 1995).

The younger (310 to 315 Ma) granites of the SDGB are predominantly, but not exclusively S-type rocks. In the Fichtelgebirge and the Oberpfalz Forest they are mostly represented by fine- to medium-grained, muscovite-bearing, S-type granites (Siebel et al. 2003). The younger granites of the South Bohemian Batholith (Frasl & Finger 1991) include both, I-type (Mauthausen granite, Freistadt granodiorite) and S-type suites (Altenberg, Schärding and Peuerbach granite).

An important observation is that, throughout the SDGB, small volumes of intermediate to mafic, K_2O-rich plutonic rocks are associated with the older coarse-grained granites. Such rocks are locally termed “Redwitzite” in the Fichtelgebirge and Erzgebirge (Siebel et al. 2003; Kovaříková et al. 2007) and “Migmagranite” or “group 1 diorites” in the South Bohemian Batholith (Frasl & Finger 1991). They are generally considered to contain melt components from the enriched mantle (Krenn 2000; Siebel et al. 2003; Sapp 2005; Kovaříková et al. 2007).

Plutonic evolution

The plutonic evolution of the SDGB started by the end of the Visean, with the formation and ascent of large volumes of high-T, lower crustal magmas, that crystallized mostly as coarse-grained K-feldspar-phyric granites. These coarse “early granites” intruded more or less simultaneously over the whole length of the SDGB. Based on the available geochronological information (Table 1) it can be estimated that two thirds of the SDGB were created within a fairy short time span of no more than 8 million years, between 328 and 320 Ma. This is a strong argument for the existance of a powerful and rapidly introduced heat anomaly below this area. A rapid temperature increase in the source region can also be inferred from the observation that magmas of different melting behaviour (I- and S-type granites; diorites) intruded contemporaneously. Since other parts of the Bohemian Massif were magmatically quiet at that time, it would appear that this strong late Visean/early Namurian heat anomaly had developed only below the south-western sector of the massif.

The geochronological data give interesting information on the growth history of the SDGB. It would appear that the SDGB came into being with a fairly narrow chain of ca. 325 to 328 Ma plutons on the north (see black triangles in Fig. 1), and then grew asymmetrically in a roughly south-westerly direction (see arrows in Fig. 1). Granites of the second generation (310 to 317 Ma) occur preferentially along the south-western periphery of the SDGB.

In search of a tectonic scenario

The extraordinary abundance of late- to post-tectonic granites is a distinct, though still little understood and much discussed feature of the Variscides (e.g. Zwart & Dornsiepen 1980; Henk et al. 2000). Various tectonic scenarios have been invoked to explain it. These include anomalously strong crustal thickening plus radiogenic heating (Gerdes et al. 2000), a late Variscan Andean-type subduction setting (Finger & Steyrer 1990), and post-collisional delamination of mantle lithosphere (Henk et al. 2000). Worldwide, delamination is now rated as a newly recognized mechanism capable of explaining the formation of large igneous provinces (Anderson 2005). Although discussed largely on a theoretical basis, and without precise space and time constraints, the idea of delamination is increasing popular for the Variscan fold belt (Zulauf 1997; Schott & Schmeling 1998; Arnold et al. 2001; Massonne 2005; Medaris et al. 2005), because it can also explain the widely observed formation and fast exhumation of HP-HT rocks during the Carboniferous, and their immediate re-sedimentation in foreland basins, as well as the widespread LP-HT metamorphic overprint of the Variscan basement.

Regarding the Bohemian Massif it was a shortcoming of many previous studies that the Variscan granites were treated as a single genetic entity. We suggest here a subdivision into different (at least five) plutonic belts of slightly but significantly different age, each having its individual petrogenesis and tectonic environment (see section “geological” background and Fig. 1). Here we focus on the south-western sector of the massif and the Saxo-Danubian Granite Belt. The widely synchronous production of high-T lower crustal melts over a ca. 400 km distance is the more remarkable, as the western, the central and the eastern sector of the SDGB are located in different plate tectonic terranes (Saxothuringian, Bohemian and Moldanubian). From the existing data (Franke 2000, and references therein) it is clear that the collisional thickening histories of these terranes were not uniform. For example, crustal thickening in the south-eastern Bohemian Massif was effected by the Moravo-Moldanubian folding phase (340 Ma) whereas in the Bohemian terrane it occurred much earlier (~380 Ma). These facts are clearly at variance with models that designate collisional crustal thickening and radiogenic heat production as the main reasons for granite magma formation in the south-western Bohemian Massif. Since late Variscan subduction models have turned out to be unlikely for the Bohemian Massif (Franke 2000), we hold the view that a process of post-collisional delamination of lithospheric mantle (Bird 1979; Houseman et al. 1981; Henk et al. 2000) can probably best explain the plutonic phenomena observed in the SDGB.

Exploring a delamination model

The basic idea of a delamination model is that the bottom layer of an orogenically thickened continental lithosphere is denser than the asthenosphere and can detach and sink into the asthenospheric mantle. Based on numerical modelling, Bird (1979) stated that detachment will be facilitated if a tectonic event first creates an elongated conduit that connects the hot asthenosphere with the base of the crust. Such a process would create a thermal anomaly with near-linear geometry at the base of the crust, along which voluminous crustal melting can be expected. The observation that the SDGB was fairly narrow during its early evolution (see above), is compatible with this scenario. It is feasible that the oldest intrusions (black triangles in Fig. 1) trace the “line” where the lithospheric mantle was initially ruptured.

Once the lithospheric mantle layer is disrupted and penetrated by a channel of hot asthenosphere, the process of delamination can proceed further (Bird 1979). In the case of the south-western Bohemian Massif, one may conclude, from the south-westward migration of the plutonic activity, that mantle lithosphere has peeled away in this direction (Gerdes et al. 2006).

There are several ways in which instabilities and failures in the mantle lithosphere below the Bohemian Massif could have developed. For example, instabilities could occur in response to the end of early Variscan subduction (slab break-off or slab roll-back), in connection with the gravitational collapse of the overthickened Teplá-Barrandian block (Dörr & Zulauf 2008), or due to large-scale plate rotations documented ca. 330 Ma (Edel et al. 2003; Finger et al. 2007). The shape of the SDGB in map view, bent around the core of the Bohemian Massif (Fig. 1), is a puzzling feature in this context, the tectonic significance of which remains unknown.

An interesting but as yet unresolved question is, to what extent mantle material below the SDGB might have melted. Theoretically, delamination creates favourable conditions for the partial melting of both the rising asthenospheric and the decending lithospheric mantle (Kay & Kay 1993; Anderson 2005). In case that some lithospheric mantle material remained at the crust-mantle boundary (cf. the thermal boundary layer delamination model of Houseman et al. 1981), this mantle material can also be expected to undergo partial melting, due to the proximity of the hot asthenosphere.

The scarcity of mafic igneous rocks in the SDGB has often been taken as an argument against the occurrence of mantle melting (Gerdes et al. 1996), and also against a delamination model. However, one should be careful with this conclusion, as it cannot be ruled out that large volumes of mantle-derived melts were ponding at the crust/mantle boundary and, for whatever reason, did not rise into the crust. Vielzeuf et al. (1990) have argued that lower crustal melting will normally extract heat from coexisting mantle magmas and cause their freezing at depth. The possibility also exists that considerable amounts of mafic mantle melts were mixed with, and assimilated by, the lower crustal melts. One could speculate that the abundant I/S transitional granites of the SDGB originated from such mixing processes. On the basis of the regular occurrence of small bodies of mafic rocks in all parts of the SDGB, we suggest that mantle melting was a significant process and not just a local feature. The rise of hot mantle melts could have considerably increased the rate of heat transport from the mantle delamination zone into the crust. Even if the mantle lithosphere were only partially removed (Houseman et al. 1981; Zulauf 1997; Dörr & Zulauf 2008), so that the asthenosphere did not make direct contact with the crust, mafic melts derived from the bottom part of the remaining lithosphere could have effectively transported heat to the base of the crust (magmatic underplating).

Finally, it remains to be mentioned that a delamination process will normally cause a domal uplift of the overlying crust (Kay & Kay 1993). Unfortunately, the Variscan P-T evolution of the south-western Bohemian Massif is still poorly understood. However, at least for parts of the Bavarian Zone, a rapid syn-anatectic uplift can be indirectly inferred from rapid cooling documented by monazite, titanite and mica geochronometry (Kalt et al. 2000).

Conclusions

There are many reasons to propose that the formation of the SDGB occurred in connection with a large-scale delamination process of lithospheric mantle beneath the south-western Bohemian Massif. As shown by numerical models, this process is capable of quickly (within a few million years) increasing the temperatures at the Moho to around 1000 °C (Arnold et al. 2001). Voluminous fluid-absent lower crustal melting (Clemens & Vielzeuf 1987) would inevitably be the consequence, if the lower crustal rocks were fertile.

Whether the prominent metamorphic high-T events that occurred somewhat earlier in the Variscan evolution of the Bohemian Massif at ca. 340 Ma (HP-HT metamorphism in the Moldanubian Gföhl Unit and in parts of the Saxothuringian) and at ca. 335 Ma (LP-HT metamorphism in the Ostrong Unit) are also connected with delamination processes (Massonne 2005; Medaris et al. 2005), is open for debate. The fact that plutonism did not reach batholithic dimensions in the time span between 330 and 340 Ma (note that most granitoids of the Central Bohemian Batholith formed prior to 340 Ma), may argue against large scale heat introduction from the mantle. It needs to be explored if other mechanisms like slab break-off (Janoušek & Holub 2007; Finger et al. 2007), radiogenic heating following crustal stacking (Gerdes et al. 2000), or heat advection through rising HP-HT granulites (O'Brien 2000), may provide equally good tectonothermal solutions in these cases.

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References

Anderson D.L. 2005: Large igneous provinces, delamination, and fertile mantle. *Elements* 1, 271–275.

Anthes G. & Reischmann T. 2001: Timing of granitoid magmatism in the eastern mid-German crystalline rise. *J. Geodynamics* 31, 119–143.

Arnold J., Jacoby W.R., Schmeling H. & Schott B. 2001: Continental collision and the dynamic and thermal evolution of the Variscan orogenic crustal root — numerical models. *J. Geodynamics* 31, 273–291.

Bird P. 1979: Continental delamination and the Colorado Plateau. *J. Geophys. Res.* 84, 7561–7571.

Breiter K., Koller F., Scharbert S., Siebel W., Škoda R. & Frank W. 2007: Two-mica Granites of the Plechý (Plöckenstein) Pluton in the Triple-Point Area (Trojmezí, Dreiländereck) of Austria, the Czech Republic, and Germany. *Jb. Geol. Bundesanst.* 147, 527–544.

Bues C., Dörr W., Fiala J., Vejnar Z. & Zulauf G. 2002: Emplacement depths and radiometric ages of Paleozoic plutons of the Neukirchen-Kdyne massif: differential uplift and exhumation of Cadomian basement due to Carboniferous orogenic collapse (Bohemian Massif). *Tectonophysics* 352, 225–243.

Chappell B.W. & White A.J.R. 1974: Two contrasting granite types. *Pacif. Geol.* 8, 173–174.

Chen F.K. & Siebel W. 2004: Zircon and titanite geochronology of the Furstenstein granite massif, Bavarian Forest, NW Bohemian Massif: Pulses of the late Variscan magmatic activity. *European J. Mineralogy* 16, 777–788.

Clemens J.D. & Vielzeuf D. 1987: Constraints on melting and magma production in the crust. *Earth Planet. Sci. Lett.* 86, 287–306.

Dörr W., Żelazniewicz A., Bylina P., Schastok J., Franke W., Haack

U. & Kulicki C. 2006: Tournasian age of granitoids from the Odra fault zone (southwestern Poland): equivalent of the Mid-German Crystalline High? *Int. J. Earth Sci.* 95, 341–349.

Dörr W. & Zulauf G. 2008: Elevator tectonics and orogenic collapse of a Tibetan-style plateau in the European Variscides: The role of the Bohemian shear zone. *Int. J. Earth Sci.* (in print).

Edel J.B., Schulmann K. & Holub F.V. 2003: Anticlockwise rotations of the Eastern Variscides accommodated by dextral lithospheric wrenching: paleomagnetic and structural evidence. *J. Geol. Soc.* 160, 209–218.

Finger F. & Steyrer H.P. 1990: I-type granitoids as indicators of a late Paleozoic convergent ocean/continent margin along the southern flank of the Central European Variscan Orogen. *Geology* 18, 1207–1210.

Finger F. & Clemens J. 1995: Migmatization and “secondary” granitic magmas: effects of emplacement and crystallization of “primary” granitoids in Southern Bohemian Massif, Austria. *Contr. Mineral. Petrology* 120, 311–326.

Finger F. & Steyrer H.P. 1995: A tectonic model for the eastern Variscides: indications from a chemical study of amphibolites in the south-eastern Bohemian Massif. *Geol. Carpathica* 46, 137–150.

Finger F., Roberts M.P., Haunschmid B., Schermaier A. & Steyrer H.P. 1997: Variscan granitoids of central Europe. Their typology, potential sources and tectonothermal relations. *Miner. Petrology* 61, 67–96.

Finger F., Doblmayr P., Friedl G., Gerdes A., Krenn E. & von Quadt A. 2003: Petrology of the Weinsberg granite in the South Bohemian Batholith: New data from the mafic end members. *J. Czech Geol. Soc.* 48, 46–47.

Finger F., Gerdes A., Janoušek V., René M. & Riegler G. 2007: Resolving the Variscan evolution of the Moldanubian sector of the Bohemian Massif: the significance of the Bavarian and the Moravo–Moldanubian tectonometamorphic phases. *J. Geosci.* 52, 9–28.

Franke W. 2000: The mid-European segment of the Variscides; tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: Franke W., Haak V., Oncken O. & Tanner D. (Eds.): Orogenic Processes: Quantification and modelling in the Variscan Belt. *Geol. Soc. London, Spec. Publ.* 179, 35–61.

Frasl G. & Finger F. 1991: Geologisch-petrographische Exkursion in den österreichischen Teil des Südböhmischen Batholiths. *Eur. J. Mineral.* 3, 23–40.

Friedl G. 1997: U/Pb Datierungen an Zirkonen und Monaziten aus Gesteinen vom österreichischen Anteil der Böhmischen Masse. *Unpublished PhD. Thesis, Universität Salzburg*, 1–242.

Friedl G., Finger F., McNaughton N. & Fletcher I.R. 2000: Deducing the ancestry of terranes: SHRIMP evidence for South America-derived Gondwana fragments in Central Europe. *Geology* 28, 1035–1038.

Förster H.J. 1998: Die variszischen Granite des Erzgebirges und ihre akzessorischen Minerale. *Habilitation Thesis, Technical University Bergakademie Freiberg*.

Förster H.J., Gottesmann B., Tischendorf G., Siebel W., Rhede D., Seltmann R. & Wasternack J. 2006: Permo-Carboniferous subvolcanic rhyolitic dikes in the western Erzgebirge/Vogtland, Germany: a record of source heterogeneity of post-collisional felsic magmatism. *Neu. Jb. Mineral. Abh.* 183, 123–147.

Förster H.J. & Romer R.L. 2009: Carboniferous magmatism. In: Linnemann U., Kroner U. & Romer R.L. (Eds.): From the Cadomian Active Margin to the Variscan Orogen: The pre-Mesozoic Geology of Saxo-Thuringia (NW Bohemian Massif). *E. Schweizerbart Science Publisher*, Stuttgart (in print).

Gerdes A., Wörner G. & Finger F. 1996: Mantelquellen in variszischen Granitoiden? *Terra Nostra* 96, 2, 75–78.

Gerdes A., Wörner G. & Henk A. 2000: Post-collisional granite generation and HT-HP metamorphism by radiogenic heating: the Variscan South Bohemian Batholith. *J. Geol. Soc. London* 157, 577–587.

Gerdes A., Friedl G., Parrish R.R. & Finger F. 2003: High-resolution geochronology of Variscan granite emplacement — the South Bohemian Batholith. *J. Czech Geol. Soc.* 48, 53–54.

Gerdes A., Finger F. & Parrish R.R. 2006: Southwestward progression of a late-orogenic heat front in the Moldanubian zone of the Bohemian Massif and formation of the Austro-Bavarian anatexite belt. *Geophys. Res. Abstr.* 8, 10698.

Harris N.B.W., Pearce J.A. & Tindle A.G. 1984: Geochemical characteristics of collision zone magmatism. In: Ries A.C. & Coward M.P. (Eds.): Collision tectonics. *Geol. Soc. London, Spec. Publ.* 19, 67–71.

Henk A., von Blanckenburg F., Finger F., Schaltegger U. & Zulauf G. 2000: Syn-convergent high-temperature metamorphism and magmatism in the Variscides: a discussion of potential heat sources. In: Franke W., Haak V., Oncken O. & Tanner D. (Eds.): Orogenic Processes: Quantification and modelling in the Variscan Belt. *Geol. Soc. London, Spec. Publ.* 179, 387–399.

Hofmann M., Linnemann U., Gerdes A. & Ullrich B. 2008: Closure of the Rheic Ocean and the final pulse of the Variscan Orogeny in the Bohemian Massif — Timing of large-scale strike-slip processes and basement exhumation by LA-ICP-MS U-Pb zircon dating from the Elbe Zone (Saxo-Thuringian Zone, Germany). *Abstracts Book, 20th International Senckenberg Conference*, 53.

Houseman G.A., McKenzie D.P. & Molnar P. 1981: Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. *J. Geophys. Res.* 86, 6115–6132.

Janoušek V., Bowes D.R., Rogers G., Farrow C.M. & Jelínek E. 2000: Modelling diverse processes in the petrogenesis of a composite batholith: the Central Bohemian Pluton, Central European Hercynides. *J. Petrology* 41, 511–543.

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. *Proceed. Geol. Assoc.* 118, 1–12.

Kalt A., Corfu F. & Wijbrams J.R. 2000: Time calibration of a P-T path from a Variscan high-temperature low-pressure metamorphic complex (Bayerische Wald, Germany), and the detection of inherited monazite. *Contr. Mineral. Petrology* 138, 143–163.

Kay R.W. & Kay S.M. 1993: Delamination and delamination magmatism. *Tectonophysics* 219, 177–189.

Klein T., Kiehm S., Siebel W., Shang C.K., Rohrmüller J., Dörr W. & Zulauf G. 2008: Age and emplacement of late-Variscan granites of the western Bohemian Massif with main focus on the Hauzenberg granitoids (European Variscides, Germany). *Lithos* 102, 478–507.

Klomínský J. & Dudek A. 1978: The plutonic geology of the Bohemian Massif and its problems. *Sbor. Geol. Věd, Geol.* 31, 47–69.

Kosler J., Aftalion M. & Bowes D.R. 1993: Mid-late Devonian plutonic activity in the Bohemian Massif: U-Pb zircon isotopic evidence from the Stare Sedlo and Mirotice gneiss complex, Czech Republic. *Neu. Jb. Mineral. Abh.* 9, 417–431.

Kovaříková P., Siebel W., Jelínek E., Štemprok M., Kachlík V., Holub F. & Blecha V. 2007: Petrology, geochemistry and zircon age for redwitzite at Abertamy, NW Bohemian Massif (Czech Republic): tracing the mantle component in late Variscan intrusions. *Chem. Erde* 67, 151–174.

Krenn E. 2000: Zur Petrologie und Geologie der sogenannten Migmagranite des Südböhmischen Batholiths. *Master Thesis, University of Salzburg*, 1–93.

Massonne H.J. 2005: Involvement of crustal material in delamination of the lithosphere after continent-continent collision. *Int. Geol. Rev.* 47, 782–804.

Mazur S., Aleksandrowski P., Turniak K. & Awdankiewicz M. 2007: Geology, tectonic evolution and Late Palaeozoic magmatism of Sudetes — an overview. *Granitoids in Poland, AM Monograph* 1, 59–87.

Medaris G., Jr., Wang H., Jelínek E., Mihaljevič M. & Jakeš P. 2005: Characteristics and origins of diverse Variscan peridotites in the Gföhl Nappe, Bohemian Massif, Czech Republic. *Lithos* 82, 1–23.

O'Brien P.J. 2000: The fundamental Variscan problem: high-temperature metamorphism at different depths and high-pressure metamorphism at different temperatures. In: Franke W., Haak V., Oncken O. & Tanner D. (Eds.): Orogenic processes: Quantification and modelling in the Variscan Belt. *Geol. Soc. London, Spec. Publ.* 179, 369–386.

Oncken O., Plesch A., Weber J., Ricken W. & Schrader W. 2000: Passive margin detachment during arc-continent collision (Central European Variscides). In: Franke W., Haak V., Oncken O. & Tanner D. (Eds.): Orogenic processes: Quantification and modelling in the Variscan Belt. *Geol. Soc. London, Spec. Publ.* 179, 199–216.

Pearce J.A., Harris N.B.W. & Tindle A.G. 1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrology* 25, 956–983.

Pitcher W. 1982: Granite type and tectonic environment. In: Hsü K. (Ed.): Mountain building processes. *Academic Press*, London, 1–263.

Propach G. 2005: Reste eines Vulkanbogens in den Diatexiten südlich vom Pfahl. In: Abstract band 3. Bayr. Wald-Kolloquium, Würzburg 2004, 11–12.

Propach G., Baumann A., Schultz-Schmalschläger M. & Grauert B. 2000: Zircon and monazite U-Pb ages of Variscan granitoid rocks and gneisses in the Moldanubian Zone of eastern Bavaria, Germany. *Neu. Jb. Geol. Paläont.* 6, 345–377.

Romer R.L., Thomas R., Stein H.J. & Rhede D. 2007: Dating multiply overprinted Sn-mineralized granites-examples from the Erzgebirge, Germany. *Mineral. Deposita* 42, 337–359.

Sapp M. 2005: Geologisch-petrographische Untersuchungen in der "Zone von St. Veit" (oberösterreichisches Moldanubikum). *Master Thesis, University of Salzburg*, 1–110.

Scheuvens D. & Zulauf G. 2000: Exhumation, strain localization, and emplacement of granitoids along the western part of the Central Bohemian shear zone (central European Variscides, Czech Republic). *Int. J. Earth Sci.* 89, 617–630.

Schott B. & Schmeling H. 1998: Delamination and detachment of a lithospheric root. *Tectonophysics* 296, 225–247.

Schulmann K., Kröner A., Hegner E., Wendt I., Konopásek J., Lexa O. & Štípská P. 2005: Chronological constraints on the pre-orogenic history, burial and exhumation of deep-seated rocks along the eastern margin of the Variscan Orogen, Bohemian Massif, Czech Republic. *Amer. J. Sci.* 305, 407–448.

Siebel W., Breiter K., Wendt I., Höhndorf A., Henjes-Kunst F. & René M. 1999: Petrogenesis of contrasting granitoid plutons in western Bohemia (Czech Republic). *Miner. Petrology* 65, 207–235.

Siebel W., Chen F. & Satir M. 2003: Late-Variscan magmatism revisited: new implications from Pb-evaporation zircon ages on the emplacement of redwitzites and granites in NE Bavaria. *Int. J. Earth Sci.* 92, 36–53.

Siebel W., Hann H.P., Shang C.K., Rohrmüller J. & Chen F.K. 2006: Coeval late-Variscan emplacement of granitic rocks: an example from the Regensburg Forest, NE Bavaria. *Neu. Jb. Mineral., Abh.* 183, 13–26.

Siebel W., Shang C., Reitter E., Rohrmüller J. & Breiter K. 2008: Two distinctive granite suites in the SW Bohemian Massif and their record of emplacement: constraints from geochemistry and zircon $^{207}Pb/^{206}Pb$ chronology. *J. Petrology* 49, 1853-1872.

Tichomirova M. 1997: $^{207}Pb/^{206}Pb$-Einzelzirkondatierungen zur Bestimmung des Intrusionsalters des Niederbobritzschers Granites. *Terra Nostra* 97, 8, 183–184.

Vielzeuf D., Clemens J.D., Pin C. & Moinet E. 1990: Granites, granulites and crustal differentiation. In: Vielzeuf D. & Vidal Ph. (Eds.): Granulites and crustal evolution. *Kluwer Academic Publishers*, Dordrecht, 59–85.

Wenzel T., Mertz D.F., Oberhänsli R., Becher T. & Renne P.R. 1997: Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen massif (northern Bohemian massif) and implications for related occurrences from the mid-European Hercynian. *Geol. Rdsch.* 86, 556–570.

Winchester J.A. & PACE TMR Network Team 2002: Palaeozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. *Tectonophysics* 360, 5–21.

Zeh A., Gerdes A., Will T.M. & Millar I.I. 2005: Provenance and magmatic-metamorphic evolution of a Variscan island-arc complex: constraints from U-Pb dating, petrology, and geospeedometry of the Kyffhaeuser crystalline complex, central Saxony. *J. Petrology* 46, 1393–1420.

Zulauf G. 1997: Von der Anchizone bis zur Eklogitfazies: Angekippte Krustenprofile als Folge der cadomischen und variscischen Orogenese im Teplá-Barrandium (Böhmische Masse). *Geotekt. Forsch.* 89, 1–302.

Zwart H.J. & Dornsiepen U.F. 1980: The Variscan and pre-Variscan tectonic evolution of Central and Western Europe: a tentantive model. *Bur. Rech. Geol. Min. Mem.* 168, 226–232.

Žák J., Holub F.V. & Verner K. 2005: Tectonic evolution of a continental magmatic arc from transpression in the upper crust to exhumation of mid-crustal orogenic root recorded by episodically emplaced plutons: the Central Bohemian Plutonic Complex (Bohemian Massif). *Int. J. Earth Sci.* 94, 385–400.