Original paper

Resolving the Variscan evolution of the Moldanubian sector of the Bohemian Massif: the significance of the Bavarian and the Moravo–Moldanubian tectonometamorphic phases

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The Variscan evolution of the Moldanubian sector in the Bohemian Massif consists of at least two distinct tectonometamorphic phases: the Moravo–Moldanubian Phase (345–330 Ma) and the Bavarian Phase (330–315 Ma). The **Moravo–Moldanubian Phase** involved the overthrusting of the Moldanubian over the Moravian Zone, a process which may have followed the subduction of an intervening oceanic domain (a part of the Rheiic Ocean) beneath a Moldanubian (Armorican) active continental margin. The Moravo–Moldanubian Phase also involved the exhumation of the HP–HT rocks of the Gföhl Unit into the Moldanubian middle crust, represented by the Monotonous and Variegated series. The tectonic emplacement of the HP–HT rocks was accompanied by intrusions of distinct magnesio-potassic granitoid melts (the 335–338 Ma old Durbachite plutons), which contain components from a strongly enriched lithospheric mantle source. Two parallel belts of HP–HT rocks associated with Durbachite intrusions can be distinguished, a western one at the Teplá–Barrandian and an eastern one close to the Moravian boundary. The combined occurrence of Durbachite plutons and HP rocks would be difficult to understand in terms of the previous tectonic models, in which the Gföhl Unit was viewed as a large flat nappe on top of the Moldanubian Zone.

In recent studies it has been suggested that Saxothuringian crust was subducted eastwards under the Moldanubian Zone during the Early Carboniferous. We discuss here an alternative tectonic scenario, in which the south-eastern Bohemian Massif is tentatively interpreted as an accretionary wedge successively underplated by material of a Gföhl and a Moravian terrane. It is suggested that parts of the HP–HT rocks of the Gföhl Terrane were exhumed along the Moravian–Moldanubian plate contact, while earlier subducted portions were steeply uplifted close to the Teplá–Barrandian block, which may have functioned as a rigid backstop of the accretionary wedge. Final stages of the Moravo–Moldanubian Phase were characterised by a strong LP–HT regional metamorphism at *c.* 335–340 Ma, which may be an expression of increased mantle heat flow after slab break-off, and is seen mainly in the Ostrong Unit along the central axis of the Moravo–Moldanubian Fold Belt.

As indicated from palaeomagnetic data, the (already established) Moravo–Moldanubian Fold Belt has then (around 330 Ma) rotated by about 90° clockwise, while the palaeogeographic position of Baltica remained widely unchanged. This implies that the Moravian Zone lost its former contact to Baltica and that a major Late Variscan fragmentation of the Old Red continental margin must have occurred in the Moravo–Silesian area at that time. Also within the Bohemian Massif, this rotation event may have caused a significant Late Variscan (fault bounded) disturbance of previous terrane relationships.

The **Bavarian Phase** (330–315 Ma) represents a fully independent stage of the Variscan orogeny in the Bohemian Massif. It is defined by a significant reheating (LP–HT regional metamorphism combined with voluminous granitic plutonism) and a tectonic remobilisation of crust in the south-western sector of the Bohemian Massif. These processes were most likely triggered by a Late Variscan delamination of mantle lithosphere. The Bavarian Phase overprinted western parts of the (widely cooled) Moravo–Moldanubian Fold Belt and transformed these rocks into various anatexites (metablastites, metatexites and diatexites). The HP–HT rocks of the Gföhl Unit, the Durbachite plutons, the LP–HT rocks of the Ostrong Unit and other typical constituents of the Moravo–Moldanubian Fold Belt can be followed from the Czech Republic southwards into eastern Bavaria and western Upper Austria (Mühl and Sauwald Zone), but are difficult to identify there due to the strong anatectic overprint. The LP–HT regions further west (Oberpfalz and western Bavarian Forest, Šumava Mts.?) may include former continuations of Teplá–Barrandian or Saxothuringian crust.

Keywords: Bavarian Phase, Moravo–Moldanubian Phase, tectonic model, delamination of mantle lithosphere, monazite dating, Bohemian Massif, Variscan Fold Belt
Received: 22 January 2007; accepted 24 May 2007; handling editor: M. Novák

1. Introduction

The past years have brought increasing evidence that the Variscan tectonometamorphic evolution of the Moldanubian sector in the Bohemian Massif was discontinuous and polyphase. Relict evidence for an Early Variscan (Late Devonian) tectonometamorphic event can be found in rock complexes close to the contact with the Teplá–Barrandian block, being possibly related to the docking of the protolithic Precambrian/Early Palaeozoic Moldanubian crust with a Teplá–Barrandian (Bohemian) Terrane (Zulauf 1997; Bues et al. 2002). It is presently uncertain whether this Late Devonian „Bohemian Phase“ has affected other parts of the Moldanubian Zone as well.

The main Variscan tectonometamorphic overprint in the Moldanubian Zone occurred between *c.* 345 and 330 Ma, and is well substantiated by geochronological data (van Breemen et al. 1982; Dallmeyer et al. 1992; Friedl 1997; Kröner et al. 2000; Schulmann et al. 2005). We suggest here the use of the term “Moravo–Moldanubian Phase” for this major orogenic period, because it involved, as its most prominent tectonic feature, the thrusting of the Moldanubian onto the Moravian Zone (Suess 1926; Schulmann 1990; Fritz and Neubauer 1993; Schulmann et al. 1991, 2005). Another important feature of the Moravo–Moldanubian Phase was the subduction of crustal rocks to mantle depths (Carswell 1991; Becker and Altherr 1992; Kotková et al. 1997; O’Brien 2000; Vrána and Frýda 2003) and their subsequent rapid exhumation to middle and upper crustal levels (Gföhl Unit). Apart from the widespread Barrovian-style regional metamorphism, a significant late-stage LP–HT overprint is recorded in large parts of the Moldanubian Zone (Petrakakis 1997; O’Brien 2000). In cordierite-bearing paragneisses of the Ostrong Unit, east of the South Bohemian Batholith, this LP–HT metamorphism was dated at ~335 Ma by U–Pb monazite geochronology (Friedl 1997).

Cordierite-bearing LP–HT migmatites and gneisses are also abundant in the south-western sector of the Bohemian Massif in the Bavarian Forest (Fischer 1967; Blümel and Schreyer 1976, 1977; Blümel 1990). It has been believed for a long time that the LP–HT regional metamorphism in this area was broadly coeval with the LP–HT metamorphism in the Ostrong Unit, and had the

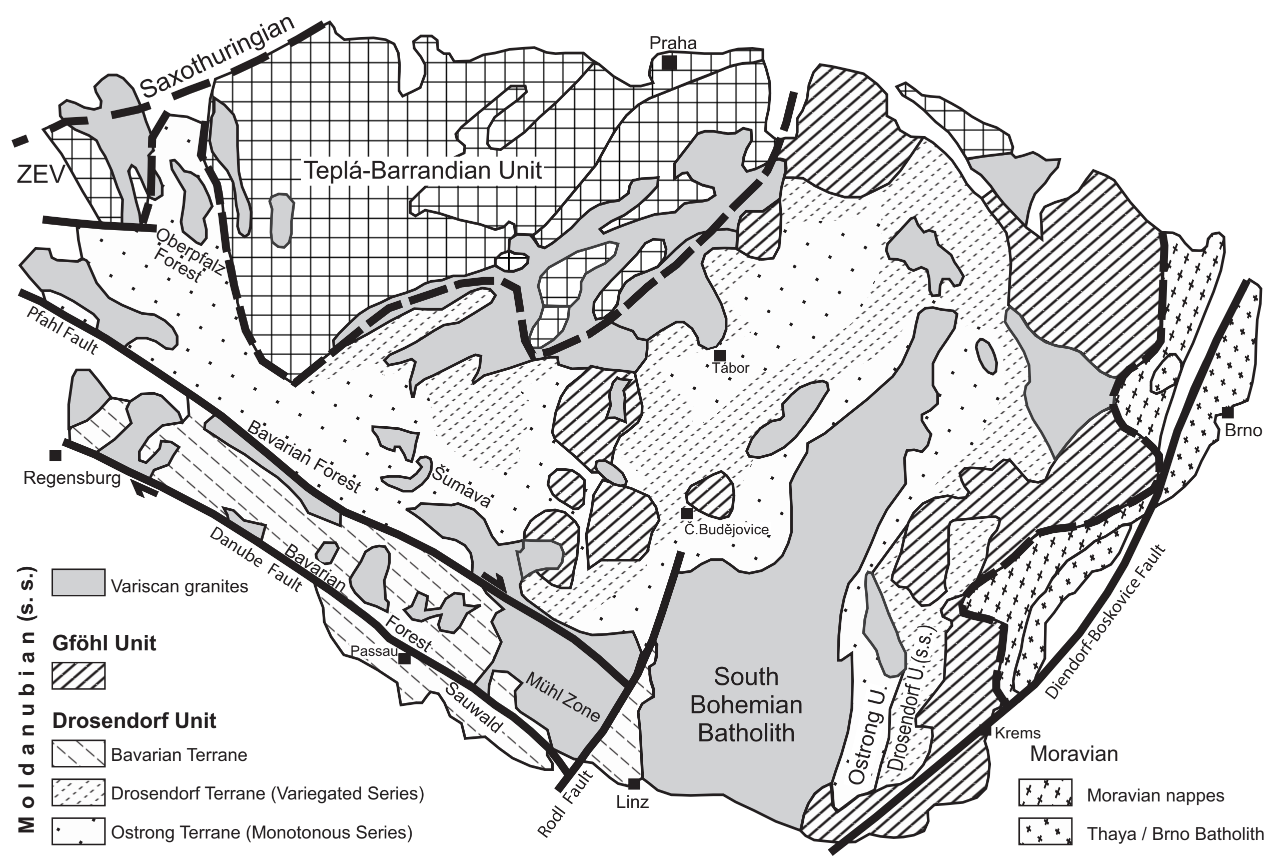

Fig. 1 Sketch map of the Moldanubian sector of the Bohemian Massif featuring the distribution of Variscan granites and rocks of the Gföhl and Drosendorf units according to Dallmeyer et al. (1995) with slight modifications. Also shown is the subdivision of the Drosendorf Unit into a Bavarian Terrane, Drosendorf Terrane (Variegated Series) and Ostrong Terrane (Monotonous Series) according to Fiala et al. (1995). Note the position of the original Ostrong and Drosendorf units (*s.s.*) as introduced by Austrian workers (Fuchs 1976).

same tectonothermal causes. However, this concept came into doubt recently. Based on the increasing body of geochronological data, Tropper et al. (2006) speculated that there may have been actually two independent Variscan LP–HT events in the Moldanubian Unit: one at *c.* 335 Ma, and a second one at *c.* 320 Ma. A breakthrough in the understanding of the Late Variscan evolution of the Moldanubian crust is the recent geochronological study of Gerdes et al. (2006), which demonstrated two important points:

1) Monazite ages in the LP–HT anatectic rocks in the south-western sector of the Bohemian Massif (Bavarian Forest, Mühl and Sauwald Zone) fall mostly between 326 and 315 Ma, and thus are clearly younger than in the LP–HT Ostrong Unit east of the South Bohemian Batholith (Fig. 1).

2) The 326–315 Ma old anatectic events in the Bavarian Forest have overprinted there an earlier generation of LP–HT rocks that formed at *c.* 335 Ma.

Since it is a temporally distinct event, we consider it necessary to introduce a new geological term for the post-330 Ma LP–HT reheating of crust that occurred in the south-western part of the Bohemian Massif. The name "Bavarian Phase" has been chosen in appreciation of the early work of Fuchs (1962, 1976) and Thiele (1962), who have first recognized that in the western Austrian sector of the Bohemian Massif (Bavaricum after Fuchs 1976) an older fold belt (considered as "Caledonian" at that time) was penetratively overprinted by later anatectic and tectonic events.

Assessing the available geochronological information we will examine in this paper, which areas of the Southern Bohemian Massif were overprinted by this Late Variscan Bavarian Phase. Furthermore, we have searched for lithological links between the Moldanubian Zone in the Czech Republic and the Moldanubian Zone in Bavaria. The outcome of this investigation sheds new light on the Variscan evolution of the Moldanubian sector of the Bohemian Massif.

2. Geological background and definitions of intra-Moldanubian units

The Moldanubian sector in the Bohemian Massif (Moldanubian *s. s.*) covers essentially the region between the Teplá–Barrandian Unit in the north-west and the Moravian Zone in the east. The overview maps given in the books of Dallmeyer et al. (1995) and Franke (2000) distinguish, in a rather simplistic way, three geological subunits in this Moldanubian sector: The Gföhl and Drosendorf metamorphic units, which represent pre-Variscan (Precambrian/Early Palaeozoic) crust, and the Variscan granitoids (Fig. 1).

The rocks of the **Gföhl Unit** are defined as having experienced Variscan HP–HT metamorphism and a subsequent rapid exhumation and re-equilibration at mid-crustal levels. The most prominent rock types therein are leucocratic granulites with the mineral paragenesis garnet + kyanite + ternary feldspar (mesoperthite) + quartz (Scharbert 1963; Carswell and O'Brien 1993; Janoušek et al. 2004), and light, biotite-bearing, migmatitic orthogneisses (often summarized as Gföhl Gneiss). The latter have been interpreted as a retrogressed granulite by some authors (Dudek et al. 1974; Cooke and O'Brien 2001). A metamorphic history involving penetrative melt infiltration has been suggested recently for an occurrence of Gföhl Gneiss in Moravia (Hasalová et al. 2007). Traditionally, the rocks of the Gföhl Unit have been interpreted as belonging to a single, large-scale, flat nappe that overlies the rocks of the Drosendorf Unit (Tollmann 1982; Behr et al. 1984; Franke 2000), even though alternative views do exist (Vrána and Šramek 1999; Franěk et al. 2006; Racek et al. 2006).

The **Drosendorf Unit** (*sensu* Dallmeyer et al. 1995 and Franke 2000) includes all those metamorphic rocks of the Moldanubian Zone that do not belong to the Gföhl Unit, i.e. mid-crustal metamorphic rocks devoid of a Variscan HP history. Included are the *Variegated (Varied)* and *Monotonous series* of the classical literature (Kodym 1966; Jenček and Vajner 1968; Zoubek 1988). Fiala et al. (1995) have integrated rock complexes previously mapped as Monotonous Series in Czech and Austrian maps (Kodym 1966; Fuchs and Matura 1976) to an *Ostrong Terrane*. Whether or not all these areas are geologically related to the original Ostrong Unit as defined by Fuchs (1976) in Austria (Fig. 1) is a matter of debate. Areas mapped as Variegated Series (with marbles, amphibolites, graphite schists, quartzites, orthogneisses etc.) were assigned by Fiala et al. (1995) to a *Drosendorf Terrane* (Fig. 1). Note that the Drosendorf Terrane of Fiala et al. (1995) is not equivalent to the Drosendorf Unit of Franke (2000).

The name Drosendorf Unit (named after a village in northern Lower Austria) was originally introduced for a variegated complex in the Austrian part of the Moldanubian Zone with orthogneisses, paragneisses, marbles, quartzites and amphibolites (Fuchs 1976; Fig. 1). We argue here that the name should be used exclusively in this original sense and not in the extended versions of Dallmeyer et al. (1995) and Franke (2000). Likewise, the term Drosendorf Terrane of Fiala et al. (1995) is misleading and should be better avoided. There is currently no proof that the Austrian Drosendorf Unit is an equivalent to the rocks of the Variegated Series in the Czech Republic. In fact, the opposite seems to be the case: Several workers have considered the Austrian Drosendorf Unit as an overthrust continuation of the Moravian Zone (Frasl

1970; Matura 1976, 2003; Finger and Steyrer 1995) and thus as a foreign element in the Moldanubian Zone. This interpretation is not unequivocally accepted (see Franke and Zelazniewicz 2000; Edel et al. 2003; Racek et al. 2006), but has recently received additional strong support from zircon provenance studies (Friedl et al. 2000, 2004; Gerdes and Finger 2005). Note also that Mísař (1994) considered the direct continuation of the Austrian Drosendorf Unit north of the Czech border (Vratěnín Unit) as a part of the Moravian Zone. According to the map given in Mísař (1994), the Drosendorf/Vratěnín Unit ends not far north of the Czech/Austrian border and has no further continuation in the Czech Moldanubian Zone.

For the south-western sector of the Bohemian Massif, south of the Pfahl Fault, Fiala et al. (1995) coined the name *Bavarian Terrane* (Fig. 1). This definition of a Bavarian Terrane builds upon the work of Fuchs and Thiele (1968) and Fuchs (1976), who recognized that anatectic rocks in the Austrian Mühl and Sauwald Zone (the "Bavaricum" *sensu* Fuchs 1976) show a Hercynian (NW–SE) fabric, oblique to the broadly N–S oriented strike of the metamorphic Moldanubian lithologies further north in the Czech Republic and east of the South Bohemian Batholith in Austria. Fuchs and Thiele (1968) and Fuchs (1976) suggested that in the "Bavaricum" an older metamorphic complex, considered as "Caledonian" by Fuchs (1976), was overprinted by a younger Variscan event, which involved strong anatexis and a top-to-the-south(west) tectonics. The LP–HT type of regional metamorphism in this south-western sector of the Bohemian Massif has been recognized early on (Blümel and Schreyer 1977; Finger et al. 1986). Since an analogous geothermal gradient has also been demonstrated in the Ostrong Unit east of the South Bohemian Batholith (Linner 1996), the LP–HT metamorphism in both regions was for a long time attributed to the same Late Variscan thermal event. However, as stated in the introductory section, recent geochronological work has led to a revival of the early ideas of Fuchs and Thiele (1968) and Fuchs (1976), according to which the crystallization and structural development of the rocks west of the South Bohemian Batholith was considerably younger. The definition of a Bavarian Terrane within the Moldanubian Unit, as tentatively suggested by Fiala et al. (1995), was therefore certainly an important step in the right direction, although it is a matter of debate whether the term "terrane" is indeed appropriate (see Discussion).

3. Which areas were affected by the Bavarian Tectonometamorphic Phase

Figure 2 shows those parts of the south-western Bohemian Massif, where Late Variscan (post-330 Ma) high-grade metamorphism/anatexis has been documented by concordant ID-TIMS U–Pb monazite ages. First of all, this encompasses the area south of the Pfahl Fault, i.e. the Bavarian Terrane of Fiala et al. (1995). Apart from the Austrian Mühl and Sauwald Zone (Gerdes et al. 2006), such Late Variscan monazite ages are known from several localities in the southern Bavarian Forest (Grauert et al. 1974; Propach et al. 2000; Gerdes et al. 2006).

However, also in the area north of the Pfahl Fault (i.e. outside of the Bavarian Terrane of Fiala et al. 1995), a post-330 Ma LP–HT metamorphic overprint has been unequivocally documented. For instance, Kalt et al. (2000) have presented a number of concordant monazite ages of 322–326 Ma from anatectic gneisses from the area between Regen and Cham. These data confirm a previous monazite age of *c.* 320 Ma presented by Grauert et al. (1974) for a paragneiss from Eck, not far south of the German–Czech border. In addition, many concordant metamorphic monazite ages of *c.* 320–325 Ma have been reported from the Oberpfalz Forest (Teufel 1988; von Quadt and Gebauer 1993). Thus there is little doubt that almost the whole Bavarian sector of the Bohemian Massif experienced high-grade metamorphism after 330 Ma.

An interesting question is how far this Late Variscan metamorphic/anatectic overprint can be followed from Bavaria northwards into the Czech Republic. We present here new electron-microprobe monazite ages for a migmatite from Lipka, S of Vimperk (Tab. 1), which yield a weighted average age of 323 ± 8 Ma. This provides a first indication that the high-grade metamorphic Boubín Complex in the Šumava Mts. bears an imprint of the Bavarian Tectonometamorphic Phase. In addition, the granitoid appearance of the rocks in the Boubín Complex reveals textural similarities to the post-330 Ma diatexites in the Bavarian Forest.

Tab. 1 Results of electron-microprobe dating of monazites from a pearl gneiss of the Boubín Complex (Lipka, S of Vimperk). For information on the method and the analytical routine used at Salzburg University see Finger and Krenn (2007).

	Th	U	Pb	Th*	Age ± 2σ
m1	8.846	0.850	0.169	11.608	**327 ± 15**
m2	7.332	0.274	0.117	8.223	**319 ± 22**
m2	7.368	0.273	0.122	8.256	**332 ± 22**
m3	6.946	0.234	0.110	7.708	**321 ± 23**
m4	8.861	1.010	0.175	12.145	**323 ± 15**
m4	8.898	0.999	0.172	12.145	**317 ± 15**
Weighted average					**323 ± 8**

In the Rittsteig area (Fig. 2), the effects of strong Late Variscan LP–HT metamorphism fade out towards north (Blümel and Schreyer 1976). However, the same type of LP–HT metamorphism can be found again north of the Rittsteig/Královský Hvozd Unit, a fact which led Scheuvens (2002) to suggest that this unit is an infolded roof

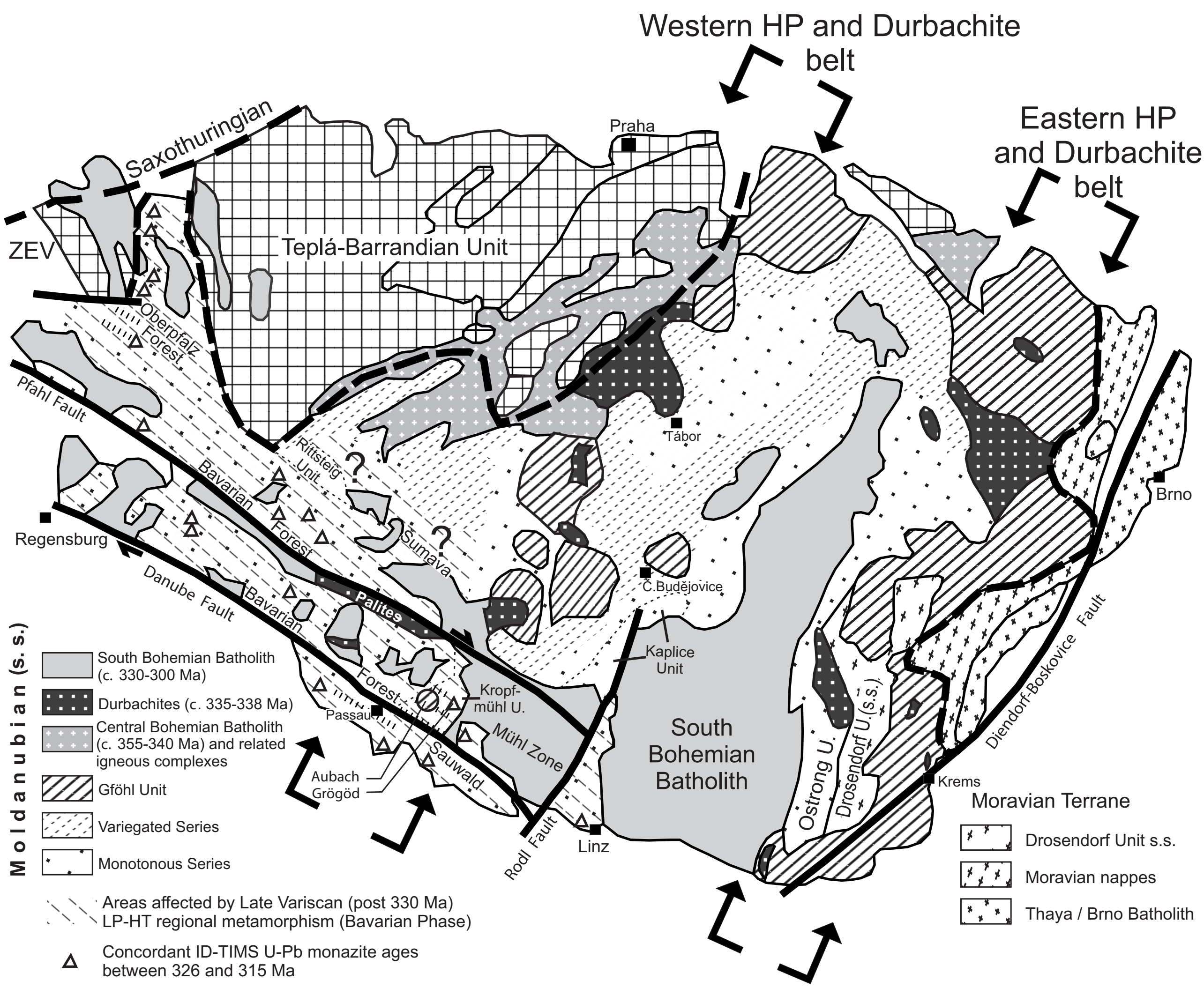

Fig. 2 Map as in Fig. 1, showing the presumed extent of Late Variscan (post-330 Ma) LP–HT regional metamorphism in the south-western Bohemian Massif. Monazite ages compiled from Grauert et al. (1974), Teufel (1988), von Quadt and Gebauer (1993), Propach et al. (2000), Kalt et al. (2000) and Gerdes et al. (2006). The Variscan plutons are subdivided into the *c.* 355–340 Ma old granitoids of the Central Bohemian Batholith, the *c.* 338–335 Ma old Durbachite plutons and the *c.* 330–300 Ma old granites of the South Bohemian Batholith.

pendant of the hangingwall crust, which was just marginally affected by the LP–HT regional metamorphism.

Apart from the new monazite age from the Boubín Complex, there are two other geochronological data, which suggest that the Šumava Mts. area was substantially reheated during the Bavarian Phase: Žáček and Sulovský (2005) recently reported a monazite age of 327 ± 7 Ma for an orthogneiss from near Horská Kvilda, and Fiala et al. (1995) mentioned unpublished U–Pb zircon ages for a leptynite from Chlum, near Kašperské Hory, recording a strong metamorphic overprint at *c.* 320 Ma. Considering in addition the dominant NW–SE strike of the rock fabrics in the Šumava Mts. region (Urban and Synek 1995), we tentatively suggest that this whole area may have suffered a strong tectonometamorphic overprint during the Bavarian Phase. Furthermore, cordierite is an abundant metamorphic mineral in the Šumava Mts. region (Dudek et al. 1973), a fact which accords with the LP–HT metamorphic character of the Bavarian tectonothermal overprint. However, as we know from the Ostrong Unit east of the South Bohemian Batholith, an earlier generation of Crd-bearing rocks formed in the Moldanubian Zone at *c.* 335 Ma, and it cannot be ruled out that the cordierite gneisses of the Šumava Mts. are partly of this older age as well. In particular in the area between the Šumava Mts. and the Central Bohemian Batholith, the extent and importance of the Bavarian tectonothermal overprint remains to be assessed.

No substantial post-330 Ma reheating seems to have occurred in the gneiss region along the Upper Austrian–Czech border, north of the Pfahl Fault. Mica cooling ages of *c.* 330 Ma were reported from this area (Scharbert et al. 1997). Also, there was definitely no substantial post-330 Ma reheating in the Moldanubian units east of the South

Bohemian Batholith, as can be seen from mica cooling ages of 330–340 Ma (Dallmeyer et al. 1992; Scharbert et al. 1997). In addition, it is clear from the field relationships that the Weinsberg and Rastenberg intrusions at the eastern margin of the South Bohemian Batholith postdated the LP–HT regional metamorphism in the Ostrong Unit. These intrusions, dated between 328 and 335 Ma (Friedl et al. 1996; Klötzli and Parrish 1996; Gerdes et al. 2003), produced just narrow contact aureoles in their country rocks (Büttner and Kruhl 1997).

Although no metamorphic ages are available yet, we consider it likely that the Monotonous Series between České Budějovice and the northern branch of the South Bohemian Batholith (Fig. 2) had its LP–HT peak at *c.* 335 Ma as well, being in this respect a direct analogue to the Austrian Ostrong Unit. A lower age limit for the LP–HT metamorphism in the České Budějovice area is provided by the intrusion age of the Eisgarn granite, which is 328 ± 4 Ma (Friedl et al. 1996). Note that there are also striking lithological similarities between the Monotonous Unit of the České Budějovice area and the Austrian Ostrong Unit, such as the occurrence of small eclogite lenses (O'Brien and Vrána 1997; Faryad et al. 2006). Whether the strip of the Monotonous Series NE of Tábor (Fig. 2) is also a metamorphic and stratigraphic equivalent to the Austrian Ostrong Unit, is questionable. However, a post-330 Ma age of the LP–HT metamorphism in this area is unlikely, given the mica cooling ages of ~ 330 Ma reported from the Bechyně orthogneiss (Van Breemen et al. 1982).

An exceptional example for a penetrative post-330 Ma retrograde recrystallization of Moldanubian crust east of the Šumava Mts. region may be the Kaplice Unit (Fig. 2), where abundant late growth of muscovite has been reported (Vrána 1979). According to Vrána and Bártek (2005) this muscovitization was caused by fluids derived from the Eisgarn granite.

4. Some remarks concerning the pre-330 Ma rock inventory of the Bavarian Zone

Due to the strong tectonometamorphic overprint in the course of the Late Variscan Bavarian Phase, which transformed most of the previous Variscan crust into a high-grade anatectic terrain, the geological history of the south-western Bohemian Massif is difficult to reconstruct. The lithological distinctions in the existing geological maps refer mainly to different grades of anatexis (metablastites, metatexites, diatexites etc.), while the nature of the protoliths is hardly considered. There is wide agreement that paragneisses (metapelites and/or metagraywackes) were the main protoliths (Fischer 1967; Fuchs and Thiele 1968; Finger et al. 1986). However, at least in places, other protolithic lithologies were present, such as amphibolite or orthogneiss (Teipel et al. 2004; Propach 2005), and even Variscan plutonic rocks. Here we attempt to identify some typical pre-330 Ma Moldanubian lithologies in the Bavarian Zone.

4.1. Durbachite plutons

A significant and widespread plutonic rock type within the Czech part of the Moldanubian Unit are the *c.* 335–338 Ma old magnesio–potassic (and ultra-potassic) "Durbachite" intrusions (Kodym 1966; Klomínský and Dudek 1978; Holub 1997; Janoušek and Holub 2007). We present here the theory that the so-called "Palites" of the Bavarian Forest (i.e. deformed and anatectic melagranitoid rocks near the Pfahl Fault – Fig. 2) belong to this distinct igneous suite as well.

A modern characterization of the (ultra-)potassic magmatism in the southern and central parts of the Bohemian Massif was given in Janoušek and Holub (2007). These authors have compiled the existing geochronological information and arrived at the conclusion that the emplacement of the (ultra-)potassic plutons (termed here for the sake of simplicity 'Durbachite plutons') took place immediately after the tectonic ascent of the HP rocks of the Gföhl Unit within a relatively narrow time window between 335 and 338 Ma. Since the Durbachite plutons are spatially connected to the Gföhl Unit (Fig. 2), Janoušek and Holub (2007) have suggested that there is a causal link in the petrogenesis of the two rock groups. We shall come back to this point later in the discussion.

Apart from their similar ages (335–338 Ma), the Durbachite plutons are defined by a special geochemical signature, unique among the Variscan granitoids of the Bohemian Massif. This includes a strong (to extreme) enrichment of the LIL elements K, Th, U, Rb, Cs, Ba (often > 2000 ppm!), Sr (often > 1000 ppm!), in combination with relatively high contents of MgO (mostly > 3 wt. %, Fe_2O_3tot/MgO mostly < 2), Cr (often > 100 ppm) and Ni (often > 30 ppm). The least felsic types of the Durbachite plutons (Durbachites *sensu stricto* according to Janoušek and Holub 2007) have an extremely K_2O-rich (ultrapotassic–syenitic) composition and intermediate SiO_2 contents, while others are comparably less (but still strongly) K_2O enriched and shoshonitic–granodioritic (e. g., Rastenberg Pluton). Macroscopically, the rocks of the Durbachite suite are mostly characterized by milky white, blocky K-feldspar megacrysts, embedded in a relatively dark, Bt- and Hbl-rich matrix. However, there are also less voluminous bodies of ultrapotassic biotite–pyroxene melasyenites to melagranites rich in K-feldspar but devoid of K-feldspar phenocrysts (Tábor and Jihlava intrusions). A distinctive macroscopic feature of all these (ultra-) potassic intrusions are the ubiquitous mafic microgranular enclaves or mafic dykes. Mixing and mingling of magma components derived from an enriched lithospheric mantle and the lower crust is generally regarded as a key process in the petrogenesis of the Durbachite plutons (Holub 1997; Gerdes et al. 2000a; Janoušek and Holub 2007).

Due to the strong anatectic (and structural) overprint during the Bavarian Phase, the originally plutonic nature of the Palites remained long unrecognized. In most previous works they were considered as syn-anatectic metasomatites (Steiner 1972). However, based on zircon dating and Sr and Nd isotopic data, Siebel et al. (2005) could demonstrate that most of the Palites are *c.* 335 Ma old igneous rocks that originated from a lower-crustal source, and contained a large proportion of a basic mantle melt. These data of Siebel et al. (2005) clearly point out a relationship to the Durbachitic magmatism described elsewhere in the southern Bohemian Massif. Already on the macroscopic scale, the coarser-grained variants of the Palites display a number of features strongly reminiscent of Durbachitic granitoids, like for instance a melanogranitoid appearance with big magmatic K-feldspars, and the widespread presence of coeval mafic enclaves and dykes. Additionally the Palites exhibit clear geochemical affinities to the Durbachite suite (in particular to the shoshonitic–granodioritic Rastenberg subtype). This concerns their high K_2O at moderate SiO_2, high MgO and low $Fe_2O_3^{tot}$/MgO ratios as well as high Ba, Sr, Ti, P and Cr concentrations (Tab. 2). Also, the Sr and Nd isotopic signature (Siebel et al. 2005) is very similar to that of the Rastenberg granodiorite in Lower Austria (Gerdes et al. 2000a). The only mismatch is the generally lower Th content of the Palites.

It is an old observation, which was mainly emphasised by Czech workers in the past (Kodym 1966; Klomínský and Dudek 1978), that there are two separate, roughly N–S oriented geographic lines of Durbachites in the Moldanubian Zone: (1) an eastern line spanning from Moravia into Lower Austria, and (2) a western line running southwards from the Central Bohemian Batholith to the Šumava Mts. region. The Palites lie almost exactly in the southern extension of the western Durbachite line (Fig. 2), taking into account a slight dextral displacement along the Pfahl Fault. It is interesting that along both these lines the ultrapotassic–syenitic intrusions are to be found mainly in the north. The southern plutons (Rastenberg intrusion and Palites) seem to have broadly the same age as the northern ones, but tend to be more granodioritic. Fuchs (2005) has recently discovered a new southernmost occurrence of Durbachitic granitoids (Rastenberg subtype) in Lower Austria, *c.* 50 km east of Linz (Fig. 2). A chemical analysis from this plutonic body is listed in Tab. 2 for comparison.

Finally it should be mentioned that dioritic rocks in the Fürstenstein area in Bavaria (*c.* 20 km S of the Palite body – Fig. 2) were dated recently yielding a comparable age of *c.* 335 Ma (Chen and Siebel 2004). We consider that they may also represent remnants of a former Durbachite-type pluton in the continuation of the western Durbachite line.

Tab. 2 Geochemical data for granitoids in Bavaria and Lower Austria considered as Durbachites (*s.l.*) in this study. a, b) Coarse-grained, foliated Palite from quarry Saunstein near Schönberg; c) Coarse-grained foliated Palite from quarry Sommersberg; d) Wolfshof syenite gneiss, Krems valley, 3 km N Krems; e) Porphyritic melagranite, forest road 1 km ESE Nöchling, *c.* 50 km E Linz. Analyses by standard XRF methods at Salzburg University.

Sample	a	b	c	d	e
	Fi-Fr3	Fi-5/03	Fi-Fr4	Fi-WOG	Fi-44a/06
SiO_2	55.73	59.34	65.78	58.70	59.92
TiO_2	1.11	1.16	0.61	1.05	0.82
Al_2O_3	17.00	16.72	14.45	16.28	16.29
Fe_2O_{3tot}	5.59	3.92	3.19	4.77	5.17
MnO	0.09	0.06	0.05	0.06	0.08
MgO	3.59	3.07	2.24	2.85	3.00
CaO	5.01	4.45	3.16	1.93	3.96
Na_2O	3.35	3.19	2.83	1.90	3.18
K_2O	5.74	4.78	5.87	8.60	4.77
P_2O_5	0.79	0.64	0.37	0.89	0.43
LOI	1.43	2.12	1.27	1.98	1.85
Total	99.43	99.47	99.82	99.01	99.47
Cl	452	376	271	71	67
Sc	25	12	10	7	15
V	114	133	67	83	60
Cr	102	144	54	50	86
Co	13	13	11	14	14
Ni	36	24	31	22	39
Zn	86	75	48	95	75
Rb	216	149	154	345	193
Sr	757	802	565	751	549
Y	39	13	16	22	20
Zr	412	289	165	692	359
Nb	19	14	11	38	18
Ga	23	21	16	23	24
Ba	1927	2000	1963	2383	1237
La	73	56	29	87	70
Ce	162	102	69	136	118
Nd	77	56	44	56	44
Pb	32	28	32	100	76
Th	5	19	5	27	41
U	1	1	2	9	6

4.2. Rocks of the Monotonous and the Variegated series

The classic stratigraphic division of Moldanubian rocks into an older (Proterozoic) Monotonous Series and a younger (Late Proterozoic/Early Palaeozoic) Variegated Series, used in early works on the territory of the Czech Republic (Kodym 1966; Jenček and Vajner 1968), has been tentatively extended by Dill (1985) into Bavaria. Based on the occurrence of small bodies of marbles, amphibolites and graphite schists, Dill (1985) considered the Kropfmühl Unit NE of Passau (Fig. 2) as belonging to the Variegated Series, as well as the region south and south-west of Passau (south of the Danube Fault). Indeed, it is quite likely that the areas around Passau, where graphite has been mined in many places (Weinelt 1973), represent the continuation of the graphite-rich variegated complex of Český Krumlov (W of České Budějovice in Fig. 2). Further north in the Czech Republic, graphite lenses are also known from near Týn nad Vltavou and east of Tábor (Tichý 1965; Suk 1974). So, as in case of the Durbachite line, we note a NNE–SSW trend of this significant graphite belt from Bohemia into Bavaria. Diatexites north of Passau have been recently interpreted by Propach (2005) as remolten amphibolitic lithologies, which underlines the affinity of this area to the Variegated Group of Český Krumlov.

Further west in the Bavarian Forest, between Vilshofen and Regensburg, intercalations of amphibolites, marbles and graphite schists play a lesser role. The anatexites there seem to be mainly derived from a former monotonous paragneiss series, possibly comparable to the Monotonous Series of the Šumava Mts. area to the north. However, light diatexites as mapped for instance on sheet Bogen (Humer and Krenn 2005) may be anatectic orthogneiss. Unfortunately, such genetic distinctions between ortho- and para-diatexites are only exceptionally available on the Bavarian maps.

It is feasible that the Oberpfalz Forest and the westernmost parts of the Bavarian Forest represent migmatized Teplá–Barrandian or Saxothuringian crust, as in these western areas less lithological and geochronological affinity to the Moravo–Moldanubian Fold Belt is to be found. However, more data would be needed to test this hypothesis properly. Note that the Moldanubian Unit is defined there mainly based on its high-grade LP–HT metamorphism, which is a Late Variscan feature independent of the pre-330 Ma lithological and tectonic boundaries. For example, Schreyer (1966) has already shown that the Moldanubian LP–HT metamorphism overprinted the Moldanubian/Saxothuringian boundary.

4.3. High-pressure rocks of the Gföhl Unit

Since the Variegated Series of Český Krumlov seems to continue southwestwards into eastern Bavaria, one may expect relics of the Český Krumlov granulites to be present there as well. Finds of relict kyanite in the Kropfmühl Unit (Ritter 1951) and recently in the Austrian Sauwald Zone (Doblmayr pers. com.) are in favour of this concept, and would deserve a modern petrological study. Based on SHRIMP zircon dating (Teipel et al. 2002) and P–T data reported in Klein (2002) it appears likely that certain leptynites of the Kropfmühl Unit (locality Aubach – Fig. 2) bear a record of Viséan HP–HT granulite-facies metamorphism. Also, short notes can be found in the literature reporting finds of “Gföhl Gneiss” in the eastern part of the Bavarian Forest (Pfaffl 2006, and in adjacent Austria (Fuchs and Thiele 1968; Teipel et al. 2002).

Light diatexites in the Bavarian Zone are basically candidates for recrystallized granulite or Gföhl Gneiss. One possibility for recognition of the former HP–HT granulites, even after strong anatectic recrystallization, would be zircon studies, as granulite zircons possess typical morphologies and internal zoning features (Hoppe 1966; Svojtka and Košler 1995; Roberts and Finger 1997) that could have (at least partly) survived. Also, it would be worthwhile searching the amphibolite bodies and mafic anatexite complexes of the Passau region (Propach 2005) systematically for relics of ultrabasic (peridotitic) rocks, which are typical for the Gföhl Unit (Vrána et al. 1995 ; Medaris et al. 2005). Unfortunately, the hypothesis that the Czech Moldanubian rock complexes might continue southwards into Bavaria has been little pursued until now.

4.4. Moldanubian orthogneisses

On the Czech territory, bodies of variably deformed pre-Variscan granitoid rocks are present in both the Monotonous and the Variegated series. According to the available geochronological information, most of these appear to represent Early Palaeozoic granites or rhyolites (e.g. Hluboká orthogneiss: Vrána and Kröner 1995; Stráž orthogneiss: Košler et al. 1996). Also for the leptynite near Kašperské Hory interpreted as a metarhyolite of the Variegated Series, an Early Palaeozoic formation age was proposed on the basis of zircon dating (Fiala et al. 1995).

A quest for former Moldanubian orthogneiss layers in the Bavarian Zone is most promising in areas where anatexis was less intense. Teipel et al. (2004) have recently documented felsic granitic orthogneisses near Passau and constrained their formation at *c.* 550 Ma (SHRIMP zircon ages). Geochemical data given in Teipel (2003) show that these have a very characteristic Zr- and LREE-rich compositions resembling A-type granites (Whalen et al. 1987). We are presently unaware of similar orthogneisses in the Czech part of the Moldanubian Zone. An amphibolite sampled near Passau gave the same zircon age of 550 Ma. Teipel et al. (2004) interpreted this association of amphibolites and orthogneisses near Passau as representing a Vendian (Late Proterozoic) back-arc magmatism.

Another group of felsic I-type orthogneisses in the area of the Hinterer Bayerischer Wald (north of the Pfahl Fault) was dated by Teipel (2003) as Early Ordovician. These SiO_2-rich granitoids correspond typologically and geochronologically to the Stráž orthogneisses of the Czech Moldanubian Unit. Finally, Teipel (2003) reported geochemical data for leucocratic S-type granite gneisses that seem to be relatively abundant in the Oberpfalz and the northwestern Bavarian Forest. Unfortunately, these gneisses remain undated. With regard to their leucocratic nature and their high phosphorous contents, they resemble the (partly tourmaline-bearing) S-type orthogneiss and metagranite bodies in the Czech Monotonous Series (Vrána and Kröner 1995; Breiter et al. 2005) but also some Saxothuringian granite gneisses (Siebel et al. 1997).

As mentioned earlier, it is likely that appreciable amounts of the diatexites in the Bavarian Zone actually had orthogneiss protoliths. Such diatexites are often exceptionally light and relatively poor in biotite (Humer and Krenn 2005). However, also darker, metatonalitic diatexites do exist, which are macroscopically hard to distinguish from diatexites derived from paragneiss. In the Austrian Sauwald Zone, several bodies of Early Palaeozoic biotite-tonalites (one of them was dated at 456 Ma by Friedl et al. 2004) have been transformed to diatexites during the Bavarian Phase (Finger et al. 2005). Summing up, the amount of anatectic orthogneisses in the Bavarian Zone (i.e. diatexites derived from magmatic protoliths) seems presently grossly underestimated. This is rather unfortunate, as these rocks may play a key role in unravelling the history of this part of the Bohemian Massif.

4.5. Pre-330 Ma cordierite-gneisses of the Ostrong Unit

The moderately anatectic Kropfmühl Unit (Fig. 2) provides evidence that at least parts of the south-western Bohemian Massif have experienced a first pulse of Variscan LP–HT metamorphism prior to the Bavarian Phase. Table 3 and Fig. 3 show the results of U–Pb dat-

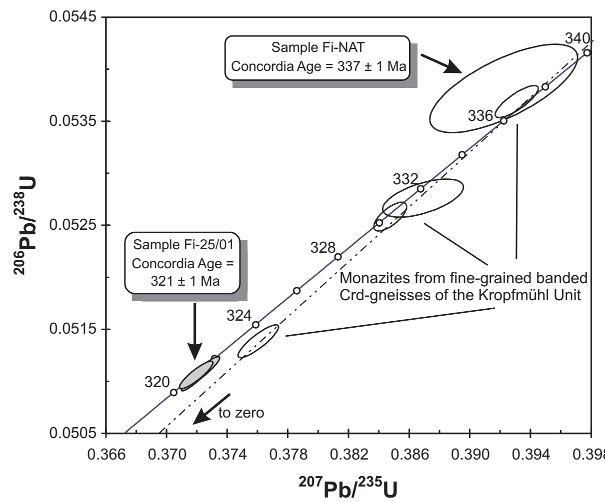

Fig. 3 U–Pb concordia diagram showing isotopic data for single-grain monazite fractions from fine-grained Crd-paragneiss (samples Fi-24/01, Fi-NAT) and coarser migmatitic paragneiss from the Kropfmühl Unit (sample Fi-25/01). While the monazites from the migmatite Fi-25/01 are concordant at 321 ± 1 Ma, those from the fine-grained cordierite gneisses are clearly older and aligned along a trend line to 337 Ma (concordia age of the two uppermost ellipses for the sample Fi-NAT is 337 ± 1 Ma).

Tab. 3 The isotope dilution TIMS ages of monazites (single grains) from paragneiss samples of the Kropfmühl Unit. Samples Fi-24/01 (quarry Grögöd) and Fi-NAT (Quarry Natschlag) are fine-grained, slightly banded, compact cordierite-bearing paragneisses. Sample Fi-25/01 is anatectic gneiss with coarse biotite and leucosome veins (quarry Grögöd). Analyses were performed at NIGL, Keyworth (U.K.), using the standard procedure as described e.g. in Timmermann et al. (2004).

Sample	Weight (µg)	U	Pb[a] (pg)	Pb[b] (pg)		$\frac{Th^d}{U}$	$\frac{^{207}Pb^e}{^{235}U}$ ± 2σ	$\frac{^{206}Pb^e}{^{238}U}$ ± 2σ	Error corr.	$\frac{^{207}Pb^e}{^{206}Pb}$ ± 2σ	$\frac{^{206}Pb}{^{238}U}$ (Ma)	$\frac{^{207}Pb}{^{235}U}$ (Ma)	$\frac{^{207}Pb}{^{206}Pb}$ (Ma)
Fi-NAT													
Mz-1	3.6	4363	2361	7.1	7133	7.4	0.3761 ±11	0.051385 ±13	0.87	0.05308 ± 8	323.0 ±0.8	324.1 ±0.9	332.1 ±3.3
Mz-2	1.0	896	471	13.3	246	31.6	0.3922 ±40	0.053816 ±35	0.70	0.05286 ±39	337.9 ±2.2	336.0 ±3.4	323.0 ±17
Mz-3	1.2	3982	2244	7.2	2267	28.7	0.3931 ±12	0.053689 ±13	0.81	0.05310 ± 9	337.1 ±0.8	336.6 ±1.0	333.1 ±3.9
Fi-24/01													
Mz-1	3.0		5463	20.7	7108	5.2	0.38457 ± 9	0.052583 ±11	0.93	0.05307 ± 5	330,4 ±0.7	330.5 ±0.8	331.7 ±1.9
Mz-2	2.0	2001	1951	67.5	215	29.5	0.38691 ±22	0.052761 ±15	0.58	0.05319 ±25	331,4 ±0.9	332.1 ±1.9	336.8 ±10
Fi-25/01													
Mz-1	2.7	8311	6765	7.4	9708	18.4	0.37189 ±8	0.051032 ±10	0.93	0.05285 ± 4	320.9 ±0.6	321.1 ±0.7	322.5 ±1.8
Mz-2	2.8	8573	9083	32.4	2404	23.8	0.37239 ±9	0.051104 ±11	0.91	0.05285 ± 5	321.3 ±0.7	321.4 ±0.8	322.3 ±2.2
Mz-3	1.7	7056	3238	9.9	3917	16.0	0.37191 ±9	0.051062 ±11	0.89	0.05282 ± 6	321.0 ±0.7	321.1 ±0.8	321.3 ±2.6

[a] Radiogenic Pb; [b] Common Pb, corrected for fractionation and spike; [c] Measured ratio, corrected for spike and Pb fractionation;
[d] Model ratio calculated from $^{208}Pb/^{206}Pb$ ratio; [e] Corrected for fractionation, spike, blank and common lead (Stacey and Kramers 1975)

ing of single monazites from relatively fine-grained, slightly banded, cordierite paragneisses widespread in the Kropfmühl Unit. Two monazites from sample Fi-NAT (quarry at Natschlag, Upper Austria) define a concordia age of 337 ± 1 Ma, considered as the crystallization age of the gneisses. Monazites from the second sample (Fi-24/01, quarry at Grögöd) gave slightly younger U–Pb ages of 330–332 Ma, but the mean points of the data ellipses are both slightly below the concordia curve. The U–Pb ages of these monazites should thus be viewed as minimum ages. In many places, as for instance in the Grögöd quarry (Köhler et al. 1989), it can be observed that a younger phase of anatexis led to a variably intense recrystallization of these older fine-grained cordierite paragneisses. Such recrystallized rock portions show a metablastic coarsening of biotite and feldspar and are veined by leucosome. Monazites from these leucosome-bearing coarse migmatites of the Grögöd quarry yielded a concordia age of 321 ± 1 Ma (sample Fi-25/01; Tab. 3), and clearly document the influence of the Bavarian tectonometamorphic overprint.

In terms of metamorphic conditions and age, the relict fine-grained Crd paragneisses of the Kropfmühl Unit correspond to the LP–HT Crd paragneisses of the Ostrong Unit (Friedl 1997). The Ostrong Unit thus seems to continue from the area E of České Budějovice southwestwards into the Bavarian Zone. Also, the (stronger anatectic) paragneiss-derived diatexites and metatexites of the Sauwald Zone (including the area N Linz – Finger et al. 2005) may be, for their most part, Ostrong Unit, re-metamorphosed and migmatized during the Bavarian Phase.

5. Discussion and conclusions

5.1. The Bavarian Tectonometamorphic Phase: delamination of mantle lithosphere as a possible scenario

The present state of geochronological research basically confirms the early ideas of Fuchs and Thiele (1968) and Fuchs (1976) that to the west of the South Bohemian Batholith (Bavarian Zone) an older, NNE–SSW striking fabrics was penetratively overprinted by a younger phase of regional metamorphism and anatexis with NW–SE striking tectonic structures. An assessment of the available geochronological data indicates a Late Variscan age of 330–315 Ma for this younger Bavarian Phase.

Furthermore, it has been argued in the foregoing text that some characteristic NNE–SSW trending lithological zones of the *c.* 345–330 Ma old Moravo–Moldanubian Fold Belt can be followed from the Czech Republic along strike south(west)wards into the Bavarian Zone. This implies that the Bavarian Zone is no foreign crustal element in the Moldanubian sector of the Bohemian Massif and therefore no terrane in the plate tectonic sense. In fact, the Bavarian Phase has mainly the character of a thermal overprint. Petrological work indicates granulite--facies P–T conditions of 700–800 °C and *c.* 4–5 kbar for large parts of the Bavarian Zone (Kalt et al. 2000; Tropper et al. 2006). These high temperatures produced a new generation of anatectic rocks, which are not always easy to be related to their respective protoliths, due to massive textural changes. The high temperatures also led inevitably to a strong softening of the crust. In the Austrian Mühl and Sauwald Zone, effects of syn-anatectic southwest-vergent folding and top-to-the-southwest thrusting have been observed (Fuchs and Thiele 1968). Strong ductile shearing and mylonite formation occurred along the dextral Pfahl and Danube faults. Unfortunately, a comprehensive tectonic study of the entire Bavarian Zone is still missing.

We follow the view of Scheuvens (2002) that less anatectic domains within the Bavarian Zone, as for example the Rittsteig/Královský Hvozd or the Kropfmühl units, are infolded portions of the hangingwall crust and therefore not really allochthonous units. The same may be true for the famous HP rocks at Winklarn (Oberpfalz), and there are possibly other as yet unrecognised gneissic units in the Bavarian Forest with a similar status. These less anatectic units play a major role in the reconstruction of the pre-330 Ma history of the area. Since the eastern part of the Bavarian Zone most likely represents a reworked southern continuation of the Moravo–Moldanubian Fold Belt, it would be worth investigating, whether western parts do not represent former southern continuations of the Teplá–Barrandian and Saxothuringian crust. Note, for instance, that the HP rocks at Winklarn yield garnet ages of *c.* 420 Ma (von Quadt and Gebauer 1993) and do not show the typical ~340 Ma garnet, monazite and zircon ages of the HP rocks of the Gföhl Unit.

In previous work it has often been stated that the LP–HT regional metamorphism in Bavaria occurred on a decompression path, during a post-orogenic uplift of the Variscan crust (Blümel 1990). However, as the new geochronological data from the Kropfmühl Unit clearly demonstrate (see above), the Bavarian Phase has overprinted a crustal segment, which was already in the cordierite stability field and thus at relatively low pressures at 335 Ma. By analogy with the situation in those parts of the Moldanubian Zone that were unaffected by the Bavarian tectonothermal overprint (e.g. the Ostrong Unit in Austria – Büttner and Kruhl 1997), we conjecture that the eastern parts of the Bavarian Zone underwent cooling between 335 and 330 Ma, before they were reheated again to 700–800 °C between *c.* 330 and 315 Ma. This post-330 Ma reheating may have been accompanied by further slight uplift. However, a decompression greater than 3 kbar (~10 km) appears unrealistic due to the presence of cordierite in the relict paragneisses metamorphosed at *c.* 335 Ma. The Early Variscan (pre-330 Ma) evolution of the western parts of the Bavarian Zone is largely unknown.

The available data indicate that the post-330 Ma LP–HT regional metamorphism in the Bavarian Zone required primarily a strong Late Variscan heat addition from the mantle. As discussed in Henk et al. (2000), such a heat pulse could be best explained by delamination of parts of the mantle lithosphere, which initially would cause widespread lower crustal melting. The large volumes of Weinsberg and Eisgarn granitic magmas in the northern and eastern parts of the South Bohemian Batholith (dated at *c.* 327–330 Ma – Gerdes et al. 2003) may have formed during this early stage of delamination. From there the delamination seems to have proceeded towards southwest, as indicated by a younging of ages in both granitic and anatectic rocks (Gerdes et al. 2006). Heat transport from the hot crust/mantle boundary into higher crustal levels was probably effectively managed through the abundant granite plutons that intruded the Bavarian Zone. It can be seen from Fig. 2 that the post 330 Ma LP–HT overprint occurred just in those parts of the Bohemian Massif, which were drenched by Late Variscan granites.

5.2. The Moravo–Moldanubian Fold Belt: a syn-collisional accretionary wedge?

At *c.* 330 Ma, before the Bavarian Phase set in, the Moldanubian sector of the Bohemian Massif constituted a (today NNE–SSW trending) fold and thrust belt between the Cadomian Moravian Zone (Bruno–Vistulicum of Dudek 1980) and the Teplá–Barrandian block. Apart from some transpressional movements in the realm of the Central Bohemian Batholith (Žák et al. 2005), the Teplá–Barrandian crust was widely consolidated since the Late Devonian (Zulauf 1997). There is general agreement that, at *c.* 340 Ma, high-grade Moldanubian rocks were steeply uplifted along the border to the Teplá–Barrandian block. According to Scheuvens and Zulauf (2000), the Teplá–Barrandian/Moldanubian boundary is represented by an extension-related high-angle normal fault (the Central Bohemian Shear Zone). Žák et al. (2005) suggested a somewhat different model in which the SE-side-up exhumation of hot Moldanubian rocks occurred in a relatively wide thermally softened transpressional zone along the NE–SW trending magmatic system of the Central Bohemian Batholith.

On the other hand, it is generally accepted since the work of Suess (e.g. 1912, 1926) that the eastern segment of the Moldanubian Zone was thrust over the Moravian Zone, and that marginal parts of the latter were tectonically mobilized and included in the Variscan deformation and metamorphism (Frasl 1970). Schulmann (1990), Urban (1992) with Fritz and Neubauer (1993) documented a top-to-the-NNE transport of Moldanubian and Moravian nappes onto the Moravo–Silesian foreland, and dextral transpressional movements along the plate contact. According to hornblende and muscovite cooling ages given in Dallmeyer et al. (1992) and Fritz et al. (1996), this thrust tectonics should have occurred before 330 Ma, which means that it may well have been contemporaneous with the exhumation of Moldanubian crust at the Teplá–Barrandian/Moldanubian boundary. It is therefore proposed here that the Moravo–Moldanubian Fold Belt represents a collisional accretionary wedge successively underplated by material of the Gföhl and the Moravian Unit in the footwall, while the Teplá–Barrandian block may have functioned as a rigid backstop, along which earlier subducted HP–HT rocks were steeply exhumed (Fig. 4a). This model would explain, why two parallel, seemingly discrete belts of exhumed HP rocks exist in the Moldanubian sector of the Bohemian Massif, one

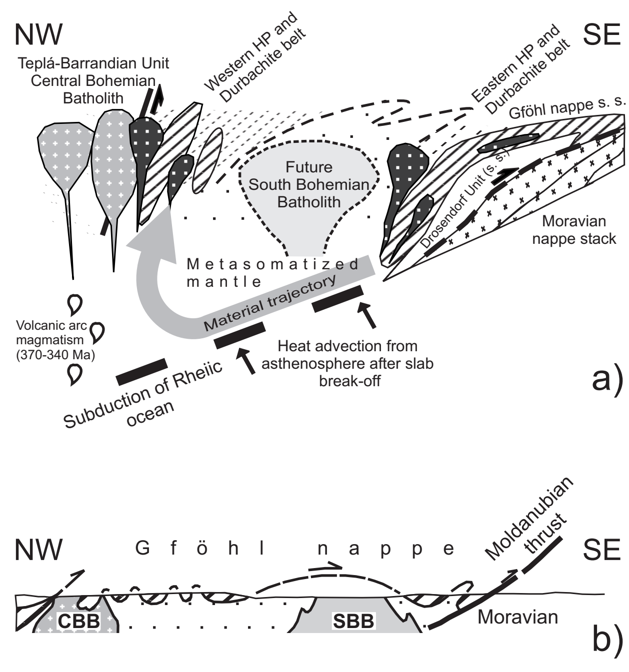

Fig. 4 a) Tentative tectonic scenario at *c.* 330 Ma, i.e. at the end of the Moravo–Moldanubian Phase of the Variscan orogeny. The south-eastern sector of the Bohemian Massif is interpreted as an accretionary wedge underplated by material of a Gföhl terrane and a Moravian terrane. Heat advection from the asthenosphere after slab break-off could have caused a significant temperature rise in the subducted Gföhl Unit and activated channel flow mechanisms, which facilitated the exhumation of these rocks. Regional details like backthrusts etc. are not considered in the profile. Rock symbols as in Fig. 2.
b) The classic tectonic interpretation of the Gföhl Unit as a large nappe on top of the Moldanubian Zone (Tollmann 1982, redrawn from Franke 1989). Position and length of profile is approximately as in Fig. 4a. CBB = Central Bohemian Batholith, SBB = South Bohemian Batholith.

close to the Moravian and one next to the Teplá–Barrandian boundary. Further investigations on that issue are necessary.

Our model follows the view of Vrána and Šrámek (1999) and of Schulmann´s school (Franěk et al. 2006), who have also proposed that the HP–HT granulite bodies in the western Moldanubian Unit (e.g. Blanský les Massif) extruded along steep channels into mid-crustal rocks and were then infolded into these. A major argument against the classic interpretation of the whole Gföhl Unit as a coherent nappe (Fig. 4b) is provided by the Durbachite intrusions. As can be seen from Fig. 2, these Durbachite intrusions are clearly associated with the HP rocks of the Gföhl Unit, whereby a western and an eastern HP and Durbachite belt can be distinguished. The new finds of Durbachite plutons (*s. l.*) in Bavaria (this paper) and close to the Danube between Linz and Krems (Fuchs 2005 – Fig. 2) have confirmed the existence of these two Durbachite lines even more clearly. The (ultra-)potassic magmas obviously used the tectonic uplift channels of the high-pressure rocks for their own ascent (Fig. 4a). Had the rocks of the Gföhl Unit been part of a large and coherent flat nappe on top of the Moldanubian Unit, as has been often suggested (Fig. 4b), the combined occurrence of deformed high-pressure rocks and undeformed plutons of the Durbachite suite would be very difficult to explain.

Closer to the contact with the Moravian Zone, the tectonic situation is rather that of a ramp (Fritz et al. 1996). However, the exhumation of the rocks of the Gföhl Unit probably also involved a channel flow mechanism (Racek et al. 2006). In Lower Austria, local backthrusts have lead to the formation of a synformal, bowl-like structure of the HP nappes (Fritz 1996). The underlying Drosendorf Unit (*s. s.*) has often been interpreted as a tectonic window and a continuation of the Moravian plate (Matura 1976; Finger and Steyrer 1995). As opposed to the previous, somewhat oversimplified tectonic models, in which the Dobra Gneiss of the Drosendorf Unit was seen as the direct underground continuation of the Moravian Bittesch Gneiss body, we suggest here that the Drosendorf Unit (*s. s.*) is an independent slice of the Moravian crust. The U–Pb zircon data of Gebauer and Friedl (1994) and Friedl et al. (2000) have shown that the Bittesch and Dobra gneisses have very different magmatic formation ages (*c.* 580 Ma vs. *c.* 1.4 Ga). However, inherited zircons and unusually unradiogenic Nd isotope ratios (Liew and Hofmann 1988) imply that both orthogneisses contain material from the same crustal source and hence belong most likely to the same terrane (Friedl et al. 2004).

Interestingly, there are distinct granitoid gneisses within the Lower Austrian Gföhl nappe complex (the Wolfshof Gneiss), which probably also represent former Durbachite-type plutons, as may be judged from their age (338 ± 4 Ma, Friedl et al. 1996) and their syenitic chemistry (Tab. 2). We believe that the magmatic protoliths of the Wolfshof Gneiss intruded in connection with the tectonic ascent of the surrounding Gföhl Gneiss/granulite nappe system, and were then included into the nappe tectonics on the “Moravian ramp”.

Regarding the LP–HT metamorphism at *c.* 335 Ma, it would appear that this has mainly occurred along the central axis of the Moravo–Moldanubian Fold Belt. Whether it can be explained in terms of radioactive heating and subsequent rapid exhumation of middle crust (Gerdes et al. 2000b) or whether extra heat input from the mantle is required (Henk et al. 2000), is presently an unresolved question. In terms of the model in Fig. 4, asthenospheric heating after slab break-off may provide a particularly attractive interpretation.

5.3. Variscan subduction zones

During recent years several attempts have been made to explain the magmatic and tectonometamorphic evolution of the Bohemian Massif in terms of modern plate tectonic models. There is wide agreement that, in the Devonian, a Saxothuringian oceanic domain was subducted from the (present day) north-west beneath the Teplá–Barrandian (Franke 1989; Zulauf 1997). According to Zulauf (1997) this subduction stage terminated at *c.* 370 Ma, when a Saxothuringian continental mass collided with the Teplá–Barrandian Unit, resulting in strong crustal thickening and widespread regional metamorphism. As opposed to this, Konopásek and Schulmann (2005) suggested that the Saxothuringian subduction system was active until *c.* 340 Ma, being responsible for the formation and NW-directed exhumation of Viséan HP rocks (e.g. the granulites of the Erzgebirge). The Central Bohemian Batholith is interpreted as a subduction-related magmatic arc in this model, which grew above the Saxothuringian subduction zone between *c.* 370 and 340 Ma (see also Janoušek et al. 2006 and references therein). Approximately the same tectonic scenario is suggested in the paper of Žák et al. (2005). Models of this kind are facing the problem that the sedimentary sequence preserved in the Barrandian records no major erosion stage at that time.

Janoušek and Holub (2007) went further and suggested that, during the Early Carboniferous, Saxothuringian continental crust was subducted far to the south-east under the Teplá–Barrandian and also under the Moldanubian, and then from there tectonically exhumed almost vertically as Gföhl Unit. In addition, these authors proposed that the Moldanubian lithospheric mantle became strongly enriched through fluids released from (and direct contamination by) subducted Saxothuringian continental material. Asthenospheric heating of this enriched mantle in a slab break-off environment is thought to have subsequently initiated the widespread (ultra-) potassic Durbachite magmatism at *c.* 338–335 Ma.

Finger and Steyrer (1995), on the other hand, have tried to describe the tectonic processes at the Moldanubian-Moravian boundary with a plate tectonic model, which involved the subduction of a Silurian–Devonian oceanic domain westwards (in present day coordinates) beneath the Moldanubian. They proposed that this "Raabs Ocean" separated the Moldanubian from the Moravian Zone until *c.* 345 Ma. The existence of a Late Devonian/Early Carboniferous oceanic basin between the Moravian and the Moldanubian is also supported by the sedimentary record in the Moravian Zone (Hladil et al. 1997). Unlike Janoušek and Holub (2007), Finger and Steyrer (1995) have suggested that the high-pressure rocks of the Gföhl nappe were brought out of this westerly dipping Moldanubian subduction zone.

Schulmann et al. (2005) put another model for discussion. They assumed that the HP–HT rocks of the Gföhl Unit are infolded portions of a Moldanubian lower crustal orogenic root, mobilized and uplifted due to their special rheological properties. Recent geochronological work has shown that the protoliths of the Gföhl Unit were mostly Early Palaeozoic granites (Friedl et al. 2004; Janoušek et al. 2004). The model of Schulmann et al. (2005) would therefore imply that the Moldanubian lower crust (i.e. the crust that underlies the Monotonous and the Variegated units) contains large amounts of Early Palaeozoic magmatic rocks. This is not unrealistic, because Early Palaeozoic intrusions (orthogneisses) are also present in the Monotonous and the Variegated units. On the other hand, the Durbachite–granulite connection can be better explained in a (B-type) subduction model (Janoušek and Holub 2007). The widespread occurrence of small peridotite lenses in the Gföhl Unit (Vrána et al. 1995) points in the same direction.

Many of the tectonometamorphic processes and crust/mantle interactions outlined in Janoušek and Holub (2007) could be accommodated into the Finger and Steyrer subduction model as well, as shown in Fig. 4a. This includes the tectonic ascent of deeply subducted crust after slab-breakoff, driven by buoyancy forces, and the formation of (ultra-)potassic magmas from metasomatized and contaminated mantle domains. Even the magmatic-arc-type plutonism in the Central Bohemian Batholith could be tentatively fitted into this model (Fig. 4a). Advantages and shortcomings of the two contrasting plate tectonic concepts need to be carefully assessed in future studies.

It remains to be discussed, what has happened to the Moldanubian crust (Monotonous Series, Variegated Series, Gföhl Unit) during the Devonian and the very Early Carboniferous (pre-345 Ma). This is an as yet fully unresolved question. If the Moravian–Moldanubian collision was preceded by the subduction of an intervening oceanic domain under the Moldanubian (Finger and Steyrer 1995), then it could be that a relatively long-lived active-plate-margin setting existed prior to the Viséan collisional stage. For instance, the MORB-type eclogites of the Ostrong Unit (O'Brien and Vrána 1997; Faryad et al. 2006) and other Moldanubian eclogites (e.g. Faryad et al. 2007) could have formed during this early subduction stage. Unfortunately, the Early Variscan history of the Moldanubian Zone is widely obscured by the Viséan Moravo–Moldanubian collisional phase and its anomalous thermal regime (HP–HT and LP–HT metamorphism), which may reflect asthenospheric heat addition after slab break-off (Fig. 4a). More information could perhaps be gathered through a systematic geochronological study of those Moldanubian rocks, which are considered to contain an inherited (Early Variscan or older) metamorphic paragenesis (see compilation of Vrána et al. 1995).

5.4. Palaeogeographic considerations

It is widely accepted today that the Moravian Zone was part of the southern margin of the "Old Red Continent" in the Devonian and connected with Baltica (Franke and Zelaznievicz 2000, 2002; Winchester et al. 2002; Navrocky and Poprawa 2006; Kalvoda et al. 2007). With the exception of the Drosendorf Unit (*s.s.*) in Austria, which may be an overthrust continuation of Moravian-type crust (Fig. 4a), the Moldanubian sector of the Bohemian Massif is commonly considered as part of the Armorican Terrane Assembly (Tait et al. 1997). In the Devonian, Armorica was separated from the Old Red Continent by the Rheiic Ocean (McKerrow et al. 2000). Finger and Steyrer (1995) proposed that the Variscan tectonometamorphic events recorded at the Moldanubian–Moravian boundary represented the frontal collision of the Bohemian segment of Armorica with the Moravian segment of the Old Red Continent. Silurian MORB-type amphibolites found at the base of the Gföhl Unit in Lower Austria (Finger and von Quadt 1995) have been interpreted as relics of oceanic crust of the Rheiic Ocean (Finger et al. 1998), while Edel et al. (2003) considered these rocks as continental rift basalts. Also, Schulmann et al. (2005) expressed doubts whether the Moravo–Moldanubian suture is "oceanic".

Interestingly, the Moravo–Moldanubian Fold Belt is today NNE–SSW oriented, i.e. roughly perpendicular to the southern margin of the Old Red Continent. This NNE orientation was probably one reason why Franke and Zelazniewicz (2002) have interpreted the Moravo–Moldanubian boundary as a Late Variscan transpressional fault zone and not as an oceanic suture in the plate tectonic sense. However, palaeomagnetic data indicate that at *c.* 330 Ma the whole Moravo–Moldanubian assembly and the Teplá–Barrandian block have rotated together for

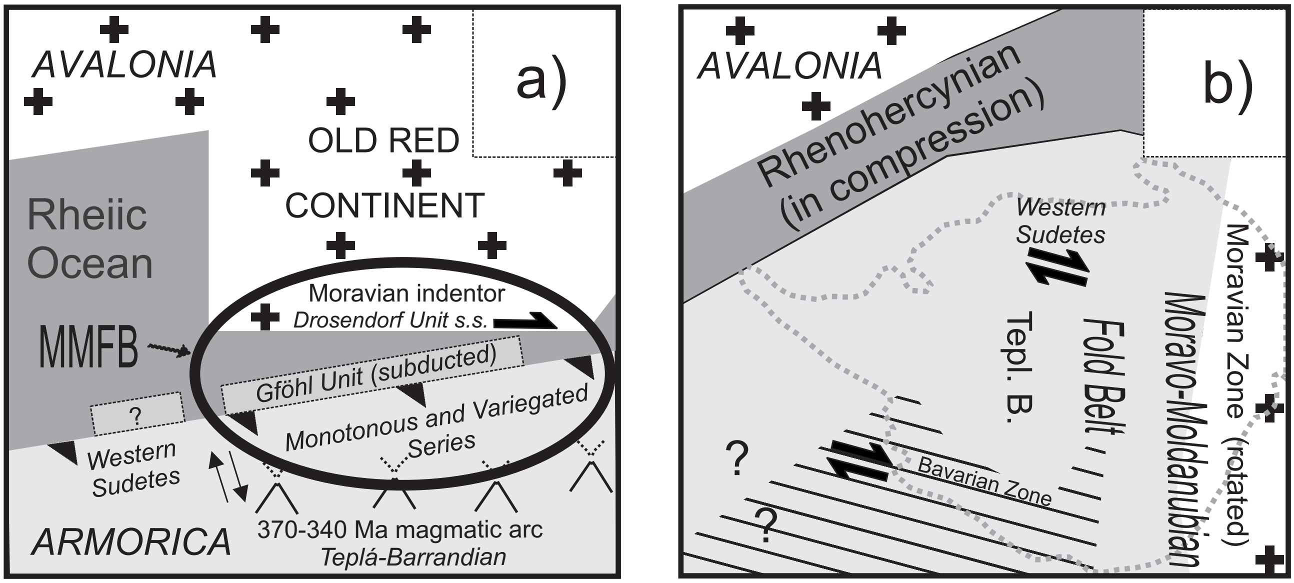

Fig. 5 Sketch illustrating the possible plate tectonic framework at *c.* 345 Ma (a) and *c.* 320 Ma (b). Following Franke and Zelazniewicz (2002) it is assumed that the Moravian Zone was part of the Old Red Continent and that Armorica approached from the south-east. However, unlike these authors we interpret the Drosendorf Unit (*s.s.*) as a marginal part of the Old Red Continent, and the Moldanubian sector of the south-eastern Bohemian Massif as a frontal part of Armorica. The ellipse outlines where the Moravo–Moldanubian Fold Belt (MMFB) is going to form. The Gföhl Unit is seen as an independent (and later subducted) Armorican microterrane. It may have rifted off from the Armorican mainland in the Early Palaeozoic. After the rotation stage around 330 Ma, the south-western parts of the Bohemian Massif were overprinted by the Bavarian Tectonometamorphic Phase (hatching in Fig. 5b). It is suggested that mantle lithosphere had peeled off in this area.

almost 90° in a clockwise direction, while the position of the Baltic craton remained roughly the same (Krs et al. 2001; Edel et al. 2003). This means that before the rotation occurred, the Moravo–Moldanubian Fold Belt was oriented roughly parallel to the margin of the Old Red Continent. Therefore, a tectonic interpretation of the Moravo–Moldanubian Fold Belt in terms of an oblique collision of Armorica and the Old Red Continent is feasible (Fig. 5). Whether or not the Gondwana megacontinent was already in contact with Armorica in the Early Carboniferous and pushed Armorica towards Baltica, has been controversially assessed (Tait et al. 2000; Edel et al. 2003, Linnemann et al. 2004).

The significant rotation of the Moravian Zone relative to the Baltic Craton at *c.* 330 Ma leads to the important conclusion that in the Moravo–Silesian area a major destabilization and tectonic rearrangement of the former southern margin of the Old Red continent must have had occurred. Such a concept has been proposed some years ago by Unrug et al. (1999), who emphasised that the basement below Moravia and Silesia should not be viewed as a coherent pre-Variscan block, as previously suggested by Dudek (1980). It was perhaps the forceful indentation of a further Armorican terrane in the east (the Lower Silesian Terrane of Unrug et al. 1999), that caused this fragmentation of the Old Red continental margin. The potential mid-Carboniferous disintegration of the Old Red continental margin in Silesia is hardly considered in the existing tectonic models for the Central European Variscides.

It also should be discussed whether the Saxothuringian sector of the Bohemian Massif has taken part in the Late Variscan clockwise rotation of the Moravo–Moldanubian Fold Belt. Edel et al. (2003) suggested that this was the case, and that almost the whole Variscides rotated relative to Baltica at that time. According to Edel et al. (2003) the movements were spatially compensated by the consumption of the Rheiic Ocean in the Rhenohercynian Zone. On the other hand, there are new palaeomagnetic data from the western Sudetes (Saxothuringian after Franke and Zelazniewicz 2000), which provide no indication for a Late Variscan rotation (Jelenska et al. 2003). The western Sudetes may therefore better be considered as an independent tectonic block. We speculate that this west-Sudetic sector of Armorica (which shows no record of a strong Viséan collisional metamorphism – Mazur and Kryza 1996) may have passed the Moravo–Moldanubian collision zone in the west and have slid northwards into a Sudetic Gulf of the Rheiic Ocean (Franke and Zelazniewicz 2002), while the Moravian Unit played the role of an indentor (Fig. 5). It is questionable whether the Saxothuringian rocks of the western Sudetes and the Saxothuringian rocks south of the Elbe Fault were in a close proximity at the beginning of the Carboniferous. Maybe they represent quite different pieces of Armorica. Also, the relation between the eastern Sudetes (Lugian domain – Štípská et al. 2001) and the south-eastern Bohemian Massif remains to be resolved. Generally it would appear to us that, in order to understand the Variscan evolution history of the Bohemian Massif, fully new terrane concepts (including a new and proper nomenclature) need to be developed and tested. The classic terms like Moldanubian or Saxothuringian may be of little help in this matter.

Acknowledgements The authors are indebted to the Austrian FWF and ÖAD, the AKTION/KONTAKT agency and the DFG. These institutions have funded several mutual research stays in the neighbouring countries, as well as joint field excursions. Without the trilateral input of regional knowledge from the Austrian, Czech and German sides of the Bohemian Massif this work would not have been possible. Many thanks to Hans Genser for informative discussions about the tectonic aspects of this paper and Malcolm Roberts for linguistic improvements. Stanislaw Mazur and an anonymous reviewer provided helpful comments and suggestions.

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