Journal of Structural Geology 36 (2012) 27–42

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Magmatic to solid state fabrics in syntectonic granitoids recording early Carboniferous orogenic collapse in the Bohemian Massif

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ARTICLE INFO

Article history:
Received 19 July 2011
Received in revised form
16 December 2011
Accepted 26 December 2011
Available online 3 January 2012

Keywords:
Bohemian Massif
Exhumation
Granite
Gravitational collapse
Teplá–Barrandian unit
Variscan orogeny

ABSTRACT

The ~354–336 Ma Central Bohemian Plutonic Complex is a Variscan magmatic arc that developed in the central Bohemian Massif in response to subduction of the Saxothuringian lithosphere beneath the Teplá–Barrandian microplate. Magmatic to solid state fabrics in the most voluminous portion of this arc (the ~346 Ma Blatná pluton) record two superposed orogenic events: dextral transpression associated with arc-parallel stretching and arc-perpendicular shortening, and normal shearing associated with exhumation of the high-grade core of the orogen (Moldanubian unit). This kinematic switch is an important landmark in the evolution of this segment of the Variscan belt for it marks the cessation of subduction-related compressive forces in the upper crust giving way to gravity-driven normal movements of the Teplá–Barrandian hanging wall block relative to the high-grade Moldanubian footwall. We use thermal modeling to demonstrate that the emplacement of huge volumes of arc magmas and their slow cooling produced a thermally softened domain in the upper crust and that the magmatic arc granitoids may have played a major role in initiating the orogenic collapse in the Bohemian Massif through lubrication and reactivation of a pre-existing lithospheric boundary and decreasing the overall strength of the rigid orogenic lid.

1. Introduction

Switches in the deformation regime from horizontal shortening to extension have been inferred to have occurred in the evolution of many orogenic belts. The existing explanations include gravitational collapse of thickened lithosphere, delamination of orogenic root, far-field changes in plate movements, or variations in slab roll-back during subduction (e.g., Dewey, 1988; Platt and Vissers, 1989; Henk et al., 2000; Rey et al., 2001; Collins, 2002; Lister and Forster, 2009). One of the major consequences of tectonic switching is the exhumation of originally deeply buried rocks and their juxtaposition against the upper-crustal units. Such major kinematic changes in the orogenic history have also been vigorously discussed for the Variscan belt in Europe, including the Bohemian Massif which represents the easternmost exposure of the orogen. The tectonic switch here was variously explained as a result of mantle delamination and gravitational collapse (e.g., Burg et al., 1994; Pitra et al., 1994; Zulauf, 1994; Lobkowicz et al., 1996; Büttner and Kruhl, 1997; Bues et al., 2002; Willner et al., 2002; Büttner, 2007; Dörr and Zulauf, 2010), far-field extension (Henk, 1999), or syn-convergent continental indentation (Schulmann et al., 2008, 2009; Franěk et al., 2011).

An excellent setting to study kinematic changes, timing, and mechanisms of juxtaposition of deep orogenic crust against the low-grade rocks, and thus to test the competing hypotheses on the nature of driving forces for tectonic switching in the interior of an orogen, is the central part of the Bohemian Massif. Here, a major lithotectonic and geophysically detected boundary intersects the orogen (Vrána and Štědrá, 1997; Hrubcová et al., 2005, 2010; Babuška et al., 2010) and separates the supracrustal Teplá–Barrandian unit (TBU) to the northwest from the mid- to lower-crustal rocks of the Moldanubian unit to the southeast (Fig. 1a). A broad zone along this boundary was intruded by the early Carboniferous Central Bohemian Plutonic Complex (CBPC), which represents a continental magmatic arc assembled during ~354–336 Ma (Fig. 1a and b; Holub et al., 1997a, b;

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doi:10.1016/j.jsg.2011.12.011

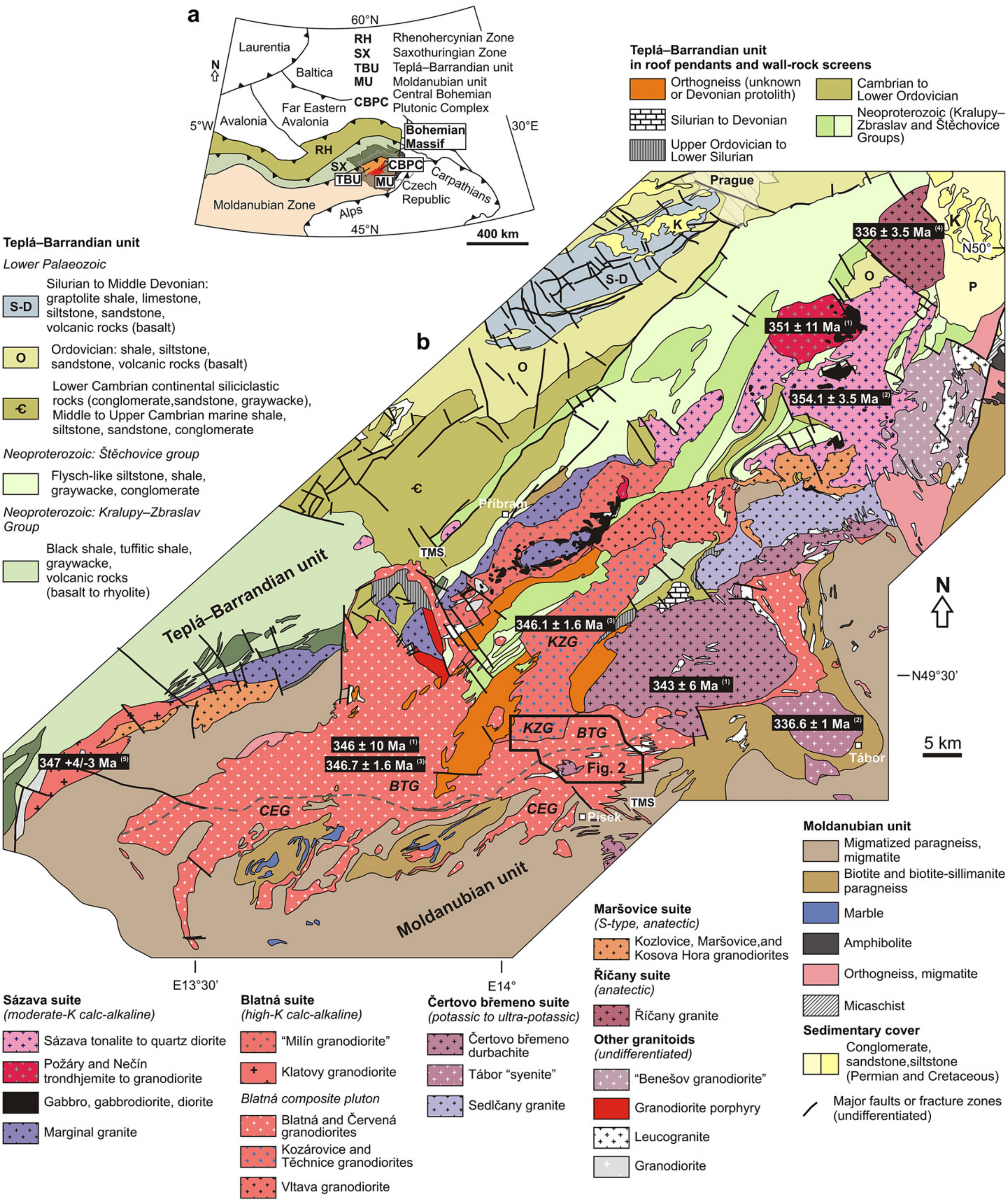

Fig. 1. (a) Simplified map showing principal plate-tectonic units of the Central European Variscan belt. The Saxothuringian/Teplá–Barrandian boundary (referred to as the Teplá suture) is interpreted as a SE-directed paleo-subduction zone; the Central Bohemian Plutonic Complex (CBPC) is a large, subduction-related continental magmatic arc that intruded the opposite (southeastern) flank of the Teplá–Barrandian unit (TBU) along the boundary with the Moldanubian unit. Redrafted from Winchester (2002). (b) Simplified geologic map of the Central Bohemian Plutonic Complex and its adjacent Teplá–Barrandian upper-crustal and Moldanubian lower- to mid-crustal host rocks. Geology based on Czech Geological Survey 1:200,000 maps (sheets Tábor, Strakonice, České Budějovice, and Plzeň) and Holub et al. (1997a). Quotation marks indicate geologic units that are poorly defined or include several granitoid types of uncertain age. Radiometric ages taken from: [1] Holub et al. (1997b), [2] Janoušek and Gerdes (2003), [3] Janoušek et al. (2010), [4] H. Maluski, unpublished data, cited in Janoušek et al. (1997), [5] Dörr and Zulauf (2010). BTG–Blatná granodiorite, CEG–Červená granodiorite (roughly corresponds to the Červená shear zone as defined in this study), KZG–Kozárovice granodiorite, TMS–thermal modeling section.

Janoušek et al., 1995, 2000, 2010). Structural relations and internal fabrics in the component intrusions of the plutonic complex indicate that they are syntectonic with ~354 to ~346 Ma arc-normal shortening/transpression in the upper crust and with the onset of exhumation of mid-crustal rocks at around 346 Ma (Žák et al., 2005a, b, 2009; Janoušek et al., 2010).

In this contribution we take an advantage of these granitoids recording the ~346 Ma orogen-scale tectonic switch and focus in detail on the key central part of the plutonic complex. Here, the high-K calc-alkaline Blatná composite pluton (Žák et al., 2005a), the largest component of the plutonic complex, is in intrusive contact with both the upper-crustal Teplá–Barrandian and mid- to lower-crustal Moldanubian units, and is continuously exposed from one contact to another along an ~18 km long, ~NW–SE-oriented transect (Fig. 2). Below we first describe field relations of the pluton to its host rocks, estimations of its emplacement depth through Al-in-hornblende barometry, structural and fabric data, anisotropy of magnetic susceptibility (AMS) of the granitoids, and microstructures including quartz microfabric determined using the electron back-scattered diffraction (EBSD). By integrating these data sets with thermal modeling of the pluton cooling, we constrain the kinematic setting of the granitoids during their emplacement and timing of the orogen-scale switch in the central Bohemian Massif. Finally, we discuss the possible driving forces in light of the present data compared to the existing models and we emphasize some broader implications for the Variscan orogenic processes in the Bohemian Massif.

2. Geologic setting and field relationships

This study concerns the 'heart' of the Central Bohemian Plutonic Complex, that is, its best exposed but also the most complex central part made up of the following principal geologic units (described from the ~NW to the ~SE; Fig. 2):

(1) The upper-crustal Teplá–Barrandian host rock is represented by the ~NE–SW-trending and generally steeply dipping Mirovice roof pendant (MRP in Fig. 2). Its southeastern margin, which is in contact with the granitoids, is composed of the Late Devonian Mirotice orthogneisses (Košler et al., 1993, 1995). Generally the roof pendant is characterized by low to medium grade of regional metamorphism corresponding to the lower greenschist to amphibolite-facies conditions.

(2) The Mirotice orthogneisses are intruded by the equigranular amphibole–biotite Kozárovice granodiorite and compositionally similar porphyritic Těchnice granodiorite. Although the pluton/host rock contact is not exposed, several thin host rock screens were mapped inside both granodiorites corroborating the intrusive nature of the contact. The Kozárovice granodiorite was dated at 346.1 ± 1.6 Ma using the U–Pb on zircon (Janoušek et al., 2010).

(3) To the south and southeast, the Kozárovice and Těchnice granodiorites are in contact with the Blatná granodiorite (amphibole-bearing biotite granodiorite to granite), which is the most widespread and compositionally relatively

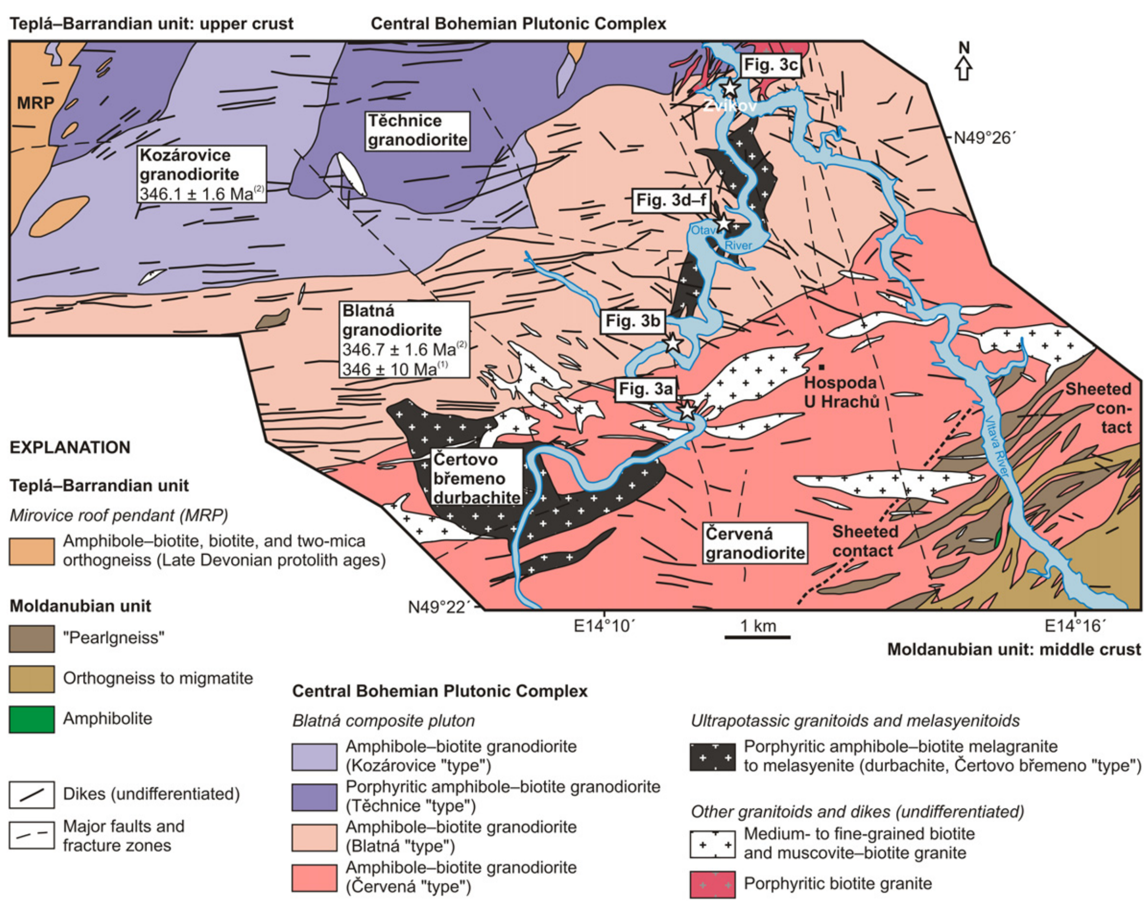

Fig. 2. Geologic map of the 'heart' of the Central Bohemian Plutonic Complex (see Fig. 1b for location). This area exposes intrusive contact of the Blatná composite pluton with the upper-crustal Teplá–Barrandian unit as represented by the Mirovice roof pendant (MRP) to the northwest and strongly sheeted intrusive contact with the mid-crustal (and relic lower-crustal) rocks of the Moldanubian unit (the Podolsko complex) to the southeast. Geology simplified from Czech Geological Survey 1:25,000 maps (sheets Oslov and Mirotice). Radiometric ages taken from: (1) Holub et al. (1997b) and (2) Janoušek et al. (2010).

homogeneous unit of the whole plutonic complex (Holub et al., 1997a; René, 1998). The contact between the Kozárovice/Těchnice and Blatná granodiorites is not exposed (?sharp intrusive; Žežulková et al., 1980), but their textural and compositional similarities suggest that these granitoids are broadly coeval. This notion is supported by the U–Pb zircon age of the Blatná granodiorite (346.7 ± 1.6 Ma, Janoušek et al., 2010; 346 ± 10 Ma, Holub et al., 1997b) which is almost identical to that of the Kozárovice granodiorite.

(4) The highly irregular southern margin of the Central Bohemian Plutonic Complex (Figs. 1b and 2) is made up of the strongly foliated, weakly porphyritic amphibole–biotite Červená granodiorite to melagranodiorite (Fig. 3a), interpreted as an outer, more mafic variety of the Blatná granodiorite (their contact is gradational; Žežulková et al., 1980; Holub et al., 1997a; René, 1999). The intrusive contact between the Červená granodiorite and the high-grade Moldanubian gneisses is a several kilometers wide (in plan view) sheeted zone. In detail, this zone consists of numerous granodiorite sheets, decimeters to a few hundreds meters thick, alternating with host rock screens in the same range of thickness, both trending ~NE–SW to ~ENE–WSW and dipping moderately (~40–60°) beneath the plutonic complex (Fig. 2).

(5) The granodiorites of the Blatná pluton were intruded by several km-sized irregular bodies and dikes of porphyritic amphibole–biotite melagranite to melasyenite, collectively referred to as the Čertovo břemeno 'durbachite' (343 ± 6 Ma; Holub, 1997; Holub et al., 1997b). Despite this radiometric age overlaps within errors with the ages of the Blatná and Kozárovice granodiorites, field cross-cutting relationships unequivocally establish that the 'durbachites' are younger than the Blatná granodiorite and also than the ~E–W dikes (Fig. 3b–e; Holub and Žežulková, 1978; Žežulková et al., 1980; Holub, 1997; Holub et al., 1997a). The melasyenite commonly encloses meter- to tens of meters-sized stoped blocks of the Blatná granodiorite and truncates magmatic fabric and dikes within the blocks (Fig. 3d, e). Unlike the Blatná and Červená granodiorites, the Čertovo břemeno melasyenite has not largely been affected by pervasive solid state deformation in this area and commonly exhibits either a random or local magmatic fabric defined by K-feldspar phenocrysts (Fig. 3d–f).

(6) The Moldanubian rocks in the sheeted zone occur as thin screens within the Červená granodiorite and comprise amphibolite-facies gneisses of unknown protolith ages, stromatic migmatites, amphibole–biotite and biotite orthogneisses, and minor lenses of amphibolite. Altogether, these rocks have been assigned to the Podolsko complex (Kodym, 1966), a polymetamorphic unit involving retrogressed high-pressure granulites and mantle-derived ultrabasic rocks (Fišera et al., 1982; Kotková et al., 1997).

3. Al-in-hornblende barometry and emplacement depth of the Blatná pluton

The presence of andalusite porphyroblasts in contact metamorphic hornfelses and mica schists of the Mirovice roof pendant (Žežulková et al., 1985) suggests pressure below 0.375 GPa (Holdaway and Mukhopadhyay, 1993) and the emplacement depth of the Blatná pluton not exceeding ~13 km. To better constrain the emplacement depth of the pluton, we use the Al-in-hornblende barometry (e.g., Hammarstrom and Zen, 1986; Hollister et al., 1987; Schmidt, 1992; Anderson and Smith, 1995); the data are provided in the Supplementary material to this article, Part 1.

Amphiboles in the granodiorites generally correspond to magnesiohornblende (classification of Leake et al., 1997) with Mg > Fe_{tot} in atomic values and occur in three varieties:

(1) Magnesiohornblende containing 7.2–8.4 wt.% Al_2O_3 and 0.9–1.6 wt.% TiO_2. This variety is common in the Kozárovice granodiorite but can also be found in more acid samples of the Blatná granodiorite. The hornblende–plagioclase thermometry (Holland and Blundy, 1994) yields equilibration temperatures well above the wet granite solidus, and the textural criteria suggest that this most Al-rich variety crystallized relatively early (denoted as 'early magmatic' in the supplementary table), perhaps even before the granodiorite magma arrived at the final emplacement level. Pressure calculation according to Anderson and Smith (1995) considering higher than near-solidus crystallization temperature is necessary.

(2) Magnesiohornblende with lower contents of Al_2O_3 (commonly 5.5–6.1 wt.%) and TiO_2 (0.65–0.8 wt.%) which may represent a late-magmatic phase co-existing with all the required minerals including quartz. However, according to the hornblende–plagioclase thermometry (Holland and Blundy, 1994) it equilibrated under temperatures up to 50 °C below the wet granite solidus for an appropriate pressure. In the supplementary table these amphiboles are denoted as 'submagmatic'.

(3) The SiO_2-rich magnesiohornblende occassionally passing into actinolite is typical of the Červená granodiorite. This variety is poor in TiO_2 and alkalis but is comparably more magnesian and forms individual grains, clots probably replacing clinopyroxene, and narrow rims on other amphibole varieties. Its textural position and composition thus typify subsolidus amphiboles; these late amphiboles are presented only for comparison.

Consequently, only selected results of the Al-in-hornblende barometry using the experimental calibration by Schmidt (1992) and its temperature-corrected modification by Anderson and Smith (1995) are presented in the supplementary table. Hornblendes of the first compositional group yield systematically higher pressures (commonly 0.25–0.3 GPa corresponding to 9–11 km) than the second group (about 0.2–0.22 GPa, ~8 km). Taken together, as both amphibole groups have their own limits on applicability of the Al-in-hornblende barometry, we regard ~8–10 km as a plausible estimation of the emplacement depth of the Blatná pluton.

4. Magmatic to solid state fabrics in the granitoids

Below we describe mesoscopic hypersolidus to solid state fabrics in the granitoids (determined using the criteria in Paterson et al., 1989) along a traverse from the Teplá–Barrandian to the NW to the Moldanubian host rocks to the SE (Fig. 4).

Hypersolidus mineral foliation, defined by the planar shape-preferred orientation of biotite flakes and feldspar and quartz grains, is steep and strikes ~NNE–SSW to ~ENE–WSW in the Kozárovice granodiorite (Fig. 4a and b). Only in some domains in the porphyritic Těchnice granodiorite, a flat-lying foliation (dip <30°) defined by K-feldspar phenocrysts has been preserved and is in some places overprinted by the steep foliation in the matrix. In the map, the steep foliation is also at a high angle to the ~E–W- or ~NE–SW-striking contact between the two granodiorite varieties (Fig. 4a). Near the granodiorite/Teplá–Barrandian host rock contact, the steep magmatic foliation grades into submagmatic and subsolidus foliation which is subparallel to the schistosity in the Mirotice orthogneiss (Fig. 4a). Magmatic to subsolidus lineation, defined by the linear shape-preferred orientation of hornblende and

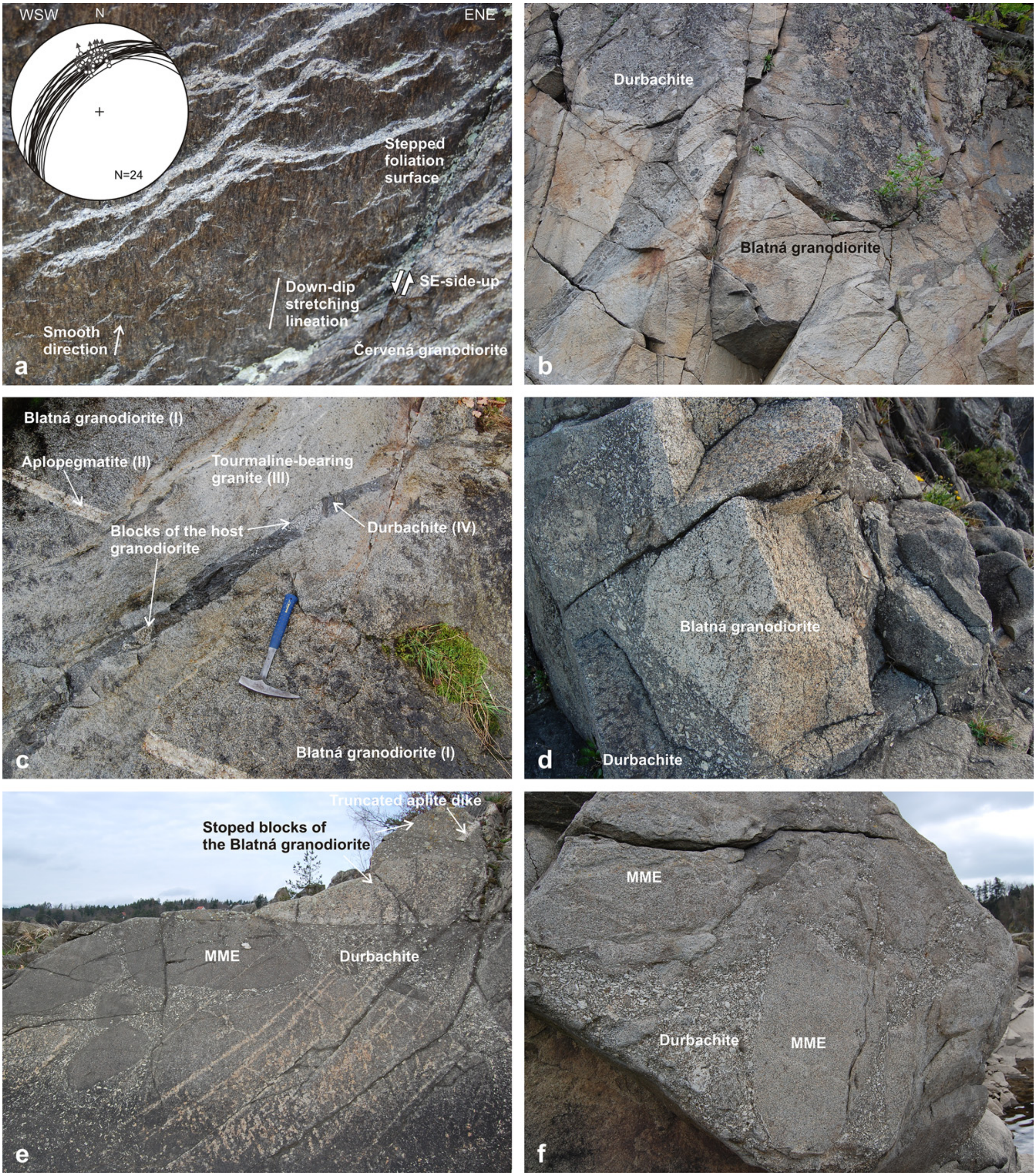

Fig. 3. Solid state deformation in the Červená shear zone and intrusive relationships that corroborate post-kinematic emplacement of the Čertovo břemeno durbachites into the Blatná granodiorite; see Fig. 2 for the location of outcrops. (a) Solid state foliation planes bearing a down-dip stretching lineation associated with the normal SE-side-up kinematics; Výří skály u Oslova. Stereonet shows orientation of foliation planes, stretching lineation, and kinematics on this locality (arrows indicate movement of the hanging wall, lower hemisphere, equal area projection). (b) Intrusion of durbachite into the Blatná granodiorite along irregularly-shaped cracks. Approximate height of the outcrop is 3 m. Cliff above the Otava River, Křivice. (c) Thin durbachite sheet emplaced into the center of a tourmaline-bearing granite dike, all host by the relatively oldest Blatná granodiorite. Letters *I–IV* denote the inferred emplacement sequence; Zvíkov. Hammer for scale. (d) Angular stoped block of the Blatná granodiorite in durbachite, magmatic foliation defined by feldspar phenocrysts wraps around the block; Štědronín-Plazy. (e) Accumulation of mafic microgranular enclaves (MME) and stoped blocks of the Blatná granodiorite in durbachite; Štědronín-Plazy. (f) Accumulation of mafic microgranular enclaves (MME) in durbachite, magmatic foliation in the host durbachite is defined by feldspar phenocrysts and is parallel to the enclave margins; Štědronín-Plazy.

stretched quartz aggregates, respectively, plunges shallowly to the ∼NNE to ∼NE or ∼SSE to ∼SE.

In terms of orientation, the dominant magmatic to submagmatic foliation in the Blatná granodiorite is similar to that of the Kozárovice granodiorite (steep, ∼NNE–SSW to ∼NE–SW strike; Fig. 4a and c). This foliation is associated with a lineation plunging shallowly to moderately to the ∼NNE. In some places, a magmatic to subsolidus foliation, however, dips moderately to the ∼NW (Fig. 4c) and is associated with a down-dip, NW-plunging lineation.

In contrast, a magmatic to submagmatic foliation is preserved only rarely in the Červená granodiorite. This granodiorite has been pervasively overprinted by a subsolidus foliation dipping moderately to the ∼WNW to ∼NNW, bearing a mineral stretching lineation plunging moderately to the ∼NNW (Fig. 4a and d). Macroscopic kinematic indicators, such as S–C relationships and asymmetric K-feldspar porphyroclasts, indicate normal (SE-side-up) movement associated with this subsolidus deformation (Figs. 3a and 4e). The subsolidus fabric in the Červená granodiorite thus defines a pluton-scale normal shear zone (Fig. 1b) that accommodated the downdrop of the upper-crustal Teplá–Barrandian unit relative to the mid-crustal Moldanubian unit (Fig. 4e). In this paper, we introduce a new name 'the Červená shear zone' for this shear zone to clearly distinguish it from the 'Central Bohemian Shear Zone', a term that has been used rather ambiguously for every possible sense of movement thought to occur along the Teplá–Barrandian/Moldanubian boundary during the Variscan orogeny (Rajlich, 1987, 1988; Rajlich et al., 1988; Matte et al., 1990; Košler et al., 1995; Pitra et al., 1999; Scheuvens and Zulauf, 2000; Dörr and Zulauf, 2010).

5. Anisotropy of magnetic susceptibility (AMS)

The AMS method (see Hrouda, 1982; Jackson and Tauxe, 1991; Tarling and Hrouda, 1993; Bouchez, 1997; Borradaile and Henry, 1997; Borradaile and Jackson, 2004, 2010 for reviews) is used here to expand on the fabric data collected in the field and to quantify gradients in fabric parameters across all the granitoids. The AMS data are presented concisely in Fig. 5 and in full in the Supplementary material to this article (Parts 2–6).

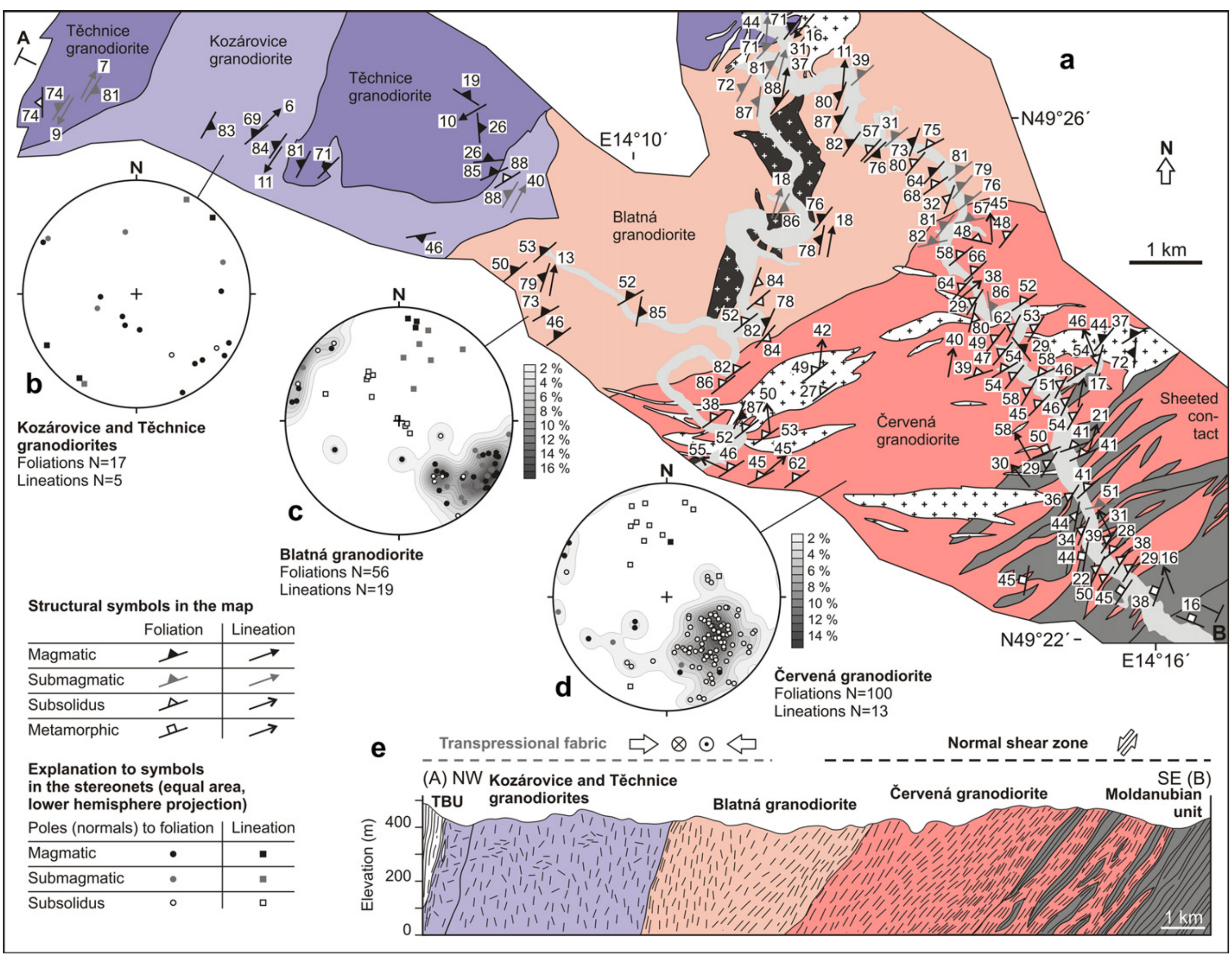

Fig. 4. (a) Structural map showing magmatic and solid state foliations and lineations across the granitoids of the Blatná composite pluton. (b–d) Stereonets (equal area projection, lower hemisphere) summarizing foliations and lineations in each intrusive unit. (e) Interpretative structural cross-section along line A–B showing transition from transpressional magmatic and solid state fabric near the northwestern margin of the Blatná pluton to the normal Červená shear zone that overprints the southeastern pluton margin including the sheeted contact with the Moldanubian gneisses.

5.1. Magnetic mineralogy

The bulk susceptibility of the granodiorites is low, on the order of 10^{-4} (SI units are used throughout this paper); the lowest bulk susceptibility in the range of $100–300 \times 10^{-6}$ was measured in the Blatná and Červená granodiorites (Supplementary material, Part 4). Such a low bulk susceptibility of the measured specimens suggests that the AMS signal is dominated by paramagnetic minerals. This notion is further supported by the theoretical paramagnetic susceptibility which was calculated for the Blatná and Červená

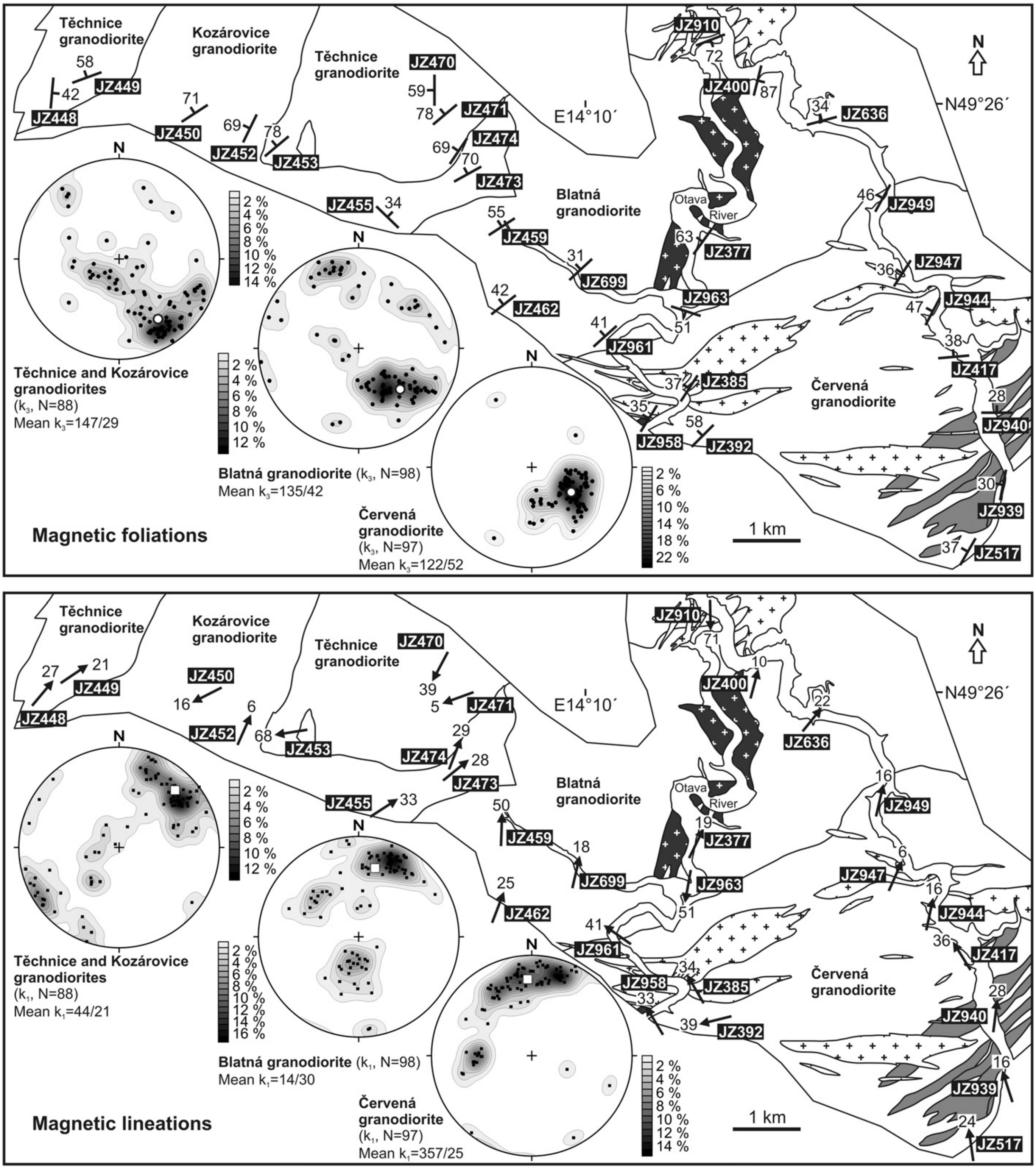

Fig. 5. Map of the mean magnetic foliations and lineations in the Blatná composite pluton. Lower hemisphere, equal area projections summarize orientation of the maximum and minimum principal susceptibilities of all specimens including the respective mean values. Station numbers are given in black rectangles; the full list of the AMS parameters at each station is included in the Supplementary material to this article.

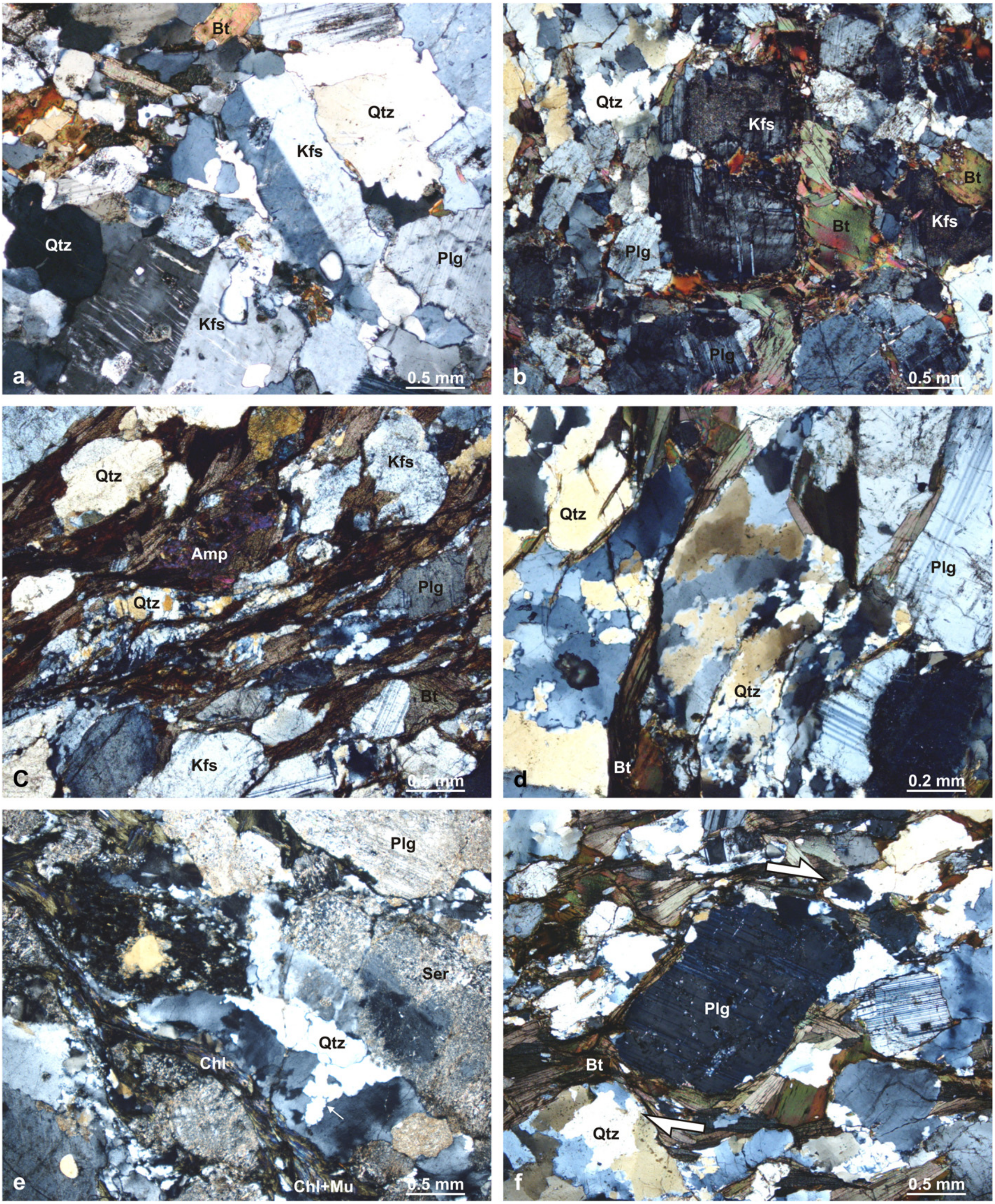

Fig. 6. Magmatic to solid state microstructures in granodiorites of the Blatná composite pluton (see Fig. 7 for location). All micrographs were taken in crossed polars; mineral abbreviations after Kretz (1983). (a) Magmatic microstructure of the Blatná granodiorite (station JZ910). (b) Submagmatic microstructure preserved in a low-strain domain of the Červená granodiorite (station JZ932). (c) Microstructures of high-temperature solid state deformation in the Červená granodiorite (station JZ915). (d) Close-up view of the sutured grain boundaries in the recrystallized quartz aggregates in the Červená granodiorite (station JZ933). (e) Microstructures resulting from low-temperature (greenschist facies) solid state deformation in the Červená granodiorite (station JZ922). The arrow points to bulging grain boundaries in a quartz aggregate. (f) Example of micro-scale kinematic indicators (rotated feldspar porphyroclasts and asymmetrically anastomosing biotite folia in the foliation-perpendicular and lineation-parallel section) that indicate normal kinematics associated with solid state fabric of the Červená shear zone (station JZ933, see Fig. 7 for location).

granodiorites from the contents of Fe_2O_3, FeO, and MnO (Supplementary material, Part 5) using the formula given in Hrouda et al. (2009) and fits well the measured susceptibilities.

For further analysis of magnetic mineralogy and carriers of the AMS, natural remanent magnetization (NRM) was measured on 16 specimens and the variation of susceptibility with temperature on 6 specimens (Supplementary material, Parts 4, 5). The NRM results corroborate the absence of ferrimagnetic or antiferromagnetic minerals with the exception of specimens JZ455 (the Kozárovice granodiorite) and JZ958 (the Červená granodiorite) that exhibit high Q-coefficients suggesting the presence of pyrrhotite.

The temperature variations of susceptibility from −195 to 0 °C follow a hyperbolic course with no sign of the Verwey or Morin transitions (Supplementary material, Part 4), which excludes the presence of pure magnetite or hematite. The temperature variations of susceptibility from 20 °C to 700 °C also indicate hyperbolic relationships between susceptibility and temperature. In specimen JZ455/3/1 (the Kozárovice granodiorite), the heating curve shows a slight but steep decrease in the bulk susceptibility at 320 °C corresponding to pyrrhotite, and the susceptibility increases above 400 °C due to newly formed magnetite-like and maghemite-like minerals with the Curie temperatures (T_C) of about 530 °C and 600 °C. In specimen JZ448/1/1 (the Těchnice granodiorite), the T_C above 480 °C indicates the presence of a primary ferrimagnetic mineral (maghemite or magnetite). Above this temperature, new magnetite forms and determining the T_C of primary magnetic minerals is not possible. The temperature variations of susceptibility of specimens JZ910/2/1 (the Blatná granodiorite) and JZ392/2 (the Červená granodiorite) reveal, in spite of low bulk susceptibility of these rocks, that they also contain a minor admixture of a ferromagnetic mineral with the T_C near 480 °C. A small amount of ferromagnetic minerals with the T_C of 350–400 °C can also be considered in specimens JZ473/3 (the Kozárovice granodiorite) and JZ939/1/5 (the Červená granodiorite).

In summary, although the granodiorites may contain a small amount of ferromagnetic minerals contributing to the total susceptibility by less than 25%, rocks with bulk susceptibilities below 300×10^{-6} can be considered as chiefly paramagnetic.

5.2. Magnetic fabric parameters and orientation

In the Kozárovice and Těchnice granodiorites, the degree of anisotropy varies from 1.018 to 1.617 but is low for most of the analyzed specimens (97% of the specimens exhibit less than 10% anisotropy, $P > 1.1$). The T parameter ranges from −0.827 to 0.941, 57% of the specimens indicate a prolate shape of the AMS ellipsoid (Supplementary material, Part 4). Magnetic foliations strike ~SSW to ~SW and dip steeply to the ~NW (mean strike/dip is 237°/61°; Fig. 5). At a few sampling sites, magnetic foliations are subhorizontal (stations JZ455 and JZ471) or the k_3 axes scatter widely around the mean k_1 axis (stations JZ448 and JZ470; Fig. 5). Magnetic lineations plunge shallowly to the ~NE–SW or to the ~NNE–SSW (mean trend/plunge is 44°/21°; Fig. 5).

The degree of anisotropy of the Blatná granodiorite is comparable to that of the Kozárovice and Těchnice granodiorites ($P = 1.011–1.125$) but the shape parameter is slightly less scattered ($T = -0.676–0.819$; Fig. 6b). Shape of the AMS ellipsoid is both prolate (57% specimens) and oblate (Supplementary material, Part 4). Except for two stations with anomalous orientations of the principal susceptibilities (JZ910, JZ963), magnetic foliations dip steeply to moderately to the ~NW (mean strike/dip is 225°/48°) and magnetic lineations plunge shallowly to the ~NNE (mean trend/plunge is 14°/30°) or moderately to the NW (station JZ961; Fig. 5).

Compared to the above granitoids, the Červená granodiorite exhibits a slightly elevated degree of anisotropy ($P = 1.052–1.175$) and mostly oblate shapes of the AMS ellipsoid (90% of the analyzed specimens); the shape parameter ranges from −0.250 to 0.891 (Supplementary material, Part 4). The k_3 axes show a strongly clustered orientation distribution, corresponding to magnetic foliations dipping moderately to the ~NW (the mean strike/dip is 212°/38°; Fig. 5). Magnetic lineations plunge shallowly to moderately to the ~NNE–NNW (a broad cluster in the stereonet about the mean k_1 357°/25°; Fig. 5). At one station (JZ392), magnetic lineations plunge moderately to the W (subordinate maximum in the stereonet in Fig. 5).

6. Microstructural gradient and quartz microfabric across the Blatná pluton

6.1. Microstructures

Microstructures were examined along the Vltava River valley which exposes continuously the Blatná and Červená granodiorites and the sheeted contact with the Moldanubian gneisses (Figs. 6 and 7). Four types of microstructure were identified in the granodiorites using the criteria of Paterson et al. (1989) and Vernon (2000, 2004).

(1) Magmatic microstructures, found at the northwestern margin of the Blatná granodiorite (Fig. 7), are characterized by euhedral to mostly subhedral grains of K-feldspar, plagioclase, amphibole, and biotite set in interstitial quartz, plagioclase, and biotite (Fig. 6a). The euhedral to subhedral grains commonly exhibit shape-preferred orientation (magmatic fabric) and along with the interstitial grains show no evidence of solid state deformation or recrystallization (Fig. 6a).
(2) Submagmatic microstructures, documented in the Blatná granodiorite (Fig. 7), preserve relics of magmatic features superposed by weak crystal-plastic deformation and recrystallization (Fig. 6b). The initial stages of crystal-plastic deformation and recrystallization are preferentially localized into quartz and biotite aggregates that occur along boundaries of larger grains and in synmagmatic fractures in feldspar (Fig. 6b). Quartz grains (0.1–0.4 mm in size) commonly show undulose extinction, blocky subgrains defined by prismatic and basal subgrain boundaries (chessboard pattern), elongate subgrains, and sutured grain boundaries in stretched aggregates (Fig. 6b and c), suggesting deformation at near solidus temperatures. Some of the biotite grains have been kinked. Feldspars were the strong phase at this stage as documented by their synmagmatic cracking and no evidence for crystal-plastic deformation. However, myrmekite growth textures and flame perthites can locally be observed.
(3) High-temperature (>450 °C) subsolidus microstructures characterize the Červená granodiorite across its entire width (Fig. 7). This type of microstructure is defined by the presence of anastomosing folia of dynamically recrystallized biotite and quartz aggregates wrapping around larger feldspar grains, recrystallized aggregates of quartz and, to a lesser degree, also feldspar showing both irregular and lobate subgrain boundaries, mechanical twinning and deformation lamellae, and abundant myrmekite and flame perthite (Fig. 6d).
(4) Low-temperature (<450 °C) subsolidus microstructures were identified in narrow zones within the Červená granodiorite (Fig. 7). Here, biotite aggregates are largely replaced by chlorite, K-feldspars are extensively sericitized, and quartz aggregates display bulging grain boundaries (Fig. 6e), all suggesting the greenschist facies conditions of deformation.

Importantly, the high- to low-temperature subsolidus microstructures in the Červená granodiorite are associated with normal

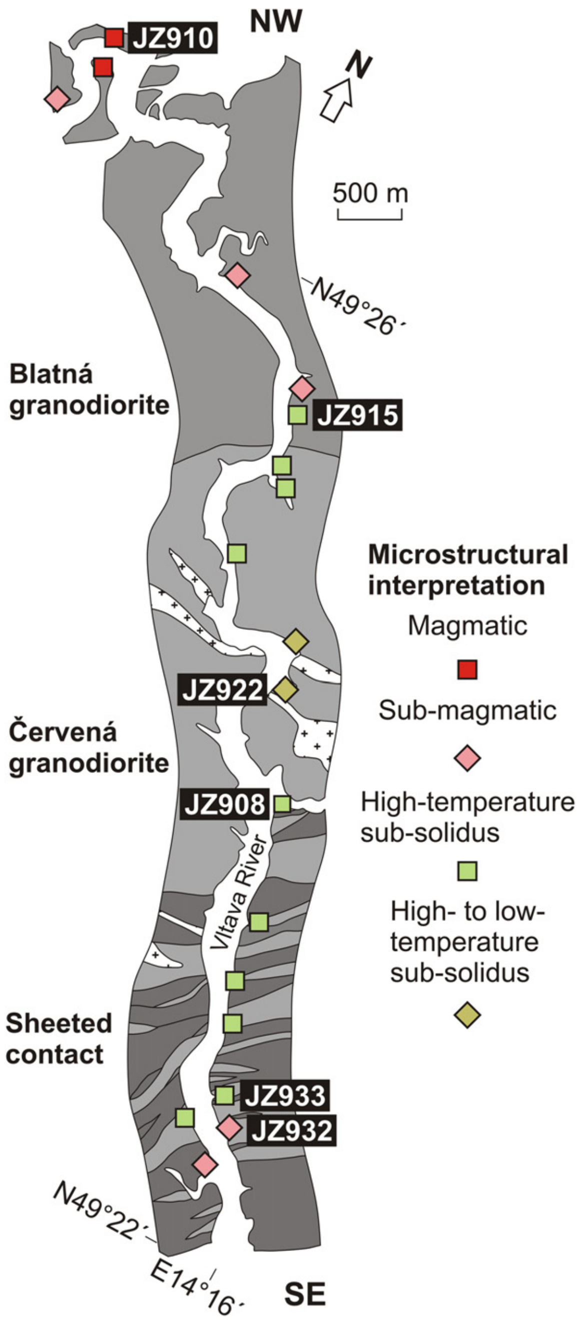

Fig. 7. Simplified geologic map and microstructural interpretation along the Vltava River valley to show the gradient from magmatic microstructures in the Blatná granodiorite to the northwest to high- and low-temperature solid state microstructures in the Červená granodiorite to the southeast.

kinematics consistent with the macroscopic shear-sense indicators. Most common asymmetric microstructures in the foliation-perpendicular and lineation-parallel section are σ-type feldspar porphyroclasts with 'tails' of recrystallized quartz and sigmoidal folia of biotite and dynamically recrystallized quartz aggregates that anastomose around the porphyroclasts (Fig. 6f).

6.2. *Quartz c-axis microfabric*

In order to further characterize the approximate temperature conditions of deformation associated with normal shearing along the Červená shear zone, the lattice preferred orientation of quartz was analyzed using the electron back-scattered diffraction method (EBSD; Prior et al., 1999) in two samples taken at the opposite margins of this zone (Fig. 7; see Supplementary material, Part 2, for the description of methodology).

Sample JZ915 is a granodiorite with high-temperature subsolidus microstructure (type 3 described above) from within the gradational boundary between the Blatná and Červená granodiorites at the northwestern margin of the shear zone (Fig. 7). The c-axis pattern is characterized by multiple maxima defining small circles about the *X* axis. One circle is well-defined and consists of three pronounced maxima, the other one is ill-defined and comprises four weak submaxima (Fig. 8a). In addition, two *c*-axes maxima of variable intensity lay close to the *Z* axis of the stereonet. Such a *c*-axis pattern corresponds to the dominant activity of prism <*c*> slip system typical for high temperatures and hydrous conditions of deformation (Blumenfeld et al., 1986; Gapais and Barbarin, 1986; Mainprice et al., 1986; Kruhl, 1996; Morgan and Law, 2004).

Sample JZ933 is the Červená granodiorite exhibiting the high-temperature subsolidus deformation microstructure (type 3 described above) taken at the southeastern margin of the shear zone (Fig. 7). The c-axes define a pronounced single girdle that is oblique at an angle of about 45° to the foliation plane. The girdle consists of two subordinate maxima close to the periphery of the stereonet and one prominent maximum close to the *Y* axis (Fig. 8b). Two additional minor c-axis maxima are close to the *XZ* plane and roughly perpendicular to the girdle. The maxima distributions are consistent with the dominant activity of prism <*a*> and could be interpreted in terms of non-coaxial deformation at medium temperatures and/or high strain rates (Schmid and Casey, 1986; Law, 1990; Law et al., 1992; Passchier and Trouw, 2005).

7. Modeling the thermal evolution of the Blatná pluton

Transient finite element analysis was carried out to estimate the evolution of the thermal field in a broader zone across the Blatná composite pluton and its Teplá–Barrandian and Moldanubian host rocks and to examine time scales for tectonic processes recorded in the granitoids. Given the elongated shape of the modeled geologic units, the analysis was performed in two dimensions, considering a representative vertical section (Fig. 9) along line indicated as TMS in Fig. 1b. The initial conditions involved the assumption of synchronous magma emplacement, which is in concert with the field relationships and geochronologic data. Uniform temperature of 800 °C was prescribed to the Blatná composite pluton (subdomain [5] in Fig. 9), the emplacement depth was set at 8–10 km according to the Al-in-hornblende barometry (Section 3). Geothermal gradient of 35 °C/km with the surface temperature of 20 °C was assigned to the 'cold' pluton roof (subdomains [1], [2] and [3] in Fig. 9). The initial temperature of the Moldanubian 'hot' middle crust (subdomain [5] in Fig. 9) also linearly increased with depth with a gradient of 35 °C/km. However, the thermal profile was shifted so that the initial temperature at a depth of 8 km was 650 °C to simulate the presumed rapid near-isothermal exhumation of the hot mid-crustal rocks. The latter assumption is also consistent with the melasyenite magmas mingled with migmatic melts in some places south of the Červená shear zone (Holub, 1997). As the boundary conditions, we prescribed the geothermal heat flux of 0.06 W/m^2 along the lower horizontal boundary and ground to air convection with coefficient of 20 W/m^2/°C along the upper surface. The ambient air temperature was assumed constant and equal to 20 °C. Zero normal heat flux was assigned to the northwestern and southeastern vertical boundaries to simulate that the whole body extended well beyond the boundaries of the model.

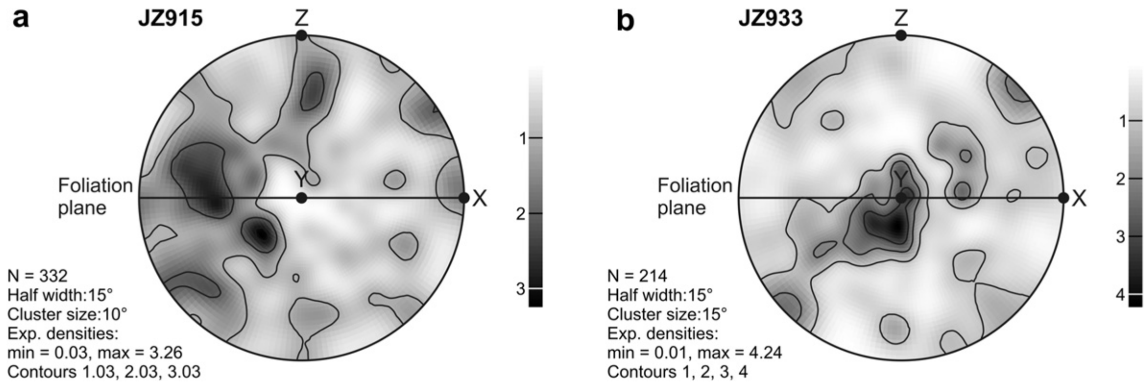

Fig. 8. Lower hemisphere, equal area projection of quartz *c*-axis orientations in granodiorites from the (a) northwestern and (b) southeastern margins of the Červená shear zone. The c-axes are plotted with respect to the sample reference frame where *Z* denotes pole to the foliation plane and *X* stands for lineation. See Fig. 7 for the location of stations.

In the numerical analysis we neglected convection by flux of hydrothermal fluids and heat production during crystallization. The heat transfer was thus represented by conduction only. Heat capacity ρc and conductivity k were considered to be temperature-dependent (Supplementary material, Part 7). The general trend of this dependency was obtained by approximating data from Vosteen and Schellschmidt (2003). The curves were then scaled for each type of rock to match the capacity and conductivity at the reference temperature (Supplementary material, Part 8).

As a result of the thermal analysis, the evolution of the temperature field throughout the modeled domain was obtained (see animation in the Supplementary material, Part 9). The thermal field is portrayed in Fig. 9 in four time increments (after 100 ky, 500 ky, 700 ky, and 1 My) and clearly shows the thermal anomaly that developed in the Teplá–Barrandian upper crust as a result of emplacement and prolonged magmatic 'life time' of the Blatná composite pluton.

Supplementary video related to this article can be found at doi: 10.1016/j.jsg.2011.12.011.

8. Discussion

8.1. The significance of magmatic to solid state fabrics in the Blatná pluton

We interpret the magmatic to solid state fabrics in the Blatná composite pluton as recording two strikingly different deformation regimes. The Kozárovice and Blatná granodiorites are dominated by the ∼NNE–SSW to ∼NE–SW steep hypersolidus foliation and the ∼NNE–SSW to ∼NE–SW subhorizontal lineation (Fig. 4). These two regional fabric elements record heterogeneous dextral transpression associated with the ∼NNE–SSW to ∼NE–SW principal (arc-parallel) stretching and ∼WNW–ESE to ∼NW–SE (arc-perpendicular) shortening in the central part of the CBPC and its adjacent Teplá–Barrandian host rocks (Žák et al., 2009). In contrast, the Červená granodiorite exhibits the ∼N- to ∼NW-dipping hypersolidus to chiefly high-temperature subsolidus foliation (Figs. 6d, 7 and 8) associated with the ∼NW-trending (down-dip) to dip-oblique (∼N-trending) lineation and normal kinematics (Teplá–Barrandian and CBPC down, Moldanubian up; Figs. 3a, 4 and 6f).

This change in the deformation regime and kinematics can also be seen in the AMS data which show consistent reorientation of the mean principal susceptibilities along a transect from the NW to the SE (Fig. 5). Accordingly, the shape of the AMS ellipsoid changes from prolate and oblate to predominantly oblate while the degree of anisotropy is systematically elevated in the Červená granodiorite (Supplementary material, Parts 4 and 6). Given the little differences in the magnetic mineralogy among the granodiorites, which are dominated by paramagnetic minerals (Section 5.1), this magnetic fabric gradient could be interpreted to reflect the increasing magmatic to solid state strain intensity toward the Červená shear zone (see also Figs. 4, 6a–e, 7).

Hence, it can be inferred that the switch from transpression to normal movements was associated with the rotation of principal strain axes from the ∼NE–SW subhorizontal principal stretching parallel to the TBU margin to stretching inclined to the N to NW, that is, below the TBU margin (Figs. 3a, 4 and 5). These inferences are also consistent with the ∼E–W dikes that cut across the Kozárovice and Blatná granodiorites (but not the durbachites; Fig. 2) and that may represent the ∼N–S brittle extension of the already cooled northwesterly granodiorites while the southeastern margin of the pluton was still 'hot' and deformed ductilely (Figs. 7–9).

Combining the published radiometric ages with our structural and AMS data (Figs. 4 and 5), microstructural analysis (Figs. 6–8), and thermal modeling (Fig. 9), we conclude that the kinematic switch from transpression to normal shearing must have commenced within the prolonged magmatic 'life time' of the ∼346 Ma Blatná composite pluton (at least 1 My according to our thermal modeling; Fig. 9). The ductile normal shearing then continued under the high-temperature to greenschist facies conditions (Figs. 6c–e, 7, 8) and ceased before the emplacement of durbachites in this part of the CBPC (note that they were at least partly synchronous with the normal shearing elsewhere; Žák et al., 2005a). The durbachites, which were collectively interpreted as representing a short-lived magmatic event in the Variscan orogeny at ∼335–343 Ma (Finger et al., 2007; Janoušek and Holub, 2007; Verner et al., 2008; Kusiak et al., 2009; Kotková et al., 2010), intrude across the margin of the Červená shear zone (Fig. 2), are discordant to the fabrics in the Blatná granodiorite (Fig. 3b–e), and have not been affected here by any tectonic deformation (Fig. 3d–f). The cessation of ductile normal shearing is also bracketed by the ∼337 Ma Tábor melasyenite pluton that intrudes discordantly the Moldanubian gneisses southeast of the Červená shear zone (Fig. 1b; Žák et al., 2005a).

8.2. Inferences on the mode and driving forces of the orogenic collapse in the Bohemian Massif

For the following reasons, we argue that the ∼346 Ma kinematic switch recorded in the Blatná pluton represents a major tectonic event in this segment of the Variscan orogen. First, it terminates a period of overall shortening/transpression in the

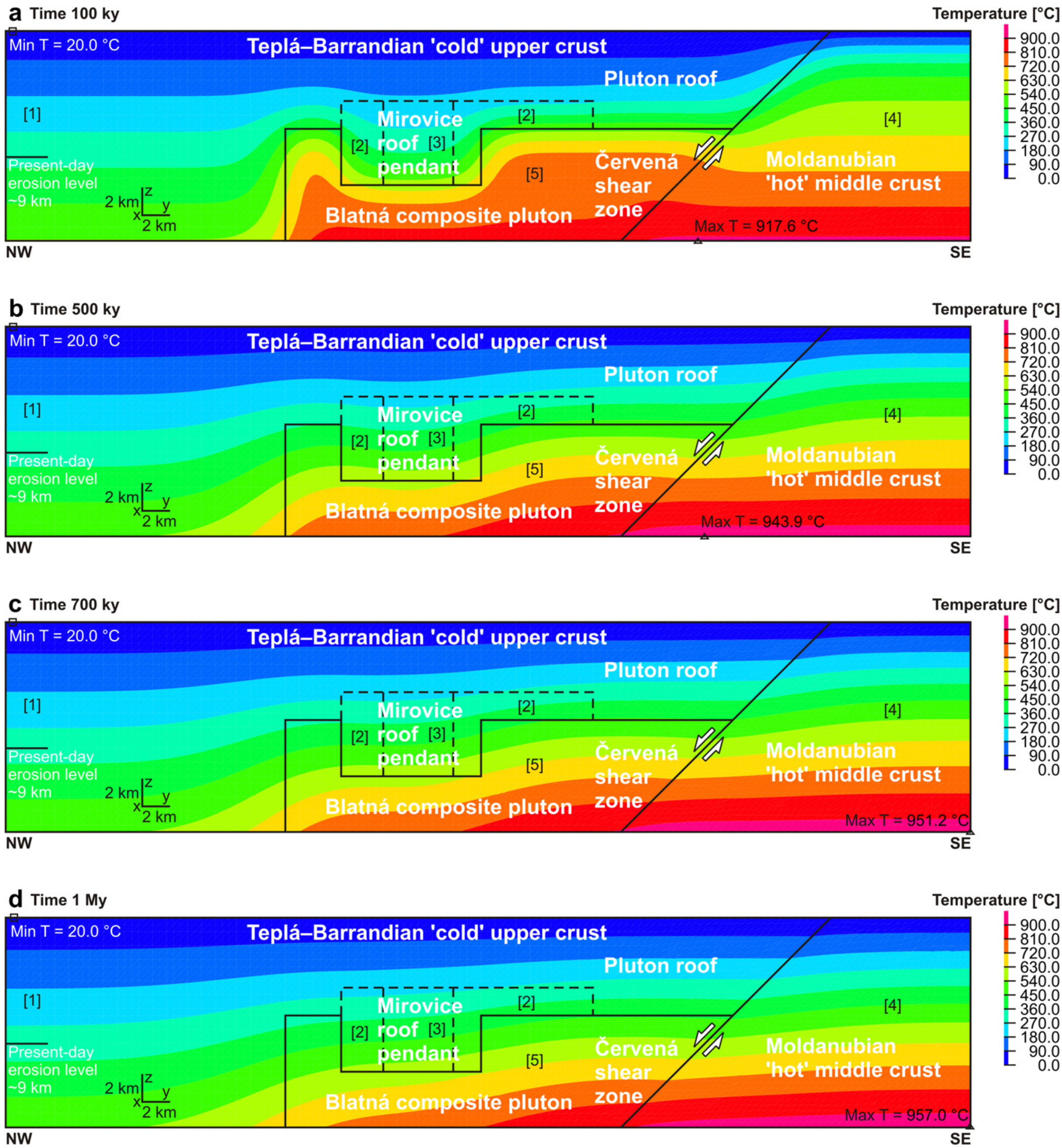

Fig. 9. Computed evolution of the temperature field in the modeled domain across the Blatná composite pluton; see Fig. 1 for location and text for discussion.

orogenic upper crust as represented by the TBU. The ~NE–SW shortening/transpression was assigned to the SE-directed subduction of the Saxothuringian Ocean and subsequent collision (at ~380 Ma; Schäfer et al., 1997; Zulauf, 1997) and underthrusting of the Saxothuringian continental crust beneath the TBU (e.g., Konopásek and Schulmann, 2005; Machek et al., 2009; Schulmann et al., 2009). This subduction-related shortening lasted intermittently from at least ~392 Ma, when the uplifted northwestern TBU sourced the Givetian flysch successions of the Prague Basin (Strnad and Mihaljevič, 2005), to ~346 Ma along the southeastern flank of the TBU (Žák et al., 2005a, 2009; this study). We interpret the latter age as an upper limit for subduction-related deformation in the TBU (*cf.* ~365 Ma according to Franke, 2000).

Second, the ~346 Ma kinematic switch represents the onset of normal movements of the whole supracrustal Teplá–Barrandian hanging wall 'block' relative to the high-grade core of the orogen (the footwall Moldanubian unit) and, in turn, it defines the end of crustal thickening in the Teplá–Barrandian unit and marks the onset of exhumation of the Moldanubian mid-crustal rocks. Given the estimated magnitude of displacement and overall length of the whole 'Bohemian' shear zone system (see Dörr and Zulauf, 2010 for details), the ~346 Ma kinematic switch must have initiated a thorough reorganization of the orogen's architecture and hence also separates two major stages in its tectonic history. Interestingly, the end of thickening and initiation of normal movements in the Teplá–Barrandian unit at around 346 Ma pre-dates the granulite facies metamorphism in the Moldanubian unit (~340 Ma; e.g., Kröner et al., 2000; O'Brien, 2000; Willner et al., 2002; O'Brien and Rötzler, 2003; Janoušek et al., 2006; Janoušek and Holub, 2007; Kotková, 2007; Franěk et al., 2011). This implies that either the peak of the granulite facies metamorphism in the orogenic root significantly postdated the maximum thickening attained in the Teplá–Barrandian upper crust at ~350–370 Ma (Suchý et al., 2002; Filip and Suchý, 2004), or that the ~340 Ma ages of granulite facies rocks record their retrograde reworking and not the peak conditions of metamorphism (e.g., Roberts and Finger, 1997; Svojtka et al., 2002; Tichomirowa et al., 2005; Tajčmanová et al., 2010).

Despite the normal kinematics and timing of collapse of the TBU are now well established, the geodynamic cause of this orogen-scale process has been debated (Zulauf, 1994; Scheuvens and Zulauf, 2000; Bues et al., 2002; Zulauf et al., 2002; Janoušek and Holub, 2007; Dörr and Zulauf, 2010; Franěk et al., 2011). In short, the existing models mostly interpret the Moldanubian and Teplá–Barrandian units as representing various levels of a single lithospheric 'block' but propose fundamentally different causes for the TBU collapse. Our further discussion thus centers on several relevant points.

First, several lines of evidence indicate that some kind of a pre-existing lithospheric-scale NW-dipping discontinuity (the Gföhl suture; Franke, 2006) must already have existed between the southeastern margin of the TBU and the Moldanubian unit before emplacement of the CBPC: (1) Investigations into seismic anisotropy reveal remarkably different orientation of olivine fabric in the lithospheric mantle beneath the Teplá–Barrandian and Moldanubian units (Babuška et al., 2008, 2010). (2) Geochemical data from the mantle-derived mafic dikes point to different mantle composition beneath the two units (Holub, 2010a, b). (3) No comparable Blatná suite granitoids nor deeper levels of the CBPC are exposed in the Moldanubian footwall to the southeast of the Červená granodiorite. This implies that the Červená shear zone not just intersects but confines the southern margin of the CBPC, most likely parallel to a pre-existing boundary. (4) The upper-crustal Červená granodiorite is in intrusive contact with the retrogressed granulite facies rocks containing relics of an (U)HP assemblage (Kotková et al., 1997). Hence, an earlier exhumation event must have occurred along the TBU/Moldanubian boundary prior to the CBPC emplacement (during the mid- to late Devonian?; e.g., Franke, 2006; Medaris et al., 2005; Faryad et al., 2009). Altogether the above data suggest that magmas of the Blatná pluton were already confined by the pre-existing NW-dipping boundary during their ascent to the upper-crustal levels, explaining the wedge-like shape of the CBPC in the ~NW–SE cross-section (Fig. 4e).

Second, it is interesting to note that the end of shortening/transpression and the onset of the normal movements coincides with the emplacement of huge magma volumes into the upper crust (8–10 km depth as inferred from the Al-in hornblende barometry, Section 3) at around 346. As suggested by our thermal modeling, the granitoids must have developed a long-lived thermal anomaly along the southeastern margin of the TBU (Fig. 9), and cooled asymmetrically with faster cooling against the northwestern contact with the TBU and significantly slower cooling along the southeastern margin adjacent to the still hot Moldanubian rocks (Fig. 9). The asymmetric cooling localized the ductile, high-temperature normal shearing into the Červená granodiorite (Figs. 4, 6d and 7). In general, a number of studies have shown that adding magma into actively deforming zones causes significant reduction in the overall strength of the magma/host rock system (e.g., Hollister and Crawford, 1986; Hutton, 1992; Pavlis, 1996; Parry et al., 1997; Zulauf and Helferich, 1997; Brown and Solar, 1998). Similarly, we envision that the emplacement of huge volumes of arc magmas along the Teplá–Barrandian/Moldanubian boundary caused thermal softening and drop in the overall strength of the previously thickened upper-crustal layer (the TBU).

Last, combining fabric information from the granitoids with the above inferences, we attempt to evaluate the far-field driving forces for the TBU collapse. Were the far-field tectonic forces to cause the TBU collapse compressive, the magma-induced thermal softening along the southeastern flank of the TBU would most likely just enhance reverse movements (e.g., Hollister and Crawford, 1986; Hutton, 1992; Rey et al., 2001). However, exactly the opposite is the case as the magmatic to solid state fabrics in the Blatná and particularly the Červená granodiorites display normal kinematics (Figs. 3a, 4e and 6f) and thus imply a reversal in the regional stress field. It follows that the two distinct fabrics in the Blatná pluton most likely record the cessation of lateral compressive forces in the upper crust resulting from the Saxothuringian/Teplá–Barrandian/Moldanubian convergence and switch to the gravity-dominated vertical tectonics in the core of the Bohemian Massif at around 346 Ma.

9. Conclusions

Magmatic to solid state fabrics in the ~346 Ma Blatná pluton are interpreted as recording two superposed orogenic events in the Bohemian Massif: dextral transpression associated with arc-parallel stretching and arc-perpendicular shortening along the southeastern margin of the TBU, and normal shearing associated with the SE-side-up exhumation of the high-grade Moldanubian unit. The switch from transpression to normal shearing occurred during the magmatic 'life time' of the pluton (at least 1 My, as indicated by thermal modeling) and continued during cooling of the granitoids down to temperatures corresponding to the greenschist facies conditions. The ductile normal movements were terminated during emplacement of melasyenite intrusions at around ~343–337 Ma.

This kinematic switch is an important landmark in the evolution of this segment of the Variscan orogen for it terminates a stage of overall shortening in the upper crust and for it marks the onset of downward movement of the supracrustal Teplá–Barrandian hanging wall 'block' relative to the high-grade core of the orogen (the footwall Moldanubian unit). The emplacement of huge volumes of arc magmas along the Teplá–Barrandian/Moldanubian boundary produced a thermally softened domain which then caused drop in the overall strength of the previously thickened upper-crustal layer (the TBU). Hence, emplacement of the large-volume magmatic arc granitoids may have played a major role in facilitating the orogenic collapse of the upper crust in the Bohemian Massif at around 346 Ma. The two distinct fabrics in the Blatná pluton most likely record this reversal in the regional stress field and are compatible with replacement of lateral compressive forces by gravity-dominated vertical tectonics.

Acknowledgments

We gratefully acknowledge Graham Borradaile and Bernard Henry for their very constructive and helpful reviews and Joao Hippertt for careful editorial handling of this manuscript. František Hrouda is thanked for discussions and assistance in interpreting and measuring magnetic mineralogies. We also acknowledge financial support from the Grant Agency of the Czech Republic through grants No. P210/11/1168 (to Jiří Žák) and No. 205/09/0630 (to František Holub), and from the Ministry of Education, Youth and Sports of the Czech Republic through Research Plans No. MSM0021620855 and MSM6840770003.

Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsg.2011.12.011.

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