ELSEVIER

Journal of Structural Geology 28 (2006) 1553–1567

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Magma emplacement during exhumation of the lower- to mid-crustal orogenic root: The Jihlava syenitoid pluton, Moldanubian Unit, Bohemian Massif

Kryštof Verner [a,b,*], Jiří Žák [a,c], František Hrouda [b,d], František V. Holub [b]

[a] *Czech Geological Survey, Klárov 3, Prague 11821, Czech Republic*
[b] *Institute of Petrology and Structural Geology, Charles University, Albertov 6, Prague 12843, Czech Republic*
[c] *Institute of Geology and Paleontology, Charles University, Albertov 6, Prague 12843, Czech Republic*
[d] *AGICO Ltd., Ječná 29, Brno 62100, Czech Republic*

Received 20 May 2005; received in revised form 27 March 2006; accepted 30 March 2006
Available online 27 June 2006

Abstract

In this study, we present structural and AMS data from the ~335 Ma ultrapotassic Jihlava syenitoid pluton, which intruded the lower- to mid-crustal orogenic root (Moldanubian Unit) in the Bohemian Massif, Central European Variscides. The emplacement of the pluton was accommodated by multiple processes, such as ductile host-rock shortening, formation of sheeted zones by magma wedging, magmatic stoping, and possibly host-rock displacement within a wide transtensional zone. Magmatic fabrics preserved in the pluton reflect both intrusive processes and regional strain. Margin-parallel and ~ENE–WSW foliations, which probably formed by strain during emplacement of inner magma pulses, were overprinted by tectonic strain within a zone of distributed wrench-dominated dextral transtension. This zone probably accommodated exhumation of different segments in the eastern part of the Moldanubian Unit during pluton emplacement. In contrast to existing models, we emphasize that the Jihlava pluton, as well as other ultrapotassic plutons widespread in the Moldanubian Unit, are structurally highly variable bodies emplaced by multiple intrusive processes. Our case study illustrates how careful documentation of structural relations around these ultrapotassic plutons may constrain the kinematic framework and local exhumation histories in different segments of the orogenic root during and shortly after the ~340 Ma mechanical event in the Central European Variscides.

Keywords: Anisotropy of magnetic susceptibility (AMS); Emplacement; Exhumation; Pluton; Transtension; Variscan orogeny

1. Introduction

One of the most intriguing aspects in evolution of orogenic belts and magmatic arcs is the exhumation of deeply buried high-grade rocks to the upper crustal levels. Recently, numerous studies focused on the mechanisms and driving forces of exhumation of lower- to mid-crustal segments and attributed the exhumation to various tectonic settings (e.g., Dewey, 1988; Allemand and Lardeaux, 1997; Thompson et al., 1997; Schulmann et al., 2002; Willner et al., 2002). The structural record of exhumation and the P-T-t paths of exhumed rocks are traditionally established using metamorphic petrology, geochronology, and structural analysis of metamorphic complexes. Interestingly, other studies (e.g., Paterson et al., 1998; Schofield and D'Lemos, 1998; Benn et al., 2001; Miller and Paterson, 2001) have also shown that the internal fabrics of plutons may record regional paleostrain fields in their metamorphic host rocks. Given that plutonic rocks are widespread, easy to date and, unlike metamorphic rocks, usually do not exhibit complex arrays of superposed structures (magmatic fabrics are easily reset; Paterson et al., 1998) we were interested in discovering whether populations of plutons emplaced episodically

---

* Corresponding author. Czech Geological Survey, Klárov 3, Prague 11821, Czech Republic. Tel.: +420 257089497; fax: +420 257531376.
E-mail address: verner@cgu.cz (K. Verner).

0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.03.037

into originally deep-seated crustal segments could provide evidence for the kinematic framework, local exhumation histories and timing of exhumation events within orogenic belts.

In the European Variscides, which formed during the Devonian to Carboniferous collision of peri-Gondwana crustal segments and the Baltica (northern European plate; Ziegler, 1986; Franke, 1989; Rey et al., 1997), major crustal thickening was followed by the exhumation of the orogenic root domain (Behr et al., 1984; Medaris et al., 1995; Willner et al., 2002). The exhumed lower- to mid-crustal orogenic root referred to as the Moldanubian Unit is now exposed in the Bohemian Massif and forms the innermost part of the Variscan orogenic belt. During the later stages of the Variscan orogeny, the orogenic root (Moldanubian Unit) was intruded by geochemically specific ultrapotassic syenitoid (melasyenitic, melagranitic or monzonitic) plutons. In the Bohemian Massif, these plutons comprise two rock groups differing in assemblages of mafic minerals; the most widespread amphibole-biotite rocks are dominated by the durbachite series (mostly K-feldspar-phyric melasyenites to melagranites; see Holub 1997), while the subordinate biotite-two-pyroxene rocks make up the Jihlava pluton in the eastern part of the Bohemian Massif and the Tábor pluton at the southeastern margin of the Central Bohemian Plutonic Complex (Fig. 1a,b). These ultrapotassic plutons are spread over the entire orogenic root but their radiometric ages indicate that they were emplaced over a relatively short time span (Klötzli and Parrish, 1996; Holub, 1997; Holub et al., 1997; Schaltegger, 1997; Janoušek and Gerdes, 2003; Kotková et al., 2003). Although the petrogenesis and geochemistry of these plutons has been previously studied and interpreted as being the result of mixing of mantle-derived ultrapotassic magmas with acid crustal melts (Holub, 1997; Janoušek and Holub, in press), their internal fabrics, emplacement processes and structural relations to the exhumed host metamorphic complexes are unknown or poorly constrained.

In this paper, we present structural and AMS data from the Jihlava pluton, which intruded the eastern part of the Moldanubian Unit (Figs. 1b, 2), as the first case example to show the importance of these ultrapotassic plutons for the interpretation of the kinematic framework and timing of exhumation in the orogenic root domain. Based on structural data, we interpret the formation of magmatic fabrics in the pluton, its relationship to the host-rock structures and regional tectonics, and we evaluate the material transfer processes during emplacement (i.e. MTPs of Paterson and Fowler, 1993a). Finally, we discuss the more general implications of our study for the exhumation and tectonic evolution of the orogenic root during the later stages of the Variscan orogeny.

2. Geological setting

The Jihlava pluton crops out in the eastern part of the Moldanubian Unit, which represents the exhumed lower- to mid-crustal orogenic root in the Central European Variscides (Fig. 1a,b; e.g., Medaris et al., 1995; Vrána et al., 1995; Schulmann et al., 1997; Konopásek and Schulmann, 2005). The Moldanubian Unit (Fig. 1b) comprises two major units with contrasting tectonometamorphic evolution, exhumed from different depths: the mid-crustal Drosendorf and the lower-crustal Gföhl Units. The Drosendorf Unit consists of metasedimentary sequences of problematic protolith age, dominated by sillimanite-biotite (±cordierite) paragneisses (referred to as the Monotonous Group) with abundant lens-shaped bodies of metaquartzites, marbles and amphibolites (summarily referred to as the Varied Group). Estimations of the PT conditions of regional metamorphism of the Drosendorf Unit range from 630 to 720 °C and 3–6 kbar (Petrakakis, 1997; Vrána et al., 1995), the age of HT-LP metamorphism was estimated as 337–333 Ma using the U-Pb method (Friedl et al., 1993). The high-grade Gföhl Unit, the protolith age of which was estimated at $\sim 482 \pm 2$ Ma (Friedl et al., 1993), is structurally the uppermost unit (Vrána, 1988; Matte et al., 1990) and comprises orthogneisses, migmatites, granulites, eclogites and peridotites. Estimations of the PT conditions of peak metamorphism in the Gföhl Unit correspond to $\sim$950–1050 °C and $\sim$14–20 kbar (in crustal peridotites) dated at $\sim 351 \pm 6$ (Carswell and O'Brien, 1993; Wendt et al., 1994) and $\sim 345 \pm 5$ (Van Breemen et al., 1982), followed by retrograde metamorphism ($T \sim$ 600–800 °C and $\sim$6–8 kbar; Owen and Dostal, 1996) at $\sim$337–333 Ma (Friedl et al., 1993; Wendt et al., 1994; Gebauer and Friedl, 1994).

In the studied area (Fig. 2), pluton host rocks are dominated by sillimanite-biotite (±cordierite) paragneisses of the Monotonous Group, which are commonly migmatized at variable degrees of partial melting. Numerous lens-shaped bodies of amphibolites, quarzitic rocks and graphite-bearing gneisses are scattered over the area. The Moldanubian paragneisses were also intruded by leucogranite sheets prior to the emplacement of the Jihlava pluton. The map-scale pattern of these bodies is parallel to the pluton margin forming a sigmoidal deflection as does the outcrop shape of the pluton. In contrast to other studies (Urban and Synek, 1995 and references therein; see also Fig. 2 in Schulmann et al., 2005), which place the presumed $\sim$N–S trending boundary thrust of the Varied Group over the Monotonous Group as intersecting the central part of the Jihlava pluton (the pluton would thus discordantly cut across the thrust plane), our detailed mapping revealed that the paragneisses of the Monotonous Group are juxtaposed against the Gföhl-like migmatites and orthogneisses along a NE–SW trending boundary located to the SE of the pluton (Fig. 2). The migmatites and orthogneisses resemble the Gföhl gneisses; however, the nature of the boundary and interpretation of this unit remains problematic.

The Jihlava pluton has a $\sim$NW–SE elongated sigmoidal shape (Fig. 2). Its contacts with the Moldanubian host rocks of the Monotonous Group are intrusive, only locally affected by post-emplacement brittle faulting. In general, the intrusive contacts dip steeply ($\sim 70°$) to the east. The pluton is composed of mafic syenitoid to granitoid rocks ranging from the most widespread quartz monzonite to (mela)syenite and melagranite. Their color index varies from 25 to 35, although it

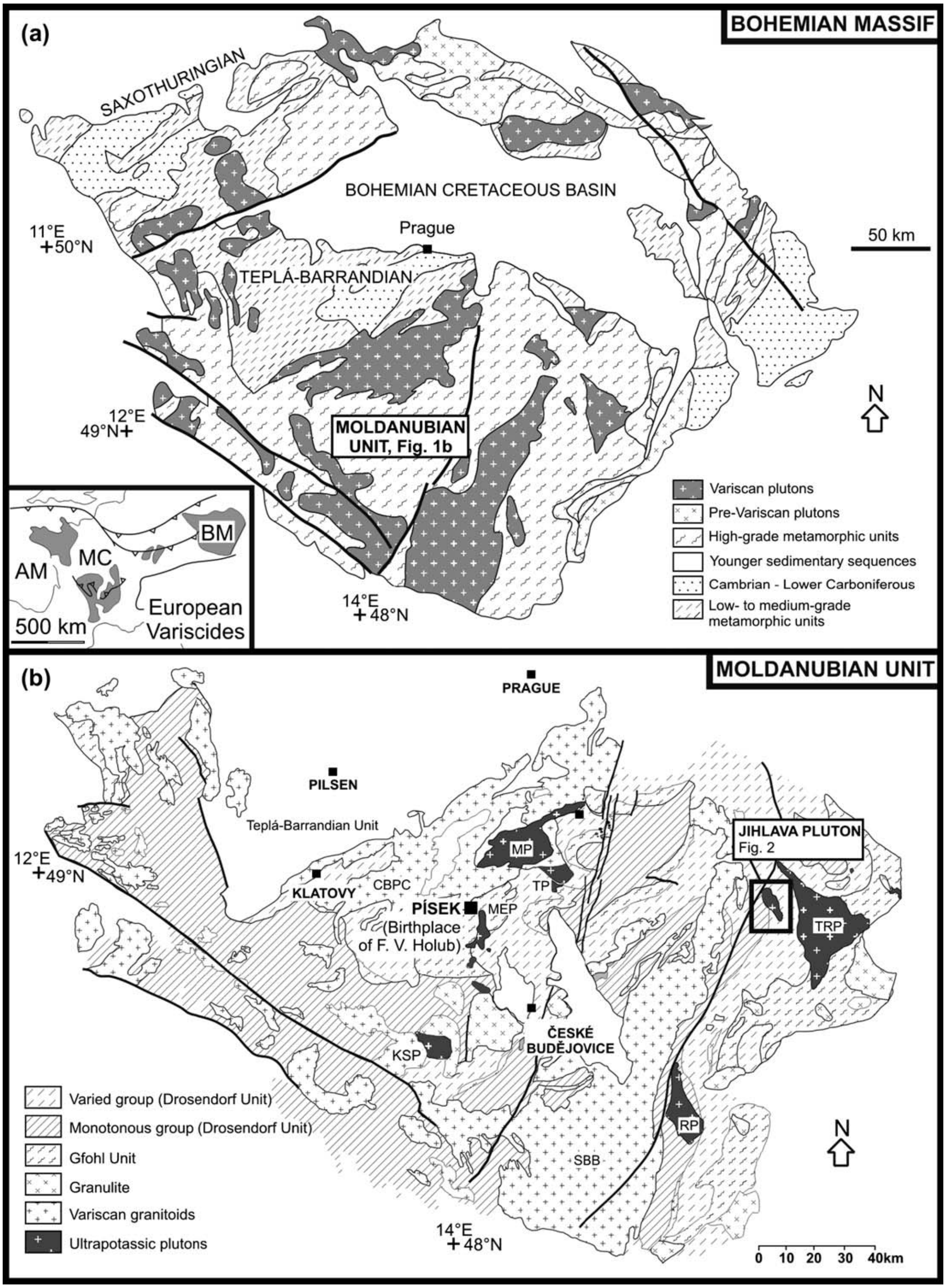

Fig. 1. (a) Geological sketch map of the Bohemian Massif and its position in the European Variscides (inset). The Moldanubian Unit forms the southern part of the Bohemian Massif. AM, Armorican Massif; BM, Bohemian Massif; MC, Massif Central. (b) Geological map of the Moldanubian Unit (according to Chlupáč et al., 2002) showing location of the study area (bold rectangle) and locations of other ultrapotassic plutons in the Moldanubian Unit. CBPC, Central Bohemian Plutonic Complex; KSP, Knížecí Stolec pluton; MEP, Mehelník pluton; MP, Milevsko pluton; SBB, South Bohemian Batholith; TP, Tábor pluton; TRP, Třebíč pluton.

locally exceeds >40. The primary mineral assemblage comprises orthopyroxene, clinopyroxene and biotite, but pyroxenes can be replaced by amphiboles of actinolitic composition in some parts of the pluton. The chemical composition is relatively rich in SiO_2 (58–62 wt%) but magnesian (MgO 3.5–6 wt%, commonly 4.5–5.5 wt%; $100Mg/(Mg + Fe_{tot})$ 61–66) and ultrapotassic (K_2O 4.5–6%, typical K_2O/Na_2O ~2.5).

Four varieties of these syenitoid rocks differing in their grain-size (medium- to coarse-grained to porphyric) and mineral composition (proportions of amphibole and pyroxenes) can be distinguished within the pluton (Fig. 2). The most

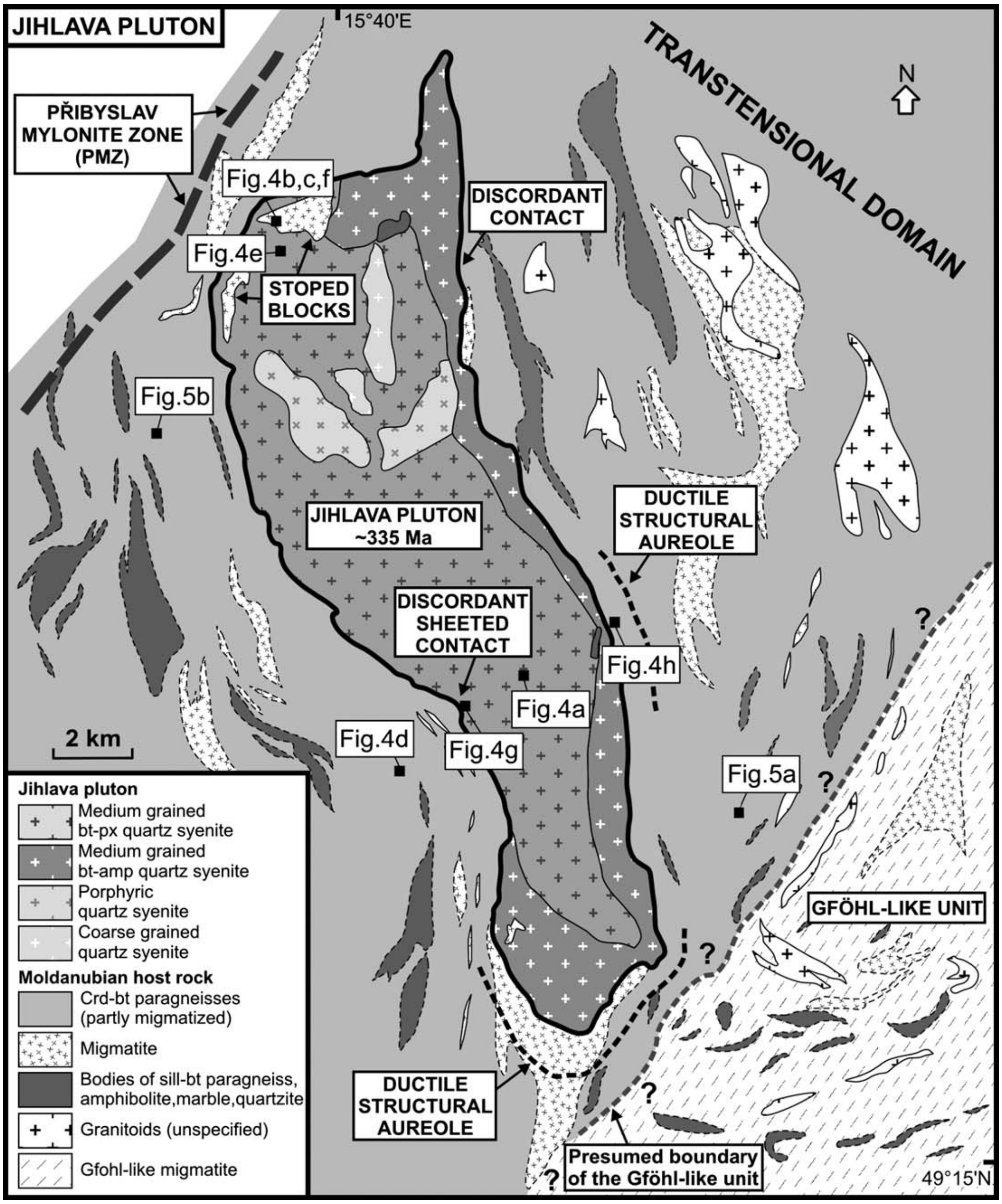

Fig. 2. Schematic geological map of the Jihlava pluton and its country rocks showing main lithological units and types of contacts (geology based on mapping by K. Verner and Czech Geological Survey 1:25,000 maps). The pluton is made up of four textural varieties of syenitoid rocks, the surrounding Moldanubian metamorphic complex is dominated by biotite paragneiss of the Monotonous Group. Both the pluton and nearby smaller elongated bodies of amphibolites and quarzitic and graphite-bearing gneisses show an asymmetric sigmoidal pattern. The Gföhl-like unit crops out in the SE part of the area.

widespread rock is medium-grained biotite-two-pyroxene quartz monzonite (±syenite and melagranite), making up much of the pluton, whereas medium-grained biotite-amphibole quartz monzonite/syenite and melagranite form the southern tip of the pluton and crop out as a narrow strip along its eastern margin. Coarse-grained and porphyritic varieties form irregular bodies in the northern part of the pluton.

The emplacement age of the Jihlava pluton has been constrained at 335.2 ± 0.54 Ma using the U-Pb method on zircons (Kotková et al., 2003).

3. Structural pattern of the Jihlava pluton and its country rocks

3.1. Country rocks

The structural pattern of the paragneisses of the Drosendorf Unit (Fig. 3) is defined by a regional metamorphic foliation (pervasive metamorphic schistosity, compositional banding or migmatitic layering; Fig. 4b) which, in general, dips steeply to moderately to the SE or NE (note the two maxima of the foliation poles in the stereogram in Fig. 3). This foliation is

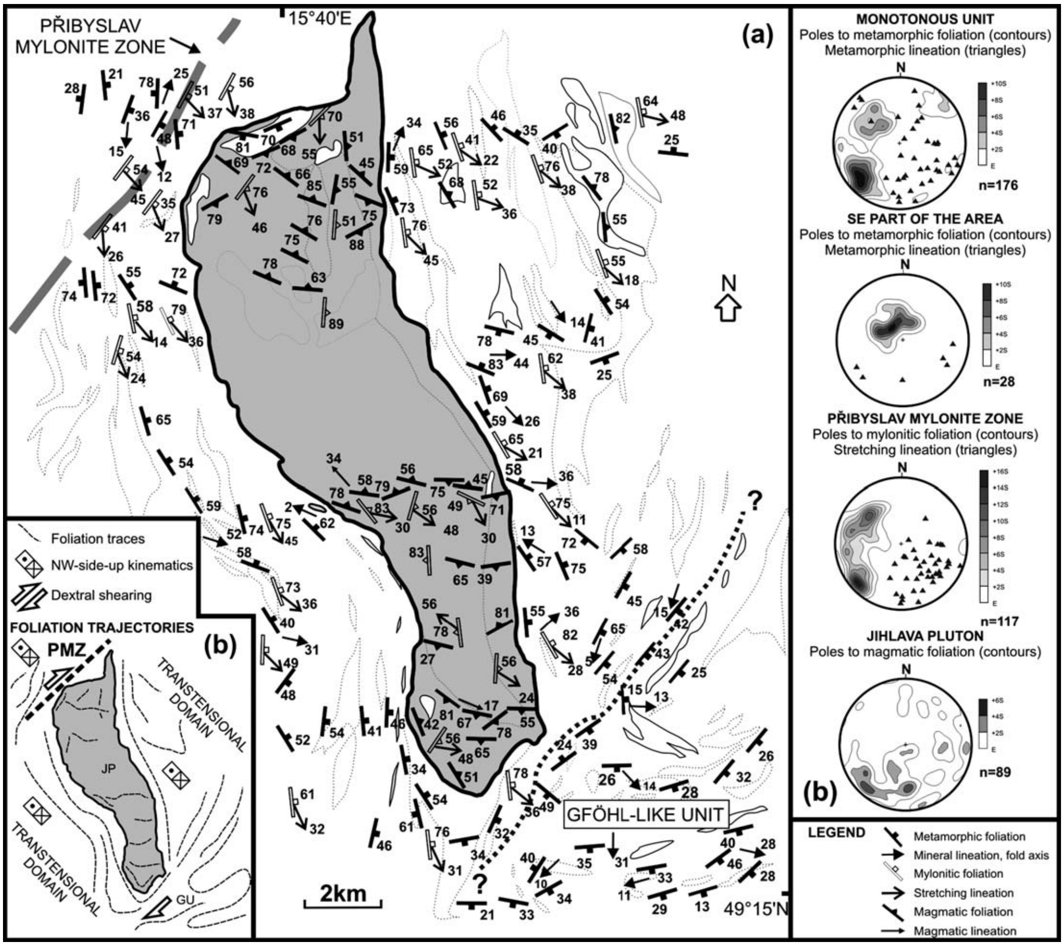

Fig. 3. Structural map of the Jihlava pluton and its host rocks. Stereograms (lower hemisphere, equal area projection) show orientation of main structural elements (lineations and poles to foliations). The inset map shows foliation trajectories and regional kinematic pattern both in the pluton and in the country rocks. GU, Gföhl-like unit; PMZ, Přibyslav mylonite zone.

associated with moderately plunging stretching lineations trending predominantly SE. On some outcrops, the foliation is folded into close to isoclinal folds with steep axial planes and fold axes parallel to the stretching lineation (Fig. 4c).

In the map view, the foliation pattern and lithological contacts show a prominent sigmoidal deflection, suggesting clockwise (right-lateral) rotation of both contacts and the metamorphic fabric in regions near both northern and southern tips of the pluton. These structures are superimposed on pre-existing, regional flat-lying foliation, which is widespread elsewhere throughout the Moldanubian Unit (referred to as S_3 by Vrána, 1988 and Vrána and Bártek, 2005) and define a more than 10 km wide zone of distributed dextral NE-side-up transtension (Fig. 3). The dextral, NE-side-up transtensional kinematics is consistent throughout the wide transtensional zone and has been demonstrated on several scales: (i) most importantly, in the map view by the asymmetry of the sigmoidal pluton shape, the same sigmoidal array of lenses and smaller granitoid bodies scattered within the paragneisses of the Monotonous Group, and the sigmoidal foliation and lineation pattern (Fig. 3); (ii) on outcrops by asymmetric minor folds; and (iii) on a micro-scale by asymmetric porphyroblasts (Fig. 5). The structural pattern (e.g., orientation of foliations and lineations, asymmetric structures) and observed characteristics of fabric ellipsoid (plane-strain, LS fabrics) correspond to a wrench-dominated (= simple shear dominated) transtension (e.g., Dewey, 2002; Teyssier and Tikoff, 1999).

In the Gföhl-like migmatites and orthogneisses to the SE of the pluton, the metamorphic foliations are locally complexly folded, but generally dip at low angles to the SE (Fig. 3). On a map-scale, the entire Gföhl-like unit is folded into major tight to isoclinal folds with wavelengths of up to several kilometers. The fold axes of major folds dip gently to the SE.

Both regional flat-lying foliation and structures of the wide transtensional zone (described above) were subsequently affected by more localized ductile to brittle shearing along the ~NNE–SSW mylonitic shear zone (referred to as the Přibyslav mylonite zone, PMZ) located mainly at the NW tip of the pluton (Figs. 2, 3). Small-scale structures (localized shears and minor faults) related to the shear zone may be observed throughout the area where younger mylonites discordantly cross-cut or reactivate the older structures (Fig. 4e). The pervasive mylonitic foliations in the shear zone dip steeply to moderately to the SW or NE and are associated with stretching

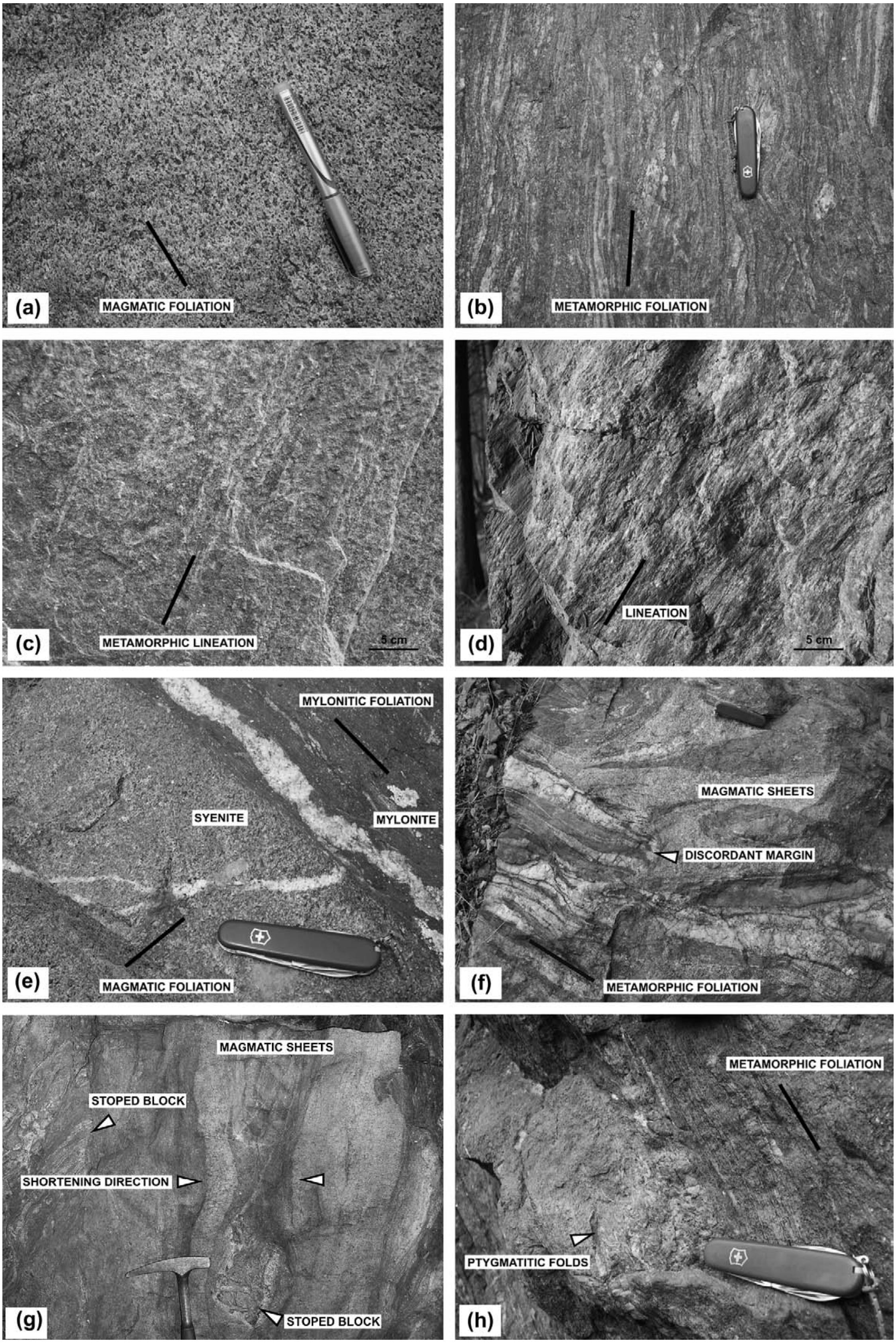

Fig. 4. Field photographs of structures from the Jihlava pluton and nearby host rocks (locations shown on Fig. 2). (a) ~ENE–WSW magmatic foliation in the quartz monzonite defined by shape preferred orientation of K-feldspars, biotite and pyroxene; (b) Pervasive metamorphic foliation in a stoped block formed by partially migmatized paragneiss, Bradlo quarry, NW part of the pluton; (c) Mineral lineation plunging to the SE (looking on a metamorphic foliation plane); (d) Lineation on an oblique-slip fault plane associated with NW-side-up dextral kinematics; (e) Magmatic fabric in the quartz monzonite overprinted by fine-grained

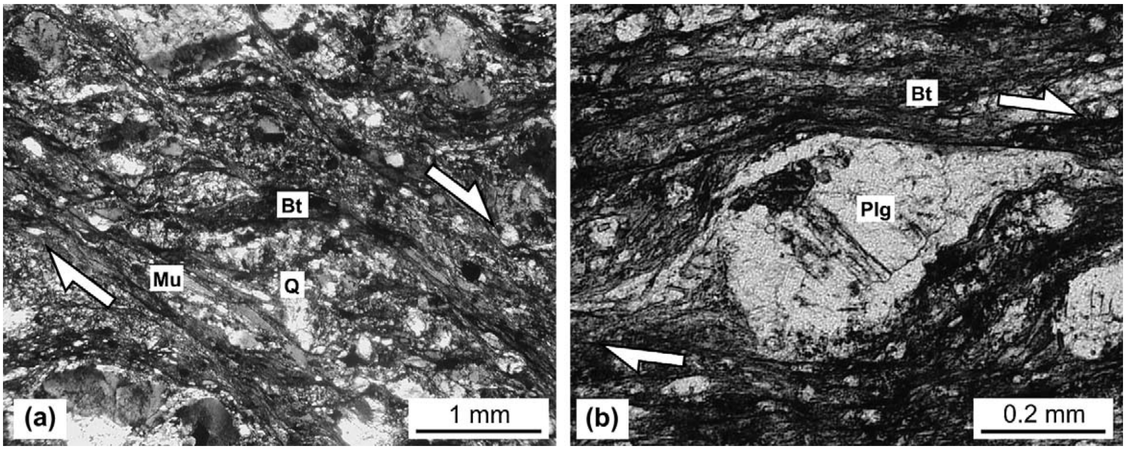

Fig. 5. Photomicrographs of kinematic indicators from the dextral transtensional zone, taken from lineation-parallel and foliation-perpendicular (*XZ*) section. (a) Shear bands in biotite paragneiss of the Monotonous Group; foliation strike is N35°E, dip 54°; lineation trend is S12°E, plunge 22°. (b) Rotated plagioclase σ-porphyroblast in biotite paragneiss of the Monotonous Group; foliation strike is N43°W, dip 62°; lineation trend is S59°E, plunge 12°. All microstructures indicate normal, right-lateral shear sense. See Fig. 2 for locations of samples.

lineation steeply to moderately plunging to the SE and dextral transtensional kinematics. These ductile mylonitic structures grade into brittle discrete faults (Fig. 4d) with consistent orientation and kinematics.

3.2. Pluton structures

At the present-day exposure level, the Jihlava pluton has a ∼NW–SE elongated sigmoidal shape (Figs. 2, 3) with both northern and southern tips deflected clockwise with respect to the central part of the pluton. In the map view, the longest dimension of the pluton is ∼15 km and the widest is ∼4 km. Our detailed structural mapping revealed complex structural and fabric patterns of the pluton, many local complications, and high variability of the geometry and character of the intrusive contacts and near-contact domains.

In the northern part of the pluton, the western pluton/host-rock contact dips moderately (∼40°), whereas the eastern contact dips steeply (∼70°) to the east. Both contacts are parallel to the metamorphic foliations (Fig. 3). No deformation gradient or changes in fabric intensity and shape of fabric ellipsoid were observed in the host rocks along both pluton margins. Abundant kilometer-scale stoped blocks and rafts of the Moldanubian metamorphic rocks are also preserved in this part of the pluton (Figs. 3; 4f).

In the central part, the western and eastern pluton margins have contrasting character (Figs. 3; 4g,h). The western contact is sheeted, i.e. consists of multiple monzonitic and more leucocratic sheets up to several meters thick alternating with host-rock rafts or stoped blocks (Fig. 4g). The outermost contact of the sheeted zone truncates sharply the host-rock metamorphic foliation. No evidence indicates syn-emplacement ductile shortening of the country rocks along the pluton margins. In contrast, the monzonitic sheets along the pluton margins (inside the pluton) commonly form magmatic pinch-and-swell structures (Fig. 4g) formed during the presence of a melt. A particularly intriguing example is shown in Fig. 4g, where the monzonitic sheets form pinch-and-swell structures around an internally deformed and partially molten stoped block. The outer margin of the sheeted zone has been overprinted by a very narrow (only 0.2 m wide) zone of sub-solidus deformation. All these features indicate that, after construction of the sheeted zone and stoping of the host-rock blocks, the zone was shortened in the direction perpendicular to sheet margins against the outer edge of the pluton (Fig. 4g). However, this shortening was not recorded in the nearby Moldanubian metamorphic rocks.

In contrast, along the eastern margin, we see no evidence for either sheeting or sharp discordant contacts. Instead, here pluton host rocks show evidence for ductile shortening (tight to isoclinal ptygmatitic folds, Fig. 4h), as well as partial melting within a ∼100 m wide ductile structural aureole. The ductile aureole is characterized by an oblate fabric ellipsoid (planar fabrics with no stretching lineation), whereas the country rocks outside the structural aureole exhibit plane-strain fabric ellipsoids (LS fabric).

The structural pattern of the southern tip of the pluton differs from its remainder described above (Fig. 3). The Moldanubian host rocks for this part of the pluton comprise highly migmatitized paragneisses and migmatites (nebulites), indicating extensive partial melting that could be broadly synchronous with the pluton emplacement. Importantly, the migmatitic foliations are parallel to the pluton margins and are bent around the southern tip of the pluton within an up to ∼2 km wide structural aureole. The ductile aureole is characterized by an oblate fabric ellipsoid (migmatitic foliations with no stretching lineation), whereas the country rocks further to the SE exhibit plane-strain fabric ellipsoids (LS fabric).

---

sub-solidus mylonite zone, Kosov quarry, NW part of the pluton; (f) Syenitoid sheets intruding a partially molten stoped block, the metamorphic foliation in the stoped block is truncated by the quartz monzonite, Bradlo quarry; (g) Magmatic sheets forming pinch-and-swell structures bent around a partially molten and internally deformed stoped block indicating sheet-normal contraction after emplacement; (h) Minor ptygmatic folds in partially migmatized paragneiss in the structural aureole.

3.3. Fabric pattern of the pluton

The magmatic fabrics in the Jihlava pluton are defined as magmatic foliations (Fig. 4a), i.e. the planar shape preferred orientation of feldspars, biotite and pyroxenes formed during the presence of a melt (criteria outlined in Paterson et al., 1989, 1998; Vernon, 2000). Due to both the fine-grained nature of the rock and the generally highly oblate fabric ellipsoid (as determined using the AMS method, see below), magmatic lineation or biotite zone axis is either not developed or is difficult to discern mesoscopically.

Multiple magmatic foliations are preserved in the Jihlava pluton: (i) Margin-parallel foliations are preserved in the southernmost part of the pluton (Fig. 3). These foliations dip moderately to steeply and, in the map view, form an ‘‘onion-skin’’ pattern parallel to the intrusive contacts and to the foliations in the Moldanubian country rocks. We also mapped these margin-parallel foliations elsewhere in the pluton, but these are more localized and restricted to narrow zones adjacent to contacts with the host metamorphic rocks. In places, these magmatic fabrics grade into sub-solidus S-C mylonites also parallel to pluton margins. (ii) The dominant, ∼E-NE–WSW foliations dip steeply to moderately to the SW or NE and are highly oblique (at high angle) to the outer pluton/host-rock contacts, to the general strike (∼NW–SE) of the pluton, and to the metamorphic foliations in the Moldanubian host rocks (Fig. 3). (iii) Locally, some of the magmatic foliations are oblique to the above foliations and strike NE–SW, and are thus parallel to the metamorphic foliations in the Moldanubian host rocks.

4. Anisotropy of magnetic susceptibility (AMS) of the pluton

We used the anisotropy of magnetic susceptibility (AMS) method to investigate the internal magnetic fabric of the Jihlava pluton in order to corroborate the structural data and to quantify the fabric parameters and fabric gradients in the pluton. One hundred and five oriented samples were collected using a portable drill at 28 sampling sites located along three E–W oriented transects across the pluton. The AMS was measured with the KLY-3S Kappabridge apparatus (Jelínek and Pokorný, 1997) and statistical analysis of AMS data was carried out using the ANISOFT package of programs (Jelínek, 1978; Hrouda et al., 1990).

The AMS data are represented by the k_m, P, and T parameters defined as follows:

$$k_m = (k_1 + k_2 + k_3)/3$$

$$P = k_1/k_3$$

$$T = 2\ln(k_2/k_3)/\ln(k_1/k_3) - 1$$

The k_m parameter represents the mean bulk magnetic susceptibility reflecting the qualitative and quantitative content of magnetic minerals in the rock. The P parameter (Nagata, 1961), called the degree of AMS, reflects the eccentricity of the AMS ellipsoid and thus indicates the intensity of the preferred orientation of the magnetic minerals in the rock. The higher the P parameter, the stronger is the preferred orientation. The T parameter (Jelínek, 1981) indicates the symmetry of the AMS ellipsoid. It varies from −1 (perfectly linear magnetic fabric) through 0 (transition between linear and planar magnetic fabric) to +1 (perfectly planar magnetic fabric). The orientations of magnetic foliation poles and magnetic lineations are presented either in contour diagrams in the geographic (*in situ*) coordinate system or as locality means in a map.

4.1. Magnetic mineralogy

The mean bulk magnetic susceptibility is relatively homogeneous and low, ranging from 209×10^{-6} to 1050×10^{-6} [SI] (Fig. 6a). The magnetic minerals were investigated through measurement of the temperature variation of the bulk susceptibility on crushed specimens in the temperature intervals from −196 °C to 0 °C using the CS-L non-magnetic Cryostat apparatus and the KLY-4S Kappabridge apparatus and from room temperature to 700 °C using the CS-3 non-magnetic Furnace apparatus and the KLY-4S Kappabridge apparatus. The specimens for this investigation were selected in order to represent the main rock types.

In all the specimens, the susceptibility vs. low temperature curves show hyperbolic shapes characteristic for paramagnetic minerals (Fig. 6b). After plotting the inverted susceptibility values against the temperature, the respective curves are represented by straight lines (Fig. 6c) with almost zero intercept at a temperature of absolute zero. These curves therefore indicate that the dominant susceptibility carriers are paramagnetic minerals and the magnetic fabric of the investigated rocks is therefore controlled by the preferred orientation of the paramagnetic minerals.

The susceptibility vs. high temperature curves exhibit hyperbolic shapes either over the entire temperature interval or with very small superimposed peaks in the vicinity of 560–570 °C (Fig. 6d).

The method developed by Hrouda (1994), based on mathematical resolution (by the least squares method) of the heating curves into paramagnetic hyperbola and ferromagnetic complex curves, enables determination of the contributions of the paramagnetic and ferromagnetic components to the bulk rock susceptibility. Using the above method, we estimate that the main AMS carriers are paramagnetic silicates (biotite and pyroxenes), even though the presence of small amounts of magnetite cannot be excluded. However, because this magnetite has not been recorded by the low temperature measurement, it is highly likely that it was created during heating.

4.2. Magnetic fabric of the pluton

In terms of orientation, we found multiple magnetic fabrics in the Jihlava pluton: (i) Magnetic foliations, which are parallel to pluton/host-rock contact regardless of the contact

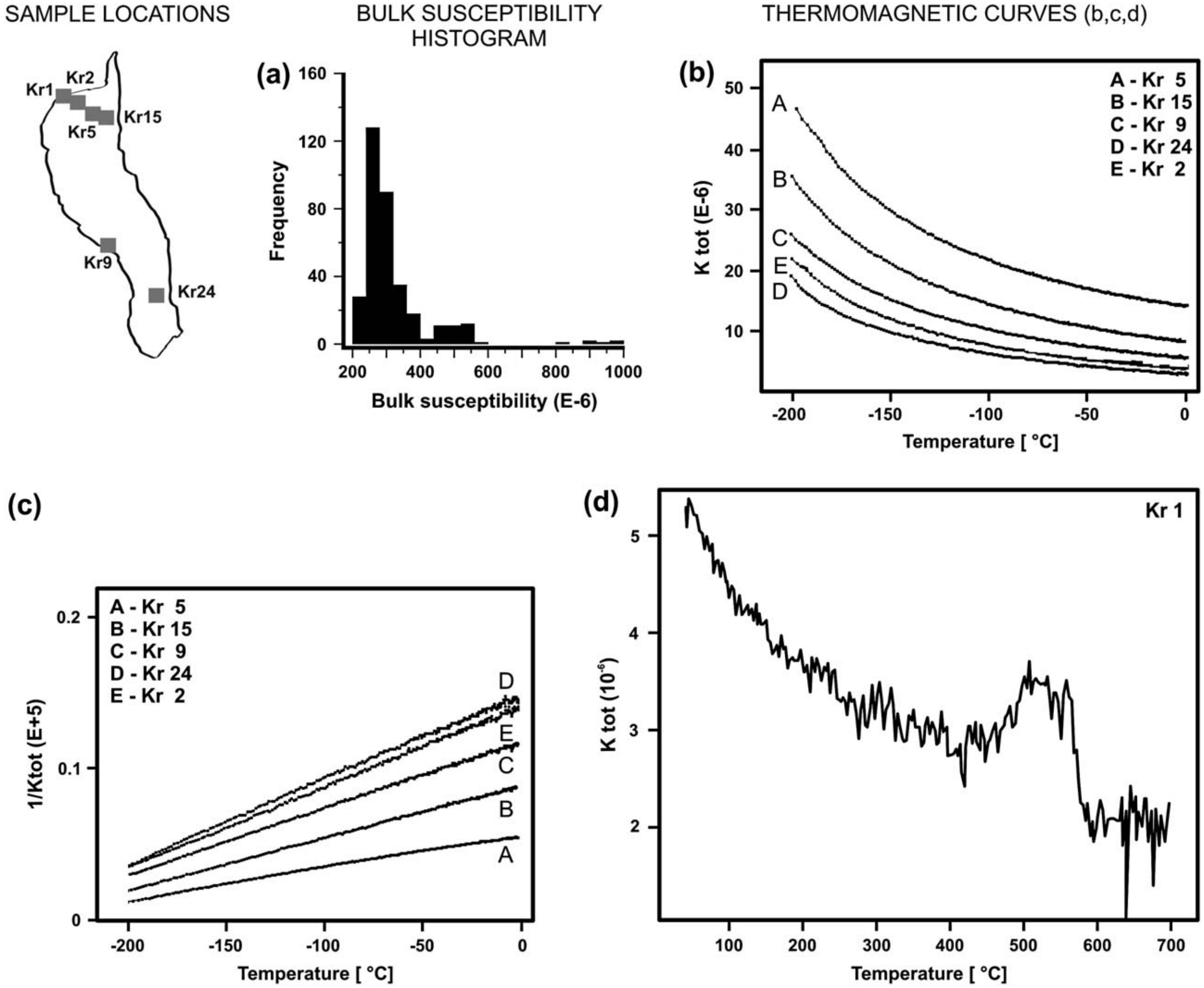

Fig. 6. Diagrams showing main parameters of AMS. (a) Bulk susceptibility histogram of all samples. (b)–(d) Thermomagnetic curves of selected samples of the Jihlava syenitoids (the inset map shows locations of sampling sites): (b) Total susceptibility vs. low temperature curve. (c) Inverted total susceptibility vs. low temperature curve. (d) Total susceptibility vs. high temperature curve showing hyperbola with superposed magnetite curve.

orientation (Fig. 7). These foliations are moderately to steeply dipping and are associated with shallowly plunging magnetic lineations and oblate AMS ellipsoids. (ii) Magnetic foliations oblique to both the strike of the pluton and its margins (Fig. 7). These foliations dip steeply to moderately to the NNE or SSW and are associated with magnetic lineations which plunge to the NW or SE at moderate angles (Fig. 7). (iii) In local domains, some magnetic foliations strike NE–SW and dip steeply to moderately to the NW, and the lineations plunge moderately to the SE, and thus have orientations consistent with the host-rock metamorphic foliations and lineations, respectively.

The degree of AMS (represented by the P parameter, Fig. 8a,b) ranges from 1.008 to 1.183. In general, the P parameter increases slightly from the internal parts of the pluton towards the contact with the host rocks (Fig. 8a). Lower P values ($P = 1.024–1.035$) were obtained from the internal parts of the pluton, whereas higher P values ($P = 1.056–1.085$) are characteristic for domains along the pluton margins. Susceptibility ellipsoids exhibit prolate to oblate character, the T parameter ranges from -0.948 to 0.919 (Fig. 8a,b).

5. Crystallographic preferred orientation of K-feldspar

We employed the electron back-scatter diffraction (EBSD; Prior et al., 1999) method to analyze the crystallographic preferred orientation of small K-feldspar phenocrysts (2–5 mm in size) in the syenitoid rocks. This method yields the orientation of the [001] and [010] and [110] crystallographic axes of the K-feldspar crystals with respect to the foliation plane in a thin section taken from oriented samples. The [010] axis directly yields the Z direction (i.e. direction perpendicular to the foliation plane) of the K-feldspar fabric ellipsoid. For this analysis, we used two drillcores previously measured for the AMS from two sampling sites (Kr 9 and Kr 30) located in the northern and central parts of the pluton. The analysis was carried out in thin sections oriented perpendicular to the magnetic foliation and parallel to the

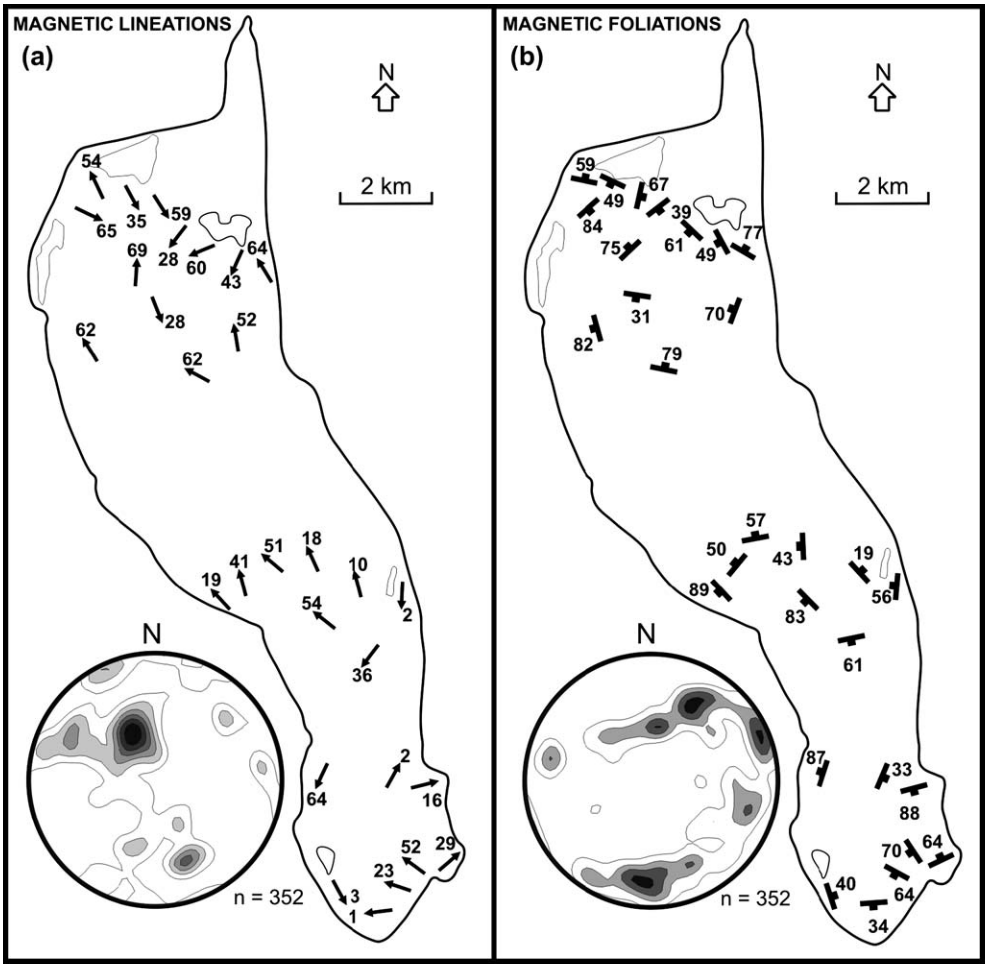

Fig. 7. Maps and stereograms (lower hemisphere, equal area projection) of magnetic lineations and foliations in the Jihlava pluton. Magnetic lineations plunge to the NW or SE at moderate angles (note two maxima in stereogram of lineations). Moderately to steeply dipping magnetic foliations are parallel to pluton/host-rock contact or are steeply to moderately dipping to the NE or SSW (oblique to both the strike of the pluton and its margins).

magnetic lineation (*XZ* sections) established using the AMS method.

We measured 133 K-feldspar crystals in sample Kr 9 and 90 crystals in sample Kr 30. The results of the EBSD analysis are depicted in Fig. 9, where the crystallographic axes are plotted in stereograms on a lower hemisphere, equal-area projection. In both samples, the [010] crystallographic axes form two strong maxima close to the minimal magnetic susceptibility (k_3), i.e. are perpendicular to the magnetic foliation of the measured sample. The [001] and [110] axes, which are at high angles to the mineral lineation, form girdles around the *Z* direction with several subordinate maxima. Apparently, the crystallographic preferred orientation of K-feldspar phenocrysts in the two analyzed samples is consistent with the orientations of the paramagnetic silicates determined using the AMS method.

6. Discussion

The ultrapotassic melasyenitoid to melagranitoid plutons represent an intriguing magmatic event in the Variscan orogeny. These plutons are made up of geochemically very specific rocks resulting from mixing of crustal melts with melts derived from anomalous mantle sources (Holub, 1997), are widespread throughout the lower- to mid-crustal orogenic root (Moldanubian Unit) and their emplacement took place over a relatively short time span (343–335 Ma; Holub et al., 1997; Janoušek and Gerdes, 2003; Kotková et al. 2003). Recent petrological and geochemical studies established that the ultrapotassic magmatism was associated with thinning of the lithosphere, upwelling of the upper mantle and the exhumation of the originally thickened crust (Schaltegger, 1997; Janoušek and Holub, in press). However, it is only generally assumed that the emplacement of these plutons ‘‘was controlled’’ by extensional tectonics.

As yet, no studies have focused in detail on the emplacement processes, internal fabrics, and tectonic setting of these ultrapotassic plutons. The importance of examining structures in and around these plutons arises when taking into account that the role of extensional tectonics during pluton emplacement may be generally problematic and that the material transfer processes may be highly spatially and temporally variable even within a single pluton (see Paterson and Fowler, 1993b; Paterson and Schmidt 1999 for discussion). In this section,

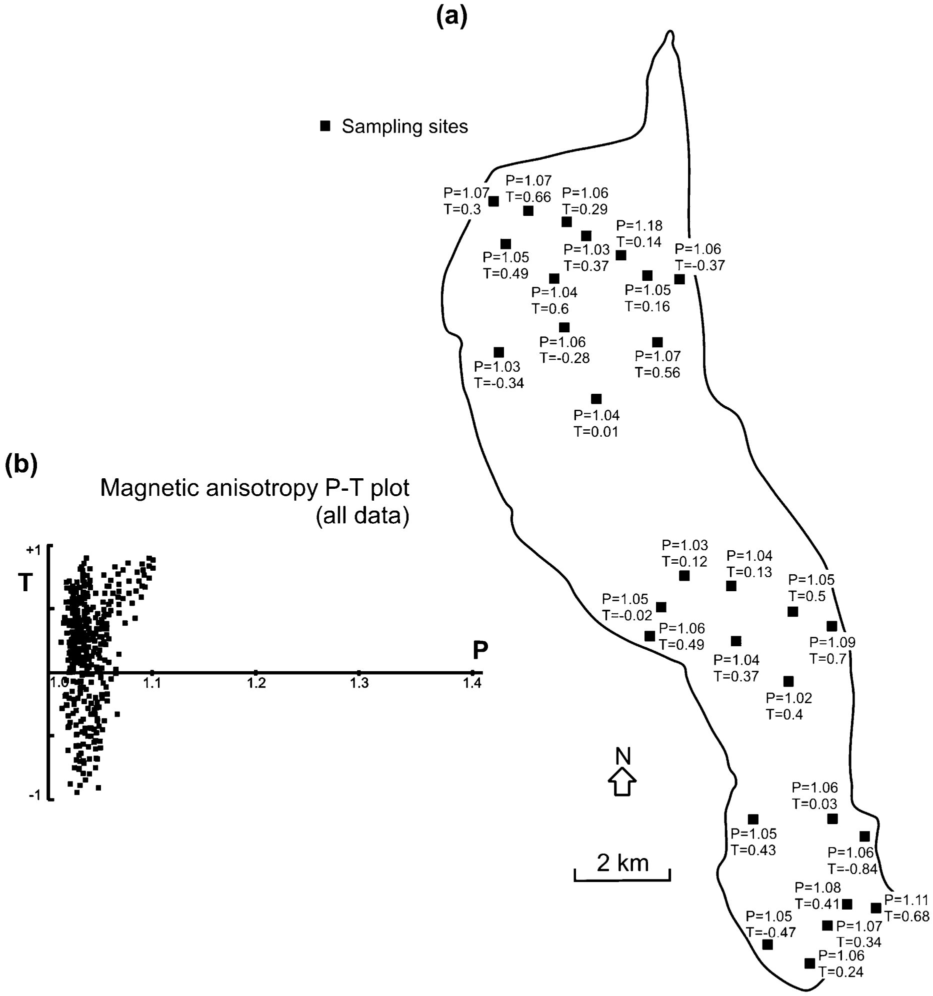

Fig. 8. (a) Map of the average values of P and T parameters at each sampling site in the Jihlava pluton. (b) Magnetic anisotropy P–T plot for all analyzed specimens from the Jihlava pluton.

we carefully evaluate the emplacement and formation of magmatic fabrics in the Jihlava pluton and discuss the more general implications for the exhumation of the orogenic root domain (represented here by the Moldanubian Unit).

6.1. Emplacement of the Jihlava pluton

At the present-day exposure level, the pluton crops out within a wide ~NE-SW trending zone of distributed wrench-dominated transtension associated with the dextral shearing and NW-side-up kinematics. This wide zone may have controlled the pluton geometry, as is suggested by its prominent sigmoidal shape parallel to the sigmoidal foliation pattern of the host-rock foliations (Fig. 3). After the emplacement and cooling of the syenitoid rocks, the originally wide transtensional zone became more localized at the NW tip of the pluton and was also later reactivated at upper-crustal levels (Přibyslav mylonite zone; PMZ in Fig. 3). However, the extent of host-rock displacement along the transtensional zone and its role as a near-field material transfer process during pluton emplacement are difficult to evaluate, as our structural data indicate that multiple material transfer processes (i.e. MTPs of Paterson and Fowler, 1993a) accommodated the emplacement of the syenitoid rocks. Below we demonstrate that the evidence for various MTPs has been preserved in different parts of the pluton and its host rocks:

(i) Ductile host-rock shortening (and possible minor lateral expansion of the pluton) within structural aureoles, marked by oblate strains, reorientation of older structures into parallelism with pluton margins and extensive partial melting, is recorded by the Moldanubian gneisses and migmatites along the eastern margin and the southern tip of the pluton (Fig. 2). The width of the deformed zones (structural aureoles) ranges from a hundred meters along the eastern margin up to one kilometer in migmatites at the southern tip of the pluton.

(ii) Sub-vertical sheeted zones preserved in the eastern and northern parts of the pluton (Fig. 2) suggest that some domains along pluton margins were constructed through sheeting, i.e. the emplacement of multiple magmatic sheets presumably by a magma wedging mechanism (i.e. by cracking and downward or lateral displacement of the host rock to form sheet-like bodies; Weinberg, 1999).

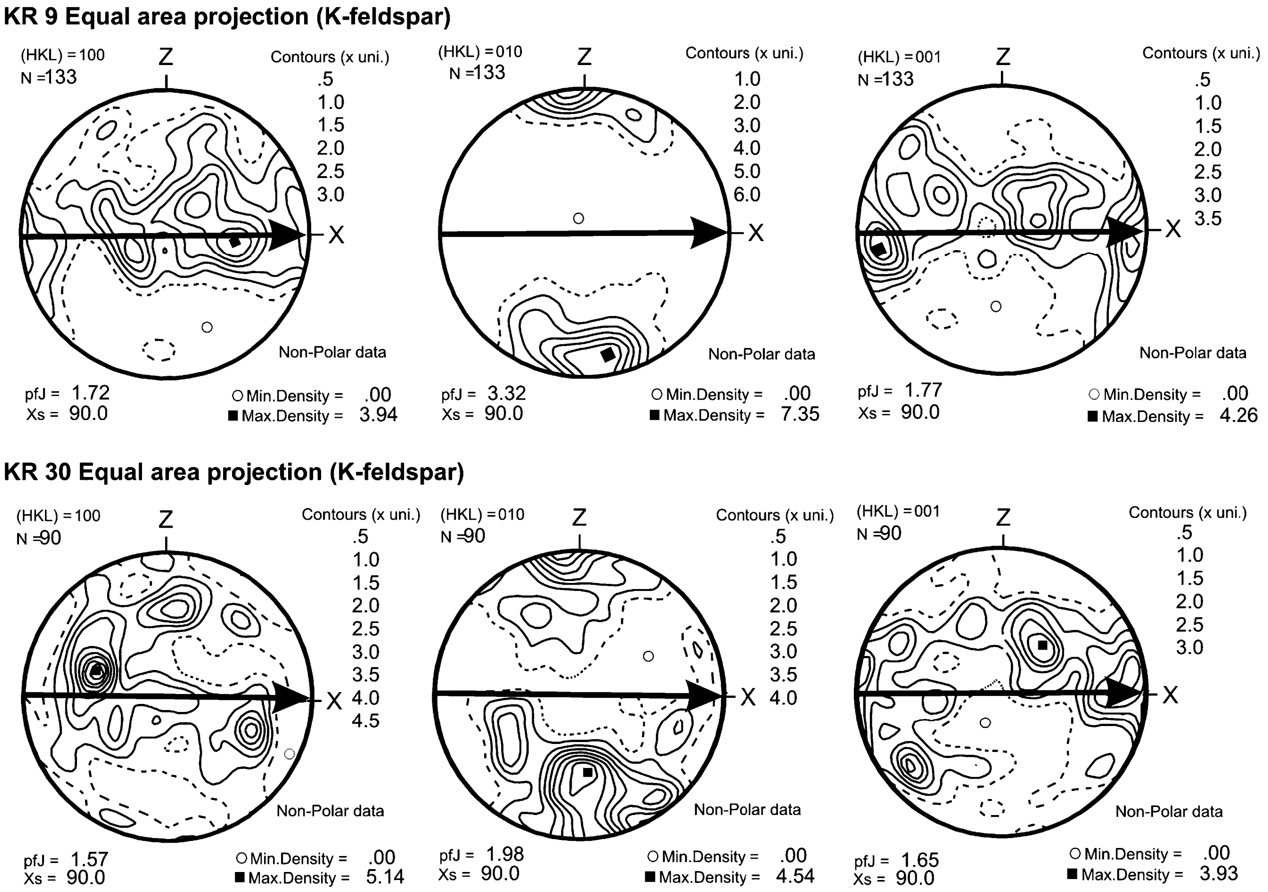

Fig. 9. The results of the EBSD analysis are plotted in stereograms on lower hemisphere, equal-area projection. In both samples the [010] crystallographic axes form two strong maxima close to the minimal magnetic susceptibility (k_3), the [001] and [110] axes form girdles around the *Z* direction with several subordinate maxima.

(iii) Two lines of evidence indicate that magmatic stoping, i.e. thermal cracking and downward transport of blocks of the host rocks into the magma, was an important emplacement process during the final stages of the pluton construction. First, abundant up to kilometer-sized stoped blocks are preserved in the pluton (Fig. 2). Second, sharp intrusive contacts, which cut off older host-rock structures and show no evidence for faulting, imply that some material must have been transferred vertically (i.e. downward into the pluton) out of the present-day exposure level.

(iv) At the western margin of the pluton, the sheeted zone and the syenitoids adjacent to the contact were affected by a margin-perpendicular contraction that is not recorded in the pluton host rocks (Fig. 4g). We assume that the partially crystallized outer carapace, constructed by sheeting or by magmatic stoping, was subsequently affected by the contraction due to the emplacement of the inner magma pulses pushing against more rigid edges of the pluton.

The high variability of the emplacement processes within a relatively small (~60 km^2) Jihlava pluton, as well as our preliminary data from other similar ultrapotassic plutons in the Moldanubian Unit, all indicate that MTPs during emplacement of these plutons were highly spatially and temporally variable. Therefore, we emphasize that the emplacement of the ultrapotassic plutons during the later stages of the Variscan orogeny cannot be explained by simple models and that these plutons may have rather complex intrusive and emplacement histories.

6.2. Interpretation of the fabric pattern

Our combined structural and AMS study revealed a complex fabric pattern and fabric gradients in the Jihlava pluton. The complexity is represented by the presence of the two pluton-wide magmatic foliations (one margin-parallel and one cross-cutting, ~ENE–WSW, i.e. at high angles to the margin) and by the AMS data which indicate several important trends (Figs. 7, 8): (i) margin-parallel magnetic foliations are associated with sub-horizontal magnetic lineations, a higher degree of anisotropy and oblate shapes of the AMS ellipsoid; (ii) discordant ~ENE–WSW magnetic foliations are associated with steeper magnetic lineations (40–50° plunge) and a lower degree of anisotropy. In the stereogram in Fig. 7, magnetic lineations form two prominent maxima, i.e. plunge at moderate angles to the SSE and NNW. The NNW plunging magnetic lineations are particularly intriguing in that they are "antithetic" to the general orientation of the transtensional zone and are not consistent with lineations elsewhere in the pluton or in the country rocks.

Our interpretation of the complex fabric pattern in the Jihlava pluton is as follows: (i) The margin-parallel magmatic (and magnetic) foliations seem to be decoupled from the regional deformation as they are always parallel to the pluton/host-rock contact regardless of the contact orientation (Figs. 3, 7). Similarly, the ∼ENE–WSW steep foliations (bearing magnetic lineations moderately plunging to the ∼NW) in the inner part of the pluton are oblique to both the outer contacts and the general strike of the pluton and are also decoupled from the metamorphic foliations in the Moldanubian host rocks. Such orientation is also not compatible with the regional dextral NW-side-up transtension. Hence, the formation of these foliations and lineations likely resulted from strain during internal magmatic (intrusive) processes (Paterson et al., 1998). In the case of the margin-parallel foliations, however, it is problematic to attribute the formation of these fabrics to some particular mechanism, as several processes may cause the margin-parallel mineral alignment (e.g., magma chamber expansion, convection, emplacement of an inner magma pulse, refraction of stress in a crystallizing chamber, and internal flow along the chamber walls; Paterson et al., 1998). Moreover, where the pluton margin is oriented parallel to the regional foliation, it is impossible to separate the fabric formed by internal processes (e.g., margin parallel flow during emplacement) from that formed by regional tectonic strain, or to separate the contribution of the two components to the final (composite) fabric.

The formation of the ∼ENE–WSW foliations and ∼NW trending lineations in the Jihlava pluton is also somewhat problematic. These foliations and lineations do not occur anywhere in the Moldanubian host rocks and thus they may have also resulted from some internal chamber processes. Interestingly, their intriguing ∼ENE–WSW orientation corresponds to the orientation of local tensional domains within the ∼NE–SW trending zone of dextral regional transtension. Therefore, we suspect that these foliations and lineations recorded strain resulting from the emplacement of multiple magma batches during the construction of the inner parts of the pluton. In such a case, if the individual magma batches were elongated ∼ENE–WSW, their successive emplacement would produce shortening perpendicular to their margins (i.e. ∼WNW–ESE) and thus the foliation pattern described above.

(ii) In contrast to the above, the SSE plunging magnetic lineations and also some of the magmatic (and magnetic) foliations, i.e. those with NE–SW orientation, are consistent with the stretching lineations and metamorphic foliations, respectively, that formed during the regional dextral transtension in the Moldanubian host rocks. Therefore, the formation of these magmatic and magnetic foliations and SSE plunging magnetic lineations can be interpreted as recording the increment of the regional tectonic strain within a zone of distributed transtension during a late stage of pluton cooling, superimposed on intrusive fabrics related to the pluton construction.

6.3. Implications for processes in orogenic root domain

It has been shown that a major mechanical event associated with a rapid exhumation of high-grade rocks (within a few million years) took place in the Central European Variscides at approximately ∼340 Ma (Willner et al., 2002 and references therein). Given the short time span (∼343–335 Ma) of emplacement of the ultrapotassic plutons, which overlaps this exhumation event, and their widespread occurrence (Fig. 1b) we suggest that careful determination of the temporal and geometrical relationships of structures in and around these plutons could provide some constraints for the kinematic framework, timing and local exhumation histories within the orogenic root.

The present study complemented by our other data sets (Žák et al., 2005; K. Verner, unpublished data) could support this hypothesis and also shed some light on the as yet poorly understood tectonic setting and emplacement mechanisms of the ultrapotassic plutons in the Central European Variscides (cf. Schaltegger, 1994; Schaltegger, 1997; Wenzel et al., 1997; Janoušek and Holub, in press). We demonstrate that, in spite of the similar age and geochemical characteristics of these plutons, the kinematic setting, and material transfer processes during emplacement (MTPs of Paterson and Fowler, 1993a) vary not only from one pluton to another, but also within a single pluton.

For example, from the west to the east (see Fig. 1b for locations of plutons), our recent research indicates that the deep-seated durbachitic ∼340 Ma Knížecí Stolec pluton (KSP in Fig. 1b) was initially emplaced via multiple cone-sheets followed by nested intrusion of large magma pulse(s) into the center of the outer cone-sheet-bearing ring complex. Verner et al. (2004) also interpreted the magmatic fabrics in this pluton as a record of intrusive strain overprinted by increments of nearly sub-vertical regional contraction in the southwestern part of the Moldanubian Unit. Holub (1997) also reported cases where durbachitic magmas of the Mehelník pluton (MEP in Fig. 1b) intruded LP-HT migmatites and were mingled with anatectic melts which were probably formed at low pressures ∼3–4 kbar (Petrakakis, 1997; Pitra et al., 1999). In the Central Bohemian Plutonic Complex (MP in Fig. 1b), we concluded that the ∼340–343 Ma Milevsko pluton was presumably emplaced by floor downdrop at upper crustal levels during normal, SE-side-up exhumation of the northwestern flank of the Moldanubian Unit (Žák et al., 2005). In contrast, the nearby ∼337 Ma Tábor pluton (TP in Fig. 1b), compositionally similar to the Jihlava pluton, intruded after the exhumation of this segment of the Moldanubian Unit. In this study, we have shown that the emplacement of the ∼335 Ma sigmoidal-shaped Jihlava pluton (JP in Fig. 1b) by multiple processes in the middle crust of the eastern segment of the Moldanubian Unit was broadly synchronous with the dextral, NW-side-up wrench-dominated transtension that overprints the formation of the regional flat-lying foliation. This wide transtensional zone continues further to the SSW where it was intruded by the ultrapotassic ∼338 Ma Rastenberg pluton (Klötzli and Parrish, 1996; RP in Fig. 1b). The Rastenberg pluton also has an asymmetric sigmoidal shape similar to that of the Jihlava pluton and, in addition, shows magmatic fabrics probably related to the transtensional zone (K. Verner, unpublished data).

The above examples illustrate how careful structural analysis of these ultrapotassic syenitoid plutons complemented with precise radiometric data may place important constraints on the kinematic framework and timing of tectonic processes in different segments within the orogenic root domain. These plutons thus may possibly track the differential exhumation paths during later stages of the Variscan orogeny. The synthesis of structural data from the remaining ultrapotassic plutons in the Moldanubian Unit as well as discussion of its broader tectonic implications for the Central European Variscides is the focus of our ongoing research.

7. Conclusions

We have drawn the following conclusions:

1. Multiple material transfer processes (MTPs) accommodated emplacement of the sigmoidal ~60 km^2 Jihlava syenitoid pluton. The evidence for various MTPs, which has been recorded in different parts of the pluton and its host rocks, includes ductile host-rock shortening (and possible minor expansion), formation of sheeted zones by magma wedging, magmatic stoping, and possibly host-rock displacement within the wide wrench-dominated transtensional zone.
2. Our combined structural and AMS study revealed a complex fabric pattern and fabric gradients in the ~335 Ma Jihlava pluton. The margin-parallel foliations and ~ENE–WSW steep foliations bearing NW trending magnetic lineations probably recorded intrusive strain during emplacement of inner magma pulses, but were overprinted by regional magmatic foliations and SSE plunging lineations. The latter magmatic fabric is interpreted as recording increments of regional tectonic strain within a zone of distributed transtension during a late stage of pluton cooling.
3. Our data show that the Jihlava pluton was emplaced in the middle crust of the eastern part of the Moldanubian Unit during dextral regional transtension. The emplacement took place within a wide transtensional zone that overprints formation of the flat-lying regional foliation and is associated with the dextral NW-side-up kinematics. We interpret that this transtensional zone accommodated exhumation of different segments in the eastern part of the Moldanubian Unit during pluton emplacement at ~335 Ma.
4. Based on our study of the Jihlava pluton and also of other ultrapotassic plutons in the Moldanubian Unit, we have demonstrated that these ultrapotassic plutons are structurally complex bodies emplaced by multiple intrusive processes. As exemplified by the present paper, careful determination of temporal and geometrical relationships of structures in and around these ultrapotassic plutons can provide important constraints for the kinematic framework, local exhumation histories and timing of tectonic processes in different segments of the orogenic root during and after the ~340 Ma major mechanical event in the Variscan orogenic belt.

Acknowledgements

The thorough reviews of Graham Borradaile and John Geissman were very helpful in improving the manuscript and are gratefully acknowledged. We also appreciate discussions with Karel Schulmann during the initial stages of the research. Financial support through Grant No. 230/2001/B-GEO/PrF of the Charles University Grant Agency (to K. Schulmann), Grant No. 271/2005/B-GEO/PrF of the Charles University Grant Agency (to K. Verner), Czech Geological Survey Internal Research Project No. 3233 (to K. Verner) and Grant No. 205/02/0514 of the Czech Science Foundation (to F.V. Holub) are gratefully acknowledged.

References

Allemand, P., Lardeaux, J.M., 1997. Strain partitioning and metamorphism in a deformable orogenic wedge: application to the Alpine belt. Tectonophysics 280, 157–169.

Behr, H.J., Engel, W., Franke, W., Giese, P., Weber, K., 1984. The Variscan belt in Central Europe: main structures, geodynamic implications, open questions. Tectonophysics 109, 15–40.

Benn, K., Paterson, S.R., Lund, S.P., Pignotta, G.S., Kruse, S., 2001. Magmatic fabrics in batholiths as markers of regional strains and plate kinematics: example of the Cretaceous Mt. Stuart batholith. Physics and Chemistry of the Earth 26, 343–354.

Carswell, D.A., O'Brien, P.J., 1993. Thermobarometry and geotectonic significance of high-pressure granulites – examples from the Moldanubian Zone of the Bohemian Massif in Lower Austria. Journal of Petrology 34, 427–459.

Chlupáč, I., Brzobohatý, R., Kovanda, J., Stráník, Z., 2002. Geological history of the Czech Republic. Academia, Prague, 436 pp. (in Czech).

Dewey, J.F., 1988. Extensional collapse of orogens. Tectonics 7, 1123–1139.

Dewey, J.F., 2002. Transtension in arcs and orogens. International Geology Review 44, 402–439.

Franke, W., 1989. Variscan plate tectonics in Central Europe – current ideas and open questions. Tectonophysics 169, 221–228.

Friedl, G., von Quadt, A., Ochsner, A., Finger, F., 1993. Timing of the Variscan orogeny in the Southern Bohemian Massif (NE-Austria) deduced from new U-Pb and monazite dating. Terra Abstracts 5, 235–236.

Gebauer, D., Friedl, G., 1994. A 1.38 Ga protolith age for the Dobra orthogneiss (Moldanubian zone of the southern Bohemian massif, NE-Austria): evidence from ion-microprobe (SHRIMP) dating of zircon. Journal of the Czech Geological Society 39, 34–35.

Holub, F.V., 1997. Ultrapotassic plutonic rocks of the durbachite series in the Bohemian Massif: petrology, geochemistry and petrogenetic interpretation. Journal of Geological Sciences, Economic Geology. Mineralogy 31, 5–26.

Holub, F.V., Cocherie, A., Rossi, P., 1997. Radiometric dating of granitic rocks from the Central Bohemian Plutonic Complex (Czech Republic): constraints on the chronology of the thermal and tectonic events along the Moldanubian-Barrandian boundary. Comptes Rendus de l'Academie des Sciences Paris. Earth and Planetary Sciences 325, 19–26.

Hrouda, F., 1994. A technique for the measurement of thermal-changes of magnetic- susceptibility of weakly magnetic rocks by the Cs-2 apparatus and Kly-2 Kappabridge. Geophysical Journal International 118, 604–612.

Hrouda, F., Jelínek, V., Hrušková, L., 1990. A package of programs for statistical evaluation of magnetic data using IBM-PC computers. EOS Trans. AGU, San Francisco. 1289.

Janoušek, V., Gerdes, A., 2003. Timing the magmatic activity within the Central Bohemian Pluton, Czech Republic: conventional U-Pb ages for the Sázava and Tábor intrusions and their geotectonic significance. Journal of the Czech Geological Society 48, 70–71.

Janoušek, V., Holub, F.V., in press. The causal link between HP-HT metamorphism and ultrapotassic magmatism in collisional orogens: case study from the Moldanubian Zone of the Bohemian Massif. Proceedings of Geologists' Association.

Jelínek, V., 1978. Statistical processing of anisotropy of magnetic susceptibility measured on groups of specimens. Studia Geophysica et Geodetica 22, 50–62.

Jelínek, V., Pokorný, J., 1997. Some new concepts in technology of transformer bridges for measuring susceptibility anisotropy of rocks. Physics and Chemistry of the Earth 22, 179–181.

Klötzli, U.S., Parrish, R.R., 1996. Zircon U/Pb and Pb/Pb geochronology of the Rastenberg granodiorite, South Bohemian Massif, Austria. Mineralogy and Petrology 58, 197–214.

Konopásek, J., Schulmann, K., 2005. Contrasting Early Carboniferous field geotherms: evidence for accretion of a thickened orogenic root and subducted Saxothuringian crust (Central European Variscides). Journal of the Geological Society, London 162, 463–470.

Kotková, J., Schalteger, U., Leichmann, J., 2003. 338–335 Ma old intrusions in the E Bohemian Massif – a relic of the orogen-wide durbachitic magmatism in European Variscides. Journal of the Czech Geological Society 48, 80.

Matte, P., Maluski, H., Rajlich, P., Franke, W., 1990. Terrane boundaries in the Bohemian Massif: result of large-scale Variscan shearing. Tectonophysics 177, 151–170.

Medaris, G., Jelínek, E., Mísař, Z., 1995. Czech eclogites – terrane settings and implications for Variscan tectonic evolution of the Bohemian Massif. European Journal of Mineralogy 7, 7–28.

Miller, R.B., Paterson, S.R., 2001. Construction of mid-crustal sheeted plutons: examples from the north Cascades, Washington. Geological Society of America Bulletin 113, 1423–1442.

Nagata, T., 1961. Rock Magnetism. Maruzen, Tokyo, 350 pp.

Owen, J.V., Dostal, J., 1996. Prograde metamorphism and decompression of the Gföhl gneiss, Czech Republic. Lithos 38, 259–270.

Paterson, S.R., Fowler, T.K., 1993a. Re-examining pluton emplacement processes. Journal of Structural Geology 15, 191–206.

Paterson, S.R., Fowler, T.K., 1993b. Extensional pluton-emplacement models: do they work for large plutonic complexes? Geology 21, 781–784.

Paterson, S.R., Fowler, T.K., Schmidt, K.L., Yoshinobu, A.S., Yuan, E.S., Miller, R.B., 1998. Interpreting magmatic fabric patterns in plutons. Lithos 44, 53–82.

Paterson, S.R., Schmidt, K.L., 1999. Is there a close spatial relationship between faults and plutons? Journal of Structural Geology 21, 1131–1142.

Petrakakis, K., 1997. Evolution of Moldanubian rocks in Austria: review and synthesis. Journal of Metamorphic Geology 15, 203–222.

Pitra, P., Burg, J.P., Guiraud, M., 1999. Late Variscan strike-slip tectonics between the Teplá-Barrandian and Moldanubian terranes (Czech Bohemian Massif): petrostructural evidence. Journal of the Geological Society, London 156, 103–120.

Rey, P., Burg, J.P., Casey, M., 1997. The Scandinavian Caledonides and their relationship to the Variscan belt. In: Burg, J.P., Ford, M. (Eds.), Orogeny through Time. Geological Society Special Publication 121, pp. 179–200.

Schaltegger, U., 1994. Unraveling the premesozoic history of Aar and Gotthard massifs (Central Alps) by isotopic dating – a review. Schweizerische Mineralogische und Petrographische Mitteilungen 74, 41–51.

Schaltegger, U., 1997. Magma pulses in the Central Variscan Belt: episodic melt generation and emplacement during lithospheric thinning. Terra Nova 9, 242–245.

Schulmann, K., Ledru, P., Autran, A., Edel, J.B., 1997. Thermomechanical evolution of Variscan collision in western and central Europe: petrological, structural and geophysical constraints. Terra Nova 9 Abstract Supplements No. 1, 112.

Schulmann, K., Schaltegger, U., Jezek, J., Thompson, A.B., Edel, J.B., 2002. Rapid burial and exhumation during orogeny: thickening and synconvergent exhumation of thermally weakened and thinned crust (Variscan orogen in Western Europe). American Journal of Science 302, 856–879.

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

Schofield, D.I., D'Lemos, R.S., 1998. Relationships between syn-tectonic granite fabrics and regional PTtd paths: an example from the Gander-Avalon boundary of Newfoundland. Journal of Structural Geology 20, 459–471.

Teyssier, C., Tikoff, B., 1999. Fabric stability in oblique convergence and divergence. Journal of Structural Geology 21, 969–974.

Thompson, A.B., Schulmann, K., Jezek, J., 1997. Extrusion tectonics and elevation of lower crustal metamorphic rocks in convergent orogens. Geology 25, 491–494.

Van Breemen, O., Aftalion, M., Bowes, D.R., Dudek, A., Mísař, Z., Povondra, P., Vrána, S., 1982. Geochronological studies of the Bohemian Massif, Czechoslovakia, and their significance in the evolution of Central Europe. Transactions of the Royal Society of Edinburgh. Earth Sciences 73, 89–108.

Verner, K., Holub, F.V., Žák, J., 2004. Structural evolution and emplacement of the durbachitic Knížecí Stolec pluton, South Bohemian (Moldanubian) batholith. Geolines 17, 97–98.

Vrána, S., 1988. The Moldanubian Zone in Southern Bohemia: polyphase evolution of imbricated crustal and upper mantle segments. Proceedings of the 1st International Conference on the Bohemian Massif. Czech Geological Survey, Prague, pp. 331–336.

Vrána, S., Bártek, J., 2005. Retrograde metamorphism in a regional shear zone and related chemical changes: the Kaplice Unit of muscovite-biotite gneisses in the Moldanubian Zone of southern Bohemia, Czech Republic. Journal of the Czech Geological Society 50, 43–57.

Vrána, S., Blümel, P., Petrakakis, K., 1995. Moldanubian Zone: metamorphic evolution. In: Dallmeyer, D., Franke, W., Weber, K. (Eds.), Pre-Permian Geology of Central and Western Europe. Springer, Berlin, pp. 453–466.

Weinberg, R.F., 1999. Mesoscale pervasive felsic magma migration: alternatives to dyking. Lithos 46, 393–410.

Wendt, J.I., Kroener, A., Fiala, J., Todt, W., 1994. U-Pb zircon and Sm-Nd dating of Moldanubian HP/HT granulites from South Bohemia, Czech Republic. Journal of the Geological Society of London 151, 83–90.

Wenzel, T., Mertz, D.F., Oberhansli, R., Becker, T., Renne, P.R., 1997. Age, geodynamic setting, and mantle enrichment processes of a K-rich intrusion from the Meissen massif (northern Bohemian massif) and implications for related occurrences from the mid-European Hercynian. Geologische Rundschau 86, 556–570.

Willner, A.P., Sebazungu, E., Gerya, T.V., Maresch, W.V., Krohe, A., 2002. Numerical modelling of PT-paths related to rapid exhumation of high-pressure rocks from the crustal root in the Variscan Erzgebirge Dome (Saxony/Germany). Journal of Geodynamics 33, 281–314.

Ziegler, P.A., 1986. Geodynamic model for the Palaeozoic crustal consolidation of Western and Central Europe. Tectonophysics 126, 303–328.

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