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Multiple magmatic fabrics in the Sázava pluton (Bohemian Massif, Czech Republic): a result of superposition of wrench-dominated regional transpression on final emplacement

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Abstract

The Sázava pluton ($\sim$354 Ma) of the Central Bohemian Plutonic Complex was emplaced syntectonically into the upper crustal Neo-Proterozoic and Lower Paleozoic host rock along the SE margin of the Teplá-Barrandian Zone, Bohemian Massif (Czech Republic). The host rock is characterized by transpressional fabric dominated by steep SE–NW dipping foliations and subhorizontal NE–SW stretching lineations associated with flattening to a plane strain ellipsoid. The strain intensity, degree of oblateness and temperature conditions of deformation increase in the host rock towards the pluton margin. In the pluton, quartz microfabric indicates progressive cooling of the syntectonically emplaced magma. The AMS method revealed multiple magmatic fabrics and lateral variations in the shapes of the AMS ellipsoid and the magnetic fabric intensity in the pluton. The central part of the pluton yields prolate shapes of the AMS ellipsoid and a low degree of anisotropy with preserved steep magnetic lineations, whereas, along the pluton margins, oblate AMS ellipsoids are associated with a high degree of anisotropy. We interpret the multiple fabrics and the partially decoupled fabric pattern between the host rock and the pluton as being a result of superposition of regional tectonic strain during highly oblique transpression on emplacement-related intrusive strain, where outer solidified and more rigid edges of the pluton enabled preservation of older steep fabrics in its interior.

Keywords: Anisotropy of magnetic susceptibility (AMS); Bohemian Massif; Fabric; Pluton; Transpression

1. Introduction

Recently, many studies pointed out the importance of interpretation of magmatic fabrics (i.e. planar and/or linear shape preferred orientation of minerals in magmatic rocks formed during the presence of a melt with no evidence for sub-solidus deformation; Paterson et al., 1989) and their map-scale patterns in plutons and adjacent host rock for evaluation of internal magmatic processes, pluton emplacement and regional tectonics (see Paterson et al. (1998) for review). Furthermore, while the formation of magmatic fabrics in plutonic rocks results in preferred orientation of ferromagnetic and paramagnetic minerals, mesoscopic structural observations are commonly complemented by using the anisotropy of magnetic susceptibility (AMS) to corroborate mesoscopic fabric geometries, to reveal invisible (cryptic) fabrics in granitoids, and to quantify the intensity and symmetry of the magnetic ellipsoid (Jelínek, 1978, 1981; Bouchez, 1997). Numerous studies have shown that AMS data may reflect the overall regional kinematics and the character of regional deformation, the internal magmatic processes and the variable physical states of the magmas during ascent and emplacement (Bouchez et al., 1990; Bouchez and Gleizes, 1995; Tobisch and Cruden, 1995; Blanquat and Tikoff, 1997; Benn et al., 1998; Hrouda et al., 1999; Neves et al., 2003).

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One of the most important aspects for interpretation of processes, both in the plutons and the host rocks, is understanding of whether magmatic fabrics preserve information about internal magmatic processes, regional tectonics, or both. This can be achieved by evaluation of the degree of coupling between the internal fabrics in the plutons and the host rock structures. Multiple magmatic fabrics preserved in a single pluton further complicate this issue. These multiple fabrics have been reported in several plutons worldwide and have been interpreted in various ways (Paterson et al., 1998, and references therein), for example as being a result of differential rotations of particles with variable aspect ratios, combination of pure and simple shear, alignment of crystals with different aspect ratios to unequal elongation components of coaxial flow, or superposition of different strain increments on a relatively static magma chamber at different times (Paterson et al., 2003).

In the present paper, we integrate structural and microstructural data, finite strain estimations, and AMS in an attempt to evaluate the relationship between host rock deformation and emplacement of the Sázava pluton (Bohemian Massif, Czech Republic; Fig. 1), and we interpret multiple magmatic fabrics preserved in the pluton. This Variscan pluton was emplaced as an irregular magma body into the upper crustal Neo-Proterozoic to Lower Paleozoic host rocks along the SE margin of the Teplá-Barrandian Zone (central Bohemian Massif) during regional transpression. Our structural mapping revealed concordant fabrics in the host rocks and the tonalite and also lateral variations in fabric intensity. Using finite strain analysis, we quantified finite strain parameters recorded both in and outside the pluton aureole and correlated the finite strain gradient in the host rocks with an increase in the temperature conditions of deformation, confirmed by microstructural and quartz microfabric analysis. Moreover, anisotropy of the magnetic susceptibility (AMS) and structural data from the tonalite allowed us to quantify the parameters of the fabric ellipsoids throughout the entire intrusion and to correlate fabrics in the pluton aureole with both the magnetic and the mesoscopic fabric in the pluton. The AMS technique also revealed multiple magmatic fabrics in the pluton, defined by non-coaxial magnetic lineations in microgranitoid enclaves and the host tonalite along the western margin of the pluton, and locally preserved steep lineations in its central part.

Based on these data, we then addressed several issues: (i) formation of the magmatic and host rock fabrics during regional transpression; (ii) interpretation of multiple magmatic fabrics and lateral fabric gradients in the pluton; and (iii) estimation of the parameters of the overall regional

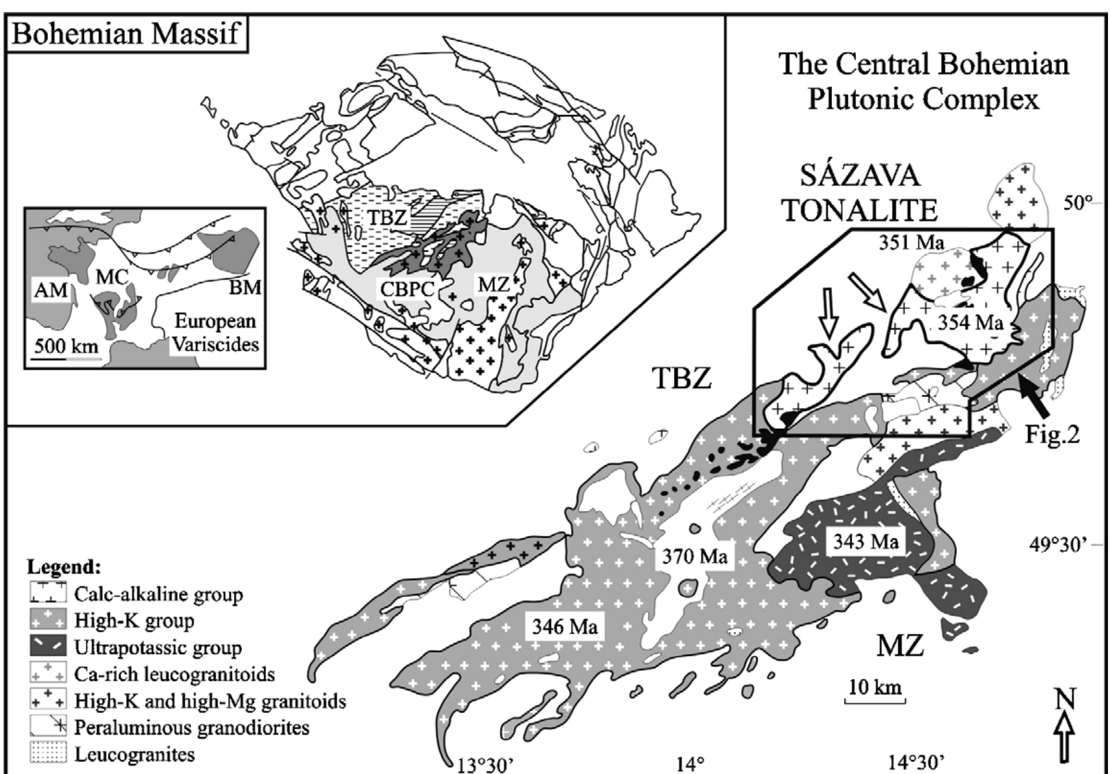

Fig. 1. Geological map of the Central Bohemian Plutonic Complex with radiometric ages (after Holub et al., 1997b) showing the distribution of the main intrusive units. The Central Bohemian Plutonic Complex is made up of multiple plutons exposed along the boundary between the Teplá-Barrandian and Moldanubian Zones, where the Sázava tonalite crops out in its northern part. The inset shows a location map of the Bohemian Massif in the European Variscides and the position of the Central Bohemian Plutonic Complex in the Bohemian Massif. AM—Armorican Massif, MC—Massif Central, BM—Bohemian Massif, TBZ—Teplá-Barrandian Zone, CBPC—Central Bohemian Plutonic Complex, MZ—Moldanubian Zone.

transpression using fabric characteristics from both the host rock and the pluton.

2. Geological setting

The Sázava pluton represents a Variscan calc-alkaline (tonalitic) pluton emplaced at ~354 Ma (Janoušek and Gerdes, 2003) into Neo-Proterozoic and Lower Paleozoic metavolcanic and sedimentary host rocks along the SE margin of the Teplá-Barrandian Zone in the central part of the Bohemian Massif (Fig. 1). In a broader context, the pluton crops out in the northern part of a large (~3200 km^2) plutonic complex (the Central Bohemian Plutonic Complex; Holub et al., 1997b), exposed between the upper-crustal Teplá-Barrandian Zone and the exhumed orogenic root domain (the Moldanubian Zone). The entire plutonic complex consists of multiple plutons and dykes emplaced over ~17 My (Holub et al., 1997a,b; Janoušek et al., 2000; Janoušek and Gerdes, 2003) during crustal thickening and subsequent exhumation of the orogenic root (Zak et al., 2002). According to radiometric ages (Holub et al., 1997a; Janoušek and Gerdes, 2003), the Sázava tonalite and other calc-alkaline sheet-like granitoid intrusions represent the earliest magma pulses of the Central Bohemian Plutonic Complex. Recent geochemical and isotopic studies (Holub et al., 1997a,b; Janoušek et al., 2000), supported by our structural investigations, indicate a magmatic-arc character of the plutonic complex emplaced above the subduction zone.

In the map view, the Sázava pluton forms an irregular body with aspect ratio 2:1 and its long axis parallel to the margin of the Teplá-Barrandian Zone and to the trend of the regional structures (Fig. 2). Although we lack constraints on the three-dimensional geometry of the pluton with steeply dipping contacts, abundant stoped blocks and preserved km-scale roof pendants suggest that the present-day erosion level is close to the pluton roof. Typically, the dominant rock type is biotite hornblende tonalite (Sázava tonalite), although gabbroic intrusions, steep gabbrodioritic sheets and microgranitoid enclave swarms are preserved along the intrusion margins. The central part of the pluton is relatively compositionally and structurally homogeneous with no evidence for compositional zonation or internal sheeting.

Pluton host rock and roof pendants are predominantly composed of Neo-Proterozoic to Lower Paleozoic volcano-sedimentary units. The former units comprise an up to 2000-m-thick sequence of volcaniclastic rocks of various compositions and subvolcanic intrusions of albitic granites (the Kralupy–Zbraslav Group), overlain conformably by flysch clastic turbidites (alternating shales, siltstones and greywackes interbedded with polymictic conglomerates—the Štěchovice Group). Roof pendants, rafts, and km-scale stoped blocks of host rock (Kachlík, 1988, 1992, 1999) comprise Neo-Proterozoic metavolcanics and associated metagranitoids, and Neo-Proterozoic to Lower Paleozoic clastic and locally carbonate sequences. Stratigraphic correlation revealed that these units correspond to the Neo-Proterozoic–Middle Devonian of the Teplá-Barrandian Zone. Low-grade regional metamorphism characterizes the host rocks along the SE margin of the Teplá-Barrandian Zone, and is documented by both thermobarometric data (Pitra et al., 1999; Scheuvens and Zulauf, 2000) and by the presence of only anchimetamorphosed sediments and lower greenschist facies assemblages in the metavolcanics, suggesting relatively shallow, upper-crustal conditions of the pluton emplacement. Regional metamorphism was enhanced by low-pressure (<4 kbar) contact metamorphism (Kachlík, 1992) in the roof pendants and in the up to 2-km-wide thermal aureole.

3. Structural and fabric pattern of the host rock

A wide ~NE–SW-trending zone of distributed transpression accompanied by NW–SE shortening developed along the SE flank of the Teplá-Barrandian Zone during the Variscan orogeny (Rajlich et al., 1988). This zone is superimposed on older pre-Variscan structures and defines the structural pattern of both pluton margins and roof pendants. The relatively homogeneous character of the structures and deformational fabrics within this zone is a result of contemporaneous development of large-scale folds, steep regional foliation and associated sub-horizontal stretching lineation (Figs. 3, 4 and 5b).

Upright, large-scale, open buckle folds of several hundred meters in wavelength with steep axial planes and sub-horizontal hinges trend NNE–SSW and are concordant with minor folds of centimeters to decimeters in wavelength at outcrop scale. Significant changes in the fold geometry are observed close to the pluton margin, where major folds become tight to isoclinal. Steep NNE–SSW-trending foliation (S_1), parallel to the axial planes of the major folds, is developed throughout the pluton host rock and almost entirely overprints pre-existing depositional (bedding, lamination, greywacke layers in pelites) and magmatic (pillow lavas, flow banding) or older deformational fabrics (S_0) in the sedimentary and metavolcanic sequences. The S_1 foliation (Fig. 5a) is mostly developed as penetrative pressure solution cleavage forming subparallel or anastomosing planes, its development is predominantly controlled by the rock competence and the distance from the pluton margin. The S_1 cleavage is most intensely developed in the incompetent sediments of the Štěchovice Group as spaced disjunctive and discrete cleavage formed by pressure solution. In metavolcanics, the intensity of the cleavage development decreases with increasing content of quartz and the cleavage has a character ranging from continuous cleavage in metabasalts to weak spaced cleavage in albitic granites.

In general, the intensity of cleavage development significantly increases towards the pluton margin where, in domains adjacent to the pluton-host rock contact,

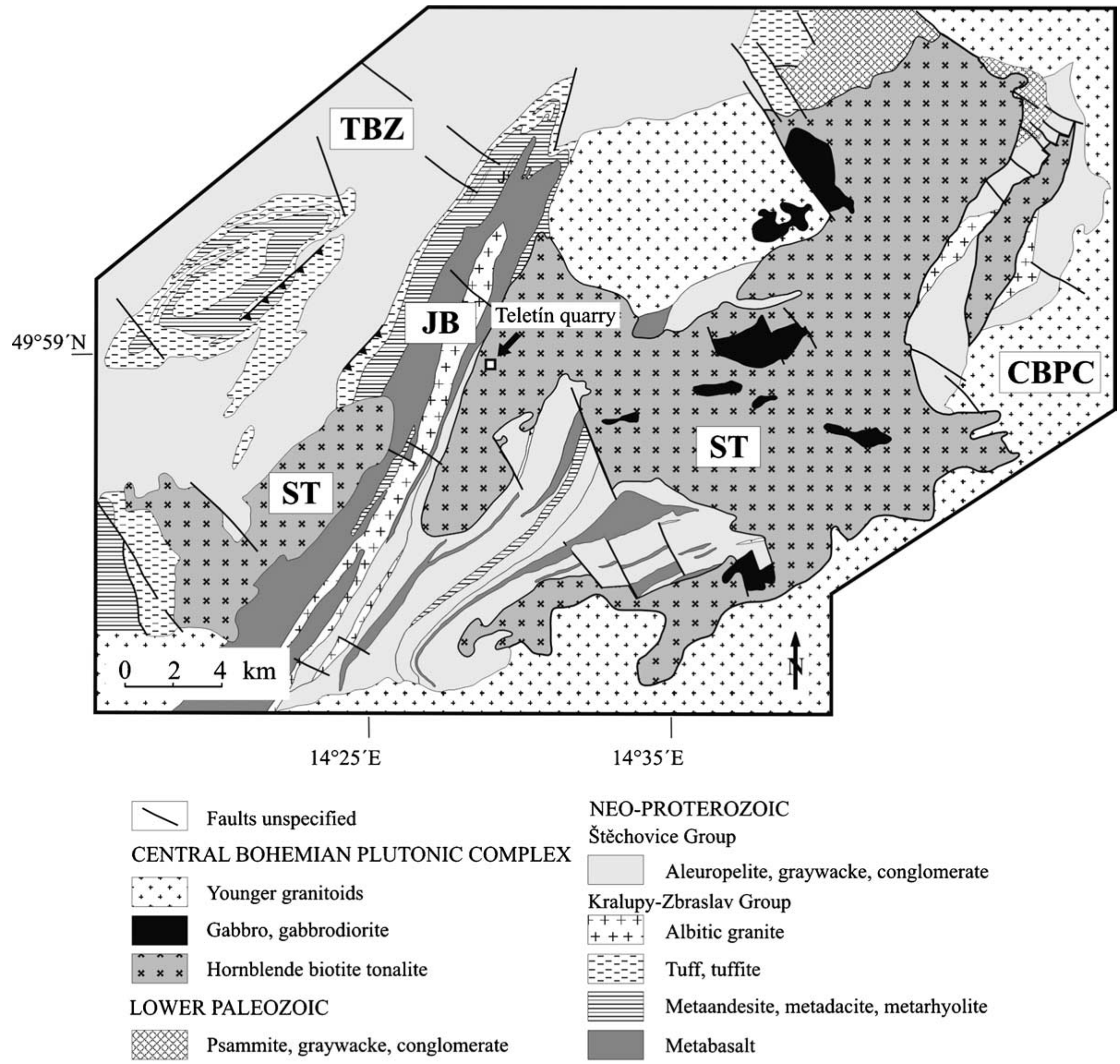

Fig. 2. Simplified geological map of the Sázava tonalite and its host rocks. Neo-Proterozoic metavolcanics and unmetamorphosed sediments of the Štěchovice Group crop out to the W of the tonalite, whereas its eastern margin has been intruded by younger plutons of the Central Bohemian Plutonic Complex. TBZ—Teplá-Barrandian Zone, JB—Jílové Belt, ST—Sázava tonalite.

low-temperature pressure solution cleavage passes into high temperature foliation, defined as compositional banding of domains rich in biotite and domains formed by recrystalized quartz. The S_1 cleavage or high temperature foliation in the pluton aureole is typically associated with shallowly plunging to sub-horizontal stretching lineation (L_1) sub-parallel to the fold axes. The L_1 lineation (Fig. 5b) is represented either by mineral stretching lineations in the metavolcanics or intersection lineations (intersections of bedding and cleavage planes) in the overlying flysch sequence. Both types are subhorizontal and trending NNE or SSW. Field relationships, including tonalite sheets emplaced along the cleavage planes and intense foliation preserved in the stoped blocks, suggest that significant deformation and cleavage development took place also prior to the tonalite intrusion.

Some finite strain characteristics and parameters of the regional transpression may be inferred from our structural and fabric data. Well-developed and homogeneously oriented LS fabric characterizes the fabric pattern throughout the pluton host rock and roof pendants. This dominant LS fabric, defined by steep foliation and shallowly plunging stretching lineation, indicates that the *XZ* plane of the finite strain ellipsoid is sub-horizontal, with maximum NW–SE shortening (*Z* axis) and maximum stretching axis (*X*) oriented in the NE–SW direction with respect to the present-day coordinates. Equally developed foliation and stretching lineation at most outcrops indicate oblate to plane strain shape of the finite strain ellipsoid recorded by the rock fabric, which has also been confirmed by our finite strain analysis presented in the section below.

3.1. Finite strain analysis in the host rock

In the present study, we complemented previous strain

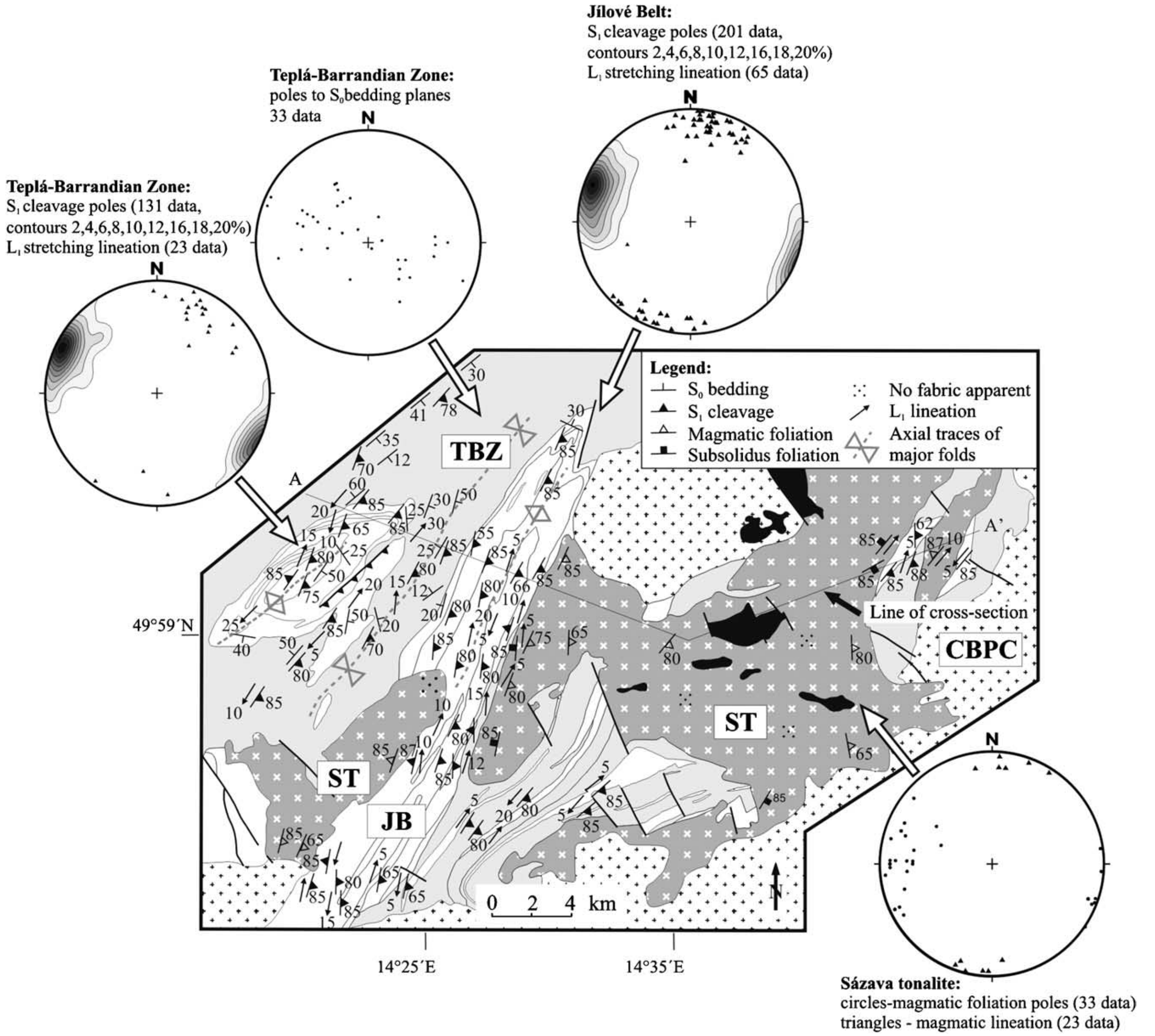

Fig. 3. Structural map of the Sázava tonalite and the adjacent Neo-Proterozoic country rock. Orientation diagrams (lower hemisphere, equal area projection) show the orientations of the major structural elements (S_0 bedding, L_1 stretching lineation, S_1 regional cleavage and magmatic foliation in the tonalite). Steep magmatic foliations and sub-horizontal magmatic lineations in the tonalite are parallel to the regional cleavage and to the stretching lineations in the host rock, respectively. Line A–A′ shows the approximate location of structural block diagram (Fig. 4).

analysis (Rajlich et al., 1988) and present new data to characterize the finite strain pattern in the country rocks along the NW margin of the pluton (Fig. 6). Finite strain analysis was carried out at 10 localities using deformed pyroclastics and conglomerates. The most reliable strain data were obtained from the deformed conglomerates (Fig. 5c), mostly consisting of greywacke pebbles embedded in a greywacke matrix. The finite strain was estimated by measuring the axial ratios and angles between the long axes of particles and the reference line and calculated using the R_f/ϕ method (Ramsay and Huber, 1983). Measurements were taken from cleavage planes and joints, representing the principal *XY* and *YZ* sections of the finite strain ellipsoid. The stretching lineation (*XY* plane) and the intersection of the cleavage with the lineation–perpendicular joints (*YZ* plane) were chosen as reference lines. We used $K = \ln R_{XY}/\ln R_{YZ}$ and $D = (\ln R_{XY}^2 + \ln R_{YZ}^2)^{1/2}$ parameters (Ramsay and Huber, 1983) to characterize the symmetry of the finite strain ellipsoid and the intensity of the finite strain, respectively. Although possible errors can arise from this method, especially from viscosity contrasts between the particles and the matrix and not exactly perpendicular orientations of the planes of the sections, we assume that this analysis provides sufficiently reliable data for at least approximate quantification of the total strain gradient (background regional strain and strain associated with the tonalite intrusion) in the host rock along the NW margin of the pluton. The results of strain analysis are summarized in the map of the *XZ* sections of the

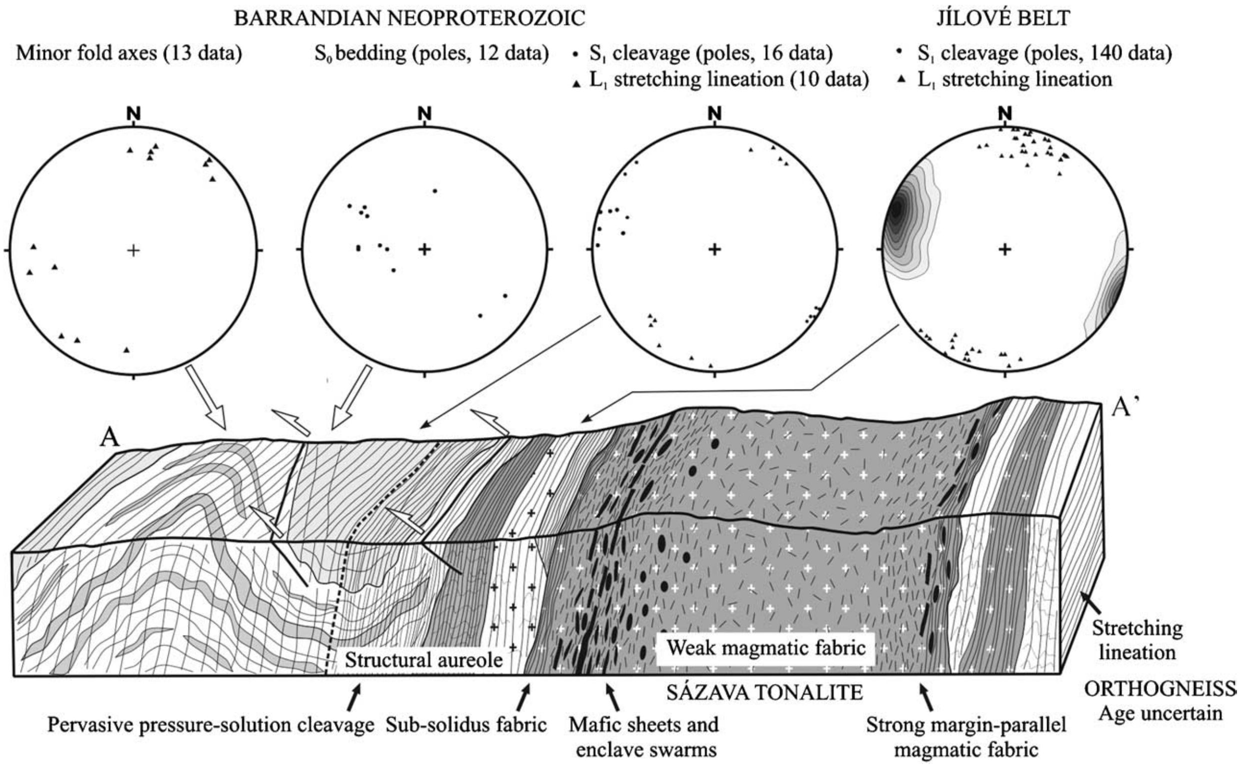

Fig. 4. Idealized structural block diagram across the tonalite intrusion and the country rock along line A–A′ with orientation diagrams (lower hemisphere, equal area projection) showing the orientations of the major structural elements (regional S_1 cleavage, stretching lineations, bedding planes and axes of outcrop-scale F_1 folds from the Barrandian Neo-Proterozoic country rock) along the A–A′ transect.

finite strain ellipsoid (Fig. 6). The strain data plotted on the Flinn K-graph (Fig. 6b) show the symmetry of the estimated finite strain ellipsoids. We obtained the plane strain character of the strain ellipsoid with K parameter ranging from 0.42 to 1.38 from measurements of less deformed conglomerates and pyroclastics (localities 1—Zbraslav, 2—Dobříš, 3—Voznice, 4—Davle and 5—Tuškovský vrch). Other data, obtained from strongly deformed rocks, indicate an oblate character of the strain ellipsoid (localities 6—Štěchovice, 8—Chlomek, 9—Librická rokle, 10—Pikovice) with K parameter ranging from 0.31 to 0.9. The only exception is the strongly prolate finite strain ellipsoid from locality 7—Hraštice with K parameter equal to 13.7.

It is apparent from our finite strain estimations that there is a strain gradient in the host rocks, approximately perpendicular to the pluton margin and related to the distance from the tonalite intrusion. According to our measurements, the intensity of deformation significantly increases towards the pluton margin, as shown in Fig. 6c, where the D parameters calculated for each locality are plotted against the distance from the limit of the pluton. In the western part of the study area, the D parameter is, in general, low, ranging from $D=0.35$ (locality of Dobříš, 20 km from intrusion margin) to $D=0.76$ (locality of Tuškovský vrch, 15 km from intrusion margin). However, towards the pluton margin, parameter D increases significantly from $D=1.1$ (locality of Librická rokle) up to $D=1.44$ (locality of Pikovice). The deformation gradient, as well as orientation of the finite strain ellipsoids, is also documented in the map of the XZ sections of the finite strain ellipsoid (Fig. 6a), where the main extension directions (X axes of the finite strain ellipsoid) were plotted parallel to the L_1 stretching lineation. Three main points may be summarized from our strain data given above: (i) the estimated flattening to the plane strain ellipsoid is consistent with the mesoscopic rock fabrics observed in the field, (ii) there is striking strain gradient in the host rock, marked by a significant increase in the intensity of the finite strain and the degree of oblateness towards the pluton margin, and (iii) the lack of other criteria prevents interpretation of whether the strain-gradient in the host rock is a result of superimposition of the strain associated with emplacement of the pluton on the regional background transpressive strain or is a result of some other process. However, our quartz microfabric analysis (given below) suggests that large strains along the intrusion margin may be associated with thermal weakening of the host rock due to tonalite intrusion.

4. Fabric pattern in the pluton

4.1. Mesoscopic fabrics

The fabric pattern of the Sázava pluton was revealed by

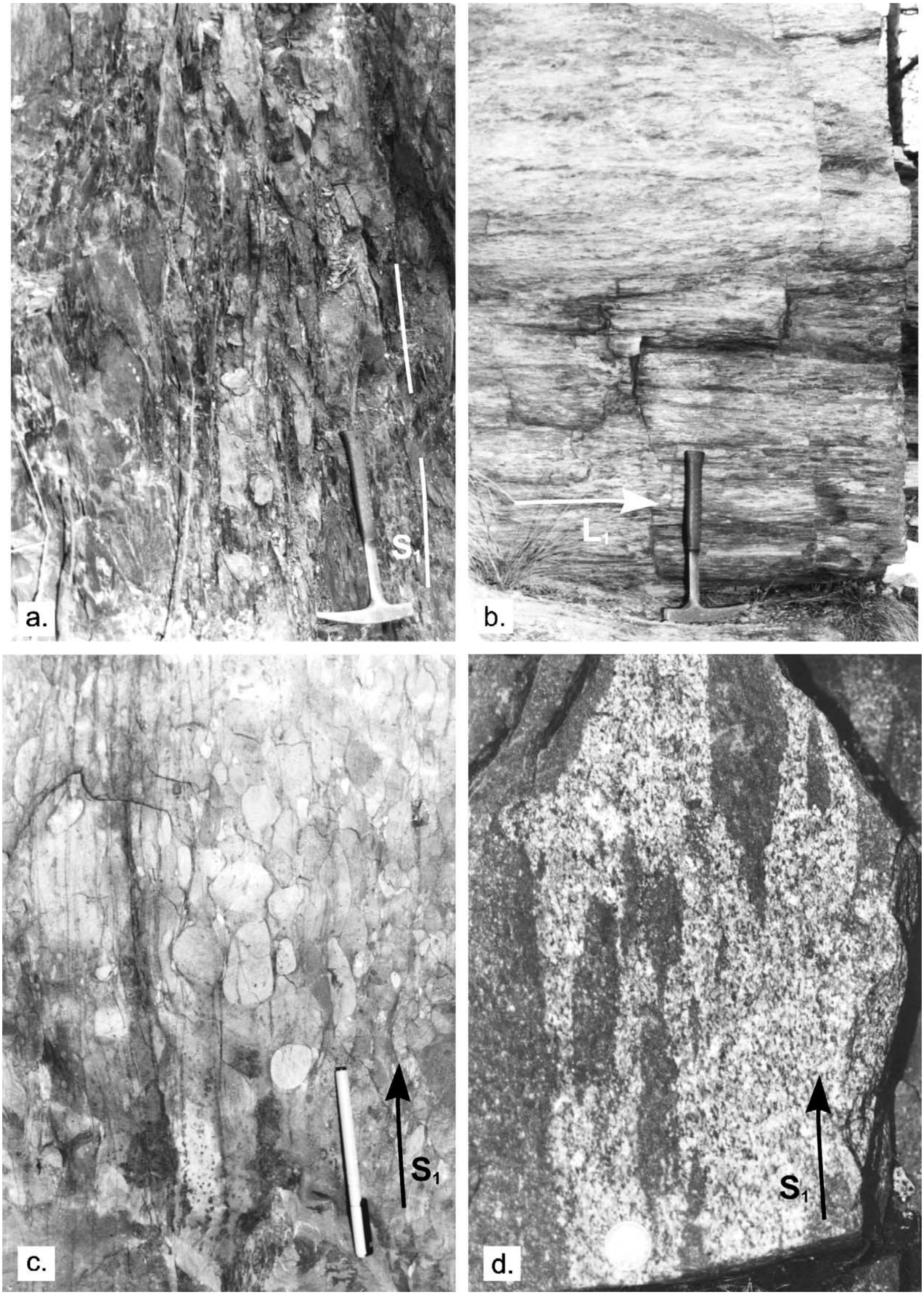

Fig. 5. (a) Intensely developed sub-vertical regional S_1 pressure-solution cleavage in the Neo-Proterozoic aleuropelites completely overprinting the original bedding, Štěchovice. (b) Subhorizontal stretching lineation in the albitic granites, Smilovice. (c) Deformed Neo-Proterozoic conglomerates, Librická rokle valley. (d) Strongly deformed micrugranular enclaves aligned parallel to the magmatic foliation in the host tonalite, Teletín quarry.

our structural mapping and AMS analysis. The widespread, well-developed mesoscopic magmatic fabric (Fig. 3) is defined as foliations and lineations formed during alignment of magmatic minerals (euhedral hornblendes, biotite) or flattened microgranitoid enclaves in the presence of a melt (Paterson et al., 1989). Microgranitoid enclave swarms are particularly abundant along the pluton margins as well as steeply dipping margin-parallel mafic sheets. Other igneous features, e.g. schlieren layering, are rare. Magmatic foliations, sub-vertical or steeply dipping to the ESE and WNW, are nearly parallel to the intrusion margins and to the trend of the regional structures in the host rock. Magmatic lineation, typically defined by shape-preferred orientation of the euhedral hornblendes, plunges shallowly to the NNE or SSW and is parallel to the stretching lineations outside the pluton. The internal parts of the intrusion are characterized by very weak magmatic fabrics, the intensity of the magmatic foliation increases towards the pluton margins where the magmatic foliations exhibit pervasive character and grade into sub-solidus mylonitic and S–C fabrics (Berthé et al., 1979). The sense of the shear, indicated by the S–C relationships, is mostly right-lateral; however, the opposite kinematics were also observed. Thus, the rock fabric along the pluton margins does not record any consistent kinematics. With the exception of local complexities, predominantly around the stoped blocks, the magmatic and sub-solidus fabrics are homogeneously oriented and concordant to the transpressional fabrics recorded by the host rocks along both margins of the pluton.

4.2. Anisotropy of magnetic susceptibility

The anisotropy of magnetic susceptibility (AMS) was studied in the Sázava tonalite, microgranitoid enclaves and mafic sheets along the pluton margins to complement the mesoscopic structural and fabric data throughout the pluton. One hundred and two oriented samples were taken using a portable drill at 20 sampling sites, covering almost the entire intrusion. The AMS was measured with KLY-3S Kappabridge (Jelínek and Pokorný, 1997), AMS data were statistically evaluated using the ANISOFT package of programs (Jelínek, 1978; Hrouda et al., 1990). Two AMS parameters (Jelínek, 1978) were used to characterize the magnetic fabric: the intensity of the preferred orientation of the magnetic minerals indicated by the degree of anisotropy $P=k_1/k_3$, and the character of the magnetic fabric indicated by the shape factor $T=2\ln(k_1/k_2)\ln(k_2/k_3)-1$, where $0<T<1$ indicates oblate and $-1<T<0$ indicates prolate shapes of the magnetic susceptibility ellipsoids and $k_1\geq k_2\geq k_3$ are the principal susceptibilities. The bulk susceptibility of analyzed samples was relatively high, ranging from 8.23 to 50.33×10^{-3} [SI].

In order to determine the contribution of particular minerals to the bulk rock susceptibility, we analyzed variations in the bulk susceptibility with temperature on the powder specimens of selected samples. Six samples (two of the tonalite and four of the microgranitoid enclaves) were measured in the temperature interval 25–700 °C, using the CS-3 apparatus and KLY-3S Kappabridge (Hrouda, 1994;

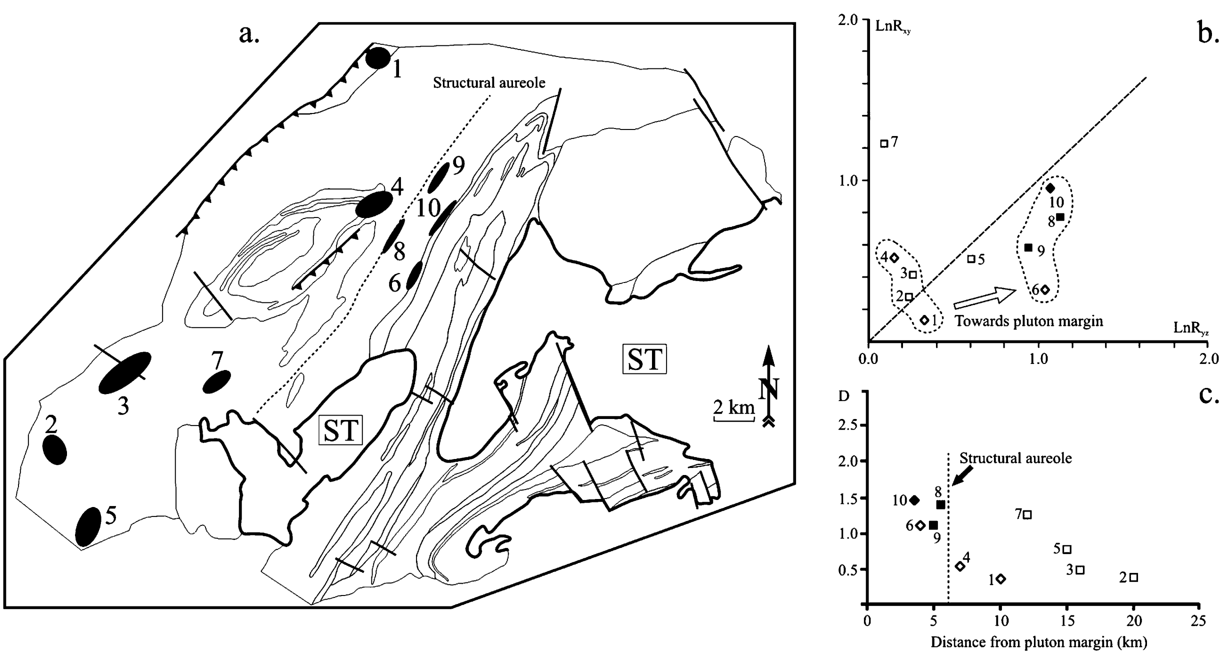

Fig. 6. (a) Schematic map showing the estimated *XZ* sections of the finite strain ellipsoid in the host rocks along the NW margin of the tonalite intrusion. (b) Flinn K-graph of the estimated finite strain ellipsoids from the localities: 1—Zbraslav, 2—Dobříš, 3—Voznice, 4—Davle, 5—Tuškovský vrch hill, 6—Štěchovice, 7—Hraštice, 8—Chlomek, 9 —Librická rokle valley, 10—Pikovice. (c) Diagram of *D* parameters vs. distance from the intrusion margin demonstrating the increasing intensity of deformation towards the SE. Localities numbered in the same manner as in Fig. 7b.

Jelínek and Pokorný, 1997). The thermomagnetic curves of the host tonalite (not given) are characterized by a very low slope in temperature interval between 25 and 570 °C. At temperatures about 570 °C (Curie temperature), the bulk susceptibility rapidly decreases to almost zero. The thermomagnetic curves of the microgranitoid enclaves show hyperbolic shapes from their initial parts up to temperatures of 450–500 °C and pronounced peaks in the vicinity of 560–570 °C. The bulk susceptibility decreases rapidly above this point. Using the method developed by Hrouda (1994), we estimate that the magnetic fabric in specimens of the host tonalite is carried by magnetite, whereas the main AMS carriers in the MME are paramagnetic silicates (hornblende and biotite) and magnetite, which contributed approximately 70 and 30%, respectively, to the bulk susceptibility.

In general, the magnetic fabrics are homogeneously oriented throughout the Sázava pluton (Fig. 7). The magnetic foliations are steeply to moderately dipping to the ESE or WNW, the magnetic lineations plunge to the NE or SW at low to moderate angles (Fig. 7). Locally, the magnetic fabric is parallel to the margins of large stoped blocks or roof pendants. Along the western margin, the degree of anisotropy increases towards the contact with the host rock (Fig. 7). Very high P values (up to $P=1.725$) were obtained from the sub-solidus deformed S–C mylonites from the intrusion margin, whereas the central part of the intrusion yields a very low degree of anisotropy ($P=1.023$–1.158). The degree of anisotropy also increases ($P=1.044$–1.270) towards the eastern margin of the tonalite. The susceptibility ellipsoids mostly exhibit oblate character ($T=-0.315$–0.917) at most sampling sites (Fig. 7), especially along the pluton margins. However, in the central part and western apophysis, the magnetic ellipsoid shapes are more variable and exhibit both prolate and oblate ($T=-0.904$–0.963) character (Fig. 7). In Fig. 8, the spatial variations of the degree of anisotropy (P) and the shape of the magnetic fabric ellipsoid (T) are represented by contour maps across the central part of the tonalite intrusion (the lack of outcrops in the northern part prevents drawing of the complete map). Apparently, the intensity of the magnetic fabric significantly increases in ~2–4-km-wide zones along both pluton margins, exhibiting oblate shape of the susceptibility ellipsoids, whereas the central part of the pluton generally yields much weaker fabrics and prolate ellipsoid shapes.

In addition, our AMS analysis revealed the presence of non-coaxial magnetic fabrics along the western margin of the pluton (Fig. 9). In the microgranitoid enclaves and mafic sheets, exposed in the Teletín quarry, the magnetic lineations are steeply inclined, in contrast to the sub-horizontal magnetic lineations in the host tonalite (Fig. 9). Magnetic foliations are subparallel (steeply dipping to the ESE or WNW) in both enclaves and the host tonalite. The degree of magnetic anisotropy is very low in the tonalite ($P=1.01$–1.02) while, in the microgranitoid enclaves, the degree of anisotropy is generally higher than in the tonalitic host ($P=1.07$–1.34). The susceptibility ellipsoid is mostly oblate ($T=-0.180$–0.938) in both microgranitoid enclaves and in the tonalite.

5. Microstructures and quartz microfabric

5.1. Microstructures

The main goal of our microstructural and quartz microfabric analysis was to approximately determine the temperature conditions of deformation in the host rock and along the W margin of the pluton. The microstructures reflect changes in the micro-scale deformation mechanisms operating in particular rock types of the Barrandian Neo-Proterozoic under different temperature conditions with respect to the lithology and distance from the pluton margin. The microstructures were studied in thin sections oriented parallel to the stretching lineation and perpendicular to the foliation. Anchimetamorphosed or weakly metamorphosed silty sediments and conglomerates, 5–15 km away from the contact with the tonalite, are dominated by low-temperature pressure solution cleavage, characterized by well developed pressure solution seams with parallel or anastomosing geometry and no preferred orientation of clasts within microlithons (discrete spaced cleavage; Powell, 1979; Passchier and Trouw, 1996). In metavolcanics, the deformation microstructures are strongly lithology controlled. Intensely deformed metabasalts are characterized by development of continuous cleavage fabric defined by oriented growth of the chlorite aggregates. The deformation microstructures in the most competent albitic granites and meta-andesites are represented in the quartz by bulging recrystallization at the boundaries of the large grain margins. The internal deformation features are characterized by strong undulatory extinction and the development of deformation bands (Fig. 10b). In the zones of intense deformation, fractured feldspar clasts up to 1 mm in size are surrounded by an ultra-fine-grained matrix (1–5 μ in 14 size) composed of quartz, feldspars and micas. Quartz forms large, weakly elongate clasts that frequently show developed undulatory extinction and deformation bands (Fig. 10a).

Metapelites and conglomerates from the thermal aureole display high-temperature foliation defined by alternating of domains rich in biotite (P-domains) with domains formed by coarsely recrystalized quartz (Q-domains). Biotite and also quartz grains display strong shape-preferred orientation. Large quartz grains with irregular to highly lobate grain boundaries imply grain boundary migration (GBM) recrystallization mechanisms (Guillope and Poirier, 1980), reflecting increased temperature conditions within the contact aureole of the tonalite intrusion. Quartz veins in the metapelites (Fig. 10c) are characterized by slightly elongate quartz grains 0.5–1 mm in size with highly lobate

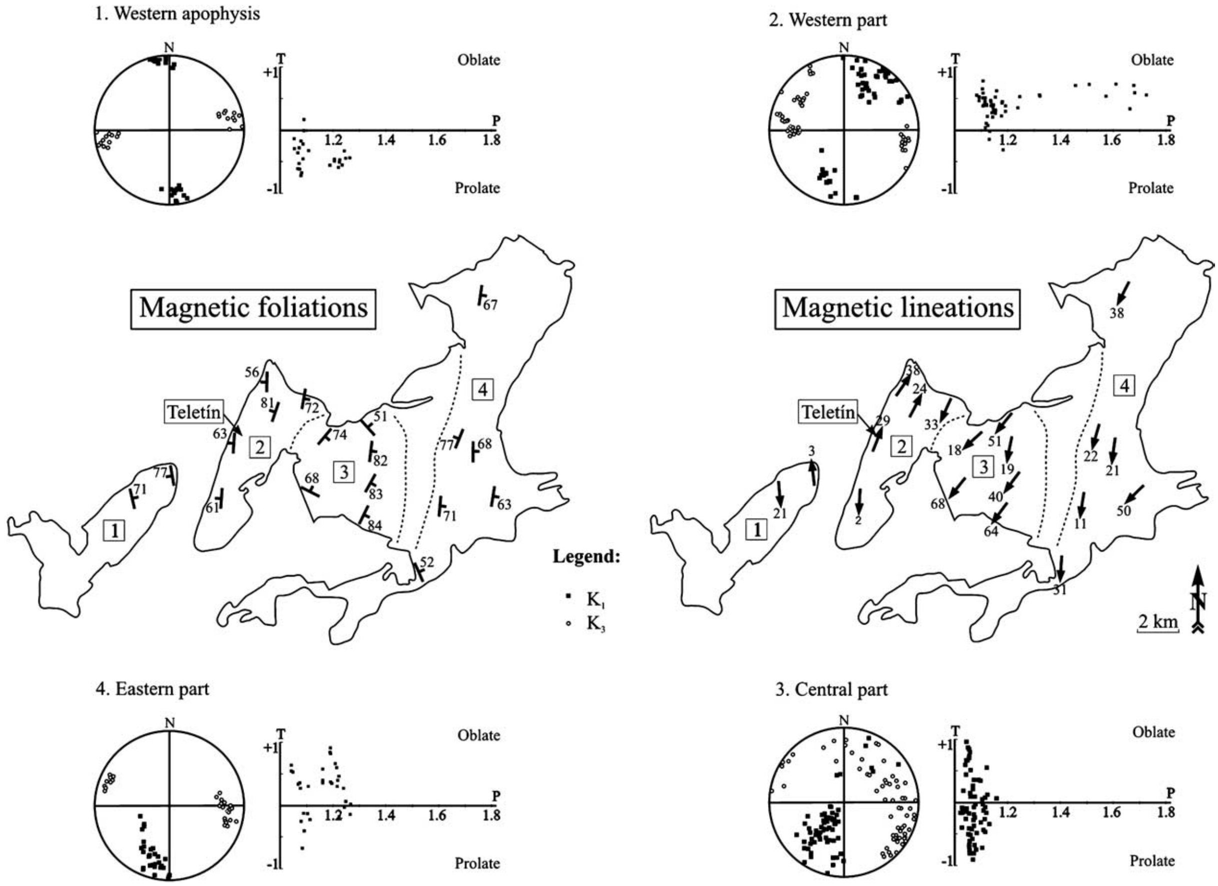

Fig. 7. Map of magnetic foliations and magnetic lineations in the tonalite with *P*–*T* plots and stereograms illustrating the orientations of maximal and minimal susceptibilities. The magnetic fabrics are mostly consistent with the observed mesoscopic fabrics.

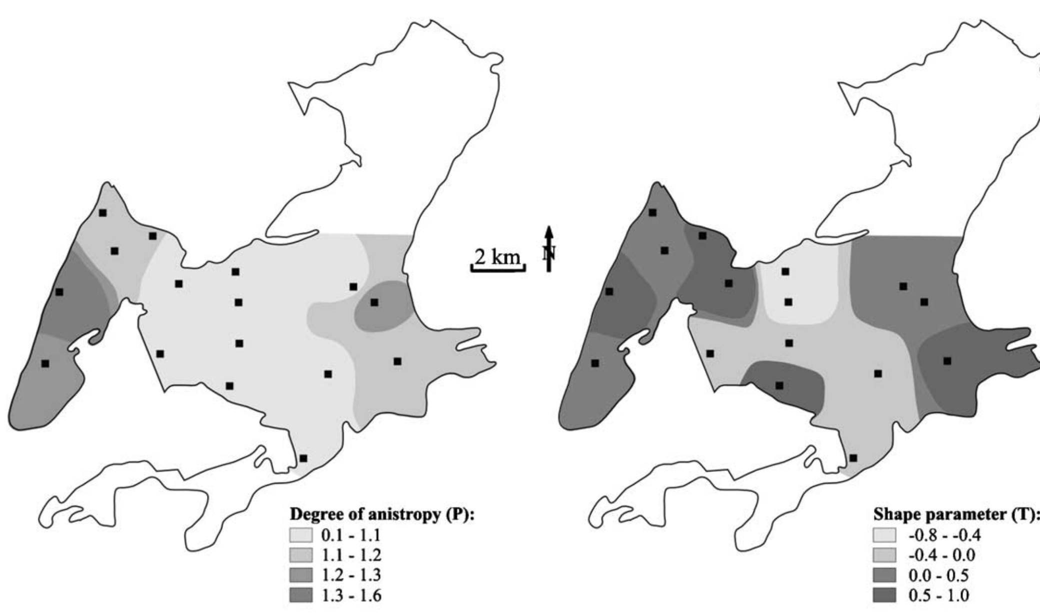

Fig. 8. Contour maps of the Sázava tonalite calculated for degree of anisotropy (*P*) and shape of the magnetic ellipsoid (*T*). The degree of anisotropy (*P*) and shape parameter (*T*) decrease towards the central part of the pluton.

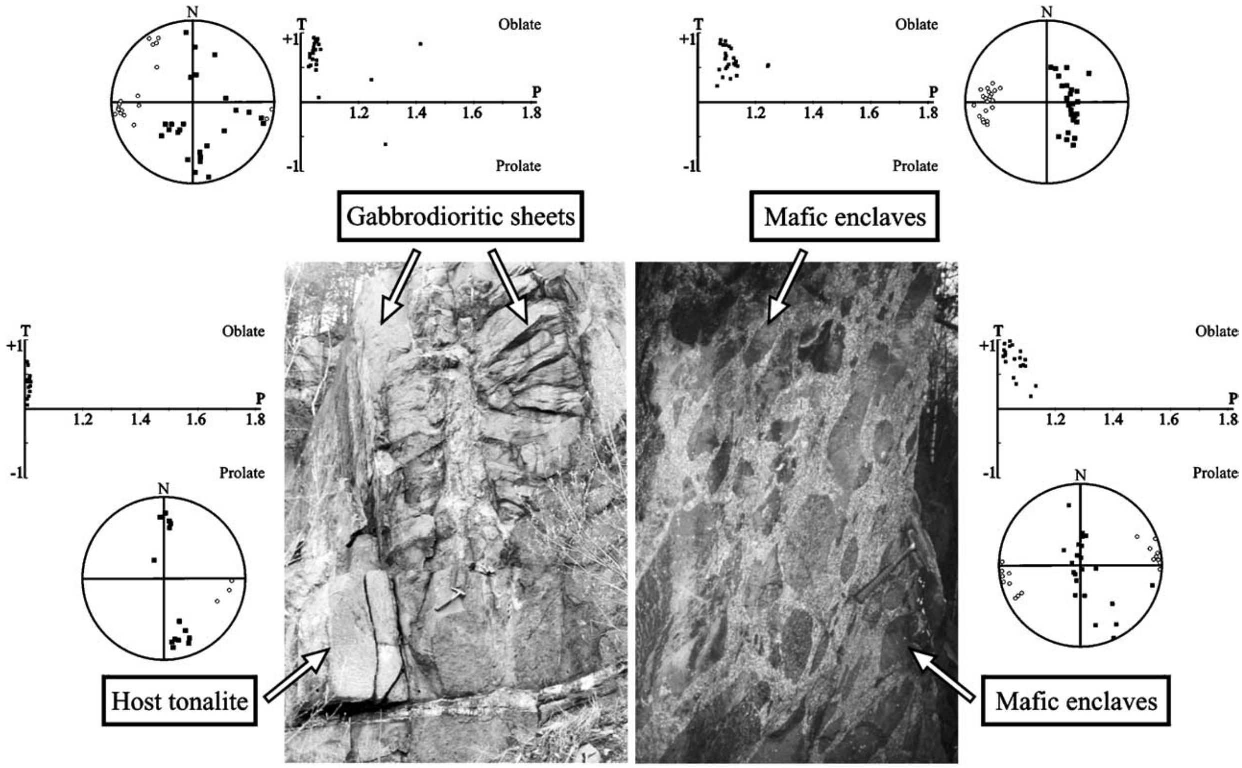

Fig. 9. Multiple magnetic fabrics in enclaves, gabrodioritic sheets and the host tonalite, Teletín quarry, 0.5 km east of the western margin of the pluton. Multiple magnetic fabrics are defined by orthogonal (sub-horizontal in the tonalite and sub-vertical in the enclaves) magnetic lineations sharing a steeply dipping magnetic foliation. The degree of anisotropy is slightly higher in the enclaves than in the host tonalite.

grain boundaries. Numerous residual grains and high curvature of the lobate boundaries indicate GBM recrystallization mechanisms. A common intra-crystalline deformation feature consists of a prismatic sub-grain boundary sub-parallel to the foliation trace.

Microstructures in the zone of sub-solidus deformation, developed along the E and W margins of the tonalite, contain plagioclase and K-feldspar crystals with well-preserved straight boundaries and idiomorphic shapes. The only sub-solidus deformation feature in feldspars is locally developed intracrystalline fracturing (Bouchez et al., 1992). The domains of undeformed feldspar cumulate fabric are surrounded by an anastomose network in shear zones affecting quartz and biotite. Recrystallized quartz is arranged in ribbons and exhibits variable grain size according to its position with respect to rigid feldspar clasts. The quartz grain boundaries are locally highly migrated but new sub-equant, strain free grains originate in some places (Fig. 10e). These features indicate transitional behavior between grain boundary migration and sub-grain rotation recrystallization mechanisms reported e.g. by Stipp et al. (2002). Locally developed prismatic sub-grain boundaries occur at a high angle to the quartz ribbons. Further away from the contact, the tonalite exhibits strong magmatic fabric that is microscopically characterized by alignment of feldspar and hornblende crystals parallel to the macroscopic fabric. Idiomorphic feldspars locally exhibit fractures filled by quartz with optical continuity with the matrix grains. Quartz forms large isolated and elongated grains 1–2 mm in size with frequently developed prismatic sub-grain boundaries sub-parallel to the grain alignment. In some places, the interstitial quartz crystals exhibit chessboard undulatory extinction (Kruhl, 1996).

5.2. Quartz c-axis microfabric

The quartz *c*-axis preferred orientations were measured using a universal stage in thin sections oriented perpendicular to the foliation and parallel to the stretching lineation (*XZ* sections). We measured about 150 *c*-axes in each thin-section, and the orientations of the *c*-axes were plotted on a lower hemisphere, equal area projection. We analyzed samples taken from both host rocks and the tonalite along a transect perpendicular to the pluton margin (Fig. 11). These samples include tonalite with well-developed magmatic fabric (sample T21), S–C mylonite with sub-solidus fabric from the intrusion margin (sample 178), a quartz layer from contact metamorphosed conglomerate (sample 179) and a quartz vein in metapelite (sample 119) exhibiting high-temperature foliation and albitic microgranite (sample 220), strongly deformed under lower temperature conditions far away from the tonalite contact. Sample T21 contains large elongate quartz grains parallel to the igneous fabric, with a well-developed chessboard

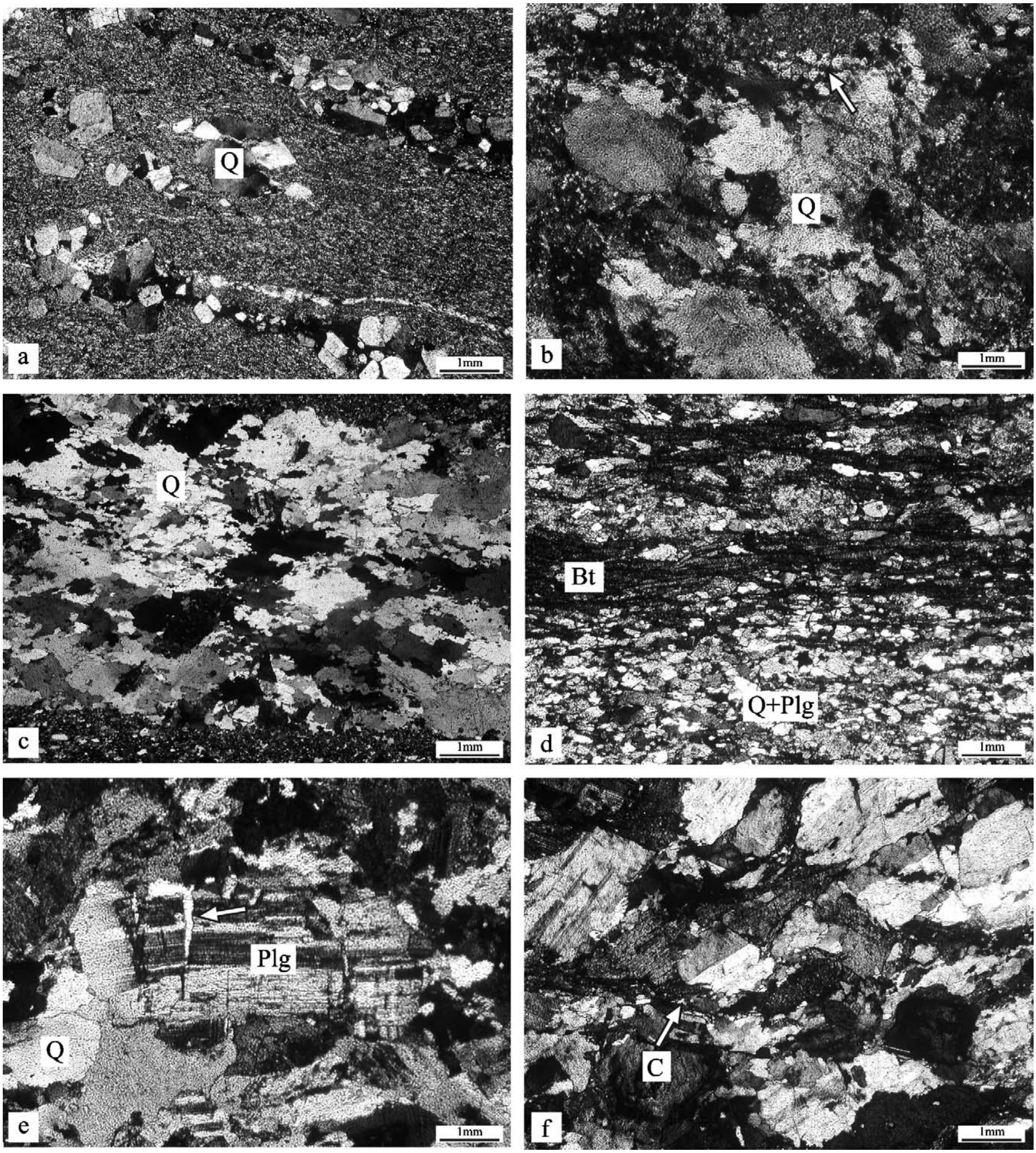

Fig. 10. Microstructures of both the host rock and the tonalite. (a) Strongly deformed metarhyolite, Jílové Belt, Barrandian Neo-Proterozoic (Štěchovice). Fractured feldspar clasts up to 1 mm in size surrounded by ultra-finegrained matrix (1–5 μ in size) composed of quartz, feldspars and micas. The internal deformation features are characterized by strong undulatory extinction and development of deformation bands. (b) Metaandesite, Jílové Belt, Barrandian Neo-Proterozoic (Psáry). Deformation microstructures are represented in the quartz by bulging recrystallization at the boundaries of the large grain margins. (c) Quartz vein in metapelite from the thermal aureole near Žampach. Numerous residual grains and the high curvature of the lobate boundaries indicate GBM recrystallization mechanisms; a common intractrystalline deformation feature is represented by the prismatic sub-grain boundary sub-parallel to the foliation trace. (d) High-temperature foliation in the metaconglomerate from the thermal aureole (near Teletín) defined by alternating of domains rich in biotite with domains formed by coarsely recrystallised quartz. Large quartz grains with irregular to highly lobate grain boundaries imply grain boundary migration (GBM) recrystallization mechanisms. (e) Sázava tonalite from the Teletín quarry. Idiomorphic plagioclase shows submagmatic microfractures, while quartz forms large isolated and elongated grains with frequently developed prismatic sub-grain boundaries. (f) S–C fabric in the tonalite (Teletín). Domains of the undeformed feldspar cumulate fabric are surrounded by an anastomose network of shear zones affecting quartz and biotite.

sub-grain pattern. The diagram shows as symmetrically distributed *c*-axis maxima distributed close to the *XZ* plane and inclined at an angle of about 50° to the foliation pole. Weak *c*-axes concentrations occur close to the *Y* direction. The whole pattern evokes a small circle distribution around the foliation pole with a high opening angle between the main maxima of 100°. The maxima distributions are consistent with dominant activity of the prism ⟨c⟩ slip and subordinate activity of the prism ⟨a⟩ slip systems (Lister and Dornsiepen, 1982; Kruhl, 1996; Morgan and Law, 2004) and are characteristic for coaxial plane strain deformation. However, the inhomogeneous density distribution of the *c*-axes suggests a weak component of the non-coaxial strain (Bouchez and Pecher, 1981). This is consistent with predominantly oblate to planar strain shapes of the AMS ellipsoid determined for this location (Fig. 7). The activity of the prism ⟨c⟩ slip is associated with high temperature and hydrous conditions (Blumenfeld et al., 1986; Gapais and Barbarin, 1986).

In sample 179, the recrystallized quartz occurs in polycrystalline ribbons. The sample displays Type 1 (Lister, 1977) cross-girdle fabric with a *c*-axis point maximum in the sample *Y* direction and two point maxima within the *XZ* plane with an opening angle of 50°. We interpret the central maximum and low opening angle of the peripheral maxima as being a result of the combined activity of the prism ⟨a⟩ and basal ⟨a⟩ slip systems (Schmid and Casey, 1986). These slip systems commonly operate under intermediate to low temperature conditions and/or high strain rate and plane strain deformation (Schmid and Casey, 1986). The latter is consistent with the shapes of the AMS fabric ellipsoid from this location (Fig. 7).

The quartz microfabric in the contact metamorphosed conglomerate (sample 178) is characterized by cross-girdle distribution with a dominant maximum close to the *Z* direction and by two maxima plotted around the periphery of the diagram at an angle of 45° to the *XY* plane. Subordinate maxima occur around the *Y* direction and close to the stretching lineation. This fabric may be interpreted by the combined activity of the prism and rhomb slip, while weak maxima close to the lineation may indicate high-grade conditions (Blumenfeld et al., 1986). Sample 220 exhibits almost the same pattern as the S–C mylonite (sample 178) with dominant basal ⟨a⟩ and prism ⟨a⟩ slip systems.

The quartz microfabrics indicate that there is a striking temperature gradient in the country rock as well as in the tonalite. In the Neo-Proterozoic host rocks, the temperature of deformation progressively increases towards the contact with the pluton, whereas the quartz fabric in the tonalite indicates progressive cooling of syntectonically emplaced magma.

6. Discussion and interpretation of fabric patterns

Our structural analysis revealed a partially decoupled fabric pattern in the Barrandian Neo-Proterozoic host rocks and the tonalite intrusion; using the AMS method, we also recognized that multiple magmatic fabrics are developed along the western margin of the pluton. In addition, using AMS data, we quantified the magnetic fabric ellipsoid shape and fabric intensity throughout the pluton, and these data can also be compared with strain measurements in the host rock. As the magmatic, sub-solidus, and host-rock fabrics along the pluton margins probably recorded increments of regional transpressional strain, our AMS and finite strain analyses allow us to infer the parameters of the overall regional transpression in the SE margin of the Teplá-Barrandian zone during or after the pluton emplacement.

The most important facts for interpretation of fabric patterns are set forth below:

(i) The pluton host rocks are characterized by strongly developed penetrative deformational fabrics mostly associated with a plane-strain to oblate type of finite strain ellipsoid. This cleavage fabric exhibits homogeneous orientation (steep NE–SW foliations, sub-horizontal stretching lineations) throughout the area; however, the cleavage intensity increases towards the pluton margin along with the intensity of the finite strain in conjunction with an increasing degree of oblateness (Fig. 12). The internal fabric pattern is more complex in the pluton. Along the pluton margins, the strongly developed mesoscopic magmatic fabric passes into sub-solidus fabric, where both have concordant orientations (equally developed steep NE–SW foliations and sub-horizontal lineations) with the host rock (Fig. 12). The mesoscopic magmatic fabric is generally very weak in the central part of the pluton.

(ii) The magnetic fabric (AMS) exhibits significant lateral variations and contrasting character from the central part of the intrusion towards the pluton margins. Along the pluton margins, the strongly developed magnetic fabric in terms of the orientation corresponds well to the observed mesoscopic fabric (steep NE–SW magnetic foliations and subhorizontal magnetic lineations). The degree of anisotropy is generally higher; the shape of magnetic fabric ellipsoid is oblate to the plane strain. The central part of the pluton yields mostly prolate shapes of the AMS ellipsoid, a very weak degree of anisotropy and magnetic lineations that are locally steeper in contrast to the oblate AMS ellipsoids and subhorizontal lineations along the pluton margins. More complex magnetic fabrics are developed along the western margin of the pluton. Here, multiple fabrics are defined by orthogonal magnetic lineations in the mafic sheets, microgranitoid enclaves (steeply plunging magnetic lineations) and host tonalite (sub-horizontal magnetic lineations) sharing a single, steeply dipping foliation. In addition, the degree of magnetic anisotropy is higher in the enclaves than in the host tonalite.

The question arises of whether the observed strain pattern in the host rock and AMS fabric in the pluton can be

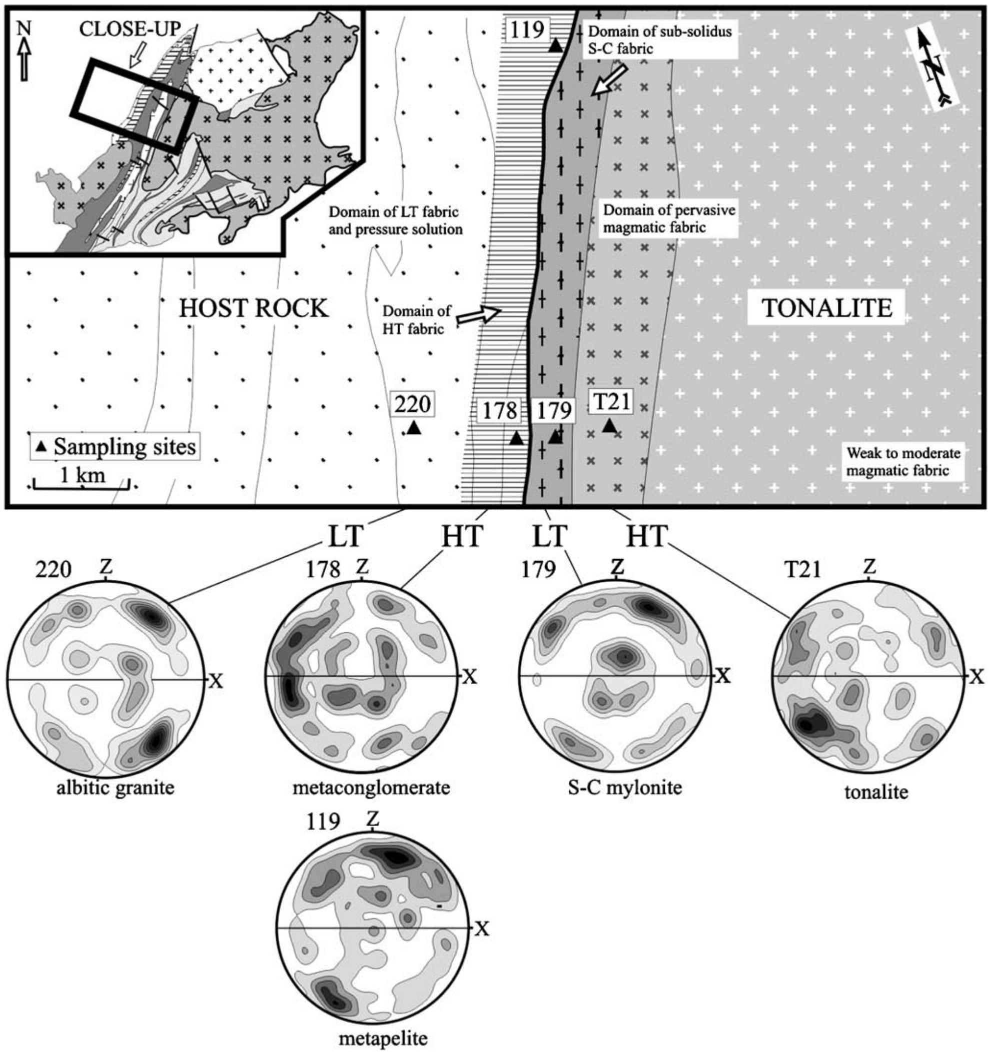

Fig. 11. Map of the tonalite intrusion and its host rocks across the NW margin with orientation diagrams showing the quartz *c*-axes preferred orientations. In the host rock, the quartz microfabric indicates increasing temperature conditions of deformation towards the pluton margin and in the tonalite cooling of syntectonically emplaced magma.

interpreted in terms of complete fabric coupling and thus a single strain field, sequential emplacement of 'nested' magma batches recording different strain increments or as a result of superposition of regional strain on the emplacement-related (intrusive) fabric. The finite strain pattern in the host rock conglomerates and pyroclastics has been interpreted as being a result of Variscan wrench-dominated transpression (Rajlich et al., 1988). The increasing finite strain intensity as well as increasing degree of oblateness towards the contact with the pluton can be interpreted as being a result of viscous partitioning (Schulmann et al., 2003). Tikoff and Greene (1997) and Tikoff and Teyssier (1994) showed that, for oblique transpression with an angle of convergence close to 20°, the degree of oblateness increases with increasing strain intensity and/or number of deformational increments. Provided that the deformation regime was constant, the strain in the structural aureole may reflect its lower viscosity due to higher temperature and therefore higher recorded strain. The AMS fabrics in the tonalite along the western margin reveal geometry and fabric symmetry consistent with oblique transpression. In addition, the AMS fabric in the mafic enclaves exhibits vertical orientation of lineation coupled with oblate strain and a higher degree of anisotropy (Fig. 9), which would be traditionally interpreted as being a result of a lineation switch in the oblique transpression (Tikoff and Greene, 1997). However, Schulmann et al. (2003) have shown that the lineation switch would occur at unrealistic high strains and for highly oblate shapes of the strain ellipsoid. Importantly, the central part of the pluton reveals steeper lineations than its margins; these lineations are associated with constrictional AMS ellipsoids for a very weak degree of anisotropy. The subsequent emplacement of the magma batches can be directly ruled out due to compositional and textural homogeneity of the central parts of the Sázava pluton. In addition, the model of the nested intrusions

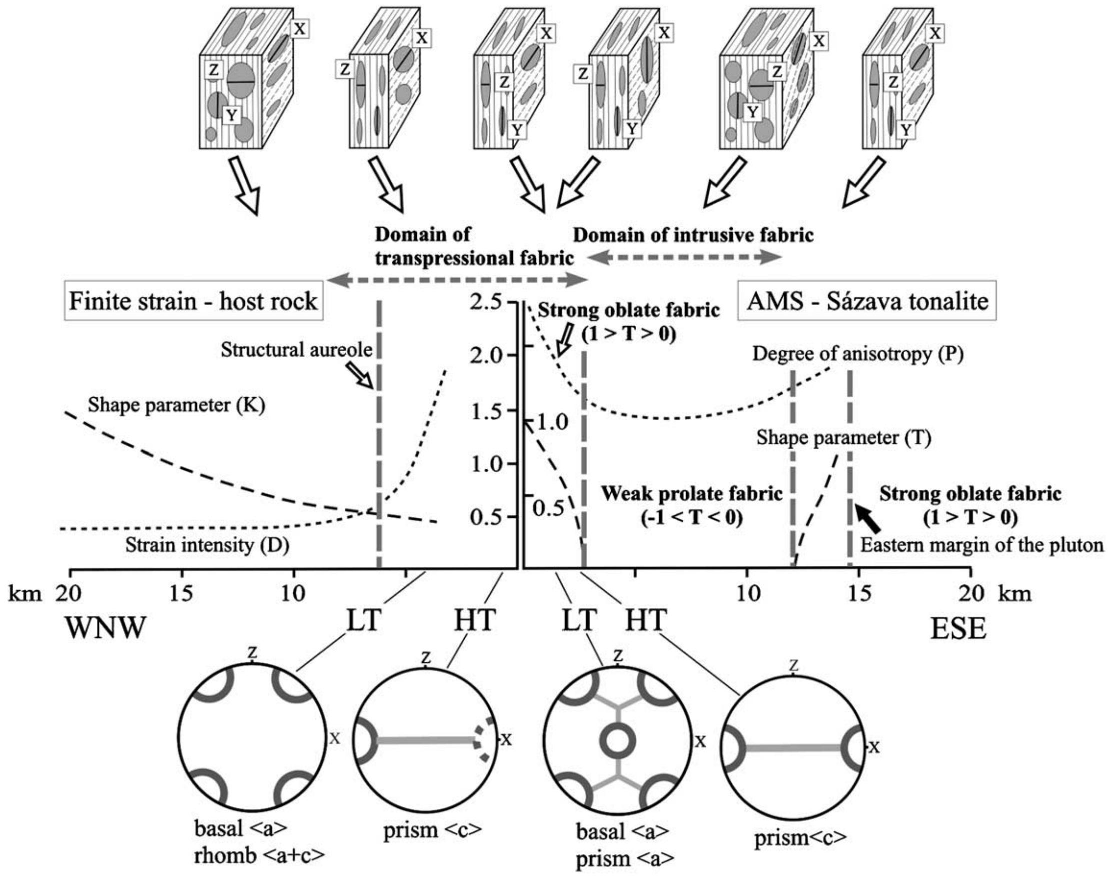

Fig. 12. Summary diagram of mesoscopic fabrics, finite strain measurements, AMS, and quartz *c*-axes preferred orientation data from both the host rock and the tonalite. Transpressional fabric (vertical foliation and horizontal lineation) developed throughout the host rock is associated with an increasing intensity of the finite strain, the degree of oblateness and the temperature conditions of deformation towards the pluton margin. Along the pluton margins, magmatic fabrics coupled with host rock fabrics in terms of their orientation and symmetry recorded transpressive strain during syntectonic cooling of the tonalite. In contrast, the central part of the pluton exhibits a high-temperature weak prolate fabric partially decoupled from the regional transpressional strain.

emplaced in the oblique transpressional regime would produce plane strain and horizontal lineation in the younger core and more intense oblate fabrics with potentially steeper lineation along older pluton margins (Parry et al., 1997).

We argue that the fabric pattern in the core of the pluton as well as the AMS fabric of the microgranitoid enclaves and sheets along its western margin are not consistent with the transpressional model alone. Instead, we propose that locally preserved steeper magnetic lineations and prolate shapes of the susceptibility ellipsoid in the central part of the pluton, resembling fabrics typical for diapiric ascent predicted by the analogue model of Cruden (1988), may represent relics of emplacement-related fabric not completely overprinted by regional strain. This polyphase model is also supported by our microstructural and quartz microfabric study, which indicates that two different microstructral evolutionary trends developed in Sázava tonalite and the host rock metasediments. The host rock exhibits an increasing temperature of deformation towards the pluton contact, while the Sázava tonalite exhibits microstructures ranging from pre-RCMP stages to the medium-temperature solid-state deformation along the pluton margins (Fig. 12).

Venera et al. (2000) numerically simulated the rheological behavior of the granodiorite and the host rock immediately after magma emplacement. These authors proposed that no shear stress can be transmitted to the solid host rocks after intrusion of the liquid magma and that ductile deformation of the host rocks could have started after the granodiorite itself became at least partially solidified allowing shear stress transfer to its surroundings. The calculations of Venera et al. (2000) suggested that, at this stage, hot and low viscosity host rocks (metasediments in our case study) become highly deformable and probably transiently weaker than the adjacent quartzo-feldspatic rocks of intrusion margin. Therefore, we suggest that the edges of the tonalite were strongly affected by regional transpressive strain overprinting older structures and enabled local preservation of older steeper emplacement-related fabrics in the pluton center.

Similarly, the preserved steep fabrics in microgranular enclaves and sheets may reflect vertical emplacement of magma into planar feeder channels, not entirely reworked by coeval transpressive strain. However, the reason for its preservation differs from that for the central part of the pluton. The observed fabric pattern in the sheets can be explained using a model of fabric development in sheet-like igneous bodies (Correa-Gomes et al., 2001) where preservation of steep lineations may be the result of fast solidification of relatively small magma bodies (maximum thickness ~1 m) in comparison with the tectonic strain rates and much slower solidification of the host tonalite affected by regional transpression. We suggest that much faster cooling caused the vertical magnetic lineations in enclaves and sheets recorded strain (vertical stretching) during the magma emplacement (Hrouda et al., 1999; Neves et al., 2003) but were frozen-in and not overprinted by regional transpression.

In summary, we suggest that the pluton recorded both intrusive emplacement-related fabrics and fabrics imposed by regional transpressional strain along the pluton margins. Numerical modeling of AMS and fabric development and quantification of its relationship to regional transpressional strain is the subject of our ongoing research.

7. Conclusions

We have reached the following conclusions:

(i) Structural and AMS analysis revealed partially decoupled fabric patterns in the Barrandian Neo-Proterozoic host rock and in the Sázava tonalite. In the host rock and along the margins of the tonalite, the fabric is characterized by steep foliations and subhorizontal lineations and is associated with plane strain to the oblate fabric ellipsoid. In contrast, the central part of the pluton is characterized by prolate fabric ellipsoids and locally preserved steeper lineations. Multiple fabrics, defined by perpendicular magnetic lineations, were also documented in gabbrodioritic sheets and microgranular enclaves along the western margin of the pluton.

(ii) Our finite strain estimations and AMS allowed us to further quantify fabric gradients both in the host rock and in the pluton. In the host rock, the finite strain intensity as well as the degree of oblateness, increase significantly towards the pluton margin. In the pluton, AMS allowed us to quantify the parameters of the magnetic fabric ellipsoids across the entire intrusion, and we have found an increase in both the degree of anisotropy and the degree of oblateness towards the pluton margins. Therefore, AMS ellipsoids correlate well with the strain and fabric ellipsoids in the host rock close to the pluton margins, whereas the central part of the pluton shows different fabric characteristics.

(iii) Microstructures as well as the quartz microfabric reflect striking temperature gradients and temperature conditions of deformation both in the host rock and in the tonalite. The quartz microfabric reflects syntectonic heating of the host rock due to tonalite intrusion and progressive cooling of the tonalite along the pluton margins. Large strains along the pluton margin may be correlated with increasing temperature conditions of deformation and interpreted as being a result of thermal weakening of the host rock due to tonalite intrusion.

(iv) We propose that locally preserved steeper magnetic lineations associated with prolate shapes of the susceptibility ellipsoid in the central part of the pluton and steep lineations in gabbrodioritic sheets and enclaves may represent relics of an emplacement-related fabric not completely overprinted by regional strain, and thus that the pluton recorded both emplacement-related strain and regional transpressional strain along the pluton margins. We suggest that the outer solidified and therefore more rigid edges of the pluton prevented its interior from being extensively deformed and thus enabled preservation of older steeper fabrics, whereas, in the case of gabbrodioritic enclaves and sheets, emplacement-related vertical magnetic lineations were frozen-in due to much faster cooling.

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