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J. Lehmann, Karel Schulmann, J.-B. Edel, Josef Jezek, F. Hrouda, et al.. Structural and anisotropy of magnetic susceptibility records of granitoid sheets emplacement during growth of a continental gneiss dome (Central Sudetes, European Variscan Belt). *Tectonics*, 2013, 32 (3), pp.797-820. 10.1002/tect.20028 . hal-00933183

HAL Id: hal-00933183

<https://hal.science/hal-00933183>

Submitted on 27 Feb 2022

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Structural and anisotropy of magnetic susceptibility records of granitoid sheets emplacement during growth of a continental gneiss dome (Central Sudetes, European Variscan Belt)

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Received 26 September 2012; revised 20 January 2013; accepted 3 February 2013; published 30 June 2013.

[1] Granitoid magmatic sheets emplaced syntectonically during growth of the Orlica-Śnieżnik mantled gneiss dome (Central Sudetes, European Variscan belt) were examined by means of structural geology, quartz, and anisotropy of magnetic susceptibility (AMS) fabric studies. Magmatic emplacement was localized along the eastern transpressive margin of the high metamorphic core and below the low-grade detached mantle rimming the southern margin of the dome. In the first area, the magmatic sheets were emplaced parallel to the dilated subhorizontal foliation of an anisotropic pre-orogenic block. The resulting melt-host rock multilayer localized the transpressive zone along which the bulk of magma was emplaced. The AMS study shows an across-strike fabric zonation underlying a strongly transpressive solid-state deformation in the hanging-wall, magmatic subhorizontal fabric in the foot-wall and a transitional fabric in the center of the intrusion. In contrast, along the southern dome margin, magmatic sheets intruded along steep foliations of weakly metamorphic mantle rocks, and are affected by recumbent folding and subhorizontal shearing. The bulk of the sheets present a shallow-dipping magmatic foliation and an along-strike magmatic lineation. The variations of the quartz and magnetic fabrics are attributed to superimposition of pure shear-dominated ductile thinning followed by simple shear-dominated detachment onto the original steep fabric. AMS modeling confirms the role of variation of orientation of pre-intrusive anisotropy during progressive deformation on the resulting fabric pattern and helps explaining observed variations in fabric orientations and symmetries. This study highlights contrasting mechanical behavior of syntectonically emplaced magmas in different parts of a growing crustal-scale mantled gneiss dome.

Citation: Lehmann, J., K. Schulmann, J.–B. Edel, J. Ježek, F. Hrouda, O. Lexa, and F. Chopin (2013), Structural and anisotropy of magnetic susceptibility records of granitoid sheets emplacement during growth of a continental gneiss dome (Central Sudetes, European Variscan Belt), *Tectonics*, 32, 797–820, doi:10.1002/tect.20028.

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0278-7407/13/10.1002/tect.20028

1. Introduction

[2] Emplacement of large magmatic sheets in orogens is directly related to the problem of the role of melt-induced deformation in deep-crustal shear zones [Hollister and Crawford, 1986; Davidson *et al.*, 1992]. It has been suggested that the melt production is responsible for melt pressure increase leading to embrittlement of the crust and development of melt-filled shear zones [Davidson *et al.*, 1994]. The relationship between shear zones developed in various tectonic settings and melt transfer through the crust in the form of magmatic sheets has therefore been matter of discussion for several decades [Weinberg and Searle, 1998]. For instance, magmatic sheets emplaced in extensional settings parallel to high angle normal shear zones were reported from many areas [e.g., Hutton, 1988]. Similarly, narrow and elongated magmatic bodies are also known from areas of oblique divergence

where magma was emplaced parallel to steep and transcurrent fault zones [e.g., *Kratinová et al.*, 2007]. In compressional settings, it is widely assumed that magma cannot rise so easily because of the horizontal maximum principal stress and vertical least principal stress [e.g., *Watanabe and Takahashi*, 1994]. In such settings, the hydraulic fractures exploited by magma should be horizontal [*Sibson*, 2003]. However, a number of modern structural studies show that magmatic sills emplaced within crustal-scale thrust zones form large tabular bodies elongated parallel to the orogen and oriented at high angle to the maximum compression [*Ingram and Hutton*, 1994; *Reichardt and Weinberg*, 2012]. Therefore, the mechanism of emplacement of magma sheets at high angle to the horizontal shortening was discussed by several authors [e.g., *Vernon and Paterson*, 2001; *Weinberg and Mark*, 2008]. *Galland et al.* [2007] explored the mechanisms of granitoid sheets emplacement along thrust zones and proposed that the horizontal shortening and injection of magma are coeval but independent processes.

[3] A common structural geology problem is to what extent the internal fabric of magmatic sheets reflects the emplacement mechanism and the ambient tectonic regime [*Paterson et al.*, 1998]. The internal fabric of magma is governed by the flow of melt and by the rotation of minerals in a displacement field generated by pressure gradient and by the geometry of the walls [e.g., *Ježek et al.*, 1994; *Ježek et al.*, 1996; *Schulmann and Ježek*, 2012]. However, the mineral fabric in granitoids is often poorly visible and then difficult to assess from mesoscopic observations. Because of this difficulty, the magmatic mineral fabrics are commonly quantified using the anisotropy of magnetic susceptibility (AMS), a method allowing rapid determination of orientation of fabric axes, intensity of deformation, and shape of fabric ellipsoid [*Borradaile and Henry*, 1997; *Bouchez*, 1997; *Borradaile and Jackson*, 2004]. Provided the magnetic mineralogy is well established, this technique yields rapid and highly precise fabric data that can be quantified [*Bouchez*, 2000], modeled [*Benn*, 1994; *Ježek and Hrouda*, 2002] and further interpreted in terms of complex flow histories [*Benn*, 2009; *Schulmann and Ježek*, 2012].

[4] In this paper, we present structural, quartz fabric, and AMS data of granitoid sheets emplaced along two structurally contrasting margins of the rising core of a crustal-scale mantled gneiss dome in the Central Sudetes (the Orlica-Śnieżnik Dome—OSD, Figure 1). The variations of AMS fabric are used to characterize emplacement of magmatic sheets, either parallel to a compressive wall of extruded gneiss dome [*Parry et al.*, 1997], or along a ductile thinning/detachment zone unroofing the apical mantle part of the gneiss dome. The study of fabric zonation together with a detailed analysis of deformation microstructures and quartz fabrics allows us to identify late deformation increments related to variations in the bulk strain axes orientation. Then, an attempt is made to provide a mechanistic explanation of instantaneous strain regimes governing mechanisms of magmatic sheet emplacement during growth of a crustal-scale gneiss dome. Such models of emplacement are subsequently simulated by means of AMS modeling.

2. Geological Setting

[5] From the NW to SE, the Sudetes are defined by an east-dipping Devonian-Carboniferous suture (Karkonosze

Complex), a Carboniferous orogenic root (OSD, Lugian Domain), and a Neoproterozoic microcontinent (Brunia, Moravo-Silesian Zone) [see *Chopin et al.*, 2012a and references therein] (Figure 1). The orogenic domain consists of an exhumed orogenic lower crust represented by migmatitic gneisses forming the core of the OSD. It is mantled by low- to medium-grade schists and metabasites consisting of the Nové Město Unit in the west, the Zábřeh Unit in the south, and by a pre-orogenic mafic lower crustal fragment, the Staré Město Unit in the east [*Chopin et al.*, 2012a].

[6] The OSD is composed of Barrovian-type middle Cambrian to early Ordovician metavolcano-sedimentary units [*Skrzypek et al.*, 2011a; *Mazur et al.*, 2012] and medium- to high-grade Cambro-Ordovician orthogneisses [e.g., *van Breemen et al.*, 1982; *Lange et al.*, 2005; *Chopin et al.*, 2012b] which contain boudins of (U)HP rocks [*Štípská et al.*, 2004; *Štípská et al.*, 2012].

[7] The adjacent eastern Staré Město Unit is represented by a narrow band of NNE-SSW trending lithologies generally dipping to the W-WNW. The boundary with the core of the dome is marked by strongly deformed metapelites and late Cambrian sheared metagabbros [*Kröner et al.*, 2000] along which, one of the two studied Carboniferous granitoid sheets were emplaced. The late Cambrian banded amphibolite complex [*Kröner et al.*, 2000], located east of the granitoid sheets, consists of a layered sequence of alternating layered amphibolites, granulite facies gneisses, anatectic metasedimentary rocks and minor serpentinites.

[8] The southern part of the OSD is flanked by the low-grade Zábřeh Unit which contains WNW-ESE trending belts of metavolcanic and metasedimentary rocks [*Verner et al.*, 2009]. The base of the sequence is formed by amphibolites, paragneisses, and calc-silicate layers which grade to migmatitic paragneisses intruded by the WNW-ESE trending granitoid sheets, the other focus of this study, and terminates with metapelites and phyllites with acid metavolcanic rocks at the top. This unit shows a Barrovian metamorphism that can be traced downwards away from the dome, ranging from sillimanite paragneisses and staurolite schists in the north to greenschist phyllites in the south [*Buriánek et al.*, 2003].

3. Geology of the OSD Granitoids

[9] The studied granitoid sheets of the OSD comprise: (1) 40 km long, up to 2 km wide, NNE-SSW trending sheeted bodies intruded in the Staré Město Unit, parallel to the eastern boundary of the OSD (here called the Staré Město Sheets, SMS), and (2) 30 km long and WNW-ESE trending magmatic sheets intruded in the Zábřeh Unit, parallel to the southern boundary of the OSD (here called the Zábřeh Unit Sheets, ZUS) (Figure 1).

[10] In the northernmost part of the Staré Město Unit, the SMS form a 1 to 2 km wide elongated and continuous granitoid intrusion in contact with mylonitic gabbros in the west, and late Cambrian amphibolite complex in the east. The boundaries between the intrusion and host rocks are always sharp. In the central part of the belt, the SMS become progressively thinner and form a sheeted array intruding the entire amphibolite complex. In the southern part of the belt, the SMS form a swarm of subparallel and discontinuous

Figure 1. Simplified geological map of the Sudetes, modified after Aleksandrowski et al. [1997] and Franke and Zelazniewicz [2000]. Inset depicts the location of the study area within the Variscan Belt of Europe, modified after Edel et al. [2003] and Skrzypek et al. [2011b].

sheets 1 m to 100 m thick, alternating with leucocratic veins, migmatitic metasedimentary rocks, and amphibolites. The ZUS form elongated bodies up to 2 km wide emplaced within a ~4 km wide belt of migmatitic paragneisses and migmatitic amphibolites.

[11] The intrusions can be divided into four rock groups according to their mineralogy. (1) The first group is represented by diorite enclaves which are confined to thick granodiorite sheets. These enclaves are composed of hornblende (60–65%), plagioclase (20–30%), very minor biotite (0–5%), and relic clinopyroxene (10%). (2) Coarse-grained (>2 mm) hornblende-biotite granodiorite is the main magmatic component through the whole area. It is composed of plagioclase (30–40%), quartz (20–25%), K-feldspar (5–15%), biotite (5–20%), hornblende (10–20%), and rare relics of pyroxene. (3) Less abundant are monzogranites rich in plagioclase (40–50%), K-feldspar (10–20%), quartz (20–35%), and rather poor in biotite (5–15%) and hornblende (0–5%). (4) The last group comprises local plagioclase

ortho- to meso-cumulates with 70–80% plagioclase, minor biotite, and quartz. These rocks occur within the main magmatic bodies either as veins or as gneissified bodies. Typical accessory phases are titanite, magnetite, apatite, zircon, monazite, as well as secondary epidote, carbonate, chlorite, and muscovite. Monzogranites and plagioclase cumulates are dominantly developed in the central and southern parts of the SMS. According to Buriánek et al. [2003], the positive LILE anomalies of granodiorites are typical for calc-alkaline magmatism, while REE spectra of the monzogranites suggest a syn-collisional context.

[12] The conditions of magma crystallization were estimated at 6.5–7 kbar and 670–725°C for the SMS using Hbl-Pl thermometry and hornblende Al contents [Parry et al., 1997], and at 2.9–4.3 kbar and 705–770°C for the ZUS using identical methods as well as zircon saturation temperatures [Buriánek et al., 2003]. Higher pressures and similar temperatures for peak conditions were estimated for contact metamorphism related to granitoid magma emplacement: 8–10 kbar

and 710–750°C for the SMS using Hbl-Pl thermobarometry [Štípská *et al.*, 2001; Baratoux *et al.*, 2005], and 4–6 kbar and 700–780°C for the ZUS estimated from a rock-bearing LP-HT mineral assemblage Grt + Bt + Sil + Crd ± Ms ± Kfs [Buriánek *et al.*, 2003].

[13] The existing geochronological data point to almost coeval emplacement and rapid cooling of the SMS and ZUS. This is attested by: (1) $^{207}\text{Pb}/^{206}\text{Pb}$ zircon evaporation ages of 339.4 ± 1.1 Ma and 344.5 ± 0.4 Ma for the main body of granodiorite and a monzogranite dyke (SMS), respectively [Štípská *et al.*, 2004]; (2) a zircon age from a ZUS foliated granodiorite with a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 338.1 ± 1.3 Ma [Kröner, unpublished data]; (3) hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 344.4 ± 4.4 Ma and 345 ± 6.8 Ma for the cooling of granodiorites from the northern and central SMS, respectively [Chopin *et al.*, 2012a], and a biotite $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age at 338.2 ± 0.5 Ma from an adjacent gneiss [Schneider *et al.*, 2006]; (4) an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 336 ± 3.2 Ma for a hornblende in amphibolites from the foot-wall of the ZUS [Maluski *et al.*, 1995]; and new $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 346 ± 9.7 Ma and 342 ± 4.3 Ma for hornblende from amphibolites of the same area, and of 339.5 ± 5.2 Ma for a white mica from phyllonites sampled at the boundary between the Zábřeh Unit and the OSD [Chopin *et al.*, 2012a].

4. Structural Evolution of the Host Rocks and Intrusions

[14] The structural record of the host rocks and internal fabric patterns of the magmatic intrusions as well as deformation kinematics were studied separately for the SMS and ZUS intrusive systems.

4.1. Staré Město Unit

[15] The metamorphic rocks of the Staré Město Unit exhibit two superposed deformation events D_{1s} and D_{2s} (subscript s for SMS). The northern part of the Staré Město Unit is characterized by a gently north-dipping compositional banding S_{1s} represented by the layered amphibolites and the gneissosity of granulitic tonalite gneisses (Figures 2a and 2b) that developed during a late Cambrian extension [Štípská *et al.*, 2001; Lexa *et al.*, 2005]. This fabric is discordant to the main NNE-SSW trend of the Staré Město Unit and SMS granitoid sheets [Parry *et al.*, 1997]. These granitoids show parallel magmatic S_m and solid-state fabric S_{2s} of early Carboniferous age and which are moderately dipping to the WNW (Figure 2a). S_{2s} is marked by dynamic recrystallization of plagioclase, amphibole, biotite, and quartz at amphibolite and greenschist facies. Locally, a strong, gently plunging NNE-SSW to N-S mineral and stretching lineation L_{2s} is developed and is collinear with a magmatic lineation L_m defined by alignment of amphiboles (Figure 2c). The sheared metagabbros from the hanging-wall were metamorphosed at LP granulite to amphibolite facies conditions during this episode [Baratoux *et al.*, 2005]. S_{2s} and L_{2s} in these metagabbros are concordant with those of the underlying granodiorite as well as to those of the overlying schists and gneisses of the OSD (Figure 2b). Numerous kinematic indicators, like asymmetrical plagioclase and amphibole augen, and shear bands document dextral shearing [Cymerman, 1997; Parry *et al.*, 1997; Baratoux *et al.*, 2005].

[16] The southern termination of the northern part of the Staré Město Unit shows a change in trend from NNE to E-W (Figure 2a: Bielice valley). Here, several magmatic intrusions were emplaced parallel to greenschist facies gently north-dipping mylonitic late deformation zones S_{3s} , themselves cross-cutting steeply north-dipping S_{2s} banding of layered amphibolites (Figures 2a and 3a). The granitoid sheets carry a weak magmatic foliation to strong solid-state greenschist mylonitic fabric S_{3s} defined by biotite elongated aggregates, recrystallized feldspars, and quartz arranged in ribbons (Figure 3b). S_{3s} is associated with a strong NNE-plunging mineral and stretching lineation L_{3s} (Figure 2c).

[17] Further south, the Staré Město Unit is dominated by metasedimentary rocks and the S_{1s} foliation is transposed, as shown by folded amphibolites (Figure 2d), towards a new S_{2s} fabric, axial plane of F_{2s} folds, moderately to steeply dipping to the west. The magmatic sheets, several decimeters to meter thick, are locally undistinguishable from the granitic veins observed in the migmatites, which can be either of Cambrian or Carboniferous age [Parry *et al.*, 1997; Kröner *et al.*, 2000; Štípská *et al.*, 2001]. In places these magmatic sheets are parallel to the former, locally preserved subhorizontal S_{1s} . More commonly, the magmatic bodies are parallel to the axial planes of F_{2s} folds, to the fold axes B_{2s} (Figure 3c), to the S_{2s} compositional layering (Figure 3d) or are accumulated in necks of D_{2s} -related boudins (Figure 3d), and locally present a strong magmatic lineation L_m (Figure 2c). In some places, both horizontal and west-dipping magmatic sheets are observed together. The structures of the SMS are broadly concordant with the deformation fabrics observed in adjacent orthogneisses and micaschists of the OSD core (Figures 2b and 2d).

4.2. Zábřeh Unit

[18] The structures recorded in the metamorphic rocks of the Zábřeh Unit result from two deformation events D_{1z} and D_{2z} (subscript z for ZUS). The D_{1z} planar structures are steep and strike WNW-ESE in the whole belt, except in the easternmost area where the steep S_{1z} fabric locally strikes NNE-SSW (Figures 4a, 4b, and 4c). S_{1z} is characterized by a compositional banding in the amphibolites and by a continuous schistosity in the metasedimentary rocks and phyllites further south. D_{1z} might be either Proterozoic or Late Devonian [Aleksandrowski *et al.*, 1999; Mazur *et al.*, 2006]. D_{2z} deformation is represented by a moderately SSW-dipping cleavage (Figures 4a, 4b, and 4c) interpreted as early Carboniferous in age [Chopin *et al.*, 2012a]. In the north and foot-wall of the ZUS magmatic sheets, D_{2z} corresponds to an amphibolite facies mylonitic foliation in the orthogneisses, and to a compositional mylonitic layering with intrafolial boudinage in the amphibolites (Figure 5a). Here, D_{1z} is completely transposed, and only scarce rootless F_{2z} folds attest for relics of its former presence. S_{2z} is commonly associated with the development of a down-dip mineral stretching lineation L_{2zd} (subscript d for down-dip) defined by alignment of amphiboles and biotites in the amphibolites and by the stretching of quartzo-feldspathic rods and parallel alignment of biotites in orthogneisses. Farther south, in structurally higher position occupied by calc-silicates and paragneisses, D_{2z} is associated with north-verging Z-shaped asymmetrical tight to isoclinal gently south-inclined to recumbent folds (Figure 5b). The

Figure 2. Structural maps, orientation diagrams of fabrics, and idealized structural profiles of the Staré Město Unit. Maps of (a) planar and (c) linear fabrics. Structural trends show extrapolations of the main orientations of fabrics measured in the field. Orientation diagrams represent average poles of foliations and orientation of lineations in equal-area lower-hemisphere projection. (b) and (d) Interpretative structural profiles modified from Lexa et al. [2005] displaying major structures relationships, lithologies of individual units, and major tectonic boundaries. (b) Profiles A-A' across the northern part, and (d) B-B' through the central part (location in Figure 2c).

Figure 3. Field photographs showing the main structural features of the Staré Město Unit (vertical outcrops). **(a)** and **(b)** Bielice valley (located in Figure 2a): **(a)** S_{2s} compositional layering in amphibolites (steep and N-dipping), bent into the greenschist facies gently NNE-dipping cleavage S_{3s} , **(b)** S_{3s} foliation developed in greenschist facies conditions in a 100 m-thick granodioritic layer. **(c)** and **(d)** Central and southern parts of the SMS: **(c)** S_{2s} fabric in migmatitic amphibolite gneisses viewed parallel to the B_{2s} axis of a F_{2s} fold; coarse-grained quartzo-feldspathic melt collection occurs parallel to the L_{2s} lineation and B_{2s} axis, producing prolate-shaped magmatic bodies. **(d)** Quartzitic paragneisses with granitic material injected along S_{2s} planes and in a D_{2s} -related boudin's neck.

S_{1-2z} and S_{2z} surfaces within calc-silicates present two sets of mineral lineations: a down-dip L_{2zd} stretching lineation, and a shallow-dipping NW-SE trending intersection and mineral lineation L_{2z} , parallel to the hinges of the F_{2z} folds and to the intersection between the S_{1z} and S_{2z} planes (Figures 4d and 5b). Farther south, in schists of the higher structural level, D_{2z} forms rather symmetrical open folds with an axial planar cleavage S_{2z} defined by the alignment of biotite, muscovite, and syn- S_{2z} andalusite (oriented parallel to S_{2z}). F_{2z} folding is associated with a strong WNW-ESE trending subhorizontal mineral and intersection lineation L_{2z} (Figures 4d and 5c).

[19] The Zábřeh Unit comprises 16 magmatic sheets broadly oriented parallel to the trend of S_{1z} (Figure 4a) and reaching a thickness of 1.5 km. To the west, these bodies are circular to slightly elliptical in map view, whereas in the east they are strongly elongated.

[20] There are metamorphic aureoles around the intrusions; their structure is characterized by intimate relationships between the ZUS and the host rock deformations. The granitic leucosomes are developed along S_{1z} and S_{2z} while the granitoid magma is mainly collected along the S_{2z} planes and the F_{2z} fold hinges (Figures 4b, 4c, and 5d). The magmatic fabric of the intrusions is characterized by the preferred orientation of meter-scale microdioritic enclaves in granodiorites, xenoliths of gneissic hornfels, numerous schlierens, and orientation of primary magmatic minerals such as hornblende, feldspar porphyroclasts, and biotites. These magmatic planar (S_m) and linear (L_m) elements commonly agree with the orientations of S_{2z} and L_{2z} of the host rocks (S_m and L_m , Figures 4e and 4d, respectively). In the western part of the Zábřeh Unit, the ZUS rocks carry a strong, pervasive, and ubiquitous solid-state S_{2z} foliation, defined by fractured amphiboles and feldspars, ribbons of quartz and

Figure 4. Structural maps, orientation diagrams of fabrics, and idealized structural profiles of the Zábřeh Unit. Maps of the (a) solid-state planar fabrics, (d) linear fabrics, and (e) magmatic foliations. (b) Interpretative A-A' and (c) B-B' structural profiles (located in Figure 4a).

Figure 5. Field photographs showing the main structural features of the Zábřeh Unit (vertical outcrops). (a) Strongly deformed and boudinaged amphibolites in the foot-wall during the D_{2z} event which produced the gently south-dipping S_{2z} . (b) Asymmetrical F_{2z} fold with WNW-ESE horizontal fold axis B_{2z} in a calc-silicate multilayer in the foot-wall. The long limb records down-dip L_{2zd} mineral stretching lineation, subparallel to the orientation of the photograph at high angles to the fold axis B_{2z} . (c) Gently folded metapelites in the S_{2z} axial plane. The mineral lineation L_{2z} is parallel to the B_{2z} fold axis (hanging-wall of the ZUS). (d) Cliff oriented approximately in the XZ plane of finite strain ellipsoid shows axial planar S_{2z} cleavage in migmatitic amphibolite gneiss of the ZUS. Veins of plagioclase cumulate are collected in S_{2z} (arrow 1), in the hinge of F_{2z} fold (arrow 2), in hybrid fractures (arrow 3) and in tensional gashes opened perpendicular to S_{2z} (arrow 4). Veins present low-strain LT solid-state microstructures. Note that the main vein shows cylindrical pinch-and-swell structures with boudin axes parallel to B_{2z} , into the wall and parallel to the Y-axis.

chloritized biotite aggregates. Magmatic to solid-state deformation along planes parallel to S_{2z} points to a syn- D_{2z} magmatic emplacement. Finally, in the OSD core, the orthogneisses show a complete fabric concordance with D_{2z} of the overlying amphibolites of the Zábřeh Unit; this is expressed by a several hundred meters wide zone of mylonites

whose foliations (parallel to S_{2z}) gently dip to the south and carry a strong down-dip stretching lineation (parallel to L_{2zd}) (Figures 4b and 4c).

[21] In summary, the contemporaneous, early Carboniferous SMS and ZUS granitoid sheets are syntectonic to D_{2s} and D_{2z} , respectively, with a locally strong solid-state

Figure 6. Photomicrographs in cross-polarized light of plutonic microstructures in K_1K_3 plane with K_1 parallel to the long side of the picture. **(a)** Magmatic fabric defined by the orientation of primary plagioclase with twin boundaries of feldspars porphyroclasts (arrows) aligned subparallel to the foliation (specimen # JL68). **(b)** Submagmatic microstructure marked by chessboard subgrains (arrow) and grain boundary migration of quartz (specimen # JL259). **(c)** HT solid-state microstructure: continuous band of amphiboles and biotites (arrow 1) and “core and mantle” features in plagioclases (arrow 2) (specimen # JL306). **(d)** LT solid-state microstructure illustrated by fractured primary minerals (i.e., hornblende, arrow 1), grain size reduction of quartz and formation of an anastomosed foliation of quartz and chlorite (arrow 2) (sample # JL399).

deformation overprinting a magmatic foliation, and are of broadly similar composition. However, they were emplaced in different settings. The SMS intruded at depth corresponding to 8–10 kbar pressure within the banded amphibolites in the foot-wall of the OSD gneissic core,

while the ZUS intruded at 4–6 kbar, in between the gneiss core and foot-wall of the supracrustal rocks of the metamorphic mantle. The inherited pre-intrusive foliation is gently north-dipping in the SMS area (S_{1s}) while it is steep and WNW-ESE striking in the ZUS (S_{1z}). The

Figure 7. Staré Město Sheets (SMS): map of the microstructure records and domains having different AMS types and associated K_1 and K_3 equal-area plots (lower hemisphere) with Pj-T graphs. The fabric (pole of foliation or mineral lineation) of the country rocks is reported in each equal-area plot with the aim to compare field structural and AMS data. Map: the color shading and line fill symbols indicate different AMS types, as discussed in the text; the microstructures of the intrusive rocks, main structural elements in the country rocks and locations of the sampled profiles of the northern part are also reported on the map. K_3 equal-area plots and Pj-T graphs of the northern part (profiles 1 to 4): **(a)** western margin marked by a Type I fabric, **(b)** center, Type III fabric, and **(c)** eastern margin, Type I fabric. **(d)** Equal-area plot of K_1 for the entire northern part of the SMS. **(e)** K_1 and K_3 equal-area plots and Pj-T graphs for the Bielice valley marked by a Type I fabric. **(f)** K_1 and K_3 equal-area plots and Pj-T graphs from the central and southern parts marked by Type I and Type II fabrics. Meaning of AMS parameters explained in section 6

Figure 7.

Figure 8. Zábreh Unit Sheets: map of the microstructure records and domains having different AMS types and associated K_1 and K_3 equal-area plots (lower hemisphere) with Pj-T graphs. The fabric (pole of foliation or mineral lineation) of the country rocks is reported in each equal-area plot with the aim to compare field structural and AMS data. **(a)** Map: the color shading and line fill symbols indicate different AMS types, the strike directions of the S_{2z} foliation in the country rocks, microstructures of the plutonic rocks, and locations of sampled localities/profiles are also reported. **(b)** to **(h)**, K_1 and K_3 equal-area plots and Pj-T graphs of distinct AMS domains: **(b)** locality 1, characterized by a Type I fabric, **(c)** northern margin of the profile 2, Type I fabric, **(d)** southern margin of the profile 2, Type III fabric, **(e)** internal part of the profile 3 and localities 4 and 5, Type II fabric, **(f)** northern and southern margins of the profile 3 and locality 6, Type I-III fabrics, **(g)** locality 7, Type IV fabric, and **(h)** western localities (8, 9, and 10) marked by Type I-IV fabrics. See text for details.

Figure 9. Magnetic mineralogy study results. **(a)** Distribution of the bulk susceptibility for each of the four zones. **(b)** to **(g)**, total susceptibility K_t [Jelinek, 1977] is in dimensionless units (in SI) of the order 10^{-6} . **(b)** Heating and cooling thermomagnetic curves, and **(c)** LT curves for specimens where magnetite is without doubt the susceptibility carrier of the AMS. **(d)** Heating and cooling curves, and **(e)** LT curves for specimens where the AMS is represented by paramagnetic minerals with a possible subordinate effect of magnetite. **(f)** Heating and cooling curves and **(g)** LT curves for paramagnetic specimens.

contact between the SMS and ZUS is characterized by an apparent dextral offset of the ZUS along a ductile greenschist south-dipping normal fault (Figure 1: Bušin Fault) [Franke and Zelazniewicz, 2000], and by a change in strike of the S_{1z} fabric from WNW to NNE. Within the SMS, textural continuity between the NNE- and EW-striking granitoids suggest that the local D_{3s} developed along the Bielice valley was active just after D_{2s} , when the magma was not entirely crystallized.

5. Deformation Microstructures

[22] The granitoids present a microstructural continuum of low- or high-strain magmatic, submagmatic, high-temperature (HT) and low-temperature (LT) solid-state fabrics at decreasing temperature. The magmatic to submagmatic microstructures are characterized by a shape preferred orientation (SPO) of euhedral feldspars, biotites, and amphiboles. Twin boundaries of feldspar porphyroclasts are often aligned parallel to the foliation, suggesting a lattice

preferred orientation (Figure 6a). Magmatic microstructures are also defined by matrix minerals with anhedral shapes, indicating their lack of plastic deformation and SPO. Submagmatic microstructures [Paterson et al., 1989] are represented by the onset of plasticity of quartz having highly lobated boundaries and typical chessboard subgrains indicating temperature of deformation close to solidus, i.e., $\sim 700^\circ\text{C}$ [Kruhl, 1996; Stipp et al., 2002] (Figure 6b). Magmatic to submagmatic microstructures are typically developed in the diorites and granodiorites of the core and eastern margin of the northern SMS (microstructure symbols of profiles 1 to 3 in map of Figure 7). In the ZUS, magmatic and low intensity submagmatic microstructures characterize the diorites and granodiorites from the northern margin of the northern and main magmatic sheets (microstructure symbols of profile 2, locality 4, and profile 3, respectively, in Figure 8a). These microstructures are also visible in the southernmost intrusions (profile 5) or in other localities (microstructure symbols of localities 6 and 7 in Figure 8a).

[23] HT (microstructure symbols in map of Figures 7 and 8a) solid-state microstructures are characterized by dynamic recrystallization of quartz aggregates through grain boundary migration with minor subgrain rotation associated with formation of continuous bands of amphiboles and biotites (Figure 6c). Feldspars with typical “core and mantle” features are usually elongated and form lenses surrounded by recrystallized grains (Figure 6c). High-strain HT solid-state microstructures are typically developed in the granodiorites of the western margin of the northern intrusion of the SMS (microstructure symbols in map of Figure 7), while low-strain ones characterize the south and center of the northern and main sheets of the ZUS (microstructure symbols of profiles 2 and 3, Figure 8a).

[24] LT solid-state microstructures are illustrated by finely recrystallized quartz grains forming anastomosing foliation planes around altered, boudinaged and fractured amphiboles and feldspars (Figure 6d). Primary minerals are altered such as plagioclase into clay, mica, epidote, and hornblende into chlorite, biotite, or tremolite-actinolite (Figure 6d). Typical high-strain greenschist facies mylonitic microstructures are widespread in the E-W trending granodiorites from the Bielice valley (microstructure symbols in map of Figure 7e), in the granodiorites, monzogranites, and plagioclase cumulates from the central and southern areas of the SMS (microstructure symbols in map of Figure 7f), and in the granodiorites from the western part of the ZUS (microstructure symbols of Figure 8a).

6. AMS

6.1. Sampling Strategy and Magnetic Measurements

[25] Measurements of the low-field bulk susceptibility and AMS were performed on 1042 specimens (2.25 cm length, 2.5 cm diameter) from 81 localities (12 to 14 specimens per locality). The samples were drilled with a portable drill, and some large hand specimens were also collected, plastered, and drilled in the laboratory. The magmatic sheets have been systematically sampled along several profiles with a spacing, along strike of the main fabric, of 1 to 10 km, depending on outcrop conditions. The sampling spacing along profiles perpendicular to the strike was approximately 100–200 m. In order to determine the contribution of specific minerals to the bulk rock susceptibility, the magnetic minerals carrying the AMS were investigated through measurement of the temperature variation of the mean susceptibility on powder specimens using the CS-L cryostat Apparatus and the MFKA-FA Kappabridge at AGICO (Brno, Czech Republic). The AMS was measured with DIGICO instruments at the Institut de Physique du Globe (Strasbourg, France). Statistical processing and evaluation of data were carried out using the ANISOFT 42 Program [Chadima and Jelinek, 2008] and standard AMS parameters were calculated according to Jelinek [1978]. The mean susceptibility calculated as $K_m = (K_1 + K_2 + K_3)/3$ where $K_1 \geq K_2 \geq K_3$ are the principal axes of the susceptibility ellipsoid. The degree of susceptibility anisotropy calculated as

$$P_j = \exp \sqrt{(\ln K_1 - \ln K_m)^2 + (\ln K_2 - \ln K_m)^2 + (\ln K_3 - \ln K_m)^2}$$

expresses the departure from an undeformed, spherical AMS ellipsoid ($P_j = 1$). The shape parameter $T = 2 \ln(K_2/K_3) / \ln(K_1/K_3) - 1$ quantifies the shape of the magnetic ellipsoid,

being linear when $-1 < T < 0$ and planar when $0 < T < 1$. The orientation of the AMS is characterized by magnetic foliations, equivalent to the K_1 – K_2 plane and magnetic lineations, defined as directions parallel to K_1 .

6.2. Magnetic Mineralogy

[26] The mean bulk susceptibility is relatively high and homogeneous for the whole series of intrusions with an average value around $450 \cdot 10^{-6}$ SI (Figure 9a). Only in the northernmost parts of the SMS, the magnetic susceptibility shows a large spread ranging from 300 to $1500 \cdot 10^{-6}$ SI. The diorites (5% of the measured population) display bulk susceptibilities around $370 \cdot 10^{-6}$ SI, the granodiorites, and monzogranites (respectively, 88% and 6% of the measured population) about $430 \cdot 10^{-6}$ SI, and the plagioclase cumulates (~1% of the measured population) around $260 \cdot 10^{-6}$ SI. Thermomagnetic curves have been established for a selection of 10 samples according to their mean bulk susceptibility values. The thermomagnetic curves show that the first set of specimens (samples # JL83-1-1, JL303A22 and JL83-5-3, characterized by $K_m > 800 \cdot 10^{-6}$ SI, representing 6% of the measured population) is marked by heating and cooling curves that are very close to each other, and by a LT curve which contains a well-defined Verwey transition (Figures 9b and 9c). In these specimens, magnetite is the principal susceptibility carrier. By contrast, cooling curves of specimens # JL25-6-3, JL49-2-2, JL265-43, and JL25-4-2 yield significantly higher susceptibilities than heating curves (Figure 9d), and the LT curves mostly define paramagnetic hyperbola (Figure 9e). In these specimens, susceptibility is predominantly due to the paramagnetic minerals, even though a subordinate effect of magnetite could be present. These two first sets of specimens are characterized by a Curie temperature close to 580°C (Figures 9b and 9d), which is typical of a nearly pure magnetite (i.e., titanomagnetite with a very low Ti content) [Lattard et al., 2006 and references therein]. Specimens # JL317A21 and JL355B21 show heating and cooling curves that are rather close together with no magnetite Curie temperature on the heating curves (Figure 9f); their LT curves do not contain the Verwey transition, but show clearly defined paramagnetic behavior (Figure 9g). The same holds for the specimen # JL399A33 although the cooling curve yields much higher susceptibilities than the heating curve (Figure 9f). Such thermomagnetic data indicate that virtually no magnetite is present in these samples. In conclusion, except for a few samples the thermomagnetic data point to the dominance of the paramagnetic minerals, here represented by biotite and hornblende.

6.3. Magnetic Fabrics

[27] The magnetic data reveal a well-defined magnetic lineation (K_1 axis) which is generally parallel to the strike of the magmatic sheets and to the trend of the mineral lineation. According to the distribution of the K_3 axis (the pole to the magnetic foliation, K_1 – K_2) in equal-area projections, three types of fabrics can be distinguished (Type I— K_3 clusters, Type II— K_3 girdles, and Type III—incomplete K_3 girdles) themselves related to systematic variations in fabric symmetry and intensity (Figures 7 and 8). K_3 girdle means that K_1 – K_2 planes have a single intersection, or define a fold. A fourth fabric type (Type IV), marked by girdle distributions of K_1 directions, can also be recognized (Figures 8g and 8h). It is

associated with a neutral to oblate shape of AMS ellipsoid and represents a well spread distribution of K_1 lineation within the K_1 – K_2 foliation.

6.3.1. SMS

[28] In the northern part of the SMS, four cross sections were investigated (Figure 7). Three of them (profiles 2 to 4) were already studied by Parry *et al.* [1997] but because of the small number of specimens, the sites were resampled in order to keep a statistical consistency of our study. The western margin of the SMS (Figure 7a) yields a ubiquitous cluster-Type I fabric, marked by west-dipping magnetic foliations parallel to S_{2s} , and by dominantly oblate ellipsoids with a relatively strong yet variable degree of susceptibility anisotropy ($P_j = 1.04$ to 1.2). The center of the intrusion shows an incomplete girdle-Type III fabric consistent with a gentle north-dipping to WNW-dipping foliation (Figure 7b). The north-dipping orientation is similar to the one of S_{1s} . The AMS ellipsoids are oblate to neutral, and the degree of anisotropy spreads from $P_j = 1.02$ to 1.25 . Finally, the eastern margin has a Type I fabric, either marked by southeast-gently-dipping foliations, neutral to oblate shapes of ellipsoids and a weak degree of anisotropy ($P_j = 1.03$ to 1.10 , profiles 1 to 3, Figure 7c), or west-dipping foliations, oblate AMS ellipsoids, and a relatively strong degree of anisotropy with P_j parameter ranging from 1.07 to 1.18 (profile 4, Figure 7c). These four northern profiles are marked by a ubiquitous NNE-SSW trending lineation (Figure 7d), which is broadly parallel to the mineral lineation of the host rocks L_{2s} and the intrusions L_m and perpendicular to the incomplete girdle-Type III observed in the center of the intrusion (Figure 7b). The foliations along the E-W trending magmatic sheets at the southern termination of the main granodiorite sheet (Bielice valley, Figure 7e) have gentle NNE dips, and down-dip lineations, compatible with mesoscopic fabric measurements. The Type I fabrics have close to neutral shapes with a slight preference for prolate fabrics and low degree of anisotropy ($P_j = 1.04$ – 1.13).

[29] The discontinuous granitoid sheets that outcrop in the central and southern parts of the SMS (Figure 7f) were sampled along discrete localities. They display strong maxima of NNE-trending lineations and either clusters of steeply west-dipping foliations (Type I, Figure 7f, upper equal-area plot), oblate to prolate fabrics and a weak degree of anisotropy ($P_j = 1.05$ – 1.12) or an E-W trending girdle of foliations (Type II, Figure 7f, lower equal-area plot) associated with a generally prolate fabric of variable intensity ($P_j = 1.04$ – 1.16). The cluster-Type I fabrics are observed in strongly deformed individual magmatic pods or along western margins of hundreds meter-thick sheets while girdle-Type II fabrics prevail through the central domain and along eastern margins of hundreds meter-thick sheets.

6.3.2. ZUS

[30] Generally, magnetic foliations and lineations of the ZUS are subparallel to the magmatic contacts and to the L_{2z} and L_m mineral lineations and B_{2z} fold axes measured in the field (Figure 8). Type I – III AMS fabrics are dominant over the whole set of intrusions, associated with steep to flat, roughly E-W striking magnetic foliations and NE-SW to NW-SE trending magnetic lineations.

[31] One AMS fabric is not consistent with the typology presented in this section. Located at the northern margin of the main sheet (locality 1, north of the main sheet in profile 3, Figure 8a), it is characterized by steep E-W trending

foliations (parallel to the local S_{1s}), steep lineations plunging to the west, neutral to oblate shapes and variable anisotropy degrees of the AMS ellipsoids ranging from 1.04 to 1.2 (Figure 8b). Type I fabric, marked by steep E-W trending foliations and two subhorizontal lineation maxima, one E-W and the other NW-SE subparallel to B_{2z} fold axis develops at the northern margin of the northern sheet (profile 2 in Figure 8a) and is associated with neutral to oblate strain and an anisotropy degree ranging from $P_j = 1.03$ to 1.15 (Figure 8c). The southern margin of the northern sheet (i.e., profile 2 in Figure 8a) displays a Type III fabric marked by an incomplete NNE-SSW trending girdle of magnetic foliations with steep maxima, several lineation maxima defining a broad region centered around shallowly plunging E-W lineations and dominantly neutral to prolate AMS ellipsoids of low intensity ($P_j = 1.02$ – 1.12 , Figure 8d). The internal part of the main sheet (profile 3), the northernmost granodiorite body (locality 4), and the southernmost granodiorite sheet (at locality 5, Figure 8a) show excellent Type II patterns defining a subvertical great circle trending NE-SW, a neutral to prolate magnetic ellipsoid and low anisotropy degrees ($P_j = 1.01$ – 1.1 , Figure 8e). The AMS axes distribution is consistent with a subhorizontal axis of rotation trending WNW-ESE, subparallel to the magmatic lineation L_m and the B_{2z} fold axis. Type I–III fabrics are prevailing along both the northern and southern margins of the main magmatic sheet (profile 3, Figures 8a and 8f) and are marked by N-S incomplete girdles of foliations with a strong south-dipping submaximum and WNW-ESE trending lineations which are parallel to the L_{2z} and L_m mineral lineation and B_{2z} fold hinge. The magnetic ellipsoid is neutral to slightly oblate, with T varying from 0.5 to -0.5 and the degree of anisotropy P_j ranging from 1.01 to 1.13 (Figure 8f). Type III patterns develop within narrow parts of the main intrusion (at locality 6, Figures 8a and 8f), which separate the region marked by eastern WNW-ESE striking magmatic sheets and the region dominated by western WSW-ENE striking sheets. The AMS fabric is characterized by a main submaximum of south-dipping foliations and a strong cluster of NNW-SSE trending magnetic lineations. The magnetic ellipsoid is represented by neutral to prolate shapes with a low degree of anisotropy ($P_j = 1.01$ – 1.13 , Figure 8f). A small NE-SW trending intrusion located in the southeast of the main body (locality 7, Figures 8a and 8g) shows a Type IV pattern marked by a strong maximum of K_3 corresponding to foliations moderately dipping to the NW, and by a girdle of lineations in the plane perpendicular to K_3 . The shape of the magnetic ellipsoid is oblate and the anisotropy degree low, with P_j parameter ranging from 1.02 to 1.1 (Figure 8g).

[32] The western termination of the ZUS is marked by two outcrops of magmatic rocks (localities 8 and 9, Figure 8a) and two large quarries (locality 10, Figure 8a). The southernmost bodies, at localities 8 and 9 (Figure 8h) show strong maximum of K_3 consistent with foliations moderately dipping to the SW and a subordinate maximum of gently north-dipping foliations. The K_1 axes also show a bimodal distribution with a strong maximum of slightly plunging to the SSE or less importantly to the west. The magnetic ellipsoid is neutral to oblate, and P_j values range from 1.02 to 1.12 . The northern magmatic outcrops, at locality 10 (Figure 8h) show a Type I–IV pattern marked by a wide K_3 maximum corresponding to foliations mostly dipping to the SW under gentle to

Figure 10. Crystallographic orientation of quartz grains measured by Electron Back Scattered Diffraction (EBSD) in the K_1K_3 sections of AMS ellipsoid (see Figures 7 and 8 for location of localities and profiles). The equal-area plots (lower hemisphere) represent the [c-axes] (poles to base (0001)), <m-axes> (poles to the first-order prism (10–10)) and <a-axes> (poles to the second-order prism (11–20)). The bold numbers indicate the sample name. The orientation of the magnetic foliation K_1K_2 plane (i.e., the equatorial line in the equal-area plot), the magnetic lineation K_1 and the number of analyzed grains (n) are also reported. Contours refer at interval of 0.5 time uniform density. Maximum densities are marked on the bottom center of each equal-area plot. The dashed line represents the lowest contour level, and the white circle corresponds to the minimum density value. The arrows indicating sense of shear are determined from inclination of the girdles with respect to the magnetic foliation. **(a)** Staré Město and Zábřeh Unit Sheets, magmatic to submagmatic microstructures. **(b)** Staré Město Sheets and Bielice valley, solid-state microstructures. **(c)** Zábřeh Unit Sheets, solid-state microstructures. The CPO of the samples # JL355, JL320, JL48, and JL25 are investigated in Figure 11. See text for the equal-area plots description and interpretation.

Figure 11. Rotation of c-axes of quartz from (a) the K_1K_3 reference frame to (b) the XZ regional frame operated to solve obliquities for the samples # JL355, JL48, JL25, and JL320. The EBSD data are represented in lower-hemisphere equal-area plot. See text for details.

moderate angles, and a girdle of K_1 corresponding to southwestward plunging lineations; the magnetic ellipsoid is dominantly oblate, and its anisotropy degree ranges from 1.04 to 1.14.

7. Quartz Fabrics

[33] The microstructural evolution of magmatic, submagmatic, HT, and LT solid-state fabrics with decreasing temperature presented in section 5 has been correlated with measurements of crystallographic preferred orientation (CPO) of quartz, in order to characterize the deformation regime, flow kinematics and conditions of granitoid crystallization, and syn-deformational cooling with respect to the thermal environment of the host rock [Paterson *et al.*, 1989; Gapais, 1989; Tribe and D’Lemos, 1996; Stipp *et al.*, 2002]. Sixty thin sections were cut parallel to the K_1K_3 plane of the AMS ellipsoid (K_1 and K_3 are the maximum and least axes of the AMS ellipsoid, respectively), which is the ideal section to determine the CPO of quartz assuming K_1 and K_3 are collinear with the X and Z axes of the bulk deformation, respectively [Bouchez, 1997; Benn, 2009] (see section 6). Deformation microstructures and textures were studied by optical and SEM microscopy. Crystallographic orientations of quartz from 15 selected thin sections were acquired with a scanning electron microscope CamScan3200 in the Czech Geological Survey in Prague using the electron back-scattered diffraction (EBSD) technique. The EBSD patterns were indexed with the HKL Channel 5 software. Diffraction patterns were measured at 20 kV accelerating voltage, 5nA probe current, and a working distance ranging from 21 to 42 mm. The procedure was carried out in manual mode in order to avoid multiple measurements on a single grain, and only well-fitted data were used.

[34] The quartz grains from magmatic and submagmatic microstructures display several and weak submaxima of c-axes (Figure 10a), drawing either an ill-defined cross-girdle perpendicular to the magnetic foliation (specimen # JL70), or weak maxima at the periphery of the equal-area plot and close

to the foliation (specimens # JL83 and JL85). Such patterns point to a weak activity of basal $\langle a \rangle$ slip system and to possible activity of prism $\langle c \rangle$ systems for c-axes close to K_1 .

[35] The solid-state microstructure of the SMS and ZUS show distinct patterns of quartz c-axes. In the SMS, a strong maximum of c-axes is located close to the center of the equal-area plot, at about 30° from the periphery, and along the periphery of the diagram, always at high angle to the foliation plane (samples # JL81, JL312, JL317, JL399, JL267, and JL382 in Figure 10b). These patterns can be considered as oblique single girdles or ill-defined Type 1 cross-girdles [Lister and Hobbs, 1980] with opening angles up to 45° with respect to the K_2K_3 plane. Such c-axes patterns are commonly interpreted as a result of combined activity of prism $\langle a \rangle$ and rhomb $\langle a+c \rangle$ slip systems with a variable contribution of basal $\langle a \rangle$ [Schmid and Casey, 1986]. The inferred dextral senses of shear deduced from macroscopic observations of shear bands and asymmetrical amphibole clasts agree with these c-axes patterns.

[36] In contrast, in the ZUS, the c-axes patterns of quartz show maxima which did not produce any obvious pattern when rotated into the magnetic foliation [Passchier and Trouw, 2005] (Figures 10c and 11a). As a matter of fact, the kinematic frame of the samples from the ZUS as defined by $K_1K_2K_3$, does not correspond to that responsible for plastic deformation of quartz. The c-axes patterns of the ZUS are more easily interpreted by rotating the equal-area plots into the regional XZ reference frame in which X is defined by L_{2zd} and Z defined as the pole of S_{2z} . Equal-area plots resulting from such a rotation are shown in Figure 11b (specimens # JL355, JL48, JL25 and JL320). The c-axis pattern of specimen # JL355, with its wide maximum located close to the L_{2zd} lineation within the foliation points to the activity of prism $\langle c \rangle$ which is consistent with the HT solid-state microstructure of the specimen. In specimen # JL48 which displays a HT solid-state microstructure, the c-axes form a maximum close to the periphery of the diagram at 30° from Z, a pattern commonly interpreted as

Figure 12. Idealized sketch model of the magmatic sheet emplacement in the frame of the evolution of the Orlica-Śnieżnik Dome.

due to the activity of basal $\langle a \rangle$ plus rhomb $\langle a + c \rangle$ during dextral shear [Schmid and Casey, 1986]. In specimens # JL25 and JL320, the strong maxima close to the center of the diagram call for c-axis incomplete girdles resulting from dominant prism $\langle a \rangle$ slip. Such reconstructed pole plots show that the plastic deformation of quartz is interpretable using the regional L_{2z} as X, meaning that the L_{2z} orientation is not the main direction of tectonic transport in the ZUS. The observed asymmetries allow to infer a top-to-the-SSW sense of shear for the ZUS, compatible with kinematic criteria in the foot-wall gneisses of the OSD [Mazur et al., 2005].

8. Discussion

[37] The tectonic significance of the distinct deformation events and relationships between the country rocks and the intrusions will be integrated into the geodynamic evolution of the OSD. Then, the deformation record of the host rock-magma systems will be discussed with the aim to propose mechanisms of emplacement of the SMS and ZUS which will be tested by the internal fabric records. Finally, the inferred deformation superimpositions will be numerically modeled to simulate the variations in shape and degree of anisotropy of the AMS ellipsoid.

8.1. Significance of Deformation Events in the Frame of the OSD

8.1.1. Staré Město Unit

[38] As already concluded by Parry et al. [1997], the WNW-dipping flow plane bearing a subhorizontal NNE-SSW trending lineation recorded by the studied magmatic sheets favors a model of dextral simple shear-dominated transpression. The collinear fold axis B_{2s} and stretching lineation L_{2s} suggest strain partitioning into simple shear along weak S_{2s} planes and pure shear in more competent lithologies where F_{2s} folds are preserved. The compatibility between the D_{2s} fabric elements of the Staré Město Unit with

those of the gneisses of the OSD indicates juxtaposition of these two orogenic units at early Carboniferous time during WNW-ESE horizontal shortening [Chopin et al., 2012a]. However, this deformation was mainly coaxial in the core of the OSD [Skrzypek, et al., 2011a; Chopin et al., 2012a; Štípská et al., 2012]. Our data show that mechanical coupling between the SMS and their country rocks was important in the southern and central parts of the Staré Město Unit (Figure 2d) and low in the northern part, where the SMS is the main decoupling horizon (Figure 2b). The northern SMS juxtaposed the eastern midcrustal lithologies (8–10 kbar in the banded amphibolites, Baratoux et al. [2005] and Lexa et al. [2005]) with the western orogenic infrastructure of the OSD (18 kbar in felsic granulites, Štípská et al. [2004]). It is suggested that this juxtaposition occurred because the SMS localized dextral transpression and enhanced oblique thrusting of the OSD over the Staré Město Unit heterogeneously reworking relics of Cambrian shallow-dipping anisotropy S_{1s} .

[39] The greenschist facies, gently NNE-dipping, synmagmatic high-strain zone D_{3s} of the Bielice valley bears a mineral lineation L_{3s} which is parallel to the regional one L_{2s} . This implies that D_{2s} and D_{3s} share the same elongation axis. Therefore, it is suggested that D_{3s} originated by an orthogonal switch in shortening direction from horizontal to vertical during progressive vertical loading of the lower crustal material of the OSD over the Staré Město Unit.

8.1.2. Zábřeh Unit

[40] The D_{1z} deformation produced a steep WNW-ESE striking metamorphic foliation which is parallel to the margin of the OSD core. S_{1z} -parallel sills attest that D_{1z} is pre-intrusive in age and might be either Proterozoic or Late Devonian [Aleksandrowski et al., 1999; Mazur et al., 2006]. The D_{2z} deformation in the Zábřeh Unit was correlated with the pervasive vertical shortening that affected the core of the OSD, interpreted by Chopin et al. [2012a] as a ductile thinning of the exhumed rocks of the dome. These authors also proposed that the Zábřeh Unit slid

Figure 13. Summary diagram of the evolution through time for (a) the SMS and (b) the ZUS. The figures show orientation diagrams illustrating mechanisms of emplacement, 3D idealized sketches of the geometric relationships between intrusions and host rocks, and internal fabric elements of the intrusive rocks. The typology of magnetic fabrics is also indicated.

progressively from an original apical position towards the flanks of the dome. Our data reveal that this deformation in the Zábřeh Unit is marked by a progressively decrease in degree of shortening from the OSD to the partially molten zone surrounding the ZUS, while southward, where stronger and colder rocks were not invaded by magmas, the subvertical S_{1z} fabric is only gently affected by F_{2z} recumbent folding (Figures 5b and 5c). Symmetrical recumbent folding and absence of syn- D_{2z} kinematic criteria in the field are in agreement with a pure shear-dominated vertical shortening. However, we argue that the formation of the down-dip lineation L_{2zd} at the bottom of the Zábřeh Unit and within the OSD is related to a late orogenic event: a major brittle-ductile detachment which is described in the western and adjacent Nové Město Unit [Mazur *et al.*, 2005] and in the core of the dome [Chopin *et al.*, 2012a]. In summary, D_{2z} could be decomposed in an upward ductile thinning propagating from the OSD to the Zábřeh Unit followed by a SSW-directed detachment in ductile-brittle conditions.

[41] It is shown here that the geodynamic evolution of the studied magmatic system is connected to the development of the OSD gneiss dome as proposed by Chopin *et al.* [2012a]. The present study reports that lithologies at the base of the Zábřeh Unit are identical with those of the Staré Město Unit, with a main difference in Variscan peak pressure metamorphic conditions of 4–6 kbar and 8–10 kbar, respectively. Based on this pressure difference, we suggest that the Zábřeh Unit forms an upper crustal continuity of deeper crust of the Staré Město Unit. Pre-orogenic crustal layering is represented by the S_{1s} shallow-dipping Cambrian metamorphic foliation preserved in the Staré Město Unit. Our structural, AMS, and microstructural study complete the model of Chopin *et al.* [2012a] and show that during the early Carboniferous, the Staré Město Unit represented a stiff heterogeneity bounded to the west by the OSD orogenic root [Štípská *et al.*, 2001]. This is along the OSD-Staré Město Unit steep interface that overpressurized magma probably percolated from a deeper magmatic chamber. The horizontal WNW-ESE shortening related to early stages of growth of the OSD dome was responsible for invasion of S_{1s} -parallel granitoid sills (Figure 12a). Development of steep crustal folds was associated with formation of the S_{1z} subvertical foliation in the ZUS (Figure 12a). This deformation in the Staré Město Unit produced folding of magma-hosting rock shallow-dipping multilayers, leading to the formation of the S_{2s} axial planar cleavage and associated dextral transpressive shearing [Parry *et al.*, 1997] (Figure 12b). The main volume of magma was emplaced along the S_{2s} axial plane cleavage, creating a steep magma lubricated low viscosity layer along which the OSD rocks were exhumed [Štípská *et al.*, 2001]. Progressive growth of the OSD permits migration of magma from the SMS towards the apex of the crustal bulge (Figure 12a). As a consequence of the upward motion of OSD lithologies, vertical shortening (or ductile thinning) of the upper horizons of the OSD and Zábřeh Unit produced horizontal dilation of the steep S_{1z} anisotropy which was filled by granitoid magma. Continuous oblique thrusting and exhumation of the OSD over the SMS is recorded by progressive solidification of magma at amphibolite and greenschist facies conditions and formation of the synmagmatic greenschist facies cleavage in the central part of the SMS (the Bielice valley). In the ZUS, S_{2z}

foliation-parallel injections of sheets were syntectonic to the ductile thinning event passing to noncoaxial SSW directed detachment of the growing OSD core (Figure 12b).

8.2. Mechanisms of Emplacement of Magmatic Sheets

[42] Here, we will evaluate the different parameters which could control the geometries of the SMS and ZUS, such as the regional stress field, strain distribution, rheological contrasts, preexisting anisotropies, and magma overpressure. The synkinematic character of emplacement of both SMS and ZUS is well supported by (1) the concordance of the intrusive fabrics with the early Carboniferous deformation affecting the country rocks; (2) magmatic, submagmatic to subsolidus microstructural evidence; and (3) coincidence between ~340 Ma age of intrusions and onset of transpressive activity in the SMS and ductile thinning in the ZUS, respectively [Chopin *et al.*, 2012a]. Therefore, syntectonic emplacements of magma in compressive and extensional tectonic regimes are discussed [Cosgrove, 1997; Brown and Solar, 1998; Vernon and Paterson, 2001; Žák *et al.*, 2005; Kisters *et al.*, 2009; Reichardt and Weinberg, 2012].

8.2.1. Emplacement of the SMS

[43] We have shown that (1) the SMS emplacement is syntectonic to the D_{2s} dextral simple shear-dominated transpression, (2) the intrusive rocks revealing magmatic and solid-state microstructures have identical magnetic fabrics (map of Figure 7 and Figures 7a, 7b, and 7d) and, (3) the mineral and stretching lineation L_{2s} in the host rocks, the magmatic lineation L_m , and the magnetic lineation K_1 are collinear (Figure 2c and 7d). Hence, the orientation of the instantaneous extension axes in the magma did not change during subsequent solid-state reworking, implying in turn that the mineral magmatic lineation L_m is close to the direction of finite extension (e_1 , Figure 13a), provided that all the lineations are parallel to the stretching axis. For such a kinematic regime, the instantaneous shortening direction ($\dot{e}_{3ss}$) belongs to a plane dipping to the ESE which bears the finite extension direction (e_1) and which is in the compressive sector for simple shear making 0 to 90° with the strike of the SMS. Plotting the S_{1s} plane and the strain axes in an equal-area plot shows that the direction of instantaneous shortening ($\dot{e}_{3ss}$) is subparallel to the S_{1s} foliation (Figure 13a).

[44] Important mechanistic implications can be derived for the emplacement of the S_{1s} -parallel magmatic sheets. Since this Cambrian crustal fragment was significantly cooled, probably to less than 450°C before the emplacement of the SMS [Štípská *et al.*, 2001], it was certainly brittle with a strong shallow-dipping mechanical anisotropy at the onset of magma intrusion [Lexa *et al.*, 2005]. Vertical dilation is produced when such an anisotropic system is submitted to horizontal shortening at high (melt) pressure (Figure 13a; Price and Cosgrove [1990] and Cosgrove [1997]). Formation of dilatant foliation-parallel veins was successfully modeled by Barraud *et al.* [2001; 2004] who showed that, at the onset of shortening, melt-filled veins with high aspect ratios open along the foliation for highly anisotropic and partially molten materials. Once the magma is emplaced parallel to S_{1s} , the whole system becomes weaker and starts to behave as a solid rock/melt multilayer marked by high viscosity contrasts. Consequently, the critical buckle stress of the horizontal anisotropy drops and the layers buckle into

Figure 14. Results of numerical simulations of AMS fabrics during **(a)** horizontal flat fabric (D_{1s}) overprinted by oblique transposition with dextral simple shear component (D_{2sa} and D_{2sb}) in the SMS and **(b)** subvertical intrusive fabric (D_{1z}) flattened by pure shear (D_{2za}) combined with horizontal simple shear (D_{2zb}) in the ZUS. Equal-area plots: gray circle, biotite; black circle, amphibole. See text for details.

east-verging overturned folds with subhorizontal axes (Figures 12a and 13a). Finally, the gabbros and the banded amphibolites become completely transposed into the WNW-dipping planar fabric. At this stage most of the magma is emplaced and solidifies parallel to S_{2s} as demonstrated by parallel magmatic, submagmatic, and solid-state fabrics with identical kinematics (Figure 13a). In conclusion, and as already described by Wickham [1987] and Vernon and Paterson [2001], magma emplacement parallel to S_{2s} is possible because magma pressure is able to overcome the principal shortening plus the tensile strength of the rock parallel to the principal shortening.

[45] The kinematic framework in the Bielice valley is marked by a synmagmatic gently NNE-dipping cleavage development, associated with a weakly prolate magnetic fabric, and a plano-linear S_{3s} with a down-dip mineral and stretching lineation L_{3s} (Figures 3a, 3c, and 7e). The minimum strain axis for pure shear ($\dot{\epsilon}_{3ps}$) belongs to a NE-SW striking steep plane which bears L_{3s} (Figure 13a). In a stereographic projection, the steep S_{2s} layering belongs to the compressive sector for shortening. Since D_{3s} took place at LT in greenschist facies conditions, we argue that the

host rock displayed a strong anisotropic tensile strength, favorable for horizontal dilation of steep anisotropy during vertical shortening, which further enhanced invasion of magma along S_{2s} . Such a magma-host rock multilayer collapsed, with magma accumulation into the F_{3s} axial planes in a similar way as discussed above.

8.2.2. Emplacement of the ZUS

[46] The magmatic emplacement is syntectonic to D_{2z} , which started and developed as a pure shear subvertical shortening. In case of oblate strain, the finite elongation occurs inside of a subhorizontal plane normal to the direction of principal shortening. In the stereographic projection (Figure 13b), the shortening direction for pure shear ($\dot{\epsilon}_{3ps}$) plots onto the S_{1z} foliation. In such kinematic frame, every subvertical plane reaches criteria for tensile failure. Buriánek *et al.* [2003] determined a pressure of 4–5 kbar for the ZUS emplacement. This indicates that the Zábřeh Unit was located at upper-structural levels and was competent enough before magma emplacement. Therefore, magma overpressure combined with S_{1z} subparallel to the vertical shortening in upper crustal conditions produced a horizontal dilation causing the intrusion of subvertical S_{1z} -parallel magmatic sills.

Independent upward movement of the magma was then possible because magmatic pressure at the tip of the sill exceeded the lithostatic pressure [Kisters *et al.*, 2009]. Such a multilayer system along with the surrounding thermally weakened host rocks likely became very weak during the outgoing D_{2z} layer parallel shortening, resulting in subvertical shortening and folding of the S_{1z} of the Zábřeh Unit. Locally, minor foliation-parallel sheets emplaced along the new S_{2z} cleavage (Figure 5d), possibly because the differential stress in such anatectic rocks was very small and smaller than the difference between the tensile strength in the rock parallel and normal to S_{2z} (according to concept of Cosgrove [1997]).

8.3. Kinematic Interpretations of the Internal Fabrics

[47] It has been demonstrated that the emplacement of the SMS and ZUS was controlled by the orientation of the pre-existing anisotropy, thermal state of the host rocks, and regional stress field. However, questions still remain about the relationships between magma flow and deformation of the host rocks, cooling rates during deformation, and rheological behavior of syntectonically emplaced SMS and ZUS.

[48] The northern SMS is a decoupling horizon between a stiff Cambrian fragment to the east and an exhuming, hot orogenic root to the west. There, an E-W zonation of the internal fabric accounts for this decoupling mechanism. Along the eastern margin, a subtle Type I- K_3 cluster fabric with shallow-dipping magnetic foliations is interpreted to result from magmatic flow along S_{1s} (Figure 7c). Fast cooling (preserved magmatic to submagmatic microstructures and weak quartz CPO, map of Figure 7, Figures 6a, 6b, and 9a) associated with inability of SMS magmatic sheets to transmit shear stress generated during OSD dome construction to the west allows this domain to be protected from D_{2s} , and to preserve fabrics that record emplacement flow of the magma during dilation of S_{1s} enhanced by onset of activity of D_{2s} (Figure 13a). Instead, the western margin was strongly affected by D_{2s} as revealed by identical host rock fabrics and Type I magnetic fabrics (Figure 7a), generally high-strain solid-state microstructures and quartz textures consistent with dextral kinematic criteria (map of Figure 7 and Figure 9b). Between these two domains, D_{2s} was moderately and heterogeneously reworking the primary shallow-dipping intrusive fabric, and produced a Type III-transitional fabric marked by K_3 E-W girdle of magnetic fabrics (Figures 7b and 13a). To the south, in the central and southern SMS, complete mechanical coupling with the deformation in the OSD rocks produced synmagmatic to solid-state folding of S_{1s} -parallel sheets (Type II-transitional fabric) and S_{2s} -axial-planar sills (west-dipping Type I-cluster fabric, Figures 7e and 13a).

[49] In the ZUS, a primary ascent-related fabric is rarely preserved and only revealed by a Type I S_{1z} -parallel foliation with a subtle steep lineation (Figures 8a, 8b, and 13b). It is suggested that Type II-III-transitional fabrics (Figures 8d, 8e, and 8f) represent incremental superimposition of D_{2z} on this steep original fabric. Indeed, the girdles which are developed around an axis broadly subparallel to the magmatic lineation L_m , and to the fold axis of F_{2z} fold and mineral and intersection lineation L_{2z} of the country rock reveal a change

from vertical magma ascent to flow in limbs and ponding in hinges of F_{2z} folds (Figure 13b). Last D_{2z} increments produced a relatively strong anisotropic Type IV solid-state S_{2z} -parallel fabric (Figures 8a, 8h, and 13b). The main magmatic sheet (profile 3 in Figure 8a) shows an internal zonation marked by Type I S_{2z} -parallel fabrics at the margins (Figure 8f) and Type II girdle in the core (Figure 8e). This indicates that the strain distribution in the magma was mainly controlled by movement of the walls. The incremental evolution of D_{2z} strain recorded in the magmatic rocks is systematically correlated with a progressive overprint of subsolidus LT microstructures on magmatic fabrics which indicates the synkinematic cooling of the ZUS (Figure 13b). In summary, the ZUS AMS and microstructural evolution is compatible with the regional ductile thinning event as revealed by (1) original buoyancy-driven ascent of magma, (2) synmagmatic folding and ponding in low pressure areas such as hinges of F_{2z} folds, and (3) final crystallization and subsolidus deformation in S_{2z} -parallel sheets. Evidence for change in kinematics from ductile thinning to normal shear is provided by the quartz fabrics data (Figures 9c and 10), meaning that this switch is a late to postmagmatic event.

8.4. A Model of Origin of Magnetic Fabrics

[50] The two different evolutions of magnetic fabrics can be schematized in terms of contrasting types of fabric superimpositions. In the SMS domain, the initially shallow-dipping fabric (D_{1s}) was overprinted by an oblique transpression with dextral simple shear component (D_{2s}). In the ZUS domain, the subvertical intrusive fabric (D_{1z}) was flattened by pure shear (D_{2za}) combined with horizontal simple shear and sliding (D_{2zb}) along the apical part of the ascending gneiss dome. To test this hypothesis, numerical models of magnetic fabric were developed under corresponding conditions. Biotite and amphibole are considered as the main carriers of magnetic anisotropy having the following parameters P (anisotropy degree) and T (shape): biotite $P=1.34$, $T=0.88$; and amphibole $P=1.14$, $T=0.53$ [Borradaile and Jackson, 2004]. Biotite is almost perfectly oblate with axial ratios 5:4:1 and amphibole is triaxial, 3:2:1. Conformably to the bulk-rock susceptibility and modal abundances, the relative contributions to bulk magnetic susceptibility of biotite with respect to amphibole is estimated as 80/20 (given the typical values of mean susceptibility and presence of both minerals in studied rock samples). Due to the strong triaxiality of amphibole, we used the model of rigid body rotation in a viscous fluid developed by Jeffery [1922] and its numerical implementation by Ježek *et al.* [1994]. Given the size of biotite and amphibole crystals and temperature conditions during fabric development, we consider the model to reflect reasonably well the creation of a magnetic fabric under given conditions of tectonic deformation.

[51] The models of fabric evolution in the SMS are shown in Figure 14a. Here, the dilation created space into horizontally anisotropic amphibolites of the Staré Město Unit along which were emplaced sills bearing shallow-dipping magmatic foliation (S_{1s}), as indicated in Figure 14a. This fabric is shown in stereoplots (left column) and is a starting point in AMS P - T diagrams calculated separately for biotite, amphibole, and then for total fabric. According to our model, the D_{1s} fabric was created by vertical flattening with slightly more pronounced stretching in the direction 120° , which is the direction of the

instantaneous elongation axis ($\hat{e}_{1ss}$) at the onset of D_{2s} . This configuration reflects the injection of magma into a horizontal anisotropy parallel to the horizontal shortening direction. D_{1s} was further overprinted by oblique transpression with a dextral simple shear component. In the first part of the overprint (D_{2sa}), a girdle of poles to (001) planes of biotite and (010) planes of amphibole develops associated with a strong lineation of long axes of amphibole and a zone axis of biotite (zone axis corresponding to highly girdled orientations of K_2 and K_3). This fabric shows prolate symmetry for the AMS ellipsoid ($T < 0$). During continuation of the deformation process, the pure shear component of transpression (D_{2sb}) becomes gradually more important and leads to the development of a vertical foliation represented by pole clusters close to the periphery of the diagram D_{2sb} of Figure 14a. At the same time, a strong linear fabric oriented NNE-SSW can be seen in the diagram of long axes. The corresponding fabric returns in the oblate region of AMS P-T graph.

[52] Modeling of the fabric evolution on the ZUS is shown in Figure 14b. The deformation D_{1z} created the vertical magmatic foliation of the ZUS emplaced in the upper part of the dome into vertically anisotropic rocks of the Zábřeh Unit (see Figure 14b). This fabric shown in stereoplots (left column) exhibits a vertical foliation striking 120° and bearing weak vertical lineation marked by zone axis of biotite and preferred orientation of long axes of amphibole. D_{1z} was flattened by pure shear (D_{2za}) and subsequently by horizontal simple shear and sliding (D_{2zb}) along the boundary of the ascending gneissic dome. The two stages of deformation approximate the process of progressive tilting (rotation around a horizontal axis) of deforming magmatic sheets as they slide from the top to the side during the upward motion of the dome. During the first stage (D_{2za}), the fabric becomes prolate, as seen in the AMS P-T diagram and illustrated by zonal lineation of biotite in the pole plot and by weak preferred orientation of long axes of amphibole. In the second stage (D_{2zb}), where simple shear produced an instantaneous shortening direction SSW-plunging at 45° and represents the deformation of the ZUS shifted to the side of the dome, the fabric gets more and more oblate (see P-T path) and develops a more inclined foliation and scattered lineations with weak maxima in the SSW direction.

8.5. Significance of AMS Fabric Patterns in Transpressive and Ductile Thinning Domains

[53] Results of modeling of the magnetic fabric evolution of the SMS (Figure 14a) indicate that the D_{1s} fabric is related to the Type I- K_3 cluster distribution, the fabric D_{2sa} corresponds to Type II- K_3 girdle distribution, and the fabric D_{2sb} matches with Type III-incomplete K_3 girdle distribution (Figure 13a). Therefore, we propose that the three distinct magnetic fabrics observed along the SMS originated as a result of progressive transpressional deformation reworking originally horizontal Type I- K_3 cluster fabric during which the Type II- K_3 girdle and Type III-incomplete K_3 girdle are a result of one deformation regime as shown in Figure 13a.

[54] Numerical simulation of the three magnetic fabrics observed in the ZUS indicates that the primary vertical intrusive fabric D_{1z} (Figure 14b, upper left column) corresponds

to a Type I- K_3 cluster distribution, the fabric D_{2za} corresponds to Type II- K_3 girdle distribution, and the fabric D_{2zb} matches with Type IV- K_1 girdle distribution (Figure 13b). Hence, we suggest that the AMS evolution in the ZUS is a consequence of a progressive reworking of an original steep fabric by a subvertical shortening which evolved in normal simple shear. The numerical simulation shows that the switch between ductile thinning to normal shearing is not late magmatic but more likely synmagmatic as evidenced by the modeled Type IV fabric of model D_{2zb} in Figure 14b (corresponding to Figure 8h) using normal simple shear kinematics. Our modeling simulates well variations of AMS fabrics as proposed in sequence of diagrams in Figure 13a and 13b and which are consistent with kinematic and mechanistic models of magma emplacement.

9. Conclusions

[55] The data reported in this study show that emplacement of the SMS and ZUS was controlled by the orientation of inherited mechanical anisotropy. The microstructures of the magmatic rocks suggest that formation of the penetrative fabrics began during crystallization of the magma and continued during cooling at upper crustal levels. The AMS and quartz fabrics are consistent with a simple shear-dominated transpression in the SMS and a ductile thinning evolving into a detachment in the ZUS. In the absence of widely developed extension lineations and kinematic criteria in the Zábřeh Unit, the quartz CPO pattern in the ZUS represents the best available evidence for the SSW-directed normal shear zone on the southern flank of the OSD. The AMS preserved composite fabrics that record emplacement flow of magma, overprinted by orthogonal deformation driven by anisotropic tectonic stresses, pinning the magnetic lineation orientation to the intersection of multiple foliations. The AMS modelling confirmed the prominence of orthogonal deformation superimpositions on intrusive fabrics to create complex fabric patterns in syntectonic granitoids.

[56] Whereas most of the previous studies have emphasized the role of the orientation of preexisting anisotropies compared to the active regional stress field for magma emplacement, this study also highlights that a complex flow of magma is linked to the different vertical position of these anisotropies with respect to the growth dynamics of the orogenic core. Detailed microstructural and AMS studies associated with AMS modeling provide key insights to unravel subtle magmatic to solid-state flow mechanisms during ascent, emplacement and crystallization of syntectonic granitoids in orogens.

[57] **Acknowledgments.** Financial support of the French National Grant Agency (06-1148784 to K. Schulmann) is acknowledged. Activities of the Center for Lithospheric Research are co-financed by the Czech Ministry of Education, Youth and Sports (LK11202). The grant MSM0021620855 of the Ministry of Education of the Czech Republic and internal research funds of CNRS UMR 7516 are acknowledged for salary and financial support of O. Lexa. The Czech Geological Survey is acknowledged for salary support of J. Lehmann. We are grateful to M. Jati for help with preparation of AMS samples. We thank A. Bouzhegaia for help with drawing figures and K. Verner and L. Vondrovic for helpful discussions. J. Honnorez, E.G. Charlesworth, and K. Saalman are warmly acknowledged for informal reviews. We thank O. Bolle and two anonymous reviewers for their helpful reviews, and R. Weinberg and J.-L. Bouchez for thorough and judicious reviews of an earlier version of the manuscript.

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