

Magmatic structures in the Krkonoše–Jizera Plutonic Complex, Bohemian Massif: evidence for localized multiphase flow and small-scale thermal–mechanical instabilities in a granitic magma chamber

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Abstract

The present paper examines magmatic structures in the Jizera and Liberec granites of the Krkonoše–Jizera Plutonic Complex, Bohemian Massif. The magmatic structures are here interpreted to preserve direct field evidence for highly localized magma flow and other processes in crystal-rich mushes, and to capture the evolution of physical processes in an ancient granitic magma chamber. We propose that after chamber-wide mixing and hybridization, as suggested by recent petrological studies, laminar magma flow became highly localized to weaker channel-like domains within the higher-strength crystal framework. Mafic schlieren formed at flow rims, and their formation presumably involved gravitational settling and velocity gradient flow sorting coupled with interstitial melt escape. Local thermal or compositional convection may have resulted in the formation of vertical schlieren tubes and ladder dikes whereas subhorizontal tubes or channels formed during flow driven by lateral gradients in magma pressure. After the cessation or deceleration of channel flow, gravity-driven processes (settling of crystals and enclaves, gravitational differentiation, development of downward dripping instabilities), accompanied by compaction, filter pressing and melt segregation, dominated in the crystal mush within the flow channels. Subsequently, magmatic folds developed in schlieren layers and the magma chamber recorded complex, late magmatic strains at high magma crystallinities. Late-stage magma pulsing into localized submagmatic cracks represents the latest events of magmatic history of the chamber prior to its final crystallization. We emphasize that the most favorable environments for the formation and preservation of magmatic structures, such as those hosted in the Jizera and Liberec granites, are slowly cooling crystal-rich mushes. Therefore, where preserved in plutons, these structures may lend strong support for a “mush model” of magmatic systems.

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1. Introduction

Unraveling the geometrical patterns and the likely physical causes of magma flow in granitic magma chambers is one of the central aspects of understanding

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magma chamber dynamics. In many (or most?) cases, however, direct field evidence for chamber-wide flow or convection is completely erased from the rock record. Magmatic fabrics in plutons (i.e., foliations and lineations formed during the presence of a melt; Paterson et al., 1989, 1998; Vernon, 2000) commonly fail to provide unambiguous evidence for chamber-wide magma flow or convection. Instead, the preserved pluton fabrics are acquired late in magma chamber history along

migrating crystallization fronts and are also easily reset by regional tectonic deformation, making inferences on large-scale convection or flow patterns difficult or rather problematic (e.g., Benn, 1994; Paterson et al., 1998; Benn et al., 2001).

Fortunately, unlike magmatic fabrics, a variety of other small-scale structures (collectively referred to as “magmatic structures” throughout this paper) found in granitic plutons may provide valuable information on

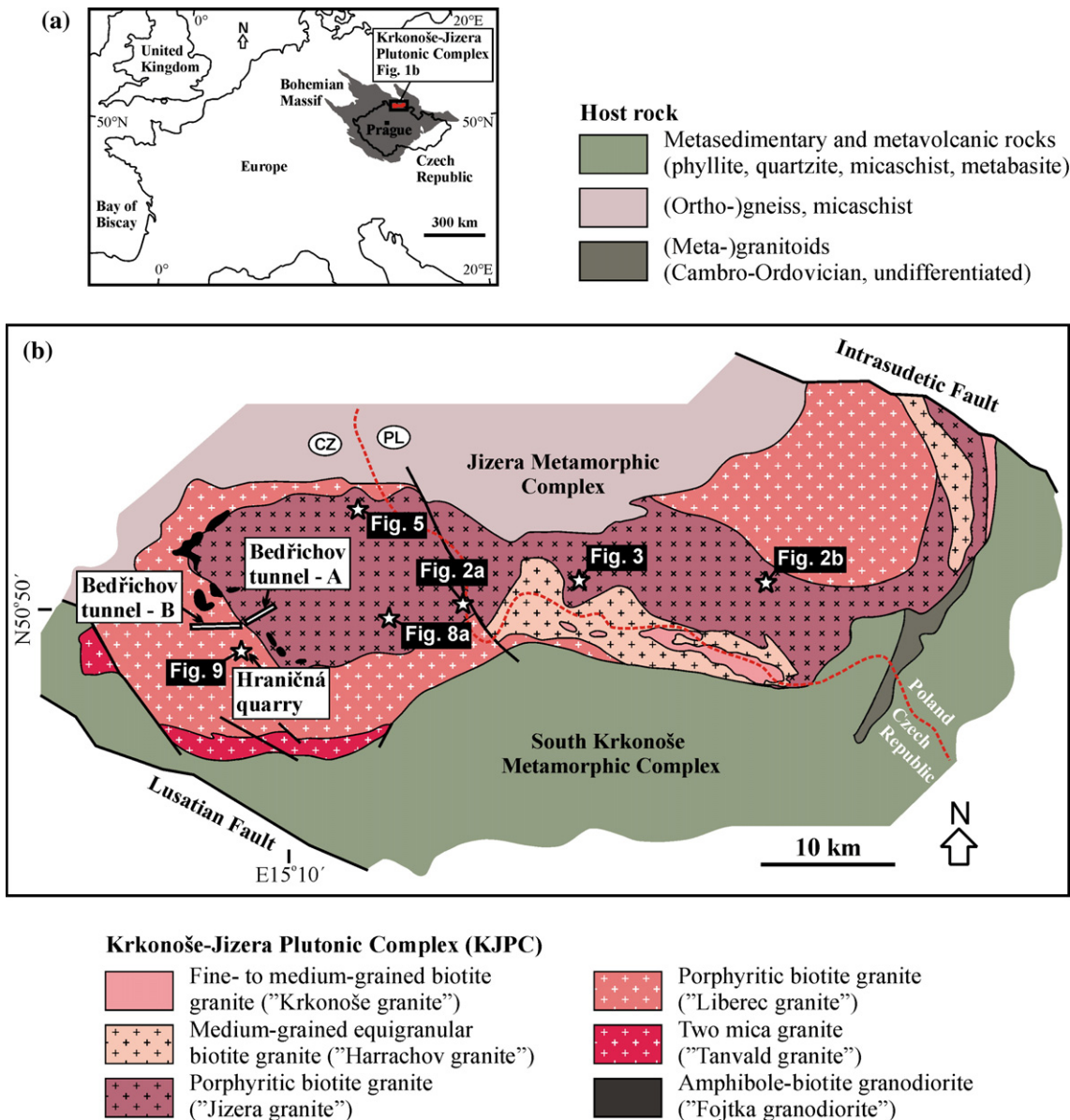


Fig. 1. (a) Simplified index map shows the position of the Bohemian Massif in Europe and location of the study area (the Krkonoše–Jizera Plutonic Complex) in the northeastern part of the Bohemian Massif. (b) Simplified geological map of the north-eastern part of the Bohemian Massif around the Krkonoše–Jizera Plutonic Complex. Stars with Figure numbers indicate approximate location of surface outcrops with magmatic structures examined in this study, other structures were found in underground tunnels (Bedřichov tunnel A and B).

physical processes (e.g., multiphase magma flow, convection, development of thermal–mechanical instabilities) in a magma chamber. These magmatic structures comprise mafic schlieren and schlieren channels, cross-beds, tubes (pipes, “magma worms”), plumes, snail structures, ladder dikes, magmatic folds, and melt segregation structures (Moore and Lockwood, 1973; Barrière, 1981; d’Ars and Davy, 1991; Stel, 1991; Reid et al., 1993; Vaughan et al., 1995; Clarke and Clarke, 1998; Wiebe and Collins, 1998; Weinberg et al., 2001; Milord and Sawyer, 2003; Law et al., 2005; Paterson et al., 2005; Žák and Paterson, 2005; Weinberg, 2006; Wiebe et al., 2007; Žák et al., 2007). By comparison to widespread magmatic fabrics (“granite is never isotropic” — e.g., Bouché, 1997), these structures are quite rare as they are preserved only under favorable conditions that prevent them from being obliterated by magma flow, crystallization, or overprinting by later fabrics. The most instructive and well-exposed examples have been reported from only a few plutons in the world such as the Ploumac’h pluton, France (Barrière, 1981), the South Mountain batholith, Nova Scotia (Abbott, 1989; Clarke and Clarke, 1998), the Tavares pluton, Brazil (Weinberg et al., 2001), the Vinalhaven intrusive complex (Wiebe et al., 2007), and several plutons in the Sierra Nevada, California (Reid and Hamilton, 1987; Bateman, 1992; Reid et al., 1993; Loetterle and Bergantz, 2003; Law et al., 2005; Žák and Paterson, 2005; Žák et al., 2007). Despite various models that have

been invoked to explain the formation of such structures, Weinberg et al. (2001) recently emphasized the role of compositional and thermal convection coupled with flow sorting and interstitial melt migration along permeability gradients in crystal-rich mushes. If preserved in a granitic pluton, the above mentioned structures may thus represent intriguing “snapshots” of processes that operate in multiphase crystal-rich mushes in a magma chamber prior to the formation of late magmatic fabrics and its full crystallization.

In this paper, we examine a wide variety of spectacular magmatic structures in the porphyritic Jizera and Liberec granites (the Krkonoše–Jizera Plutonic Complex, Bohemian Massif), in a classic area of granite geology first explored by Hans Cloos in the 1920s (Cloos, 1925). Here, a wide range of magmatic structures formed by multiple processes are exceptionally well-exposed in three dimensions not only in outcrops but also in several underground tunnels in the deep interior of the granite body. Below we first briefly outline the geological setting of the examined granitoids, and we describe the most spectacular structures found in the Jizera and Liberec granites. We then interpret likely processes that may have accounted for their formation, and we discuss their role as markers of localized flow and physical processes in crystal-rich magma mushes. Finally, we briefly point out broader significance of magmatic structures for interpreting the nature of evolving magmatic systems.

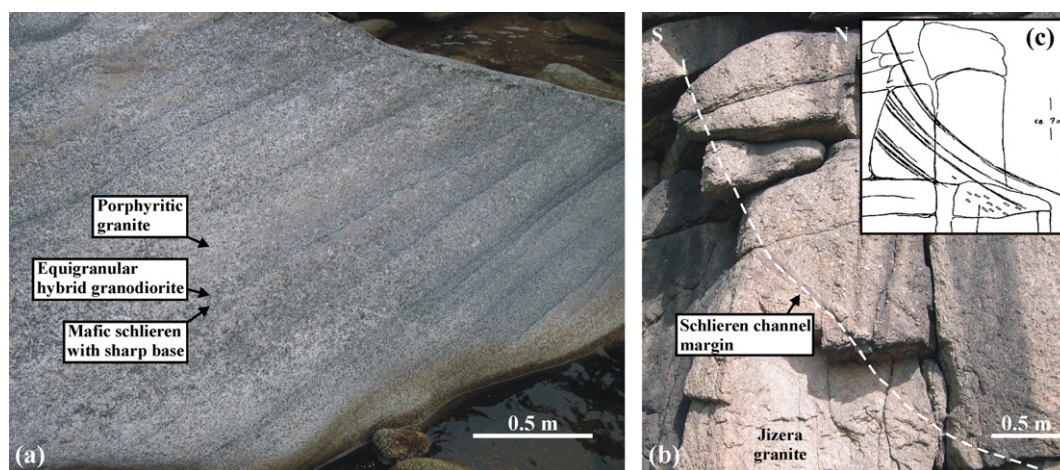


Fig. 2. (a) Rhythmic layering defined by modally graded planar layers in the Jizera granite. Each individual unit has a sharp base delineated by mafic (biotite) schlieren and grades upward through equigranular hybrid granodiorite to porphyritic, felsic granite. The schlieren stack is interpreted to record repeated magma injection followed by internal differentiation of each unit after the flow cessation. Unoriented block, the Jizera River valley. (b) Margins of several large schlieren channels in the Jizera granite, K-feldspar phenocrysts are commonly aligned parallel to the marginal schlieren, Podgórzyn, Poland. This outcrop is a classic locality (known as “Himmelreich”) explored by Hans Cloos in the 1920s. (c) Original line drawing by Hans Cloos depicting the structure (referred to as the “Schlierenkaskade”) shown in Fig. 2b.

2. Geological setting

The $\sim 1000 \text{ km}^2$ Carboniferous Krkonoše–Jizera Plutonic Complex (also variably referred to as the Krkonoše–Jizera pluton, Krkonoše–Jizera massif, or Karkonosze batholith) crops out in the northeastern part of the Bohemian Massif (Fig. 1a and b), having a “double lobed” shape in a map-view with the narrowest central part and its longest dimension ($\sim 70 \text{ km}$) oriented $\sim \text{E–W}$. The existing radiometric ages of granitoids of the plutonic complex range widely from $329 \pm 17 \text{ Ma}$ (Rb–Sr) to $304 \pm 14 \text{ Ma}$ (Pb–Pb; see Pin et al., 1987; Duthou et al., 1991; Kröner et al., 1994; Mierzejewski et al., 1994; Marheine et al., 2002 for geochronological data). The plutonic complex intrudes several lithotectonic units, each exhibiting polyphase deformational structures and contrasting metamorphic histories (Hladil et al., 2003; Winchester et al., 2003; Mazur et al., 2006 and references therein).

The plutonic complex is a composite body that comprises several intrusive units (Fig. 1b; Klomínský, 1969; Klomínský et al., 2000; Žák et al., 2006). Its southwestern margin is made up of two-mica granite (the Tanvald granite) whereas much of the remainder of the plutonic complex is made up of two distinct types of coarse-grained porphyritic biotite granodiorite to granite (the Jizera and Liberec granites) which host the magmatic structures examined in this paper. The Liberec granite makes up the lowermost exposed part of the plutonic complex, whereas the Jizera granite is exposed in the upper sections through the complex. The two granites differ in modal and chemical composition (the Liberec granite has higher content of Na and K and lower content of Ca and Mg), magnetic properties (the bulk magnetic susceptibility of the Liberec granite is around 20 times higher than that of the Jizera granite), and average size of K-feldspar phenocrysts (2–3 cm in the Liberec granite, 5–7 cm in the Jizera granite). The K-feldspar phenocrysts in both

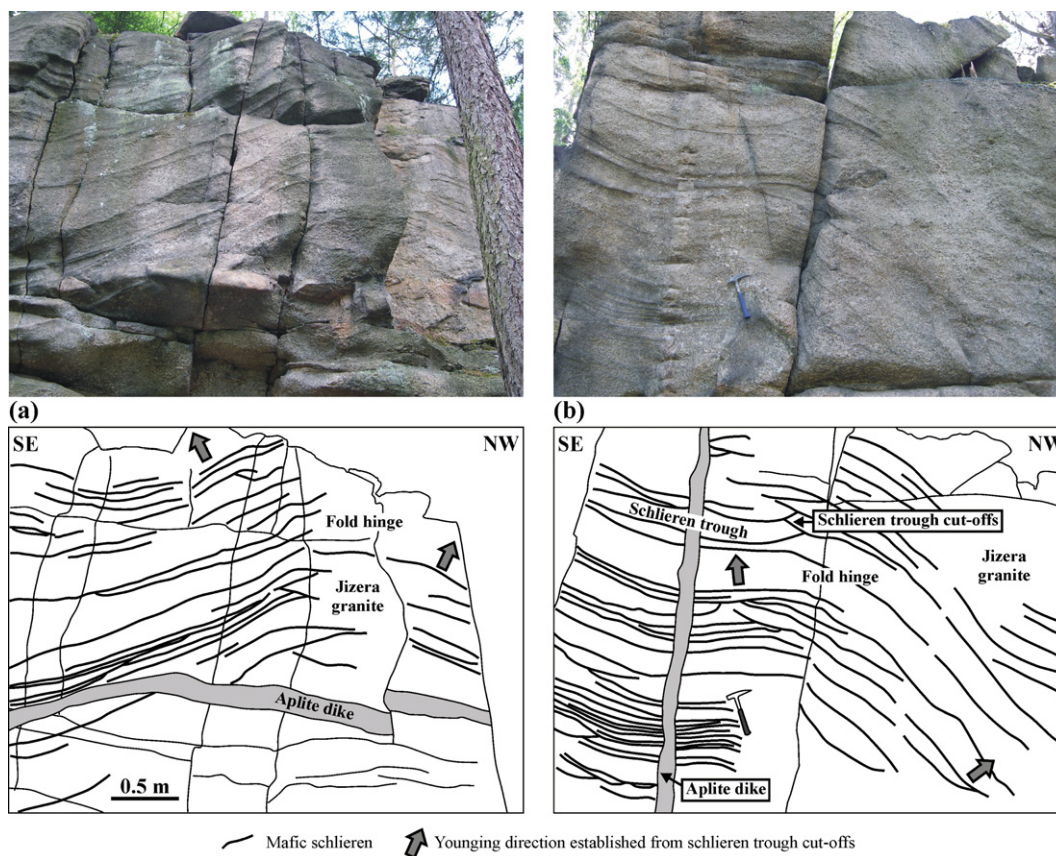


Fig. 3. Photos and line drawings of schlieren stacks made up of multiple superposed (migrating) schlieren channels (troughs). (a) Anticlinal, upward-younging schlieren stack in the Jizera granite. A late aplite dike which cuts across the schlieren has been gently folded but recorded a significantly lesser amount of shortening than the host schlieren. (b) Stack of superposed schlieren channels in the Jizera granite. Truncations of individual schlieren channels indicate an upward younging direction. A discordant steep aplite dike cuts across the schlieren. Hammer for scale. Both photos are from one large outcrop located in the Kamienna River valley, 3 km northeast of Sklarska Poreba, Poland.

granites are commonly mantled by a thin (up to a few millimeters) plagioclase rim (rapakivi texture). The internal gradational contact between the Jizera and Liberec granites is delineated in places by smaller bodies of more mafic, amphibole–biotite granodiorite (the Fojtka granodiorite). Medium-grained biotite granite (the Harrachov granite) crops out in two isolated bodies in the eastern half of the plutonic complex. The uppermost exposed part of the plutonic complex is made up of fine-to medium-grained equigranular biotite granite (the Krkonoše or Crestal granite).

The granitoids of the plutonic complex are mainly peraluminous, subordinately metaluminous. Importantly, Slaby et al. (2002, 2007), Slaby and Götze (2004), and Slaby and Martin (2005) noted that the porphyritic granitoids exhibit many field textures indicating crystallization under disequilibrium conditions and compatible with magma mixing (e.g., abundant rapakivi feldspars) and viewed the porphyritic granitoids as one hybrid facies (see Slaby et al., 2007 for details). Based on the investigations of K-feldspar megacrysts and geochemical modeling, these authors proposed that extensive mixing of coeval magmas influenced the formation of porphyritic granites, whereas fractional crystallization was an important process in the petrogenesis of the equigranular granite facies.

3. Magmatic structures in the Jizera and Liberec granites

The porphyritic Jizera and Liberec granites are rather unique in preserving a wide spectrum of the magmatic structures mentioned above. The magmatic structures were first investigated by Cloos (1925) who documented various geometries of mafic schlieren, mapped their patterns in the eastern part of the plutonic complex, and inferred the schlieren as being parallel to the flow plane of flowing magma. He also noted that the mafic schlieren define a large-scale dome-like structure. Similarly, schlieren patterns were mapped by Klomínský (1969) in the western part of the plutonic complex. In this study, we focus on examining the diversity and processes of formation of the magmatic structures; their regional pattern and spatial distribution will be addressed elsewhere. The most informative examples, discovered during our regional mapping and investigations in several underground tunnels (Figs. 2–10; see Fig. 1b for locations), seem to fall into several categories and are described in detail below.

(a) *Simple and stacked schlieren channels* (Figs. 2 and 3). In the Jizera and Liberec granites, mafic schlieren are typically defined by accumulation of biotite, having sharp bases and passing gradationally through hybrid granodiorite to more felsic granite over a few centimeters (normal grading; Fig. 2a). In some cases, the schlieren

are both modally-graded and size-sorted, i.e., biotite schlieren pass into a layer with plagioclase phenocrysts (0.5–1 cm in size) which passes into a K-feldspar phenocryst-rich layer (1.5–3 cm in size). Mafic schlieren occur either as irregularly scattered single patches or delineate margins of individual channel-shaped structures (schlieren channels) entirely enclosed in the host granite (Fig. 2b). In many cases, multiple superposed (migrating), concave-upward individual channels delineated by marginal schlieren make up vertical stacks. Fig. 3 depicts a schlieren channel stack which consists of multiple superposed troughs and planar or gently curved schlieren and has a lateral extent that is larger than its thickness (the exposed part of the stack is approximately 3–4 m thick and more than 10 m wide). The superposed schlieren channels truncate one another as indicated by crosscutting marginal schlieren on the bottom of each channel, and thus closely resemble cross-bedding and scour-and-fill structures in sedimentary rocks. Both modal grading of individual schlieren and younging (defined by schlieren truncation) indicate an upward growth (aggradation) of channel stacks (Fig. 3).

(b) *Schlieren tubes (pipes, ring schlieren, “magma worms”), snail structures and ladder dikes* (Figs. 4 and 5).

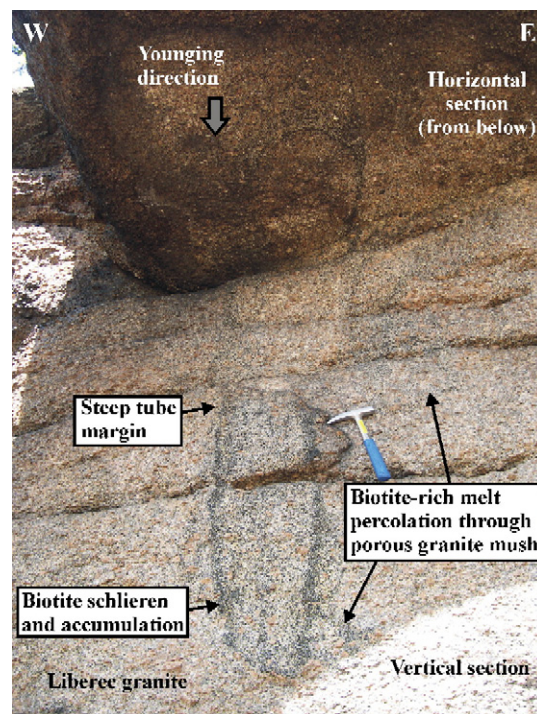


Fig. 4. Three-dimensional section through a vertical ladder dike in the Liberec granite. The ladder dike is delineated by mafic schlieren with irregular, diffuse outer boundaries suggesting melt percolation through the porous crystal-rich mush. Hammer for scale. Outcrop 4 km east of Hejnice, Czech Republic.

These structures differ geometrically from those described above in that they consist of entirely enclosed tube-shaped channels. The individual tubes have typically steeply plunging axes. In horizontal section (perpendicular to the tube axis), the tubes have subcircular to weakly elliptical outline delineated by the outer marginal schlieren. The tubes are either single or occur in swarms to form snail structures and ladder dikes (e.g., Weinberg et al., 2001). The snail structures and ladder dikes consist of superposed (migrating) multiple tubes, arranged randomly or in one direction, respectively, and have been interpreted as vertically oriented diapir-like plumes driven by thermal and compositional convection (Weinberg et al., 2001).

The most intriguing examples of snail structures and ladder dikes discovered in the Jizera and Liberec granites are the following. In Fig. 4, a ladder dike hosted in the Liberec granite is intersected by two nearly perpendicular

joint planes (vertical and horizontal), providing a unique view into the ladder dike geometry in three dimensions. The sides of the dike are subvertical (as seen on the vertical joint), whereas in the horizontal section the joint plane exposes several cross-cutting tubes. The dike interior is composed of equigranular and more melanocratic (biotite-rich) granite passing upwards into porphyritic granite. Interestingly, the biotite-rich granite has irregular, diffuse outer boundaries and extends outward from the ladder dike (as delineated by schlieren) into the host porphyritic granite. The lowermost exposed part of the dike is made up of an accumulation of biotite and closes downwards — this may be caused either by the effect of section oblique to the channel axis, or the lowermost part of the dike may represent a source zone where the dike initiated.

Most of all known examples of snail structures and ladder dikes (e.g., Reid et al., 1993; Weinberg et al., 2001;

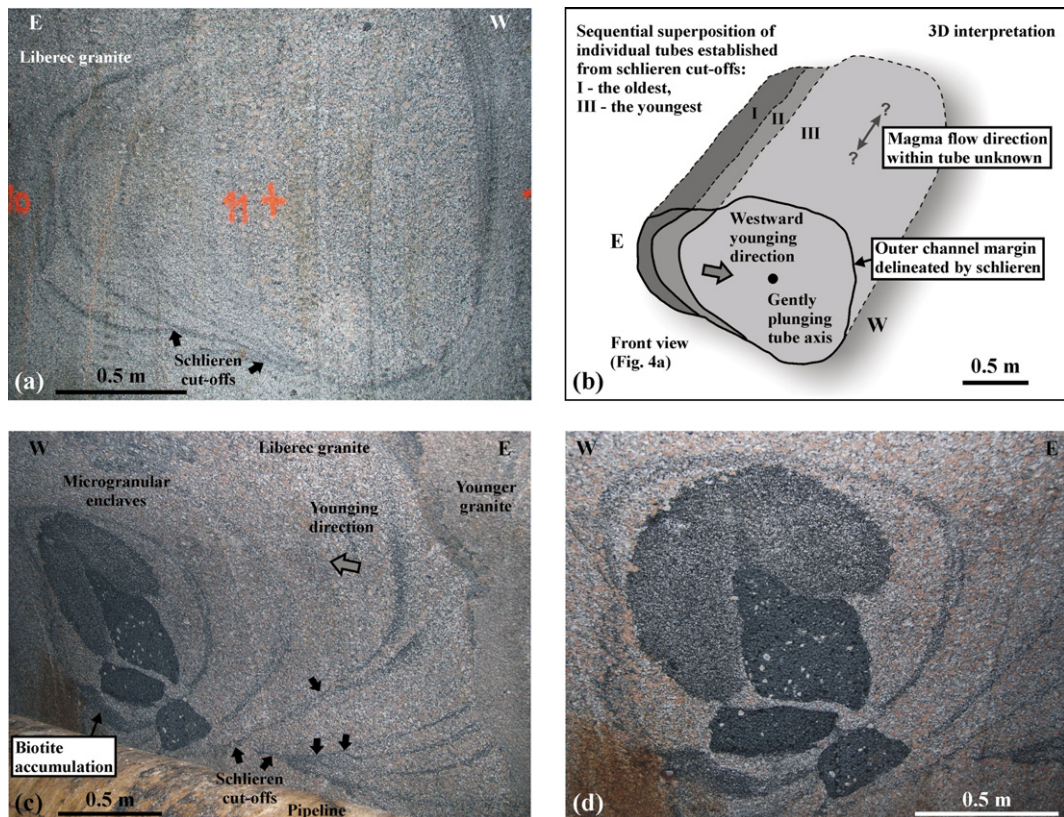


Fig. 5. Gently plunging schlieren tubes in the Liberec granite. (a) Laterally migrating schlieren tubes delineated by mafic schlieren. The individual tubes presumably have gently plunging axes and their truncations indicate a westward-relative movement (superposition) of the individual channels. The view is on a vertical tunnel wall (approximately perpendicular to the tube axis), Bedřichov tunnel, section B. (b) Interpretive line drawing to show inferred three-dimensional geometry of the structure in Fig. 4a. (c) Laterally migrating schlieren tubes in the Liberec granite. The individual tubes presumably have gently plunging axes and their truncations indicate a westward-relative movement of individual channels. The innermost tube encloses several microgranular enclaves which seem to logjam the innermost flow channel. Some of the enclaves are roughly parallel to tube margins (delineated by mafic schlieren), some enclaves are molded against each other, perhaps due to their different viscosities. The structure is discordantly intruded by younger, medium grained equigranular granite. The view is on a vertical tunnel wall, Bedřichov tunnel, section B. (d) Detail of the innermost tube of the structure in Fig. 4c with the closely-packed microgranular enclaves.

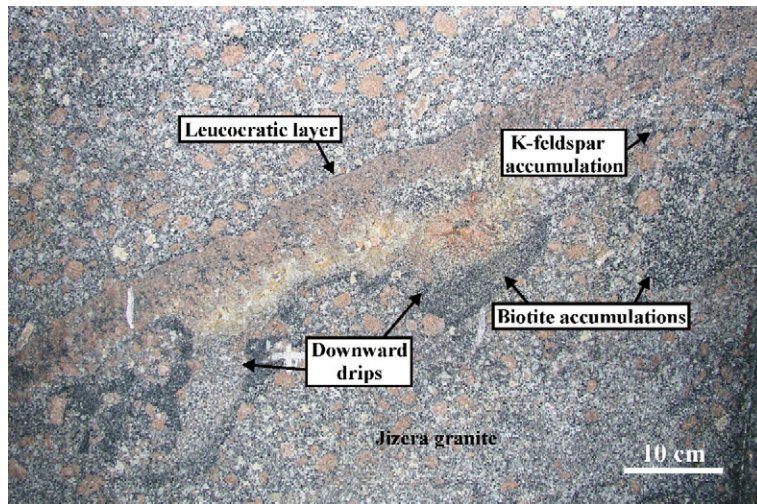


Fig. 6. Complex, internally differentiated downward drips with biotite accumulations on the bottom, passing upwards through intermediate granite to the leucocratic (pegmatitic) layer. Note the base of biotite accumulation draping the underlying K-feldspar phenocryst. Bedřichov tunnel, section A.

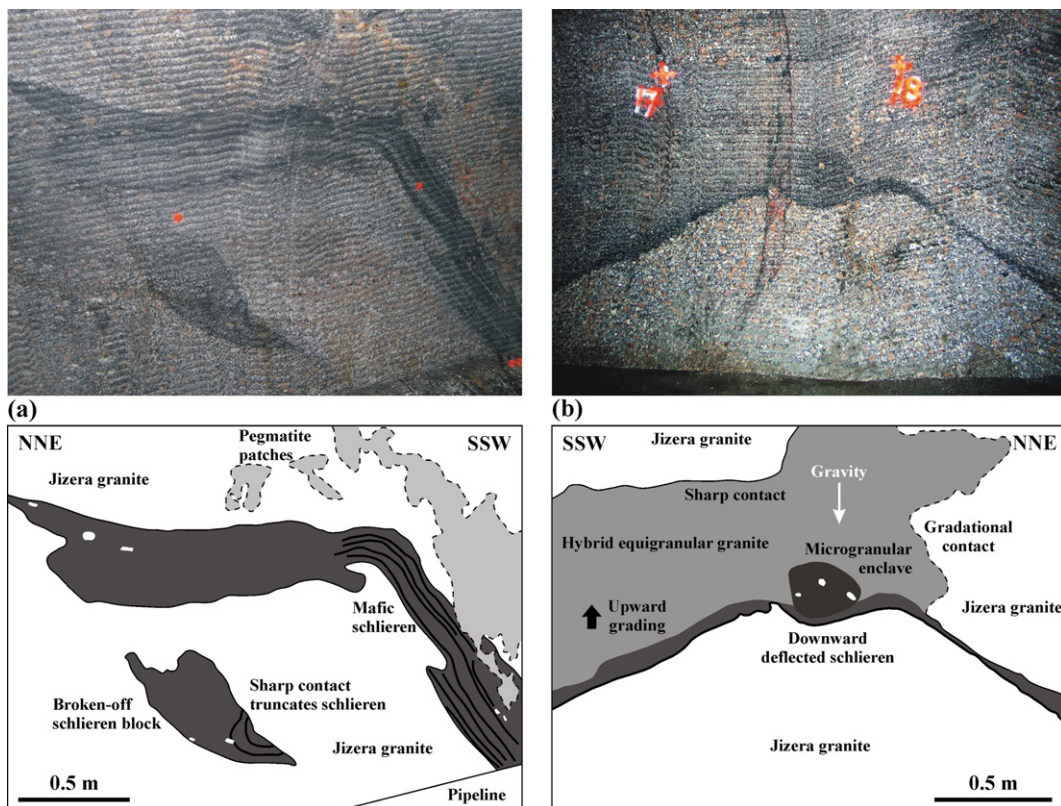


Fig. 7. Photos and line drawings of folded schlieren and antiformal schlieren stacks. (a) Antiformal structure in the Jizera granite defined by upward-grading schlieren and overlying a more irregular leucocratic layer. Broken-off block of sharply truncated schlieren layering occurs enclosed within the host granite below the schlieren antiform. Bedřichov tunnel, section A, approximately 210 m from the western entrance. (b) Schlieren antiform in the Jizera granite. A microgranular enclave rests within the hybrid equigranular granite and deforms the underlying mafic schlieren in the crestal part of the antiform. Bedřichov tunnel, section A, approximately 336 m from the western entrance.

Žák and Paterson, 2005) are typically steep-sided bodies (plumes or diapirs) with vertical to steeply plunging axes (e.g., the ladder dike shown in Fig. 4). By contrast, we documented a few rather unique examples of these structures with similar architecture that however had remarkably different orientations. The unusual ladder dikes and snail structures were observed in the Liberec granite in the Bedřichov underground tunnel (section B) on nearly vertical tunnel walls in sections roughly perpendicular to the tube axes. Fig. 5a and b depicts a ladder dike which consists of several entirely enclosed migrating schlieren tubes with gently plunging axes. Cross-cutting relationships indicate that the individual tubes migrated laterally (westward) and that the tubes widened parallel to the younging direction. We also found one intriguing example where several mafic microgranular enclaves occur within a ladder dike (Fig. 5c and d). The ladder dike consists of several gently plunging tubes (migrating laterally — westward), the enclaves are contained in the youngest tubes. The long axes of the two lowermost enclaves are roughly parallel with the outer tube-bounding schlieren and, interestingly, the outer schlieren terminate sharply against the enclave margins. In the upper (central) part of the youngest tube, one presumable rheologically weaker enclave is wrapped around the tip of the other, more rigid enclave. Biotite accumulation fills the concave-upward bottom side of the youngest schlieren tube.

(c) *Downward drips* (Fig. 6). In a few rare cases, downward drips or bulges extend downward from gently dipping composite layers or mafic biotite schlieren. The drips are delineated by mafic schlieren and form bulges which seem to propagate downward from the gently dipping layers. In Fig. 6, the downward-pointing, irregularly-shaped bulges are internally differentiated; their bottoms (tips) are filled by mafic biotite cumulate, commonly wrapped around the underlying K-feldspar phenocrysts, and pass upwards through hybrid equigranular granite to an overlying leucocratic (pegmatitic) layer. Where K-feldspar phenocrysts are present, they “float” (concentrate) between the biotite cumulates and the pegmatite layer (Fig. 6).

(d) *Magmatic folds, antiformal (younging unknown) or anticlinal (younging upward) schlieren stacks and folded schlieren channels* (Figs. 3 and 7). In some cases, aplite dikes, mafic-felsic layers and stacks of superposed schlieren channels have been folded into magmatic folds (with no evidence for subsolidus deformation). These folds occur at variable scales, up to several meters in wavelength, typically are upright and have large interlimb angles (open folds) with a few exceptions of some tightly folded aplite dikes. In the folded schlieren stacks, upward-graded individual schlieren and upward-younging schlieren

cross-beds have been folded and reoriented from their original positions, rotating with opposite limbs of the folds (Fig. 3a). In Fig. 3a, a late aplite dike intrudes discordantly into the anticlinal schlieren stack which had been magmatically folded prior to dike emplacement. The dike also seems to have been gently folded and exhibits a much smaller interlimb angle suggesting that the schlieren stack and the dike have recorded different amounts of shortening.

Other intriguing cases of magmatic folds were discovered in the Bedřichov tunnel (Section A) in the Jizera granite (Fig. 7). Here, an upward-grading schlieren stack was intruded by the underlying granite to form an antiformal structure (Fig. 7a). Some parts of the schlieren stack were also broken off and displaced within the granite. In Fig. 7b, an upward-grading schlieren antiform

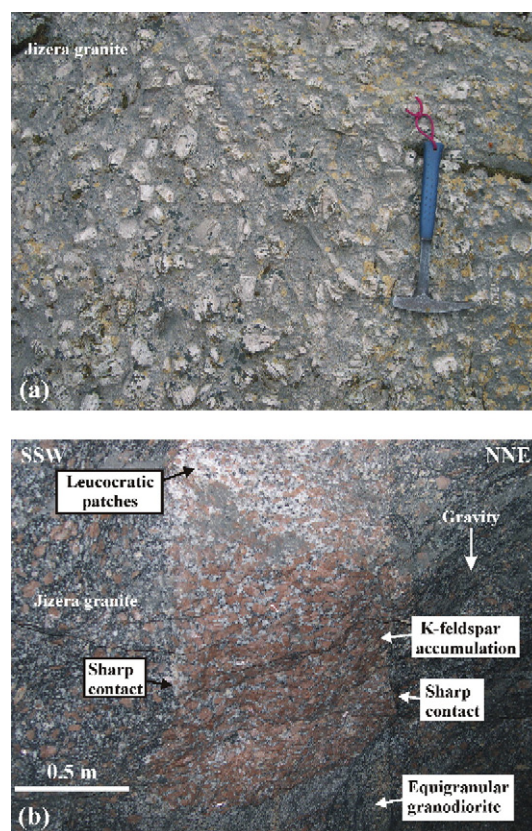


Fig. 8. (a) Accumulation of large (5–6 cm in size) K-feldspar phenocrysts (weathered out) in the Jizera granite. Hammer for scale. The Bílá Desná River valley. (b) Sheet-like accumulation of K-feldspar phenocrysts bounded by sharp intrusive contacts against the host Jizera granite. Inside, the accumulation is vertically differentiated from equigranular hybrid granodiorite in its lower part through closely packed K-feldspar phenocrysts in the middle to the uppermost leucocratic patches. The modal grading inside the sheet suggests gravitational differentiation, accompanied by gravity-driven compaction of the K-feldspar phenocryst mush and by extraction and upward migration of lower-density leucocratic melt. Bedřichov tunnel, section A.

is overlaid by hybrid (more mafic), medium-grained equigranular to weakly porphyritic granite. The contact between the host porphyritic Jizera granite and the hybrid granite is mostly sharp, but drapes around K-feldspar phenocrysts within the Jizera granite. In some places the contact is gradational. A microgranular enclave rests on the crestal part of the schlieren antiform (within the hybrid granite) and deforms the underlying mafic schlieren. Along its strike ($\sim 120^\circ$, parallel to the fold axis), this complex structure passes into a single, 20 cm thick antiformal sheet which is compositionally homogeneous (made up of the hybrid granite) and has sharp contacts against the porphyritic granite.

(e) *K-feldspar accumulations* (Fig. 8). Meter-scale K-feldspar accumulations, i.e., phenocryst-rich bodies in much greater modal proportions than expected for the composition of the magma (for other examples and further discussion see Vernon, 1986; Paterson et al., 2005), are ubiquitous in the porphyritic granites throughout the Krkonoše–Jizera Plutonic Complex. Their three-dimensional shapes vary from irregular patches or clusters (Fig. 8a), through layers to steep blob-like or sheet-like bodies (Fig. 8b). Margins of the K-feldspar clusters against the host granites vary from sharp to diffuse. The K-feldspar accumulations are commonly associated with other magmatic structures such as those described above (e.g., biotite accumulations). In detail, the individual phenocrysts in clusters are closely packed, touching each other with little interstitial matrix around the phenocrysts. In some cases, the K-feldspar clusters are internally

graded, i.e. domains of closely packed phenocrysts pass gradationally upwards into domains of more loosely packed phenocrysts with interstitial leucogranite and further up into leucogranite pockets or layers (Fig. 8b).

(f) *Magma-filled submagmatic cracks and composite sheets* (Fig. 9). Of several submagmatic cracks we have found in the porphyritic granites, the largest and the most spectacular example is exposed in the Liberec granite in the Hraničná quarry (Fig. 9; see Fig. 1 for location). Here, a submagmatic crack cuts across the entire quarry wall. The crack is roughly planar, strikes 320° (N40°W) and dips to the southwest at a moderate angle (40° – 50°). The thickness of the crack is 0.2–1 m and it extends for at least 30 m along the strike. The outer crack margins are typically sharp, subparallel (Fig. 9a), and cut discordantly across flat-lying magmatic foliation defined by K-feldspar phenocrysts in the host granite. Inside, the crack is filled by multiple individual schlieren which cross-cut each other (Fig. 9b). The schlieren truncations indicate an upward (to the southwest) younging direction with new intrusive material being added along the upper crack surface during episodic growth and opening history of the crack.

(g) *Complex structures* (Fig. 10). In addition to the preceding examples, we found a few complex (composite) magmatic structures that do not fall into any of the above categories. In Fig. 10, a schlieren anticline is defined by planar, upward-graded schlieren to form fold limbs with cross-cutting schlieren channels preserved in the crestal part of the anticline. K-feldspar phenocrysts are concentrated above the schlieren of one fold limb, with

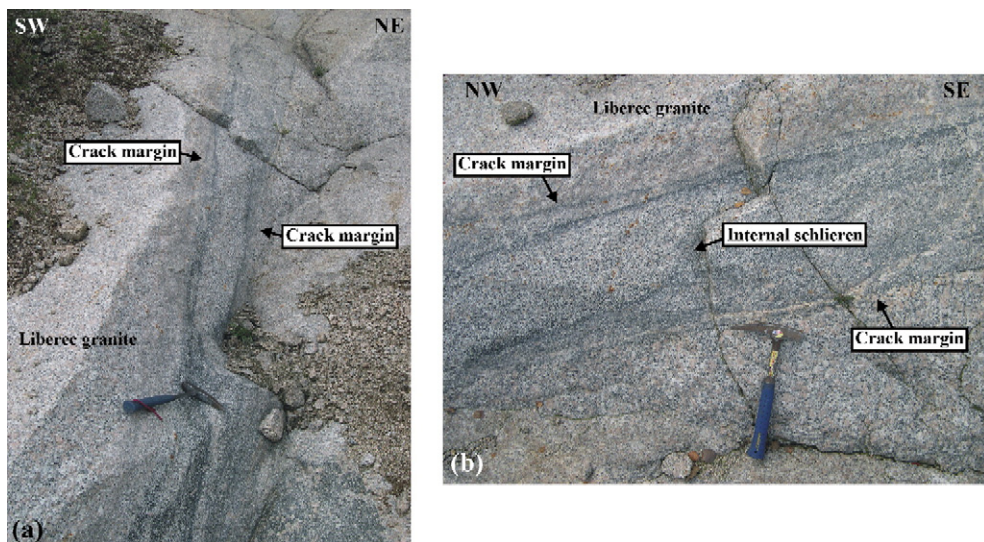


Fig. 9. Distant view (a) and close-up (b) of a large submagmatic crack in the Liberec granite, Hraničná quarry. The crack has sharp and straight outer margins that are discordant to the foliation in the host granite. Inside, the crack is composite and consists of schlieren channels superposed in an upward younging direction. The internal schlieren point to multiple magma injections being drawn into the slot-like opening during an episodic growth history of the crack. Hammer for scale.

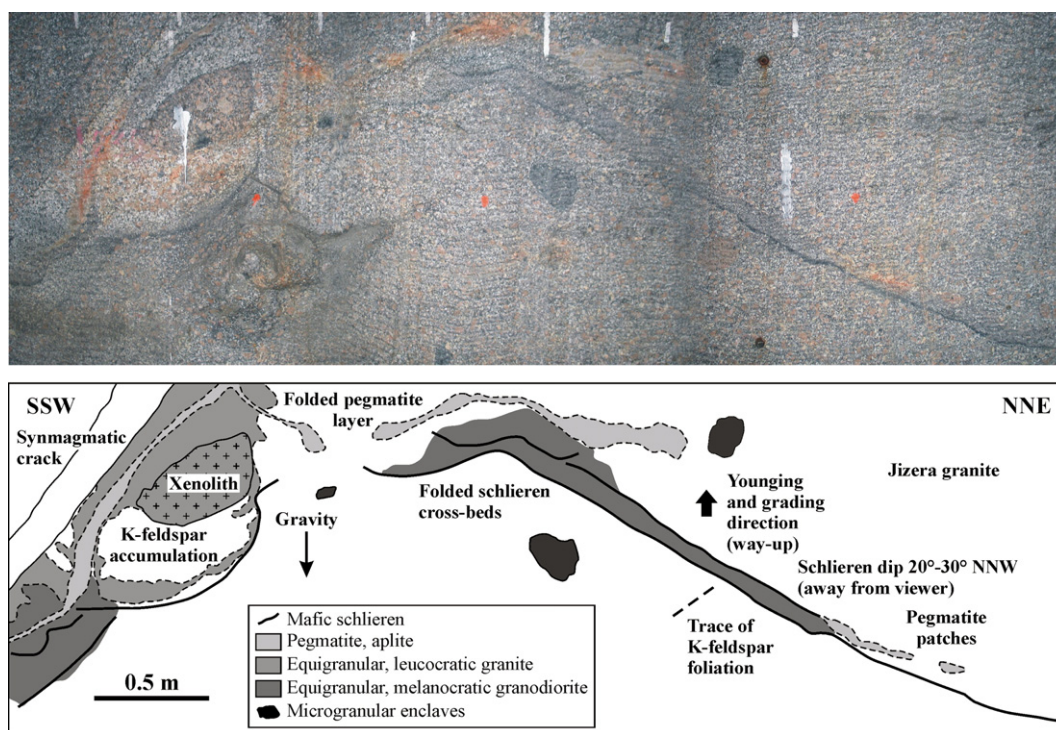


Fig. 10. Photomosaic and line drawing of a complex (composite) magmatic structure in the Jizera granite, Bedřichov tunnel, section A, approximately 210 m from the western entrance. The structure comprises a schlieren anticline (younging and grading upwards) with an overlying folded pegmatite layer. One limb of the schlieren anticline (on the right-hand side) is straight, the other limb is molded around the overlying K-feldspar accumulation (left-hand side). The xenolith rests on the top of the K-feldspar accumulation and does not disrupt the overlying pegmatite layer. A submagmatic crack with sharp outer margins and filled by the Jizera granite truncates the schlieren anticline.

the schlieren being deflected around the base of the accumulation. A large xenolith of coarse-grained porphyritic granite of uncertain origin rests on top and deforms the underlying K-feldspar accumulation. The upper part of the complex structure is formed by a leucocratic (pegmatitic) layer, also being folded roughly parallel to the mafic schlieren. Interestingly, the pegmatite layer is not disrupted by the xenolith. The magmatic fold is discordantly truncated by a submagmatic crack with sharp outer margins delineated by mafic schlieren and filled by the “normal” porphyritic Jizera granite.

4. Discussion

4.1. Interpretation of physical processes and rheological state of magma during formation of magmatic structures

The wide variety of magmatic structures preserved in the Jizera and Liberec granites provide unique field evidence for localized magmatic differentiation, multiphase magma flow, and a variety of physical processes that may operate in crystal-rich mushes in granitic magma chambers. Complemented with the existing petrological studies and

our yet unpublished fabric data, these structures also afford intriguing insight into the history of a crystallizing granitic magma chamber during different stages of its rheological evolution.

On the basis of disequilibrium textures, chemical composition, and thermal history of crystallization of mantled K-feldspar phenocrysts, Slaby et al. (2002), Slaby and Götze (2004), and Slaby et al. (2007) recently proposed that extensive mixing and magma hybridization in a dynamic environment are important processes in the petrogenesis of porphyritic granites of the Krkonoše–Jizera Plutonic Complex. This conclusion is consistent with our present observations as the mantled (rapakivi) K-feldspar phenocrysts, put forward as an evidence for magma mixing, are ubiquitous throughout the porphyritic granites. Importantly, the euhedral rapakivi K-feldspar phenocrysts are enclosed in the microgranular enclaves and incorporated in the magmatic structures as already grown, rigid objects (are parallel to or wrapped by marginal schlieren, indent microgranular enclaves, form accumulations, and are constituents in modally graded layers). We therefore infer that the wholesale magma mixing and mingling represent the earliest recorded

events in the magma chamber history and mostly preceded the formation of the preserved magmatic structures.

We propose that after vigorous, chamber-scale mixing as suggested by recent petrological studies, the magma attained higher crystallinities and the physical processes became highly localized with respect to chamber size. Presumably, this process took place diachronously in different domains and depths within the chamber as a result of its complicated thermal history. The magmatic structures in the Jizera and Liberec granites then recorded a variety of small-scale physical processes in the environment of a weak, highly permeable crystal mush consisting of a porous crystal framework (~50% solid crystals according to Weinberg et al., 2001) and interconnected melt. This permeable environment was favored by the porphyritic nature of the granites with large size of K-feldspar phenocrysts (up to 5–6 cm in the Jizera granite) and thus perhaps large crystal/melt wetting angles.

Our observations on the origin of the magmatic structures in the Jizera and Liberec granites corroborate interpretations of Weinberg et al. (2001) and Weinberg (2006) and add some additional information on possible driving mechanisms and processes involved in their formation. We interpret that the observed mafic schlieren delineated flow rims during localized, laminar magma flow and that three main physical processes, or a combination of them, may account for the formation of modally-graded schlieren: (1) gravitational settling in subhorizontal to gently inclined layers, (2) velocity gradient flow sorting along the channel wall (Bagnold effect), and (3) intersitial melt extraction along permeability gradients within the crystal mush (e.g., Weinberg et al., 2001). The geometry of schlieren channels indicates that the flowing, mobile magma utilized a network of small-scale weaker channel-like domains (conduits) through the more rigid crystal framework. Some of the flow channels were open and widened upwards (Figs. 2b and 3) whereas others were entirely enclosed having a pipe-like shape (Fig. 5). The higher strength of the host crystal framework is documented, for example (1) by the bent enclave in Fig. 5d, which seem to logjam the flow channel and had to be deformed against rigid channel walls during flow, or (2) by the observation that the channel walls do not collapse or mingle with magma inside the channels.

The vertical tubes or ladder dikes (Fig. 4) could be interpreted as instabilities formed during local thermal or compositional convection (e.g., Weinberg et al., 2001). On the other hand, the inferred subhorizontal orientation of some migrating tubes (Fig. 5) is highly unusual in granitic plutons and thus mechanisms other

than vertical gravity-driven compositional and thermal convective flow should be invoked to explain their formation. We suppose that one of the permissive explanations is that the subhorizontal flow in both concave-upward and pipe-like channels was driven by lateral gradients in magma pressure at their ends (the Bernoulli law). The absence of reliable kinematic indicators, however, prevents the determination of the direction of flow (upslope or downslope) within the gently dipping channels (Fig. 5b). We also envision that the bulk laminar magma flow in the channels was partitioned into flow laminae or surges. The differential movements of flow laminae or surges sliding past each other and channel avulsion (superposition) produced the schlieren stacks, scour-and-fill structures and schlieren cross-beds (e.g., Fig. 3).

During or after laminar flow in channels had slowed down or ceased, other physical processes started to operate in the crystal mush within channel domains. In many cases, the flow-related structures also record later settling of enclaves (Fig. 7b), xenoliths (Fig. 10), or crystals (Fig. 8b), and show evidence for compaction and melt extraction (Fig. 8b). Some domains are characterized by the vertical differentiation into modal mafic–felsic layers (Fig. 2) and by the development of downward dripping instabilities delineated by mafic schlieren (Fig. 6). Apparently, the differentiation and compaction was accompanied by filter pressing and melt segregation (e.g., Park and Means, 1996; Weinberg, 2006) into pegmatite or leucogranite patches or layers in the upper parts of the magmatic structures (Figs. 6, 7a, 8b, 10). We envisage that gravity, temporarily overridden by local magmatic flow in channels, was the main driving force for settling, vertical differentiation, compaction, and melt segregation in the magmatic structures.

The mafic schlieren and leucocratic layers in some of the magmatic structures were affected by magmatic folding which postdates the localized magma flow and gravitational differentiation (Figs. 3, 7, 10). In some cases it seems that the development of magmatic folds was controlled by schlieren-parallel shortening whereas in other cases it was driven by the upward (schlieren-perpendicular) movement of the underlying magma. During the latter process, parts of the schlieren stack were presumably also ripped off and displaced within the host granite magma (Fig. 7a). The presence of magmatic folds, as well as our study on magmatic and magnetic (AMS) fabrics (J. Žák, unpublished data), all indicate that the high-strength crystal-rich mush of the Jizera and Liberec granite magma recorded complex, late magmatic strains within the magma chamber at high magma crystallinities (perhaps of more than ~70–80% solid fraction). Episodic, late-stage magma pulsing

into highly localized submagmatic cracks cutting across high-strength, semi-brittle magma (e.g., Figs. 9 and 10) represents the latest events in the magmatic (hypersolidus) history of the chamber prior its final crystallization.

4.2. What can magmatic structures tell us about the nature of evolving magmatic systems?

Considering that localized magmatic structures may reflect the physical state of magma during their formation (e.g., Weinberg et al., 2001; Wiebe et al., 2007; this study), an important question emerges: can they also provide some additional constraints on the nature of magma chambers at larger scales? A vigorous debate has been recently centered on whether granitoid plutons represent ancient long-lived, thermally oscillating magma chambers, or whether plutons grow incrementally through the amalgamation of numerous discrete, small, sheet-like injections that solidify between successive intrusion events (for discussions of the issue see, e.g., Glazner et al., 2002, 2003, 2004; Coleman et al., 2004; Christiansen, 2005; Žák and Paterson, 2005; Lipman, 2007; Žák et al., 2007; Walker et al., in press).

Although a thorough discussion of the two end-member models is beyond the scope of this study, we emphasize here that the most favorable environments for the formation and preservation of magmatic structures, such as those described in this paper, are slowly cooling crystal-rich mushes. Thus where preserved in plutons, these structures may lend strong support for a “mush model” of magmatic systems (Bachmann and Bergantz, 2003, 2004; Hildreth, 2004; Bachmann and Bergantz, 2006), rather than for the “incremental diking model” model which implies fast flow of crystal-poor magma within narrow dikes with a short residence time of melt within plutons.

Our reconnaissance mapping indicates that magmatic structures are irregularly scattered over a large area of porphyritic Jizera and Liberec granites of the plutonic complex, suggesting a widespread occurrence of mushy zones. In addition, the felsic, equigranular and “granophyric” granite varieties, interpreted as a result of fractional crystallization, mostly crop out structurally above porphyritic granites. Taken together, the Krkonoše–Jizera Plutonic Complex may provide a fascinating natural case example of a large upper-crustal magmatic system, fitting well with the predictions of recent multiphase fluid dynamics experiments: vigorous mixing over broad scales (e.g., Bergantz, 2000), which may have homogenized large volumes of granitic magma now occupied by the porphyritic granitoids (Slaby and Götze, 2004; Slaby et al., 2007), was followed by more localized processes in large regions of the crystal-rich mush (this

study), and perhaps by the extraction of melt from the underlying mush to form bodies of more felsic granite in upper parts of the plutonic complex (e.g., Bachmann and Bergantz, 2004; with the small-scale analogy of the process shown in Fig. 8b).

5. Summary

The magmatic structures in the Jizera and Liberec granites give evidence of localized magmatic differentiation, multiphase laminar flow, and other physical processes that operated in crystal-rich granitic magma after chamber-scale dynamic mixing and hybridization. The formation of mafic schlieren presumably involved gravitational settling, velocity gradient flow sorting, and interstitial melt escape within the crystal mush along flow rims. The schlieren geometry indicates that the flowing, mobile magma utilized a network of small-scale weaker channel-like domains through the high-strength crystal framework, and that bulk laminar magma flow in the channels was partitioned into flow laminae to produce schlieren cross-beds. The vertical schlieren tubes or ladder dikes formed during local thermal or compositional convection whereas the flow in subhorizontal tubes or channels was perhaps driven by lateral gradients in magma pressure. After the cessation or deceleration of the channel flow, gravity-driven processes (settling of crystals and enclaves, gravitational differentiation, development of downward dripping instabilities accompanied by filter pressing and melt segregation) dominated the crystal mush. Subsequently, magmatic folds developed during schlieren layer-parallel shortening or upward movement of underlying magma, and the crystal-rich mush recorded complex, late magmatic strains at high magma crystallinities. Late-stage magma pulsing into submagmatic cracks completed the hypersolidus history of the chamber prior its final crystallization. As a general conclusion, we suggest that where preserved in granitoid plutons, magmatic structures, such as those described in this paper, may reveal not only important information on the physical state of magma during their formation, but also provide another supporting evidence for a “mush model” of magmatic systems.

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