Lithos 116 (2010) 321–339

Contents lists available at ScienceDirect

Lithos

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

Tube-like schlieren structures in the Fürstenstein Intrusive Complex (Bavarian Forest, Germany): Evidence for melt segregation and magma flow at intraplutonic contacts

C. Dietl [a,*], H. de Wall [b], F. Finger [c]

[a] Institut für Geowissenschaften, Goethe-Universität Frankfurt (Main), Germany
[b] Geozentrum Nordbayern, Universität Erlangen-Nürnberg, Germany
[c] Abteilung Mineralogie, Universität Salzburg, Austria

ARTICLE INFO

Article history:
Received 28 February 2008
Accepted 22 November 2009
Available online 2 December 2009

Keywords:
Schlieren structures
Intraplutonic contact
Magma flow
Magnetic susceptibility
Trace element geochemistry
Microdiapirs

ABSTRACT

Tube-like schlieren structures occur at the boundary between two units of the Fürstenstein Intrusive Complex, the Tittling and the Saldenburg granites. We have analysed the magnetic fabrics, petrographic variation and geochemistry of key examples of these structures in order to test the hypothesis that they originated as granitic microdiapirs. The rims of the schlieren structures have high magnetic susceptibility compared to their interiors and surrounding granite due to the enrichment of biotite ± opaques. The low anisotropy that characterizes the AMS fabric is probably caused by magmatic flow. Hypersolidus microfabrics support this interpretation. Magnetic fabric orientation within the schlieren structures differs significantly from the NE–SW-trending magnetic foliation generally observed within the hosting Tittling granite. A steeply plunging magnetic lineation and a NNE–SSW girdle distribution of the magnetic foliation poles within the schlieren structures are consistent with the conical geometry of the schlieren structures evolved during the rise of the magma. Based on geochemistry, granite in the schlieren structures is interpreted to be differentiated melt expelled from the Tittling granite mush that formed after early crystallization of plagioclase. We suggest that the schlieren structures are pockets of residual melt of the Tittling granite that were mobilized buoyantly due to a thermal input from the neighbouring Saldenburg granite. The mafic rims of the schlieren structures formed as a result of early crystallization and subsequent accumulation due of the Bagnold effect. The results of the magnetic and geochemical investigations allow us to interpret the schlieren structures as diapiric in nature and consequently as "within-chamber diapirs" (sensu Weinberg et al., 2001).

1. Introduction

Mafic schlieren in granites provide important information about plutonic processes because they are likely the result of material sorting due to physical and chemical gradients. Consequently they occur close to contact zones, either at the contact between pluton and host rock or an intraplutonic contact between different magmatic pulses (Pitcher, 1997).

It is not yet clear at which stage during the evolution of a magma chamber schlieren may be formed. Fernandez and Gasquet (1994) suggest that schlieren develop below the first rheological threshold when the granitic magma probably contained more than 70% melt and essentially behaved as a Newtonian fluid. On the other hand, Vernon and Paterson (2008) suggest that these structures form well above the first rheological threshold. Nevertheless, there is a general agreement that schlieren can be the result either of (1) the assimilation of host rock material (Pitcher and Berger, 1972); (2) magma mingling, i.e. incomplete magma mixing (e.g. Frost and Mahood, 1987); (3) gravitational sedimentation of crystals (Irvine, 1987); or (4) flow segregation of crystals near boundaries, such as pluton-host rock contacts or intraplutonic interfaces between individual magma pulses.

Schlieren derived from assimilated host rock (1) provide information about the thermal and mechanical interaction between the magma and its host rock during magma chamber formation. In (2) and (3) the schlieren provide information about processes within an existing magmatic body, either about the interaction between several magma pulses (mingling schlieren) or about the crystallization sequence of individual mineral phases and their crystal nucleation and crystal growth rates, respectively. In (4) crystals segregate and form schlieren due to flow sorting close to any boundary surfaces within or at the margins of a pluton. Shear flow and synplutonic deformation may be involved in the formation of mafic schlieren (Pitcher, 1997 and references therein).

Controlling factors for the accumulation of mafic minerals in schlieren are the so-called wall and Bagnold effects (Barrière, 1981) which drive larger crystals away from the contact with a rigid wall. The crystals move away from the interface into regions of faster flow.

* Corresponding author. Altenhöferallee 1, D-60438 Frankfurt (Main), Germany. Tel.: +49 69 79840197; fax: +49 69 798 40185.
E-mail address: c.dietl@em.uni-frankfurt.de (C. Dietl).

0024-4937/$ – see front matter
doi:10.1016/j.lithos.2009.11.011

This kind of flow sorting is of particular efficiency as long as not more than 50% crystals are present within the magma (Barrière, 1981). However, Vernon and Paterson (2008) suggest, that the wall and Bagnold effect might play an important role in magma chamber processes even at crystal contents >50%.

Weinberg et al. (2001) describe a peculiar type of schlieren which is strongly convex, has tube-like shape and is only several mm to cm thick. They interpret these mafic schlieren as the rims of "within-chamber diapirs", which they first observed within the Tavaraes pluton in Brazil. Similar schlieren structures were also described for the Tuolumne batholith (Sierra Nevada, California) by Paterson et al. (2005) and Žák and Paterson (2005). Actually, the Tuolumne batholith hosts, besides such "microdiapirs", many other spectacular magmatic fabrics (Žák et al., 2007).

According to Weinberg et al. (2001) these diapirs could be remobilized magma that melted owing to intrusion of hotter, mafic magma, which rose buoyantly in response to lower density relative to the surrounding host magma. The reason for the development of these melt pockets could be a heat perturbation formed by renewed magma pulses, or simply the local segregation of melt from the crystal mush of the magma, e.g. by filter pressing (Kerr and Tait, 1986; Park and Means, 1996). Filter pressing is a process in which the interstitial melt of a magma or a partially molten rock is separated from the crystals by an applied pressure and compaction. The schlieren rims around the microdiapirs possibly form in response to flow sorting due to the Bagnold effect. Thus, a shear flow acts along the contact of a microdiapir rising through the surrounding magma and drives early crystallizing mafic minerals towards the inside of the diapir. These concentrate a few millimeters to centimeters away from the interface between host magma and microdiapir and coalesce into a mafic schlieren rim around the interior of the diapir. Nevertheless, filter pressing also plays an important role for the formation of the schlieren rims in the microdiapirs. Thus, a pressure gradient between the interior and exterior of the melt pockets drives melt out of the diapir structures, leading to an enrichment of mafic and opaque minerals at the boundary of the microdiapirs. Similarly, Weinberg et al. (2001) suggest the formation of the schlieren rim around a magma diapir to be the result of filter pressing from the diapir interior to the surrounding mush. This would allow the melt to escape and filter out early formed mafic minerals at the interface between the diapir and the surrounding mush.

If these structures represent classical diapirs, they and their "aureoles" should comprise certain flow and deformational features. Cruden (1990) applied the three types of non-uniform flow described by Mackin (1947) to explain the flow within a rising magmatic diapir and the resulting fabrics. Accelerating flow in the lower and central parts of the magma diapir leads to prolate fabrics with steep magmatic lineations parallel to the flow direction of the magma. On the other hand decelerating flow in the upper part of the diapir leads to oblate flow fabrics with a pronounced magmatic foliation parallel with the diapir rim (i.e. flat lying) and perpendicular to the flow direction, as well as a less pronounced roughly horizontal and radial magmatic lineations. Aureole structures around those diapirs reflect downward directed flow of the overburden of the rising diapir and include rim synclines and down-dip stretching lineations, but also an intense concentric foliation in the host material close to the diapir (Buddington, 1959; Dixon, 1975; Schmeling et al., 1988). However, in the case of microdiapirs (sensu Weinberg et al., 2001) the flow and fabric pattern inside and outside the diapiric structures may deviate from ideal and classical diapirs. According to Weinberg et al. (2001, Figs. 10 and 13) the buoyancy driven upward movement of microdiapirs and the formation of their schlieren rims is assisted by outward directed flow of the melt inside the microdiapirs into the host magma. Consequently, typical accelerating and decelerating flow fabrics can only be expected from these microdiapirs if the diapiric strain pattern as described by Cruden (1990) is preserved during the outward directed melt flow. Moreover, microdiapirs within host granite magma move through a mobile medium which reacts easily on external stresses. Consequently, foliation and lineation patterns around a microdiapir, which are the result of its buoyancy driven rise, may be obliterated during the subsequent magma flow or deformation. Besides a distinct internal fabric, which could also be obliterated and overprinted during the course of subsequent hyper- and subsolidus events, diapirs (sensu Weinberg et al., 2001) should exhibit a geochemical fingerprint different from the host magma if they represent a residual melt of their host and not remobilized magma. Therefore, it is reasonable to apply both fabric and geochemical analyses to verify the microdiapir hypothesis of Weinberg et al. (2001) and to test if tube-like schlieren structures are true microdiapirs.

During geological work in the Fürstenstein Intrusive Complex in Bavaria several tube-like schlieren structures were documented within the Tittling granite body, close to the contact with the neighbouring Saldenburg granite (Dietl, 2005). Accepting the model of Weinberg et al. (2001), Dietl (2005) interpreted these structures as microdiapirs. The tube-like schlieren structures are investigated in this study in detail. We have recorded fabric data from the schlieren structures and the host granite by means of magnetic susceptibility measurements, which may be strongly sensitive to compositional and structural heterogeneities in granites (e.g. Bouchez, 1997). Furthermore, geochemical investigations were carried out to determine if there are differences in geochemistry between the schlieren structures and the granite inside the tube-like schlieren structures in comparison with the surrounding Tittling granite.

2. Geological setting

The Fürstenstein Intrusive Complex (FIC) is a composite granitoid pluton in the Moldanubian basement of the Bohemian Massif (Fig. 1). It covers an area of roughly 140 km^2 and consists of four magma pulses of dioritic, granodioritic and granitic composition with distinct intrusion ages (Chen and Siebel, 2004) and distinct fabrics (Dietl et al., 2006).

The oldest intrusive phase is represented by xenoliths and stoped blocks of dark, medium-grained, biotite ± hornblende ± sphene bearing diorites, which form an E–W trending girdle within the center of the FIC (Fig. 2). Also the magmatic foliation within the diorite blocks follows an E–W trend (Dietl et al., 2006). Chen and Siebel (2004) reported U/Pb and $^{207}Pb/^{206}Pb$ zircon ages of ca. 330 Ma, which are considered as crystallization ages of the diorites.

A fine to medium-grained, yet undated two-mica granite occupies a NW–SE-trending shear zone at the south-eastern rim of the FIC. From cross-cutting relationships with the diorites and the so-called Tittling and Saldenburg granites (to the north) we infer that this granite is the second intrusion phase (Dietl et al., 2006). It has a steep, NW–SE-trending magmatic to solid-state foliation (Fig. 2).

The Tittling granite at the eastern rim of the pluton is the third intrusive phase. Zircon yields ages in the range of ca. 320 Ma (Chen and Siebel, 2004). Compositionally similar to this granite is the ca. 315 Ma old Eberhardsreuth granite (Chen and Siebel, 2004) at the northern margin of the FIC. Both are dark-grey, medium- and even-grained biotite granites with more than 10 vol.% biotite. It contains ~40 vol.% plagioclase, ~20 vol.% K-feldspar and ~25 vol.% quartz. The granites are characterized by steep rim-parallel magnetic and magmatic foliations. These trend NE–SW to NNE–SSW in the Tittling granite (Fig. 2) and E–W in the Eberhardsreuth granite (Dietl et al., 2006).

The youngest intrusive phase is the Saldenburg granite, which makes up about 80 area% of the FIC and encompasses the western and central part of the plutonic complex. It is characterized by a steep, NE–SW-trending magmatic flow fabric defined by K-feldspar megacryst (Troll, 1964; Dietl et al., 2006). K-feldspar phenocrysts up to 5 cm long are surrounded by a leucocratic matrix rich in plagioclase, K-feldspar and quartz with biotite and muscovite. The zircon ages published for