Melt segregation structures in granitic plutons

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ABSTRACT

When melt fraction increases beyond a critical value, migmatites behave as magmas. Conversely, when melt fraction decreases, crystallizing magmas form solid-framework mushes and behave as solids. The richness in preserved mesoscopic melt segregation structures in migmatites is not matched by melt segregation structures in granitic bodies. This paper identifies melt segregation structures in granites and compares them to structures in migmatites. The rarity of segregation structures in granites is a consequence of the solid-framework mush allowing for cryptic melt extraction from its pores, the relatively short duration of solidification of the mush, and the fragile nature of the solid framework. Identifying segregation features in granitoids at outcrop scale provides the basis for understanding the physical processes that lead to chemical and mineralogical differentiation in granitic magmas.

Keywords: migmatites, granites, solidification, extraction, segregation, magma fractionation.

INTRODUCTION

This paper focuses on structures recording the removal of interstitial melt from solid-framework granitic magmas. Although it has been argued that the high viscosity of granite magmas tends to inhibit crystal settling and the development of cumulates (Bea, 1996), accumulation of feldspar in granitic rocks is inferred by the presence of a touching framework of feldspar phenocrysts or tightly packed phenocrysts, associated with geochemistry indicative of feldspar accumulation such as high values of alkalies, Ba, and Sr (e.g., Miller and Miller, 2002; Wiebe et al., 2002). Another potentially efficient mechanism to produce cumulate textures is the removal of melt from the interstices of an effectively solid mush (McCarthy and Groves, 1979). Philpotts et al. (1998) showed how in slowly cooled basalts, chains of plagioclase provide a solid framework to magmas with as little as 25% solid fraction. This chain provides strength to the magma, which permits melt segregation from pores through compaction and deformation of the chains. Bachmann and Bergantz (2004) modeled this process to explain extraction of interstitial melt from a crystal framework in magma of intermediate composition to give rise to voluminous crystal-poor, evolved rhyolites and granitic bodies at the roof of batholiths (e.g., Mahood and Cornejo, 1992).

Migration and removal of melts from an effectively solid mush is driven by a combination of melt buoyancy and pore pressure gradients created by deformation of a heterogeneous medium (e.g., Ribe, 1987). Although geochemical and textural evidence have been used to infer such processes (e.g., Hibbard, 1987; Philpotts et al., 1998), outcrop-scale features of melt segregation have remained poorly explored (e.g., John and Stünitz, 1997; Sawyer, 2000; Weinberg et al., 2001).

MIGMATITES AND SOLID-FRAMEWORK MUSHES: A COMPARISON

Anatectic migmatites start as solids and undergo partial melting (anatexis), giving rise to banding (or patches; Vernon et al., 2003) characterized by pale, quartzofeldspathic layers within melanocratic layers. In contrast, magmatic rocks start as melts (plus or minus crystals and bubbles), and undergo solidification. Melt topology in either solidifying or melting rocks is essentially similar and is controlled by differential stress, finite strain, including anisotropy, and melt fraction. The rheological critical melt fraction is defined as the fraction that controls whether partially molten rocks behave as a solid or as a liquid (Arzi, 1978; Rosenberg and Handy, 2005). The critical melt fraction depends on factors such as crystal shape and size distributions and strain rates, and can be reached at crystal fractions as low as 50% (Miller et al., 1988) or as low as 25% for basalts (Philpotts et al., 1998). As melting progresses migmatites start behaving as liquids, lose their ''pervasive inhomogeneity'' (Ashworth, 1985), and enter the realm of magmas (diatexites; Brown, 1973). As solidification progresses, magmas cross that boundary in the opposite direction and become an effectively solid material, comprising both melt and crystals. In this paper, the term solid-framework mush describes magma in this state.

Differences

Migmatites and solid-framework mushes are both characterized by an effectively solid mush. Despite this, migmatite and granite have different physical appearances. The profusion of melt segregation structures in migmatites (e.g., Mehnert, 1968; Brown, 1994; Sawyer, 2001) contrasts with the more homogeneous appearance of granitic outcrops, resulting in fewer descriptions of their melt segregation structures (e.g., John and Stünitz, 1997; Sawyer, 2000; Weinberg et al., 2001).

Three differences may explain their contrasting appearance: (1) migmatite protoliths are commonly anisotropic, whereas crystallizing magmas are initially isotropic, and anisotropy develops late during crystallization (Paterson et al., 1989); (2) migmatites undergo a general history of melt production, whereas magmas undergo a general history of melt crystallization, evolving through a period as solid-framework mushes; and (3) melting during regional metamorphism is generally a longer process than solidification of a pluton from a solid-framework mush to a rock.

In migmatites, deformation and rock anisotropy control melt segregation (Sawyer, 2001). Leucosomes grow, generally parallel to the dominant foliation in the rock, and enhance anisotropy through feedback with external stresses, whereby a weak, melt-rich zone attracts more pore melt from the stronger melt-poor zones (Wickham, 1987; Stevenson, 1989; Mancktelow, 2002). Leucosomes interconnect (Sawyer, 2001), commonly with the help of shear zones (Brown, 1994), and melt escapes, leaving behind a residual refractory rock. High melt fractions may be reached in migmatites but at high melt fraction most of the melt is to be found in the leucosomes rather than in pores between grains (Sawyer, 1991; Milord et al., 2001).

Despite the absence of strong initial anisotropy in solid-framework mushes, external stresses should still lead to melt segregation from pores into larger melt pockets. This is because the feedback between external stress and segregation requires only minute initial variations in rock strength (Stevenson, 1989), i.e., melt fraction. Segregation structures in magmatic rocks are apparently rare in part because the initial stages of the evolution of a solid-framework mush are characterized by large volumes of melt in pores (up to 50%; Miller et al., 1988). High porosity and permeability allow for efficient melt flow through the pores and cryptic segregation through gravity-driven processes of compositional convection (Tait and Jaupart, 1992) or compaction of the solid framework (McKenzie, 1984).

As the melt fraction in a solid-framework mush decreases, cryptic melt segregation becomes less efficient, and like migmatites, segregation becomes driven primarily by tectonic pressure gradients (Wickham, 1987; Brown and Solar, 1998; Sawyer, 1991, 2001), and should

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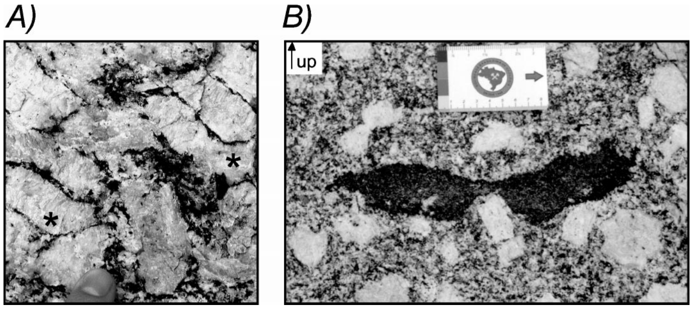

Figure 1. Compaction features in K-rich, calc-alkaline, syntectonic, Brasiliano age (630–580 Ma) Itaporanga pluton (Weinberg et al., 2004). Outcrop is nearly vertical and arrow points upward. A: Magmatically packed K-feldspar megacrysts. Compaction is suggested by narrow films separating megacrysts and impinging of phenocrysts into each other causing them to bend (indicated by asterisks). Deformation of megacrysts may have continued into and been overprinted by subsolidus deformation. In thin section, megacrysts have subgrains and new grains in bent area. B: Isolated dioritic enclave (same outcrop as A), settled on and squeezed against K-feldspar megacryst indentor in center of figure. Indentation does not involve solid-state deformation, but flow of interstitial liquid in enclave. Enclave is parallel to magmatic foliation in granodiorite. Upward narrowing of film separating enclave and megacryst suggests that groundmass was mobile, but upright position of megacryst suggests that surrounding groundmass provided support for the megacryst during indentation. Evidence thus suggests that groundmass is solid-framework mush capable of indenting mafic enclave and of being squeezed and compacted by same enclave. Note gentle indentation of enclave caused by large megacryst on right.

therefore give rise to melt segregation structures as the mush deforms (Sawyer, 2000). Despite their perhaps more subtle nature, segregation structures should still be preserved in granitic rocks (Sawyer, 2000).

SEGREGATION STRUCTURES

Compaction of solid-framework mushes may lead to melt segregation (Philpotts et al., 1998) and development of cumulate textures in granites (Wiebe et al., 2002). Connected networks of crystals may be difficult to determine unambiguously in granitoids, as it requires assumptions about which crystals existed at any particular time. However, interconnected plagioclase or K-feldspar phenocrysts, combined with evidence for feldspar deformation in the presence of melt (e.g., Bouchez et al., 1992), are good indicators. Occasionally, outcrop features may strongly suggest compaction (Fig. 1), particularly in plutons where mafic magma batches intrude a solidifying granitic chamber (e.g., Wiebe et al., 2002).

Some structures in the Tavares pluton, Borborema Province, northeastern Brazil (Weinberg et al., 2001), suggest melt segregation (Fig. 2). They are generally revealed by irregular patches of leucogranite surrounded by mafic patches within a homogeneous granodiorite. As for migmatites, the leucocratic patches represent leucosome segregated from a mesosome (the granodiorite), leaving behind a melanosome. Whereas in some places this separation between felsic and mafic minerals is related to local fluidization of the mush by disruption of the solid framework, and separation of an evolved melt and settling of mafic grains (see Weinberg et al., 2001), in others it represents melt segregation from the pores of a solid-framework mush.

Other features related to melt segregation from solid-framework mushes are dikes with irregular contacts, down to grain scale, and evidence of communication between the melt in dike and matrix in the surroundings. Hibbard and Watters (1985) detailed several features indicative of diking in crystal mushes; Figure 2 expands on these. Figures 2A and 2B are linked in outcrop (see inset in A), and the structure is interpreted as representing two overstepping fractures that acted as melt extraction pathways. The fractures are straight in outcrop and are characterized by irregular patches enriched in mafic minerals (the inferred melanosome) and irregular narrow pools of leucocratic granite in communication with the matrix of the surrounding granodiorite (Fig. 2B). In the transfer structure where the two fractures overlap, there is an accumulation of leucocratic material, which is interpreted as a dilational site, and the escape pathway of the melt.

Figure 2C shows a sharp planar leucocratic dike cutting through a granodiorite. The dike is linked to an irregular leucocratic pocket from where it fingers into the surrounding granodiorite. Around this leucocratic pocket the granodiorite is heterogeneous with mafic and felsic patches. I infer that the planar dike has arisen from the heterogeneous area. Interstitial melt was transferred from the matrix to the fingers and to the leucocratic pocket to feed the propagating dike.

These structures suggest that multiple scales of melt segregation, from pores to pockets (Figs. 2C, 2D) or fractures (Fig. 2B), produce dikes (Fig. 2C) and irregular channels in regions of dilation (e.g., fracture overstep, Fig. 2A). Similarly, Weinberg et al. (2001) recognized a number of irregular fracture-like features, characterized by mafic-rich material surrounding irregular pods of leucogranite and linked together, and postulated that they may represent a three-dimensional melt channel.

DISCUSSION AND CONCLUSION

A number of other differences between the history of migmatites and granites have not been discussed here. Most important may be the duration of the process of melting versus that of solidification. The thermal history of regional migmatites is linked to lithospheric-scale thermal evolution, where the duration for melting events is 10^6–10^7 yr. This contrasts with the typical solidification duration of a magmatic body, from the formation of a solid framework to the solidus, 10^5–10^6 yr, or the development of a crystal-poor rhyolite from a more primitive magma chamber, 10^4–10^5 yr (Bachmann and Bergantz, 2004). Thus migmatites may register more intensely the effects of external stresses than would a crystallizing magma, leading to higher bulk strain and better developed melt segregation features. Sawyer (2000) described a pluton that was intensely deformed during the late stages of crystallization and that has segregation structures very similar to those developed in migmatitic gneisses. The contrast with the apparent rarity or subtlety of segregation features in plutonic rocks recording weak strain suggests that it is the bulk strain undergone by the solid-framework mush that controls the development of mesoscale melt segregation structures. Nevertheless, the rare or subtle melt segregation features in plutonic rocks may provide key information related to the fractionation of granitic chambers and to the origin of cumulate-like features in granites.

Ductile fracturing and separation of a liquid phase from a sintering solid known from liquid-phase sintering of metal and ceramics (German, 1996; Eichhubl et al., 2001) may be an important mechanism of compaction within a solid-framework mush; in addition, the coarsening of large grains at the expense of smaller ones may allow melt to migrate upward and crystals to settle (Miller et al., 1988). Local fluidization may also be important in melt segregation (Weinberg et al., 2001). Disruption of the solid framework of sediments (Jolly and Lonergan, 2002) may lead to fluidization and may be achieved through seismicity (e.g., Galli, 2000) or fluctuations in pore pressure related to the dynamic evolution of the magma chamber. Diachronous crystallization of the melt across the chamber, chamber expansion and contraction, magma inflow and outflow, or any other source for pressure gradient within the chamber will influence the pore pressure distribution within the mush. During periods of local or generalized high pore pressure, the framework may be locally or generally destroyed. If melt pockets form within the solid-framework mush, tips of the fluidized pockets may amplify regional stresses and crack the pressurized solid-framework mush (Rubin, 1993).

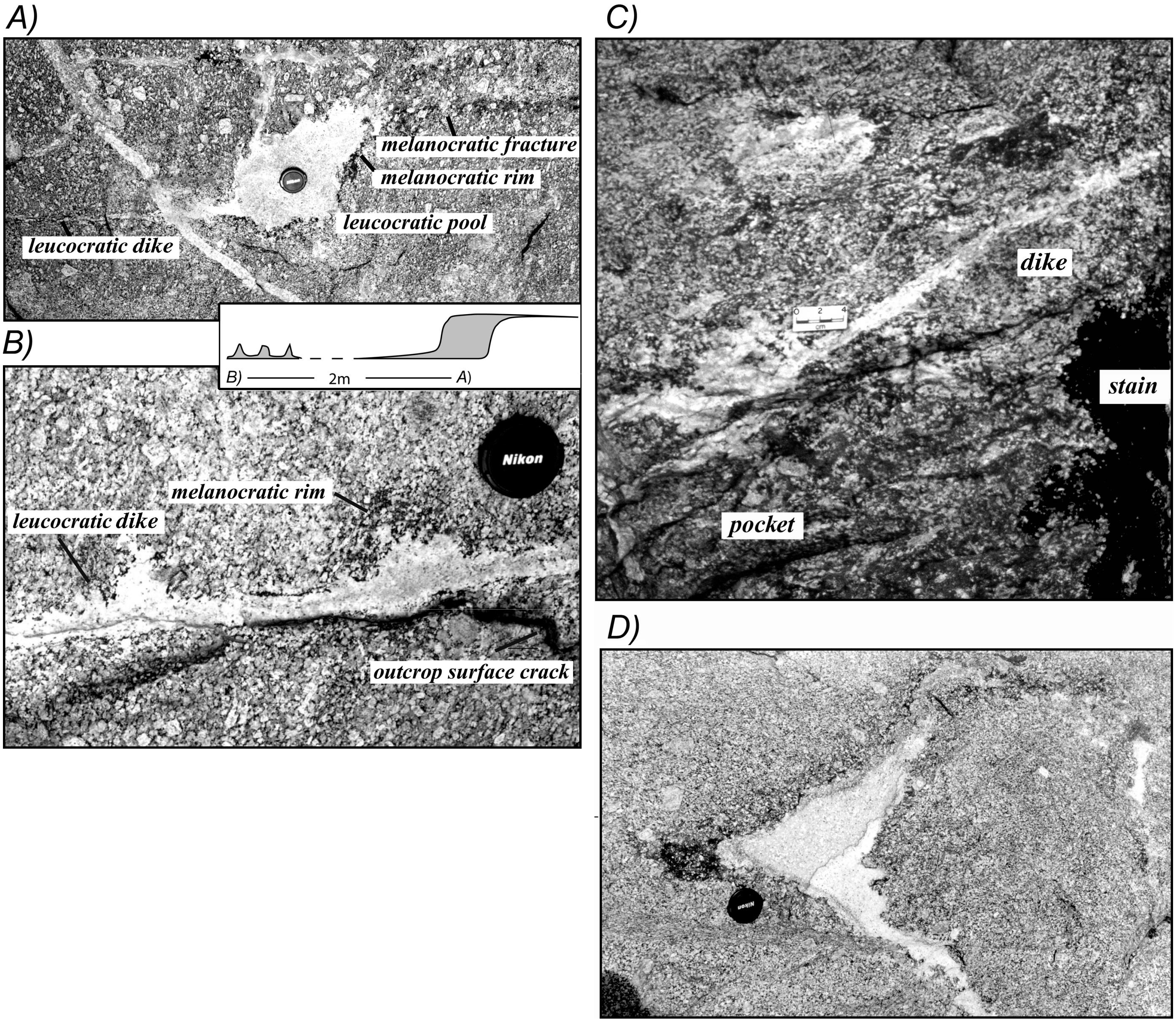

Figure 2. Melt segregation from solid-framework mush. All structures depicted are from same outcrop within the K-rich, calc-alkaline, syntectonic, Brasiliano-age Tavares pluton (Weinberg et al., 2001). A, B, and D are from horizontal exposures, C is from vertical exposure; no way-up indicators were documented. A: Melt accumulation in transfer structure where two E-W fractures overlap in granodiorite crystal mush. E-W leucocratic dike on lower left is only partly filled with leucogranite, and E-W melanocratic fracture on upper right is defined only by its darker color related to increased proportion of mafic minerals, which I infer to represent melanosome from which interstitial melt was extracted. B: Dike along strike from A with irregular mafic rim and irregular contacts merging with matrix of surrounding granodiorite. Inset in A shows field relationship between A and B. C: Irregular leucogranite pocket with fingers into matrix of surrounding granodiorite, linked to planar, crosscutting leucogranite dike. I infer that leucogranite pocket is intermediate stage transferring melts from pores to dike. D: Irregular leucogranite patch, partly surrounded by what I infer to be melanosome characterized by higher proportion of biotite and hornblende in otherwise homogeneous granodiorite.

The history of crystallization of a magma body may be characterized by several phases of formation and destruction of a solid framework, as pore pressure waxes and wanes, or seismicity destroys preexisting crystal frameworks. As long as there is an interconnected melt network through the pores of the mush, melt pore pressure responds to variations of the bulk magma pressure in the chamber. In this way a solid framework may form, from which melt of an evolved composition may be extracted, leading to melt extraction structures and differentiation of the magma chamber. This process leaves behind a compacted residual solid-framework mush with a cumulate texture. Subsequently this residual solid-framework mush may be remobilized through increased melt pressure in its pores, destroying the melt segregation structures while the internal differentiated stratification of the chamber could be preserved.

Thus the puzzling rarity of melt segregation features in granitic rocks is explained by: (1) cryptic processes allowed for by their high initial porosity; (2) the shorter duration of the extraction process in cooling plutons compared to melting rocks; and (3) the fragile and impermanent nature of the solid framework, where remobilization may destroy early formed segregation structures. It is possible that only the shorter duration of the solidification process might prevent them from fully developing, and the variety of fractionated melt pods and lenses common in granitic bodies may attest to these processes.

The evolution of magma within its chambers to form voluminous highly fractionated melts may require a combination of crystal settling in the early stages of crystallization of the magmatic suspension, with melt segregation from the solid framework. The latter would be particularly effective if a magma system went through a fluctuating history of partial solidification, melt segregation, and destruction of the solid framework through remobilization.

A number of segregation structures from solid-framework mushes were described here, but their importance has not yet been fully recognized. These structures are important records of the chamber history and have the potential to provide fundamental clues to understanding magma fractionation and to support geochemical interpretations of chamber evolution.

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