Compaction-driven melt segregation in migmatites

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ABSTRACT

A common and puzzling feature of migmatite terranes is the presence of synkinematic leucosomes oriented perpendicular to the maximum principal compressive stress axis, σ_1, particularly leucosomes oriented parallel to the axial plane of folds. These are parallel to planes of compaction, but experiments predict that leucosomes should form in dilational bands oriented instead at small angles to σ_1. This discrepancy suggests that our understanding of melt extraction is incomplete. We propose that leucosomes at high angles to σ_1 are results of ductile compaction instabilities that arise in compressive environments as a result of compaction of porous media with nonlinear rheology and interstitial fluids. These instabilities form at high angles to σ_1 and their spacing can be regular, controlled by the compaction length.

INTRODUCTION

Anatectic terranes are characterized by complex networks of leucosomes interpreted to form by segregation of melt from the interstices of partially molten surroundings and thought to represent the roots of channels that extract magma from its source. Leucosomes have varied shapes and orientations, commonly in complex relationships. Some form sheets that are subparallel to dilational shear zones, at small angles to the maximum principal compressive stress axis, σ_1, as predicted by experiments (e.g., Butler, 2010; Holtzman et al., 2003; Katz et al., 2006; Kohlstedt and Holtzman, 2009; Rabinowicz and Vigneresse, 2004). Many others form sheets at high angles to these, and are parallel to the axial plane of folds or to contractional shear zones. These are interpreted to form at high angles to the inferred σ_1 (Fig. 1) (see Hand and Dirks, 1992; Rabinowicz and Vigneresse, 2004; Vernon and Paterson, 2001; Weinberg and Mark, 2008). At a larger scale, it is common in magmatic arcs to have elongated sheeted plutons also at right angles to the contractional direction (Ingram and Hutton, 1994; Miller and Paterson, 2001). This is puzzling because this orientation is perpendicular to mode 1 tension fractures, and at a high angle to melt segregations in dilational bands in experiments (cf. Figs. 2A and 2B).

Vernon and Paterson (2001) proposed a number of explanations for the origin leucosomes parallel to axial plane of folds, including (1) occasional switches between σ_1 and σ_3 during deformation, (2) melt injection into axial planar foliation, (3) localization of later folds by the anisotropy represented by leucosomes, (4) preferential melting along the axial plane due to preferential fluid diffusion or influx, or (5) increased strain along these planes (Hand and Dirks, 1992). Alternatively, Weinberg and Mark (2008) proposed that axial planar leucosomes result from the self-organization of the melt network during folding so that volume is reduced through melt transfer along axial planar leucosomes, causing fold amplification.

Brown et al. (1995) recognized that compaction could explain layering at a high angle to σ_1 in migmatites. Compaction in migmatites may be gravity or stress driven (Bagdassarov et al., 1996), and Brown et al. (1995) used McKenzie's (1984) theory to investigate whether melt buoyancy (gravity driven) alone could account for separation of granitic melts from layered rocks with multiple permeability barriers. Length scales derived from the Brown et al. (1995) analysis are in accordance with those measured in many stromatic migmatites, but the inferred speeds of the process were too slow. Furthermore, field evidence indicates that compaction alone has little effect on segregation, with inefficient segregation in

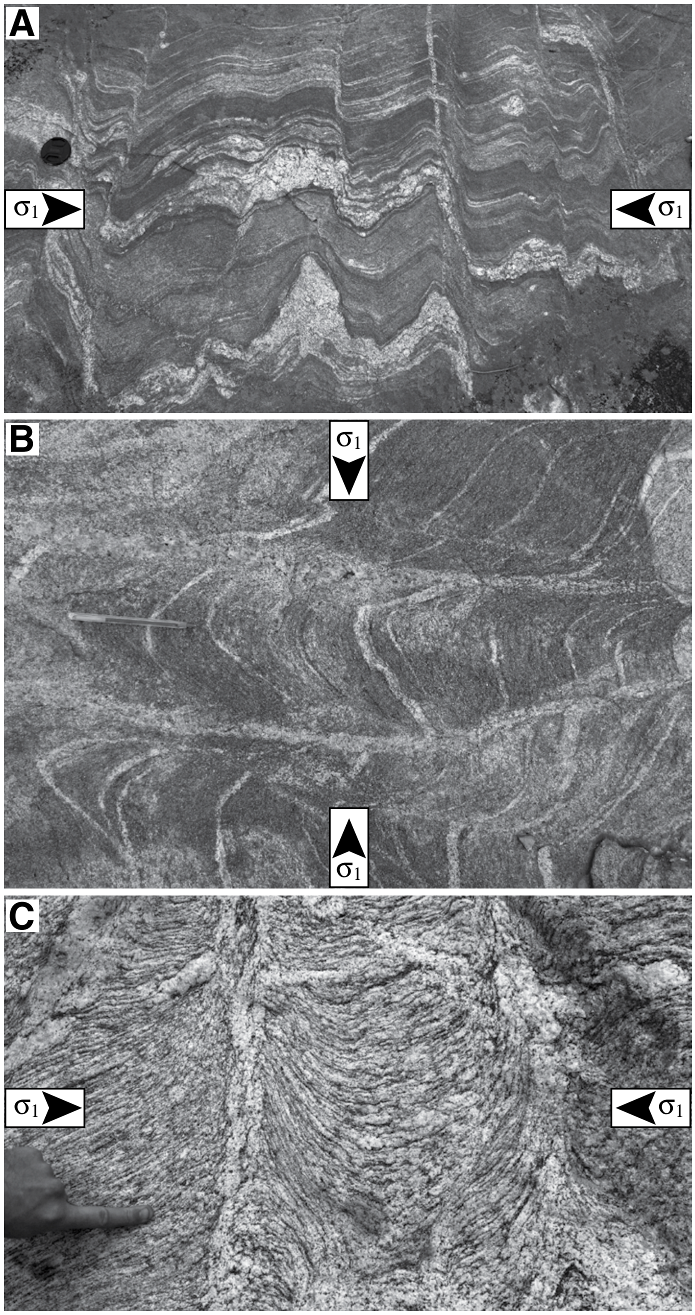

Figure 1. A: Folded Archean tonalite gneiss with layer-parallel pegmatite intrusions and regularly spaced (20–50 cm) axial planar leucosomes. Horizontal outcrop with vertical leucosomes and vertical gneissosity, Yalgoo Dome, Yilgarn craton, Western Australia. B: Axial planar leucosomes truncating preexisting foliation-parallel leucocratic bands in tonalite migmatite in 2700 Ma Lakeside pluton, Yilgarn craton, Western Australia (Zibra, 2012). C: Leucosomes in axial planes of folds in migmatites, Sikkim, Himalayas. Note that leucosomes (particularly for B and C) have diffuse and gradual transition to surrounding rock. Orientation of maximum principal stress axis, σ_1, is inferred from field evidence for dominant pure shear.

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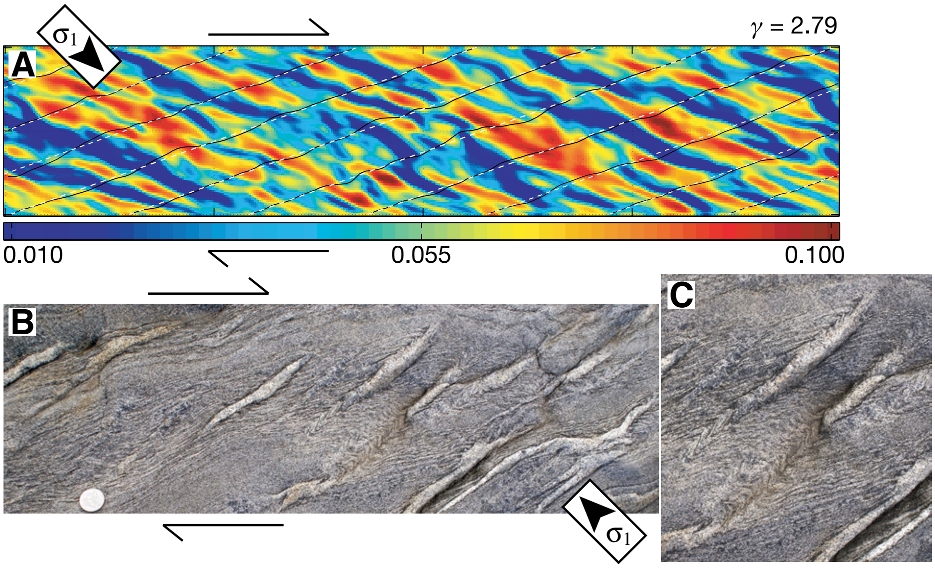

Figure 2. A: Results of shear modeling of partially molten rocks (from Katz et al., 2006) showing dilational melt bands marked by increased porosity (red bands) at a small angle (~20°) to maximum compressive stress and to horizontal shear plane. Top-to-right shearing is indicated by half arrows. Gamma value in upper right indicates shear strain. B: Leucosomes in axial planes of asymmetric folds with limbs that lost melt and compacted. Melt flowed into leucosomes, destroying layering continuity. Fold asymmetry indicates top-to-right shearing. Leucosomes are nearly perpendicular to model results in A and to inferred σ_1. Kangaroo Island, Australia (Weinberg et al., 2013). C: Detail of B.

regions of low differential stresses lacking shear zones, but well developed where shear zones are present (e.g., McLellan, 1988; Sawyer, 2001). It has been concluded that differential stress is necessary to drive melt into veins (Brown et al., 1995, Brown, 2013).

Here we return to the issue of compaction of a solid with interstitial melt. We consider tectonic differential stresses, and focus in particular on the origin of axial planar leucosomes where they developed perpendicular to the inferred maximum compressive stress, σ_1. Veveakis and Regenauer-Lieb (2015) and Veveakis et al. (2015) demonstrated that compaction of porous media with power-law rheology and interstitial melt leads to an instability with regions of compacted solid groundmass separated by regularly spaced bands of increased porosity (ductile compaction instabilities; Fig. 3). They expanded on McKenzie's (1984) compaction theory and explained how leucosomes form at a high angle to σ_1 under overall compressive stresses. This paper summarizes ductile compaction instabilities, followed by a description of natural leucosomes in migmatites, and their possible link to compaction bands.

PREVIOUS WORK AND METHODS

McKenzie (1984, 1987) developed a solution for gravity-driven compaction of partially molten rocks. He defined compaction length as: $\delta_c = (k\ \eta_s/\eta_f)^{1/2}$, where η_s is the viscosity of the solid matrix, η_f is the viscosity of the pore fluid (silicate melt), and k is permeability. In McKenzie's (1984, 1987) solution the matrix is supported by the flowing melt and has a linear viscous rheology. Later work extended McKenzie's concepts and found that an instability occurs in compacting porous media subjected to deformation, if the viscosity of the medium decreases with increasing porosity (Stevenson, 1989). A change in porosity causes changes in stresses on the solid matrix that in turn result in pressure variations that drive fluid flow.

McKenzie's (1984) and Stevenson's (1989) theoretical considerations were followed by a number of deformation experiments and numerical models in partially molten rocks exploring the nature of instabilities and their potential impact on melt extraction under mid-ocean ridges. These were carried out for either simple shear (Butler, 2009; Holtzman et al., 2003; Holtzman and Kohlstedt, 2007; Katz et al., 2006; King et al., 2010; Spiegelman, 2003) or pure shear deformation (Butler, 2010; Richardson, 1998) under relatively low confining pressure. Simple shear models typically result in dilational shear bands oriented at low angle to the maximum compressive stress, σ_1 (Figs. 2A and 3). Spacing between melt-rich bands was shown to vary linearly with the compaction length (Holtzman et al., 2003; Holtzman and Kohlstedt, 2007; King et al., 2010). In pure shear experiments or in those approximating pure shear (summarized in Butler, 2010), melt-filled bands formed microscopic alignments at 15°–30° to the direction of σ_1 (e.g., Zimmerman and Kohlstedt, 2004)

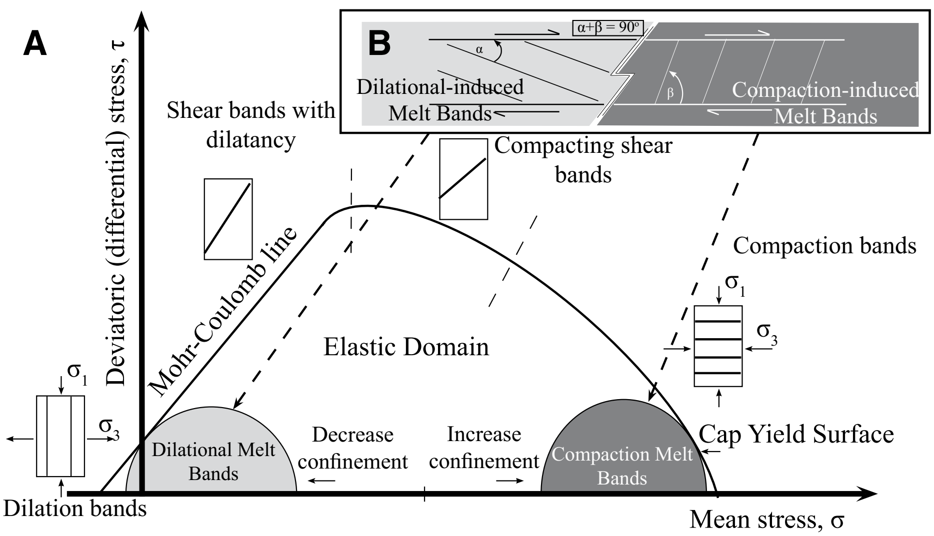

Figure 3. A: Generalized Mohr diagram showing deviatoric stress versus mean stress for failure of porous rocks. The Mohr-Coulomb yield surface at low pressure combines with the cap yield surface at high pressure (Issen and Rudnicki, 2000) to form the initial yield envelope. Dilation bands parallel to maximum compressive stress (σ_1) occur when Mohr circle is in the tensile field where confining pressure is low or pore pressure is high (left side). Shear bands develop for intermediate pressure conditions defined either by the Mohr-Coulomb interface (dilatant) or the cap (compaction). Compaction occurs at high confining pressures and low pore pressure (right side), and is at or close to right angles to σ_1. B: Two kinds of instabilities arising from the same principal stress axes orientations. The difference is a change in σ_3 from tensional, forming dilational bands, to compressional, forming compaction-induced melt segregation bands.

and did not develop an instability because sample sizes were below the compaction length for the materials used (Butler, 2010). In contrast, instabilities in pure shear numerical models developed parallel to σ_1 (Butler, 2010; Richardson, 1998).

The experiments cited here lead to instabilities that are either dilational bands or dilational shear bands at low angle to σ_1 (Fig. 3A). Dilational structures require that the effective σ_3 be negative, so as to place the Mohr circle in the dilational quadrant of the Mohr space (left side in Fig. 3A). This is required in order to obtain positive work and not violate the second law of thermodynamics, and can be achieved either in regions of low or absent confining pressure or where pore pressure is high (Veveakis et al., 2015).

While dilational instabilities may dominate at shallow levels and are possible at depth, when pore pressure is high, we argue that tensile forces are not the dominant feature of continental crustal regions that undergo partial melting. These regions will typically be under general compression, and we therefore expect that the dominant failure mode will change with depth from dilational (low angle to σ_1) to compactional (high angles to σ_1), as depicted in Figure 3.

DUCTILE COMPACTION INSTABILITIES

Compaction bands form at high angles to σ_1 and are typically observed in soft and porous geomaterials, such as unconsolidated sediments (Sternlof et al., 2006), sandstones (Mollema and Antonellini, 1996), mudstones (Oka et al., 2011), and core samples of creeping permafrost (Harris et al., 2009). Solid mechanics explain these bands as resulting from instabilities of the rate-independent solid matrix. Bands of crushed grains and decreased porosity develop under these conditions (Issen and Rudnicki, 2000). Figure 3 shows the yield curve for porous rocks, which combines the Mohr-Coulomb yield curve with the cap curve (Issen and Rudnicki, 2000). The cap curve controls the development of compaction bands and indicates that they develop at higher confining pressures than dilation bands and require that the least principal stress, σ_3, be compressive (Mohr circle, Fig. 3). This paper focuses on instabilities that are likely to dominate the deeper, ductile sections of the continental crust or the upwelling mantle underneath mid-ocean ridges, where the stress field is usually compressive with high confining pressures and normal fluid pressures.

Materials at these conditions effectively behave like viscous fluids. The theory of compaction band formation was developed for rate-independent solids. Veveakis et al. (2015) expanded the solution for gravity-driven compaction of McKenzie (1984), from linear viscous rheology (m = 1 in Equation 1) to power-law (rate-dependent) rheology, in the case of an imposed uniaxial compression equivalent to tectonic loading. They assigned a nonlinear viscous rheology to the porous rock mass:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \left(\frac{\sigma}{\sigma_0} \right)^m e^{-\frac{Q}{RT}}, \quad (1)$$

where $\dot{\varepsilon}$ is the total volumetric strain rate, and σ is the trace of the stress tensor minus the fluid pressure (i.e., the pressure of tectonic loading plus the lithostatic stress minus the fluid pressure). The stress σ_0 is a reference stress value, $\dot{\varepsilon}_0$ is a reference value of strain rate, m ≥ 2 is the rate sensitivity in the nonlinear case (m = *n* + 1, where *n* is the power law exponent in classical power law rheology), Q is the activation enthalpy, and R is the universal gas constant. Using this rheology and pores saturated with a separate phase, such as silicate melt, Veveakis et al. (2015) showed that rate-dependent deformation may cause an instability when the rate of loading is significantly larger than the rate of fluid flow, causing an imbalance where the melt is trapped inside the porous matrix and forces the medium to periodic patterns of compaction. The result is regions of compacted solids separated by regularly spaced bands of increased porosity (compaction-induced melt segregation bands).

Ductile compaction instabilities, like their solid mechanical equivalent, are oriented at high angles to σ_1, but can develop under much lower differential stresses. The characteristic length controlling the periodicity of the instability is a modification of McKenzie's compaction length,

$$\delta_c = \sqrt{\kappa \frac{\eta_s}{\eta_f}}$$

using the modified viscosity of the solid matrix, η_s, defined by the ratio between applied stress and strain rate. This simple extension and the finding of periodicity can be used to estimate either permeability or one of the two viscosities from simple observations of the distance *L* between compaction bands in the field, which was found to be

$$L \approx 4\delta_c. \quad (2)$$

A compressive environment, whether pure shear or simple shear, is a prerequisite for the rock with interstitial melt to exhibit the nonlinear rheology of Equation 1 because in extension the matrix support may be lost at a critical dihedral angle (McKenzie, 1987). This shifts the response of the skeleton from that of the nonlinear solid framework into the linear regime, where melt viscosity controls the response, preventing ductile instabilities and reducing the problem to the traditional approach (e.g., Stevenson, 1989).

AXIAL PLANAR LEUCOSOMES: COMPACTION INSTABILITIES

Based on these findings, we suggest that leucosomes at high angles to σ_1, including axial plane–parallel leucosomes, can be a result of ductile compaction instabilities. These give rise to high-porosity bands formed at high confining pressures in rocks with nonlinear rheologies and in the absence of highly pressurized fluids. Except for their orientation in relation to σ_1, these leucosomes are similar to any other melt segregation band, marked by diffuse boundaries merging with the surrounding matrix (Figs. 1, 2B, and 2C). While we emphasize their close relationship to folds, compaction-driven leucosomes may also form as a result of simple shearing (e.g., Fig. 2B). The periodic spacing between leucosomes that arises from compaction instabilities (tens of centimeters; Fig. 1) can be used to estimate material parameters like matrix permeability or viscosity ratio. Equation 2 indicates that permeability scales with leucosome spacing *L* and the viscosity ratio between host matrix and melt. The values of permeability obtained for the examples in Figure 1 vary widely between the realistic values of 1 mDarcy (10^{-15} m^2) to 1 kDarcy (10^{-9} m^2). Assuming a solid framework effective viscosity of 10^{18} Pa·s and a silicate melt viscosity of 10^6 Pa·s, we obtain migmatite permeability between 1 and 10 mDarcy (10^{-15} to 10^{-14} m^2).

DISCUSSION AND CONCLUSIONS

We argue that in most circumstances, partially molten rocks on Earth are in the compressional field (high confinement), where dilational bands at low angle to σ_1 are inhibited. In this case, melt segregations at high angle to σ_1 result from stress-driven compaction instabilities, explaining axial planar leucosomes in migmatites, sometimes with well-defined periodic spacing (Figs. 1A and 2B). More generally, compaction instabilities may explain layer-parallel segregation and the origin of stromatic migmatites (Brown, 2004). The ability of gravity-driven compaction alone to drive melt segregation to form stromatic migmatites is limited by low speeds of melt segregation (Brown et al., 1995). In contrast, melt segregation related to ductile compaction instabilities is accelerated by increased differential stresses (Darcy's law).

Despite inhibition of dilational bands, they are not entirely prevented by high confining pressures. Conditions in anatectic terranes may fluctuate, leading to intermittent increases in pore pressure or local development of tensile stresses, leading to cycling between development of compaction-driven melt bands and dilational bands. Swapping between σ_1 and σ_3 (Vernon and Paterson, 2001) could lead to further complexities and difficulties of interpretation of natural features (e.g., Brown, 2004).

We conclude that deformation of anatectic terranes with rate-dependent (nonlinear) rheology and melt-filled pores leads to ductile compaction instabilities. Instabilities control the formation of melt segregation bands at high angle to the loading direction, and McKenzie's (1984, 1987) modified compaction length controls their spacing. The dominance of such leucosomes in anatectic terranes is likely a result of the high confining pressures inhibiting dilation. Compaction instabilities may also dominate melt extraction under mid-ocean ridges and control the geometry of networks focusing magma toward the ridge.

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