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Melt segregation and far-field melt transfer in the mid-crust

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Abstract: Migmatites in the Damara Belt in Namibia preserve relationships between anatectic leucosomes and intrusive leucogranite sheets illustrating the consecutive stages of partial melting, local melt segregation and far-field mobilization of melts over hundreds of metres and out of the anatectic region. Initial melting and localized segregation of melts are controlled by gradients in fluid pressure created by pervasively developed, shallowly dipping dilatant fractures. Subsequent melt transfer out of these initial sites of melting and melt storage occurs along subvertical, disc-shaped leucogranite sheets that intersect the leucosomes. The leucogranite sheets propagate as isolated, melt-filled hydrofractures, driven by the pressure differential along the subvertical fractures. The collapse of wall rocks into former melt-bearing fractures, and the presence of residual peritectic phases of the melting reaction trapped in wall rocks testify to the efficient extraction of melt by the mobile hydrofractures during their ascent. This process of melt drainage into and transport by hydrofractures leaves almost no trace of the ascent conduits. This study also shows that melt transport and the stability of melt pathways in strongly layered mid-crustal levels characterized by low deviatoric stresses are determined by the presence of pre-existing anisotropies and the progressively evolving structure in deforming orogens.

The physical processes that lead to the formation of granite plutons are commonly conceptualized into four main consecutive stages, from the process of initial crustal melting, via small-scale melt segregation to far-field melt ascent and the eventual emplacement of granites (e.g. Brown 1994; Bouchez *et al*. 1997; Petford *et al*. 2000; Vigneresse 2004). Melting reactions recorded in mid- to lower crustal migmatite terranes occur on a grain scale, whereas large granitic batholiths represent the accumulation of up to hundreds of cubic kilometres of melt, sourced from an even larger volume of protolith (Clemens & Vielzeuf 1987; Bons *et al*. 2004; Brown 2004, 2007). This may explain why the central steps of melt segregation, accumulation and ascent that bridge several orders of magnitude in scale are only poorly documented and arguably the least understood processes in the formation of large, composite granite plutons (Clemens & Mawer 1992; Rushmer 1995; Rutter & Neumann 1995; Weinberg 1999; Bons *et al*. 2001; Sawyer 2001).

Localized melt segregation and far-field melt transport are both determined by three main factors: (1) the magnitude and orientation of far-field stresses; (2) the existence of hydraulic gradients; (3) the presence and connectivity of permeabilities, particularly fracture permeabilities, in the otherwise largely impermeable mid-crustal rocks (Sleep 1988; Brown 1994, 2007; Sawyer 1994; Bons *et al*. 2004). Gradients in fluid pressure at the source of melting mobilize and segregate distributed intergranular melt films or pockets into larger melt bodies or fracture networks (e.g. Sleep 1988; Rutter & Neumann 1995; Collins & Sawyer 1996; Kisters *et al*. 1998; Vigneresse & Burg 2000; Guernina & Sawyer 2003; Marchildon & Brown 2003). Similarly, melt ascent through the crust must be driven by gradients in magmastatic head, related to the buoyancy of the granitic melts, but also influenced by localized zones of high permeability and, hence, areas of reduced mean stress, such as shear and fault zones, or large-scale lithological or rheological heterogeneities that result in mean stress variations (e.g. Brown & Solar 1999; Weinberg & Mark 2008). The extraction of melt through dykes and interconnected fracture networks allows for the relatively rapid ascent of granitic melts through the, for the most part, subsolidus continental crust (Lister & Kerr 1991; Clemens & Mawer 1992; Rubin 1998).

This paper presents field observations from an exceptionally well-exposed upper amphibolite- to granulite-grade migmatite terrane in rocks of the Pan-African (*c*. 550–500 Ma) Damara Belt in central Namibia (Fig. 1) (Jung & Mezger 2003; Ward *et al*. 2008). *In situ* anatectic and intrusive features are spatially and temporally closely related, and the excellent 3D exposure allows for the semiquantitative characterization of melt extraction processes and the geometries of melt drainage systems. The two main questions addressed in this paper are (1) how melts are collected from a migmatitic protolith, and (2) how these melts are mobilized over tens and hundreds of metres and out of the region of partial melting. These processes have regional implications for melt transport and the eventual emplacement of granites that will be discussed at the end of the paper.

Geological setting

The rocks studied are part of the south Central Zone of the NE–SW-trending, Pan-African (*c*. 550–500 Ma) Damara Belt in central Namibia, which represents the collisional suture between the Congo and Kalahari cratons (Fig. 1). The geological evolution of the Damara Belt, from early rifting (*c*. 780–760 Ma) to marine sedimentation (740–580 Ma), is chronicled by the mixed siliciclastic–carbonate succession of the several thousand metre thick Neoproterozoic Damara Supergroup. Convergent tectonics and the subduction of the Kalahari plate below the Congo plate commenced at *c*. 580 Ma, culminating in the collision of the two cratons, the effects of which are recorded from *c*. 550 to *c*. 510 Ma (e.g. Miller 1983; Jacob *et al*. 2000; Johnson *et al*. 2006). A complex and long-lived thermal evolution succeeded