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Episodic granite accumulation and extraction from the mid-crust

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ABSTRACT The processes of long-range granitic magma transfer from mid- and lower crustal anatectic zones to upper crustal pluton emplacement sites remain controversial in the literature. This is partly because feeder networks that could have accommodated this large-scale magma transport remain elusive in the field. Existing granite ascent models are based largely on numerical and theoretical studies that seek to demonstrate the viability of fracture-controlled magma transport through dykes or self-propagating hydrofractures. In most cases, the models present very little supporting field evidence, such as sufficiently voluminous near- or within-source magma accumulations, to support their basic premises. We document large (deca- to hectometre-scale), steeply dipping and largely homogeneous granite lenses in suprasolidus (~5 kbar, ~750 °C) mid-crustal rocks in the Damara Belt in Namibia. The lenses are surrounded by and connected to shallowly dipping networks of stromatic leucogranites in the well-layered gneisses of the deeply incised Husab Gorge. The outcrops define a four-stage process from (i) the initial formation and growth of large, subvertical magma-filled lenses as extension fractures developed at high angles to the subhorizontal regional extension in relatively competent wall-rock layers. This stage is followed by (ii) the simultaneous lateral inflation and (iii) subcritical vertical growth of the lenses to a critical length that (iv) promotes fracture destabilization, buoyancy-driven upward fracture mobilization and, consequently, vertical magma transport. These field observations are compared with existing numerical models and are used to constrain, by referring to the dimensions of the largest preserved inflated leucogranite lens, an estimate of the minimum fracture length (~100 m) and volume (~2.4 × 10^5 m^3) required to initiate buoyancy-driven brittle fracture propagation in this particular mid-crustal section. The critical values and field relationships compare favourably with theoretical models of magma ascent along vertical self-propagating hydrofractures which close at their tails during propagation. This process leaves behind subtle wake-like structures and thin leucogranite trails that mark the path of magma ascent. Reutilization of such conduits by repeated inflation and drainage is consistent with the episodic accumulation and removal of magma from the mid-crust and is reflected in the sheeted nature of many upper crustal granitoid plutons.

Key words: granite; magma batches; magma buoyancy; magma transport; self-propagating hydrofractures.

INTRODUCTION

The transport of crustally generated granitic magma from sites of anatexis in the mid- to deep continental crust to shallower emplacement levels is an important mechanism of intracrustal mass and heat transfer. The first stage in this transfer is accomplished by the deformation-driven extraction of melt from sites of partial melting along grain triple junctions (e.g. Jurewicz & Watson, 1984; Brown, 1994; Rutter & Neumann, 1995) into the secondary magma storage networks represented by leucogranite networks in migmatite terranes worldwide (e.g. Marchildon & Brown, 2003; Sawyer, 2008; Hall & Kisters, 2012; Weinberg *et al*., 2013). This manuscript addresses the secondary drainage of the melt/magma storage networks and the relatively poorly understood mechanism whereby the long-range transport of magma through the continental crust is initiated.

The ubiquity of upper crustal granitoid plutons attests to the effectiveness of long-range granitic magma transport in the continental crust. However, apart from a few examples (e.g. Sawyer, 1998; Weinberg & Searle, 1998), field evidence of large-scale, long-range magma ascent through the crust between deep granite source regions and shallow crustal plutons remains elusive (Reichardt & Weinberg, 2012). Moreover, plutons are increasingly being recognized as composite bodies (e.g. Hutton, 1992; Miller & Paterson, 2001; Coleman *et al*., 2004; Glazner *et al*., 2004; Rocchi *et al*., 2010; Miller *et al*., 2011; Leuthold *et al*., 2014; Olivier *et al*., 2016) that are assembled

