Organizing Melt Flow through the Crust

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Melt that crystallizes as granite at shallow crustal levels in orogenic belts originates from migmatite and residual granulite in the deep crust; this is the most important mass-transfer process affecting the continents. Initially melt collects in grain boundaries before migrating along structural fabrics and through discordant fractures initiated during synanatectic deformation. As this permeable porosity develops, melt flows down gradients in pressure generated by the imposed tectonic stress, moving from grain boundaries through outcrop-scale vein networks to ascent conduits. Gravity then drives melt ascent through the crust, either in dikes that fill ductile-to-brittle–elastic fractures or by pervasive flow in planar and linear channels in belts of steep structural fabrics. Melt may be arrested in its ascent at the ductile-to-brittle transition zone or it may be trapped en route by a developing tectonic structure.

KEYWORDS: dike, ductile fracturing, granite, granulite, melt flow, migmatite

INTRODUCTION

The transport of melt from sites of generation in the deep orogenic crust to sites of accumulation at a shallow level is the most important mass-transfer process affecting the continents. As a result the continents became internally differentiated and stabilized. The volume and composition of melt generated is a function of source-rock composition, pressure (P) and temperature (T) of melting, and the presence or absence of an aqueous fluid. The range of fertility for melt production among common crustal rocks (greywackes, pelites, amphibolites, and granites sensu lato) at granulite facies P–T conditions requires that the volume of crust involved in granite production was much greater—perhaps by an order of magnitude—than the volume of orogenic granite. The spacing of plutons in orogens suggests sources of broadly similar volume in any one setting (Brown 2007, 2010). When combined with evidence from inversion of gravity anomalies related to a root of granite extending to depth beneath plutons (Vigneresse 1995a), which represents the infilled ascent conduit, these observations require that lateral flow of melt must be a common occurrence in the source (Brown 2007, 2010).

In comparison with likely source-rock compositions, many granulites and migmatites are chemically depleted with respect to a granitic component (Solar and Brown 2001; Guernina and Sawyer 2003; Brown and Korhonen 2009; Korhonen et al. 2010a). The preservation of peritectic minerals (see glossary on page 234 for definition of terms in italics) in leucosomes (Fig. 1), the lack of extensive retrogression of peak metamorphic mineral assemblages in residual granulites (White and Powell 2002), and the collapse of formerly melt-filled structures (Brown et al. 1999) confirm that this chemical signature reflects loss of melt from these rocks. Thus, most of the melt generated in the source was extracted. This melt rose through the crust until the ductile-to-brittle transition zone or other factors arrested ascent (Brown and Solar 1999; Brown 2007).

Evidence from thin section studies of residual granulites and migmatites shows that initially melt collects at grain boundaries and then migrates either along structural fabrics that are related to a shape-preferred orientation of matrix grains or through tensile microcracks (Marchildon and Brown 2002), to accumulate in lower-pressure sites, for example, strain shadows associated with peritectic minerals...
(Brown et al. 1999) and deformation bands (Brown 2004). As observed on the outcrop, pathways by which melt has migrated are recorded by leucosome, peritectic minerals ± leucosome, and melanosome. Leucosome is commonly found in layer-parallel veins and in structurally discordant sites such as dilation and shear bands; these leucosomes may link to define a former melt-flow network in three dimensions (Brown et al. 1999; Brown 2004). When active, these melt-flow networks allowed redistribution and accumulation of melt and provided pathways that allowed melt to flow to conduits in which it was transferred to the shallow crust.

The inferred depth to the anatectic front in an orogenic belt varies—it may be as little as 15 km in high-temperature–low-pressure belts or deeper than 100 km in Phanerozoic ultrahigh-pressure belts—but is commonly between 20 and 70 km. Thus the length scale of melt ascent varies. Ascent may be independent of tectonic structures and occur via dikes (FIG. 2; Brown 2004; Weinberg and Regenauer-Lieb 2010) or it may be controlled by regional deformation and tectonic structure (Vigneresse 1995a, b; Collins and Sawyer 1996; Brown and Solar 1999). Structurally controlled melt flow generally occurs at a high angle to the principal compressive stress, either along the lineation in the case of constrictional strains (FIG. 3A) or in the plane of the foliation for flattening strains (FIG. 3A), or associated with crustal-scale shear zones (Roman Berdiel et al. 1997).

THE RELATIONSHIP BETWEEN RESIDUAL GRANULITES, MIGMATITE–GRANITE COMPLEXES, AND OROGENIC GRANITES

Melts that crystallize as granite plutons in the shallow orogenic crust originate from migmatites and residual granulites in the deep orogenic crust. By contrast, regional-scale migmatite–granite complexes represent a level in the crust where some of the migrating melt becomes trapped during ascent and crystallizes as granite within the formerly suprasolidus crust now represented by host migmatites. These complexes correspond to an intermediate level—previously at depths of 15–40 km—deeper than the anatectic front but shallower than the strongly residual deep crust. The rocks in these complexes record the superimposed effects of melting, melt migration, melt loss, and melt passage; ascending melt may have interacted with the former melt-bearing crust at the level now exposed. Thus, regional-scale migmatite–granite complexes are intrinsically complicated but exceptionally informative about the processes of melting, melt extraction, and melt ascent. We illustrate these points with two examples.

Western Maine, USA

In western Maine, Silurian–Devonian turbidites were deformed within a Devonian crustal-scale shear zone system (Solar et al. 1998, Brown and Solar 1999) and metamorphosed to high- T–low-P upper amphibolite facies conditions (T > 700 °C and P > 4.5 kbar (Johnson et al. 2003) along a counterclockwise P–T path leading to water-fluxed muscovite-breakdown melting (Solar and Brown 2001). The shear zone system comprises kilometer-scale zones of apparent flattening strain that anastomose around zones of apparent constrictional strain (Solar et al. 1998; Brown and Solar 1999). The onset of melting is recorded by the first appearance of leucosomes in the up-temperature direction, which represents the maximum rise in the crust of the solidus at the peak of metamorphism (FIG. 4). Stromatic metatexite migmatites occur in the zones of apparent flattening strain whereas diatexite migmatites occur in the zones of apparent constrictional strain, and contemporaneous decameter-scale granites occur as either concordant planar or linear bodies according to the structural zone in which they occur, forming a regional-scale migmatite–granite complex. Although the leucosomes and granites exploit the mechanical anisotropy, pinch-and-swell structures and the absence of solid-state fabrics in the leucosomes and granites show that deformation and emplacement were synchronous (FIG. 3A), suggesting that these features record syntectonic pervasive melt flow through the deforming crust (Solar et al. 1998; Brown and Solar 1999).

Granite in coeval syntectonic plutons, which have ages in the range 408–404 Ma (Solar et al. 1998), was sourced from crustal rocks with chemical characteristics similar to those of the host Silurian–Devonian succession (Pressley and Brown 1999; Tomascak et al. 2005). The migmatites have residual compositions relative to the associated subsolidus metapelites, consistent with loss of a granite component, and the leucosomes represent the cumulate products of fractional crystallization of the melt, with variable melt loss (Solar and Brown 2001). Decameter-scale granites have a range of chemistries that reflect variable entrainment of residual plagioclase and biotite, the accumulation...
of products of fractional crystallization, and the loss of most of the evolved liquid (Solar and Brown 2001). Granite from hectometer-scale bodies that occur in the migmatite domains have compositions consistent with crystallization of evolved liquids produced by fractional crystallization of primary muscovite-breakdown melts derived from a source similar to the exposed migmatites (Solar and Brown 2001).

At the peak of the thermal evolution, as the isotherms moved up through the core of the actively deforming orogenic belt, the anatectic front migrated to shallow levels in the crust, perhaps as shallow as 15 km (Brown and Solar 1999). Thus, melt transferring through the crust in lineation- and foliation-parallel conduits was able to reach shallow crustal levels without freezing. The melt would have been superheated with respect to the solidus (Leitch and Weinberg 2002), so it could have migrated across the migmatite front into the unmetulcrust to ascend some distance before solidification. The level of exposure of the larger (kilometer-scale), apparently discordant plutons corresponds to the former ductile-to-brittle transition zone, whereas the smaller (decimeter- to hectometer-scale), apparently concordant plutons correspond to a deeper level in the crust (Brown and Solar 1999). For a geotherm consistent with these inferences, the plutons would likely extend downward into increasingly more residual migmatite at deeper crustal levels. As deformation waned and the isotherms moved down through the core of the orogenic belt, the height to which any batch of melt could ascend in the crust from the source decreased and the intervals between arrivals of melt batches into the root zone of plutons became longer. In this circumstance, individual batches of melt may have crystallized before the arrival of subsequent batches, constructing a downward-growing composite root zone in which the top of the active system moved progressively downwards.

**Fosdick Mountains, West Antarctica**

The Fosdick migmatite–granite complex is exposed as a gneiss dome in the Fosdick Mountains of West Antarctica. It comprises interlayered migmatitic gneisses intruded by multiple phases of anatectic granite (Fig. 5). A Lower Paleozoic metasedimentary succession and a suite of Devonian granodiorites exposed outside the dome are the primary source rocks of the migmatitic gneisses and anatectic granites inside the dome (Korhonen et al. 2010a, b; Siddoway and Fanning 2009). Two episodes of crustal anatexis are recorded in the gneisses; both involve biotite-breakdown melting at granulite facies conditions \((T = 820–870 \, ^\circ \text{C}, P = 7.5–11.5 \, \text{kbar}, \text{and } T = 830–870 \, ^\circ \text{C}, P = 6–7.5 \, \text{kbar}, \text{respectively; Korhonen et al. 2010a)}\). The first episode was related to Andean-style convergence during the Upper Paleozoic, whereas the second was related to a change from wrench deformation to oblique divergence and gneiss dome formation during the Cretaceous (McFadden et al. 2010).

The deepest structural level exposed in the central Fosdick Mountains preserves evidence of an Upper Paleozoic melting event. This domain comprises a ~5 km thick interlayered sequence of migmatitic gneisses, with granite distributed in decimeter- to decameter-scale sills (see McFadden et al. 2010 for a detailed description of units and architecture). The gneissic layers exhibit centimeter-scale leuco- and melanosome deformed into recumbent folds with subhorizontal axes. Within this domain the granites are dominantly ca 369–336 Ma in age (Siddoway and Fanning 2009; Korhonen et al. 2010b). Sr–Nd isotope compositions show that the granites were mainly derived from anatexis of the granodiorites (Korhonen et al. 2010b), but mineral equilibria modeling indicates that these rocks would have produced only ~2–3 vol% melt at the level exposed (Korhonen et al. 2010a), suggesting that the granites were related to more extensive melting at deeper crustal levels. By contrast, modeling of several metasedimentary rock compositions shows that ~4–25 vol% melt could have been produced from this source. Preservation of the peak mineral assemblages and the absence of retrograde reactions in residual migmatitic gneisses require a minimum of 70% of this melt to have been lost to a shallower crustal level that is no longer preserved (Korhonen et al. 2010a); this scenario is consistent with the scarcity of Carboniferous granites derived from a metasedimentary source this deep in the complex.

At the higher structural levels exposed in the southern and eastern Fosdick Mountains, residual migmatitic gneisses host granites from the Cretaceous melting event (Figs. 6a, b). Granites associated with subvertical fabrics (ca 115–110 Ma; Fig. 6a) were derived from a dominantly metasedimentary source (Korhonen et al. 2010b). The proportion of leucosome and meter- to decameter-scale granite sills interlayered with residual gneisses increases upward, forming a ~2 km thick section of voluminous granite that is localized in and beneath the South Fosdick detachment zone (Fig. 5). Beneath the detachment zone the granite sills are up to 100 meters thick and are separated by meter-thick layers of residual migmatitic gneiss, resulting in a sheeted granite complex with dominantly shallowing dipping fabrics (McFadden et al. 2010). The change in source and geometry with decreasing age corresponds to a well-documented transition from wrench deformation to oblique divergence in the region at ca 100 Ma, the formation of the detachment associated with the emplacement of the sheeted granite complex, and rapid exhumation of the Fosdick migmatite–granite complex as a gneiss dome (McFadden et al. 2010).

**EXTRACTION OF MELT**

Melt segregation is a consequence of relative motion between melt and residue. Viscous grain-boundary sliding, deformation-assisted formation of pore space, and ductile fracturing create a dynamically evolving permeability during the production of the first few volume percent

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**Figure 4** Schematic section through the crustal-scale, dextral-transpressive shear zone system in western Maine, USA. Dashed lines are boundaries between structural domains. ACZ = zone of apparent constrictional strain (no pattern), which occurs within anastomosing zones of apparent flattening strain (dashed pattern); BHB rocks = Bronson Hill Belt rocks; CMB rocks = Central Maine Belt rocks; TAD and WAD = Tumbledown and Weld anatectic domains, respectively; P = Phillips pluton; Bt = biotite; Ms = muscovite. This figure is modified from a similar version published in Solar and Brown (2001) and is used in accordance with the publications rights policies of Oxford University Press.
Gravity-induced melt-pressure gradients are on the order of ~0.003–0.004 MPa m$^{-1}$ (Rutter and Mecklenburgh 2006). By contrast, local gradients in differential stress potentially can generate gradients in melt pressure that may be hundreds to thousands of times greater than those due to the gravitational potential. Although such stress differences tend to relax, reducing their effectiveness, and the flow strength of melting rock decreases significantly with increasing melt volume, tectonically induced melt-pressure gradients are expected to remain larger than gravity-induced melt-pressure gradients at the outcrop scale. It is these gradients in pressure that drive local melt flow, resulting in the formation of a network of channels. The spacing of the compositional layering, the strength of the fabric and the compaction length control the scale of these networks (Rutter and Mecklenburgh 2006; Brown 2010).

Ultimately, it is gravity that drives melt ascent through the crust, but the link between melt segregation into a network of channels and melt ascent is problematic. In some orogenic belts, exhumed residual granulites and migmatites exhibit a range of grain- to outcrop-scale structures that imply that pervasive melt migration occurred at various scales (e.g. Collins and Sawyer 1996; Brown et al. 1999; Weinberg 1999). Weinberg (1999) argued that pervasive migration gives rise to melt sheets preferentially emplaced parallel to high-permeability zones, such as foliation or lithologic contacts. On the other hand, Brown and Solar (1999) made a case for pervasive migration in strain-controlled planar and linear structures in zones of apparent flattening and apparent constrictional strain in western Maine. For western Maine, Brown and Solar (1999) showed that the granites were emplaced at the ductile-to-brittle transition zone and were rooted in the underlying residual migmatites. In both cases, pervasive melt migration was proposed based on the three-dimensional form of the leucosomes and decameter- to hectometer-scale granites and their conformable relationship to the tectonic structures. The hypothesis proposes that advection of heat with migrating melt drives expansion of the suprasolidus domain, allowing melt to ascend to shallower depths (Brown and Solar 1999; Weinberg 1999). The feedback relation between pervasive migration of melt and heating of the country rock allows subsequent batches of melt to reach increasingly shallower levels. This process has been
modeled numerically by Leitch and Weinberg (2002), who demonstrated that pervasive migration of superheated melt into subsolidus crust is an efficient way of moving the anatectic front to shallower levels in the crust. As melt reaches the front, a layer composed of about half granite and half crust forms below it, so that the total rise of the front corresponds to about half the thickness of granite that crystallizes below the moving front. The result is a regional-scale migmatite–granite complex, as represented by the two examples from western Maine and West Antarctica described above.

Partially molten crust represents an overpressured system with melt-pressure gradients and spatial and temporal variations in permeability. Permeability has a power law dependence on melt volume, which may lead to instabilities in the form of waves of melt-filled porosity. Connolly and Podladchikov (2007; see also Connolly 2010) use numerical simulations to investigate fluid expulsion from a large volume of elevated porosity obstructed above by a layer of low porosity; their results show that such a configuration can induce strongly channelled fluid flow. In partially molten crust, the channels are propagated by waves of melt-filled porosity that leave behind trails of incompletely compacted porosity, and these trails act as preferential pathways for subsequent waves; this scenario is consistent with the batch model of pluton construction. The waves propagate because compaction expels melt upward from deeper in the crust to create a region of melt overpressure at the anatectic front. This overpressure dilates the solid matrix and propagates the porosity beyond the anatectic front. At this point the porous domain may propagate independently as a solitary wave of anomalous porosity filled with superheated melt. Passage of the waves reduces the background porosity in the suprasolidus crust and the waves gain melt as they propagate. Connolly and Podladchikov (2007) infer that the channels will develop with radial symmetry in three dimensions, but in nature the effect of far-field stress would tend to flatten the channels. These instabilities may manifest themselves in nature either as domains of concordant decameter- to hectometer-scale granites that mimic the strain state in the host rocks (e.g. western Maine, USA) or as domains of dikes and sills representing former melt-filled fractures that propagated from the suprasolidus to the subsolidus crust, enabling melt to ascend (e.g. Fosdick Mountains, West Antarctica).

How do these fractures form? Although field observations show that leucosome networks may connect with petrographic continuity to granite in centimeter-scale dikes (Marchildon and Brown 2003; Brown 2004), the dikes are commonly discordant to foliation and lineation in the host, indicating that their formation was related to stress-controlled fracturing. Blunt fracture tips and irregular (zigzag) propagation paths (Fig. 2a) demonstrate that the thin dikes represent ductile opening-mode fractures (Brown 2004). Ductile fractures result from creep deformation and growth of microscopic melt-filled pores that become interconnected, leading to failure (Eichhubl 2004). Weinberg and Regenaur-Lieb (2010) postulate that melt-filled ductile fractures may reach a critical length, where melt pressure at the tips overcomes fracture toughness and leads to brittle–elastic ducting. Thus, melt ascent through the suprasolidus crust is postulated to occur via the formation of ductile fractures, and this process is expected to switch to brittle–elastic fracturing to allow migration of melt through the subsolidus crust (Fig. 2; Brown 2004, 2010).

Theory, field relationships, and petrological results suggest that melt extraction is strongly self-organized from the bottom up (Brown 2010). Where ascent occurs in dikes, the number of dikes decreases as their width increases from the suprasolidus crust through the subsolidus crust to the site of accumulation as a body of granite (Connolly and Podladchikov 2007; Hobbs and Ord 2010). Sites of melt accumulation are controlled by the physical properties of the crust and the stress field, as well as by tectonic structures. Melt ascent may be arrested at the ductile-to-brittle transition zone (Vigneresse 1995b; Brown 2010), corresponding to depths of 12–18 km, as proposed for western Maine, or it may be stepped on route by a developing tectonic structure, such as a major detachment zone, as occurred in the Fosdick Mountains of West Antarctica.

What is the timescale involved? On the one hand, a pluton represents a large volume of magma (10³–10⁴ km³ or more) aggregated from many batches of melt (each perhaps 10³–10² km³) that crystallized during tens of thousands to several millions of years (Pressley and Brown 1999; Brown 2010). On the other hand, the timescale for melt extraction and ascent from the source is expected to be short (10⁴ years), based on geochemical considerations.
and calculated rates of ascent in dikes (Brown 2010). Given the batch construction of plutons, these two views are not incompatible. Furthermore, Hobbs and Ord (2010) have argued that the maximum melt flux at the anatectic front is on the order of $10^{10}$ m s$^{-1}$ for a maximum thickness for the anatectic zone of 21 km. is sufficient to produce a pluton about 3 km thick over a period of 10$^6$ years. Smaller values of the melt flux at the anatectic front result in longer timescales, up to a limit imposed by the rate at which thermal conduction can provide heat to drive crustal melting.

**CONCLUSIONS**

Granites generated during orogenesis originate from migmatites and residual granulites in the deep crust. Outcrop-scale networks of remnant granite within these rocks record the temporal and spatial relations between melt flow and syn-anatectic deformation. When active, these networks allow redistribution and accumulation of melt, and provide links for melt flow to ascent conduits. Ascent occurs in dikes, which form in ductile fractures in suprasolidus crust that switch to brittle–elastic fractures in subsolidus crust, or by pervasive flow, evidenced by congruence between the form of steeply oriented planar and linear granites and host-rock state of strain. The process of melt extraction is self-organized from the bottom up.

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**REFERENCES**


