

# Melt segregation mechanism controls on the geochemistry of crustal melts

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## Introduction

Crustally-derived granites may be generated in a variety of tectonic settings, but whatever the ultimate cause of heating - crustal thickening, crustal extension, enhanced heat flux from the mantle, or magmatic advection by mantle-derived melts - crustal melting likely occurs in a dynamic environment. Under these conditions deviatoric stress acting on an anisotropic crustal source region will lead to heterogeneous deformation at all scales. Deformation-enhanced melt segregation and melt ascent through the crust along major shear zones and fracture systems are to be expected. This dynamic environment will be reflected in the metamorphic  $P$ - $T$ - $t$  path for the source, which will be clockwise in  $P$ - $T$  space for most orogenic belts regardless of whether the crust is responding to overthickening or extension. In both cases upper crust is replenished from below so that former middle and lower crust is displaced towards the surface relative to some material marker, and decompression melting and melt segregation leading to magma ascent and granite emplacement may occur. However, our knowledge of what happens between the beginning of anatexis in the middle and lower crust and the emplacement of granite plutons at structurally shallower levels remains poor. Understanding the physical mechanisms of melt segregation will allow evaluation of controls on initial magma chemistry. For example, why does melt segregation occur in some circumstances whereas bulk magma mobility with restite entrainment occurs in other circumstances, and why do some melts segregate before equilibrium with the residues has been achieved? This paper evaluates what we can learn from migmatites and residual granulites concerning the physical mechanisms of melt segregation and the control of these on magma chemistry, and indicates how we can relate this knowledge to information derived from upper crustal granites clearly separated from their sources.

## Physical mechanisms of melt segregation

The driving force for melt segregation in the crust

in general is physical, either related to buoyancy of the melt, driven by gravity, or related to deviatoric stress, driven by pressure gradients. In detail, whether melt remains essentially *in situ* and freezes to form a migmatite or whether melt migrates away from the site of generation to leave a residual granulite may be a function of the melt-producing reaction. For water-rich volatile phase-present melt-producing reactions is negative, whereas for volatile phase-absent dehydration melt-producing reactions is positive. In the first case the volume reduction may encourage melt retention, whereas in the second case the increase in fluid pressure due to volume increase on melting may lead to melt-enhanced embrittlement and melt escape. The spectacular variety of migmatites at outcrop scale partly is a function of these two different types of melt-producing reactions which lead to different segregation mechanisms.

Stromatic migmatites characterized by a symmetrical tripartite structure of leucosome, melanosome and mesosome remain poorly understood. Migmatite layering is developed on a scale of millimeters to centimeters, and original compositional layering in the protolith commonly is preserved. This structure is characteristic of water-rich volatile phase-present melting. The inheritance of subtle compositional differences from the parent rock has been recognized as an important contributory factor in the generation of some stromatic migmatites. However, the suggestion that a higher amount of melting in the leucosome layers was the result of accumulation of a larger volume of water seems unlikely to be correct in circumstances where water probably was confined to grain boundaries in rocks of similar sub-solidus porosity. Compaction models for melt segregation do not work for crustal protoliths (Brown *et al.*, 1994). In contrast, rheologically-driven porous-media flow filter-pressing at moderate (20–40%) degrees of melting, above the critical melt fraction (CMF) in at least some protolith layers, yields segregation rates that are very much faster than those for compaction (Brown *et al.*, 1994). In this mechanism, it is differences in modal mineralogy and grain shape that result in different packing

densities and, therefore, different CMFs for each layer, so that layers with similar melt proportions may have very different effective viscosities. Mass transfer by advection will occur from source layers of lower viscosity to sink layers of higher viscosity. The near perfect separation of leucosome from melanosome in stromatic migmatites, together with the observation that individual grains in the melanosome commonly may be coarser than those of the same phase in the mesosome, requires recrystallization of refractory phases that form the melanosome. This may indicate diffusive transfer of material through the melt phase and concentration of refractory phases, such as biotite, at the margins of the leucosome by liquid-phase sintering (*c.f.* Maaløe, 1992).

In some cases, the stromatic structure evolves by reduction of the amount of mesosome until the solid matrix breaks down and magma mobility with restite entrainment begins. However, the limited number of such examples suggests that special conditions may be necessary in the crust for the volume of melt in the source to accumulate above the CMF in most of the protolith, and so permit convective overturn and limited diapiric ascent. An example of such a process may be represented by the St. Malo migmatite belt, but even here magma ascent to the upper crust occurred along major crustal shear zones and not by diapirism (Brown, 1994 and references therein).

In contrast, in terranes where water-rich volatile phase-present melting either is limited in volume or does not occur, stromatic structure is either rare or absent. Under these circumstances Sawyer (1994) has argued that melt segregation occurs when the source becomes permeable once an interconnected network of melt forms, melt being driven by pressure gradients towards dilatant sites set up in the heterogeneously deforming source. However, melt segregation may occur as a direct consequence of the positive volume change for most volatile phase-absent dehydration melting reactions. If the rate of melt production exceeds the rate at which melt can leave the system, the melt pressure increases. Eventually, the melt pressure may become sufficiently high that tensile shear failure may occur. Due to the temporary local drop in pressure during the formation of dilatant fractures, melt flows into the fractures and thereby leaves the system efficiently. This process will result in extraction of small melt fractions from the protolith, and repeated episodes of melt-enhanced embrittlement may be a mechanism for progres-

sive segregation of successive batches of melt (Davidson *et al.*, 1994). The result is to progressively deplete the protolith of its fusible components and ultimately to leave a residual granulite, commonly with preserved mesoscopic phase layering.

#### Geochemistry of crustal melts: consequence of different segregation mechanisms

Whether water-rich volatile phase-present melting or volatile phase-absent dehydration melting occurs and whether the resultant melt is frozen *in situ*, or the resultant bulk magma becomes mobile with restite entrainment, or the resultant small percentage melt fractions are able to segregate sequentially will affect the chemical evolution of the crust. In the first case, the bulk chemical composition of the protolith is substantially unchanged since the melt is frozen essentially *in situ*, even though small-scale segregation to form stromatic migmatites may have occurred. The granite leucosomes will have equilibrium chemical compositions. If this granite is separated from the residue, for example by melt migration into ductile shear zones that cut through the source before the melt is frozen, then magma may migrate up the shear zone and it also will have an equilibrium chemical composition. In the second case, bulk magma mobility with restite entrainment may result in restite unmixing during ascent and the emplacement of S-type granites at shallower crustal levels. It has been argued that the St. Malo migmatite belt and the Mancellian Granites in NW France represent an example of this process (Brown, 1994 and references therein). Further, such a mechanism may occur as a consequence of crustal extension, and the best example of this may be the S-type granites of the Lachlan Fold Belt (Zen, 1993). In the third case, the protolith is periodically drained of melt, and so need never contain more melt than that required to maintain an interstitial network of melt along grain edges, probably < 5%. Thus the source remains coherent even at large degrees of melting, but has bled granite melt in batches. If melt segregation occurs more rapidly than chemical equilibration can be reached between melt and solid, then disequilibrium compositions will be preserved by the magma (Sawyer, 1991; Watt and Harley, 1993) and may be recorded in the resultant granite; features consistent with this are characteristic of the leucogranites in the Himalayas (Deniel *et al.*, 1987).