

Chemical disequilibrium during crustal anatexis

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Introduction

The geochemistry of melts formed from crustal melting is controlled by the nature of the melt reaction, the activities of the volatile species during melting and the degree of equilibrium established between melt and restite. Of these, equilibrium is probably the most significant single determinant, and can only be established when diffusion rates are more rapid than the rates of reaction and of melt extraction. Evidence for chemical disequilibrium is most likely to be preserved where melts have been generated by the incongruent melting of muscovite, due to the low temperatures at which such melts are formed ($<750^{\circ}\text{C}$ during fluid-absent melting, $<650^{\circ}\text{C}$ during fluid-saturated melting at mid-crustal levels). In contrast to equilibrium melts, the trace-element compositions of granites and their constituent minerals formed under disequilibrium conditions are not determined solely by source mineralogy, but constrain the rates of melt formation and extraction.

Melt geochemistry

Himalayan leucogranites provide an example of melt formation from a pelitic source through muscovite breakdown under fluid-absent conditions (Harris and Inger, 1992). The bulk abundances of trace-elements Rb, Sr and Ba in the protolith reside almost entirely in micas and feldspars and are sufficiently dilute in such minerals for Henry's Law to be obeyed thus allowing quantitative modelling. Petrogenetic modelling of Himalayan granites indicates that equilibrium between melt and a pelitic restite was established for Sr, but probably not for Rb, consistent with known diffusion rates for these elements.

Zr and Ce abundances in the melt are controlled by the dissolution of accessory phases zircon and monazite since these elements are essential structural constituents for these phases. Abundances of ESCs from Himalayan granites indicate that the melts were saturated to slightly

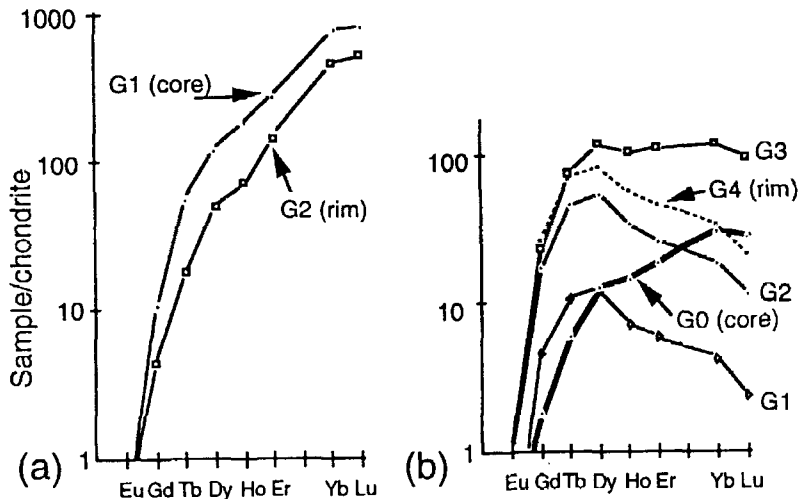


FIG. 1. Chondrite-normalised diagram for HREE showing zoning in a single garnet ($r=1\text{mm}$) from leucogranites in western Himalayas, northern India. (a) Gumberanjun granite. (b) Haptal Granite: analyses record a traverse from core (G0) to rim (G4) of garnet. Analyses determined by MJA using Cameca ion-microprobe (Edinburgh University).

undersaturated in both accessory phases at temperatures of $\sim 700^\circ\text{C}$. Undersaturation may reflect rapid extraction rates but is more likely to reflect the spatial distribution of accessory phases in the protolith where they commonly occur as inclusions in biotite and garnet. For other trace elements, such as Y and HREE, their distribution in the protolith is partitioned between garnet and accessory phases thus undermining their use for equilibrium petrogenetic modelling. Moreover these phases are strongly zoned which indicates slow diffusion rates (relative to crystal growth) consistent with low solidus temperatures. The low LREE/HREE ratios observed in many crustally-derived granites and rhyolites (resulting in flat chondrite-normalised REE profiles) is probably not indicative of a garnet-free source region but of the sluggish REE diffusion rates in garnet at the low temperatures of fluid-absent melting of micas.

REE zoning in garnets

Ionprobe traverses across single garnets from Himalayan granites provide evidence for the evolution of magmatic compositions. Simple garnet growth in a closed system is accompanied by a decrease in the HREE abundance of the garnet, reflecting strong partitioning of these elements into the growing garnet. For the Gumberanjun granite (Figure 1a), the observed depletion during garnet growth requires a volume proportion of $\sim 5\%$ garnet in the granite, consistent with its modal composition.

More complex zoning has been observed in smaller Himalayan granites (Figure 1b); within a single garnet evidence can be preserved of processes that occurred both before and during melting. In one example, an inherited garnet core (G0) is mantled by zones that show an outward increase in HREE concentrations in the garnet (G1-G3). Increasing REE abundances in the melt during garnet growth can not be caused by fractional crystallisation and must record part of the prograde melting history during the dissolution of REE-rich phases, such as monazite (Sevigny, 1993). The outer rim of this garnet (G4) shows 'normal' crystallisation zoning.

Kinetic constraints on magma formation

Although disequilibrium characteristics have been identified from Himalayan granite geochemistry it appears that for major-elements and some trace-elements, including Sr, chemical equilibrium was approached. Extraction rates over timescales > 10

ka are indicated by Sr restite/melt equilibrium. Kinetically controlled disequilibrium melting of pelitic rocks is extremely rapid, achieving significant melt fractions in < 1 year (Rubie and Brearley, 1990). For granites derived by incongruent melting of muscovite low melt fractions are indicated which suggest that neither buoyancy nor compaction played a significant role in their segregation. Rapid transport of low melt fractions can be effected by fracture propagation, over a timescale < 1000 years (Clemens and Mawer, 1992). Hence a slower rate-determining step is required between initiation of melting and melt extraction to account for apparent equilibrium of Sr between melt and protolith. Evidence for the relationship between melting, extraction and crystallisation can be obtained from REE zoning in some garnets. Where a decrease of HREE towards the rim and high overall high HREE abundances are observed (Figure 1a), melting rates allowed saturation levels of monazite and zircon dissolution to be reached, followed by melt extraction and crystallisation. In contrast, the preservation of an outward increase in HREE in garnet (Figure 1b) indicates that crystallisation of garnet must be underway during the melting process. Here melting and crystallisation of refractory phases are concomitant and predate melt extraction. Both zoning profiles and low overall REE abundances indicate that temperatures barely rose above the solidus temperature.

The evidence from garnet zoning is consistent with thermal buffering during melting. Once the heat required for fusion reaches the heat flow into the rock, the reaction rate is no longer kinetically controlled but is determined by the thermal diffusivity of crustal rocks over periods of 1-10 Ma. Such a timescale would result in the specific disequilibrium features observed in Himalayan leucogranites, formed by incongruent melting of muscovite at mid-crustal levels.

References

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