Focussed flow of melt in the upper mantle: Extraction of MORB beneath oceanic spreading ridges

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Summary

This paper summarizes studies on focussing of melt flow into high porosity channels in the mantle, and the geochemical effects of such flow focussing. In particular, it is proposed that focussed porous flow plays an important role in formation of dunite channels and extraction of mid-ocean ridge basalt (MORB) from the upper mantle beneath spreading ridges. This process may be as important or more important than melt flow in open fractures. Recent results are reported from experimental studies on analog systems [1], and field studies of dunites formed by syn-tectonic focussing of porous flow along ductile shear zones [2]. Then, new geochemical analyses of dunites and harzburgites from the mantle section of the Oman ophiolite are discussed. Dissolution of pyroxene (and some olivine) in ascending melt forms high-porosity channels for focussed melt extraction. Within such channels, high melt/rock ratios produce solid products near equilibrium with MORB. Diffuse flow of melt outside these channels at very low melt/rock ratios has a comparatively minor effect upon the composition of residual harzburgites.

Analog experiments and field studies on focussed porous flow of melt

As predicted by Chadam *et al.* [3], diffuse porous flow in partially soluble porous media is unstable under many conditions, and will become organized in discrete, relatively high porosity channels. This instability is demonstrated in a series of laboratory and numerical experiments with growth of solution channels parallel to the fluid flow direction [1]. Regions with initially high porosity have high ratios of fluid volume to soluble solid surface area, and have more rapid fluid flow at constant pressure, so that dissolution reactions in these regions produce a relatively rapid increase in porosity. As channels grow, large ones entrain flow laterally inward and extend rapidly. As a result, small channels are starved and disappear. The growth of large channels is an exponential function of time, as predicted by linear stability analysis for growth of infinitesimal perturbations in porosity. Experiments demonstrate channel growth in the presence of an initial solution front, and without an initial solution front where there is a gradient in the solubility of the solid matrix.

In the Earth's mantle, adiabatically ascending partial melts of mantle peridotite are undersaturated in solid phases. Reaction of such ascending melts with mantle peridotite will initially cause dissolution of all solids, and cooling, followed by saturation with olivine. Continued reaction will involve dissolution of pyroxene and crystallization of olivine, producing an increase in liquid mass under most conditions. This may eventually produce saturation in pyroxenes. After pyroxene saturation, continued cooling and reaction will produce a decrease in the liquid mass. Where liquid is undersaturated in all solid phases, or where liquid is saturated only in olivine, dissolution reactions may lead to formation of porous channels composed of dunite ($>$ 95% olivine). Formation of dunite channels is likely to be an important result of melt extraction beneath mid-ocean ridges where the mantle ascends adiabatically almost to the base of the crust [1]. Focussed flow of polybaric partial melts of ascending peridotite within dunite channels may explain the observed trace element disequilibrium between most shallow mantle peridotites and mid-oceanic ridge basalts (MORB).

Results of a field study [2] demonstrate that melt flow in the shallow mantle was focussed along actively deforming ductile shear zones in the Josephine peridotite in SW Oregon. Intergranular flow of ascending liquids dissolved pyroxene and precipitated olivine, forming zones of dunite replacing harzburgite. Syn-tectonic formation of dunite occurred along near vertical shear zones, with both vertical and dextral displacement, in the shallow mantle at less than 30 km depth and 950

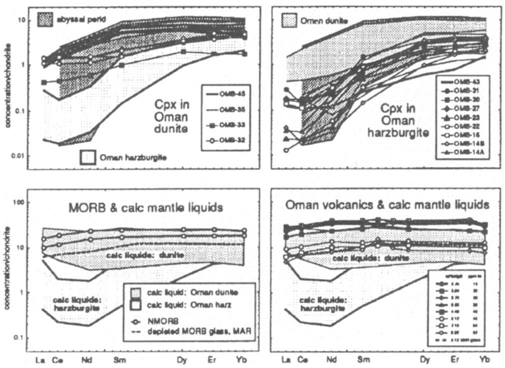

FIG.1.

to 1100C. Explanations for focussing of melt flow along shear zones include the presence of a pressure gradient between strong and weak material during active deformation [4] and rapid infiltration of liquid when grain boundaries are aligned in mantle tectonites [5]. Focussed flow of melt may, in turn, lead to localized deformation and the development of shear zones. It is likely that melt-lubricated shear zones provide an important locus for both melt extraction and strain in the shallow mantle.

Geochemistry of dunite & harzburgite, Oman ophiolite [Kelemen & Shimizu, in prep.]

Clinopyroxene (Cpx) and spinel in samples from a traverse across the mantle section in the Wadi Tayin region of the Oman ophiolite [6] have been analyzed by ion and electron microprobe. There is a first order difference in Cpx and spinel composition between dunites and harzburgites. Dunite Cpx, and Cpx in a chromitite, has a slightly light *REE* depleted, chondrite-normalized pattern. Harzburgite Cpx from the Wadi Tayin section is as depleted in REE as the most depleted Cpx in abyssal peridotite samples [7,8]. Dunite spinels have higher Cr/(Cr + Al) , higher Ti/(Cr + Al), and higher Sc/Ga ratios, than those in harzburgite.

Calculated liquids in equilibrium with Cpx from dunite have *REE* slope and abundance similar to MORB-type lavas at the base of the volcanic section in the Oman ophiolite. Calculated liquids in equilibrium with Cpx in Wadi Tayin harzburgite are strikingly different from MORB. Similar results were reported for samples recovered during ODP Leg 148 at Hess Deep, from mantle formed at the East Pacific Rise. Dunites near the transition zone include Cpx in equilibrium with MORB, while harzburgite host rocks are strongly depleted in light *REE* [9].

Calculated liquids for harzburgite Cpx are significantly enriched in La and Ce compared to Nd. This may be attributed to reaction between small amounts of migrating liquid and residual peridotite [e.g. 10], and/or to small amounts of retained liquid in peridotite [e.g. 11].

Like the dunite spinel from Wadi Tayin, spinel in MORB has higher Cr/(Cr + Al), and higher Ti, than spinel in most abyssal peridotite [12]. Combined with the *REE* data, the spinel analyses strongly support the hypothesis that dunites formed during extraction of liquids similar to MORB from the mantle. At first glance, the MORB and Oman spinel data seem paradoxical, since higher Cr/(Cr + Al) is generally taken to be indicative of equilibrium with liquid formed by a relatively high degree of partial melting, whereas higher Ti concentration (and higher Ce/Yb in coexisting Cpx) is generally taken to be indicative of equilibrium with liquid formed by a relatively low degree of partial melting. However, an open system process in which liquid dissolves pyroxene and precipitates olivine may produce increasing Cr/(Cr + Al), and increasing Ti and Ce/Yb, in derivative liquids. Ion probe data, together with field and petrographic evidence, may constrain melt extraction processes in the mantle beneath oceanic spreading ridges. Like abyssal peridotites, Wadi Tayin harzburgites have been substantially depleted in light *REE* by near-fractional partial melting. Although they may have interacted with small amounts of liquid migrating by pervasive, porous flow, it seems unlikely that this is the dominant mode of MORB extraction from the mantle to form the crust. Dunites, on the other hand, fulfill many of the geometrical and geochemical requirements for conduits of focussed flow in which incremental melts might coalesce, mix to form MORB, and be transported to the surface.

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