

# Melt movement in the mantle

D. McKenzie

*Institute of Theoretical Geophysics, Bullard Laboratories, Dept. of Earth Sciences, Madingley Road, Cambridge CB3 0EZ, UK.*

It is now ten years since the fluid mechanical equations governing the generation and movement of melt in a deformable matrix were obtained by several authors. Because they worked independently, they used slightly different approaches and their equations look different, though in fact they are all identical. Two results of this early work were of obvious petrological importance. The first was that melt fractions of as small as 0.1% can separate from their residue, and the other was that decompression melting at constant entropy can produce the observed crustal thickness of 7 km of normal spreading ridges if the mantle temperature is about 1300°C. If the mantle temperature is 1500°C, the melt thickness increased to about 25 km, or similar to that beneath Iceland. Since hot plumes are expected to be about 200°C hotter than the bulk of the upper mantle, these results accounted for the principal geophysical observations. Over the last ten years a considerable effort has been concerned with showing that the same ideas can also account for the major, minor and trace element geochemistry of magmas from spreading ridges, from plumes and from plate interiors. This work will be briefly reviewed, and has largely been successful. It has strongly supported the earlier geochemical arguments that some melts are generated from sources that differ from both the MORB source and the primitive Earth in having been enriched by the addition of a small (0.3%) melt fraction. The modelling further suggests that this small melt fraction comes from the MORB source, not the primitive Earth. Two other ideas from the early work on melt migration have not yet been widely accepted. The first is concerned with the fluid dynamics. All attempts to find steady state solutions to the governing equations have failed, and it is now clear that all solutions break down into three-dimensional solitary waves. Estimates of the volume of melt contained in such waves range from  $10^{-2}$  to  $1 \text{ km}^3$ , and are similar to the volumes of individual basaltic eruptions. It is therefore tempting to argue that eruptions result from the arrival of a solitary wave at the base of a magma chamber, though there is as yet no other evidence in favour of such a proposal, or indeed even for the existence of the solitary waves themselves. The second is concerned with chemical changes that can occur as

the magma percolates through the matrix. Estimates of the rate of uniform percolation show that it is sufficiently slow to equilibrate with the matrix after percolation through a vertical distance of about 1 km. If such equilibration occurs, the percolation process should act as a chromatographic column, and the melt should be in local equilibrium with the matrix. Though various authors have proposed that such chromatographic effects may explain certain puzzling geochemical observations, there is as yet no convincing evidence that such effects are important.

In contrast there is now good evidence that the composition of MORB corresponds to the simple average composition of the melt generated beneath ridges. Because the melt is produced over a considerable depth range, it has initially considerable variations in major element composition. When averaged, these variations can account for the composition of MORB, which is not in equilibrium with the residue at the top of the melting column. Other observations, of the composition of clinopyroxenes in abyssal peridotites (Fig. 1), and of trapped melt within olivine (Fig. 2) can also be explained if melt does not percolate upwards in equilibrium with the matrix, but instead separates into channels where the upward flow is rapid. Recent observations of uranium series disequilibrium, from Hawaiian lavas and from basalts from oceanic ridges, also require melt to be transported from the bottom of the melting zone to the surface in times that are short compared to 1600 years, the half-life of  $^{226}\text{Ra}$ . No solutions of the original equations can describe this behaviour. The equations were derived on the assumption that D'Arcy's law describes the melt movement, with a permeability that depends only on a constant grain size and a variable melt fraction, and that the grains of the matrix are in contact everywhere. The geochemical observations suggest that the interaction between the melt and matrix is more complicated than envisaged, and that there is some instability that generates channels through which rapid melt movement occurs that is not in chemical equilibrium with the matrix. There are two difficulties with such a model: one observational and one theoretical. The first is that rapid

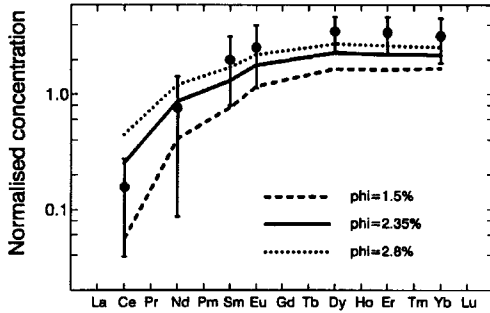


FIG. 1. Diopside compositions in MORB nodules. Diopside from Johnson *et al.*, *J. Geophys. Res.*, **95**, 1990, 2661.

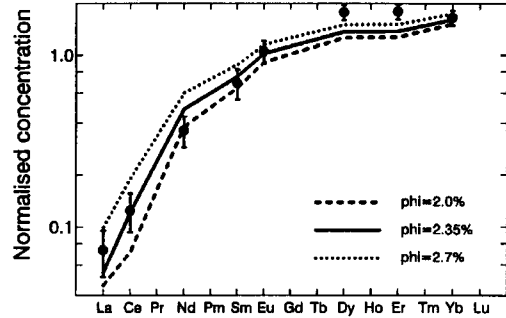


FIG. 2. Olivine melt inclusion. Inclusion 1, Sobolev and Shimizu, *Nature*, **363**, 1993, 151–3.

percolation reduces the melt fraction present in the source region. Geochemical modelling and geophysical observations of gravity over the East Pacific Rise both suggest that the melt fraction in the melting region is about 2–3%, the value expected from the percolation model for a dry basaltic melt. The theoretical difficulty is that it is not easy to study the behaviour of instabilities that

cause the governing equations to change. The rapid progress of the last ten years has occurred because it has been possible to use chemical observations to constrain fluid dynamical models. Progress will be much slower if it is not possible to provide a theoretical basis for the interpretation of the observations.