Geochemistry

Mid-ocean-ridge basalt genesis

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WHAT do the topographic depths of mid-ocean ridges, the thickness of their crusts and the compositions of their extruded lavas have in common? A great pleasure of science is the way simple unifying principles emerge to link a series of seemingly disparate parameters into a coherent pattern; even if the simplicity of the first attempt becomes less apparent after future research. It is agreed that the Earth's silicate mantle convects and that — at least beneath mid-ocean ridges — this leads inevitably to partial melting of peridotite that upwells within a few tens of kilometres of the surface, to yield liquids that proceed buoyantly to eruption or near-surface intrusion. The amount and composition of this melt varies according to the temperature of the upwelling peridotite (if its composition is essentially constant). Lateral variation of the mantle heat beneath mid-ocean ridges also controls their topographic depths. Thus, the three parameters listed above could all be related to one underlying principle. In their recent work¹, Klein and Langmuir are remarkably successful in analysing the depths and crustal thicknesses of mid-ocean ridges, and the compositions of their lavas, along these lines.

Klein and Langmuir start with major-element analyses of basalt glasses from ocean ridges throughout the world. To compare the compositions of these, they first correct for the effects of the variable fractional crystallization of each magma since its genesis. To do this they recalculate each composition to a fixed MgO content (approximately equivalent to a single magmatic temperature), using a simple empirical closed-system fractional crystallization model. Those who are convinced that the compositions of the individual upwelling magma batches beneath ocean ridges are indecipherably scrambled, by open-system multiple magma-mixing and crystallization events in near-surface reservoirs², will probably criticize this first stage. Nevertheless, Klein and Langmuir find that their simple normalization produces excellent world-wide correlations between water depth along the mid-ocean ridges and such parameters as Na₂O and FeO content, and the ratio CaO/Al₂O₃.

Melting experiments

Klein and Langmuir compare these trends with those observed within the liquids produced in experiments on the polybaric fusion behaviour of natural peridotites. This stage of the argument is complicated because a single parameter

can often reflect more than one process. Thus Na₂O content is sensitive to both the extent and the pressure of fusion during partial melting of peridotite. But FeO in the liquid is remarkably insensitive to the degree of isobaric melting in mantle peridotite (although sensitive to the pressure), and this enables Klein and Langmuir to decide which of several explanations of their composition–depth trends is correct.

It emerges that basalts from shallower-than-average segments of the global mid-ocean ridge system, such as the Kolbeinsey Ridge, are distinguished by relatively low Na₂O, SiO₂ and Ni contents and ratio Sm/Yb, and high FeO, Sc and CaO/Al₂O₃. This seems to be because they are generated by above-average fusion of the subaxial mantle, with the melt escaping from its source at greater-than-average mean pressures. Basalts from deeper-than-average segments of the ridges, such as the mid-Cayman Rise, show contrasting chemical features attributed to below-average mantle fusion and shallower-than-average melt escape. Between these two extremes there is a remarkably systematic variation between basalt chemistry and ridge depth.

Links

What do these links between ridge depth, degree of mantle fusion and mean depth of magma escape reveal about the convective behaviour of the upper mantle? As Klein and Langmuir point out, all these parameters are related to lateral variations in the heat of upwelling mantle beneath spreading centres. Thus, locally hotter mantle — in a plume or jet — begins to melt at a greater depth during adiabatic uprising, and eventually melts to a larger extent, than the relatively cooler mantle between jets. Both the locally greater crustal thickness (formed by melt products) and the direct effect of a hotter-than-average upwelling jet contribute to the shallowness of the sea above such regions.

The approach used by Klein and Langmuir — analysing the compositional variations of ocean-ridge basalts — is one way to quantify the melt output from upwelling mantle. The other approach uses the experimental phase-equilibria data obtained for peridotites³. These provide the compositions of isobaric, polythermal liquids which can be re-cast to give the polybaric liquids that form within a volume of partially molten mantle peridotite undergoing isentropic upwelling⁴. The upper limit of mantle fusion by adiabatic

decompression along mid-ocean ridges is generally agreed to be 20–25 per cent melting, perhaps slightly more for different bulk compositions atop the convective jets that underlie such places as the Azores and Galapagos^{1,3,4}. Between the hottest and coldest parts of the upwelling mantle there seems to be a potential (pressure-corrected) temperature difference of only 200–250°C (refs 1, 4).

Applications

There are perhaps two main applications of these studies and two important areas for future work. As Klein and Langmuir point out, the compositions of lavas from old parts of existing ocean basins could be used to deduce the former distribution of convective jets in the mantle beneath oceans. McKenzie and Bickle⁴ quantify the effects of the stretching of pre-existing lithosphere, so that the amount and composition of the consequent magma may be deduced from knowledge of the thickness of lithosphere, the amount of its extension and the potential temperature of the subjacent convecting mantle. Further studies may clarify two questions. First, as the partially molten mantle upwells, does all the released melt percolate upwards through the deforming matrix (mixing with other melts produced nearer the surface) and emerge as a 'magmatic cocktail' at the top of the melting column, or can some liquid batches escape from the mantle residuum at depth and proceed to the surface in a state of physical isolation or near isolation?

Second, how can the behaviour of strongly incompatible elements — those which have very small bulk-distribution coefficients between melt and residuum during mantle fusion — be quantified? Klein and Langmuir and many others^{4, 8} have deduced that these elements obey a different set of rules from the major and compatible trace elements during fusion of upwelling mantle. But we are not yet able to quantify the rules. To do so would help in clarifying the geochemistry of the three main radiogenic isotope systems — Sr, Nd and Pb — upon which most of our understanding of the time-integrated behaviour of the convecting mantle depends. All their parent and daughter elements are strongly incompatible in mantle-melt systems. □

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