Refertilization in a convecting mantle: effects on primary MORB compositions

D. Elthon

Department of Chemistry, University of Houston, Houston, TX 77204 USA.

Introduction

The widely held view is that mid-ocean ridge basalts (MORBs) are produced by polybaric fractional melting of the sub-oceanic mantle in which the composite primary MORBs are derived from a relatively fertile mantle by 10–25% total melting (McKenzie, 1985; Johnson *et al.*, 1990). The differences in primary MORB compositions are inferred to result principally from differences in the pressure and extent of melting (Klein and Langmuir, 1987; Kinzler and Grove, 1992). The compositional variations between abyssal peridotites, in this scenario, reflect different degrees of fractional melting in which the least depleted peridotites represent the residues of ~10% melting and the most depleted peridotites represent the residues of ~25% melting (Dick and Fisher, 1984; Michael and Bonatti, 1985).

It has been suggested, however, that the abundances of moderately incompatible elements (e.g., Na) in abyssal peridotites are not compatible with these rocks having been formed as residues of variable degrees of partial melting (Elthon, 1992). It was suggested instead that abyssal peridotites are a mixture of two distinct components. One component is a depleted harzburgite that has either no clinopyroxene (CPX) or that has <2% CPX with very low abundances of Na2O (0.01 wt. %), Ti (300 ppm), Zr (0.1 ppm), and Ce (0.02 × chondrites). The other component is a basaltic liquid, which is potentially highly variable in composition. If the chemical variations in abyssal peridotites reflect some type of melt addition (or refertilization) process into depleted harzburgite mantle, there are profound implications for how the source regions of MORBs have evolved. Most importantly, if the mantle melts to produce a harzburgite (<2% CPX) on a routine basis, the differences in primary composite MORBs will reflect most strongly the differences in the local mantle composition as the mantle enters the mid-ocean ridge melting regime. In light of the variable compositions of mantle xenoliths and peridotite massifs as well as the strong evidence for melt addition processes in these samples, it might also be expected that the sub-oceanic mantle is both variable in composition and is influenced by melt-addition (refertilization) processes.

It is proposed here that the MORB source region has been through the mid-ocean ridge melting regime at least 1 to 5 times during normal mantle evolution and consists of a highly depleted harzburgite mantle (similar to that found in peridotite massifs) mixed with basaltic/komatiitic material that has refertilized the mantle. In this scenario, the ascending mantle beneath mid-ocean ridges varies significantly in composition, depending on the amount and type of basaltic/komatiitic mantle added. Within the melting regime, the mantle melts to whatever extent is necessary to deplete the mantle to harzburgite (± a few percent clinopyroxene) where thermal considerations stop further melting. It is proposed, therefore, that differences in primary MORB compositions are principally due to differences in the amount and composition of basaltic/komatiitic material added into the source region.

Mantle recycling and refertilization: petrological effects

It is clearly established that the sub-oceanic mantle has been depleted by the production and extraction of basaltic/komatiitic magmas over geologic time. Present-day mid-ocean ridge spreading (70,000 km length with an average spreading rate of 5 cm/year) would cycle all of the mantle through a mid-ocean ridge melting regime in 2.6-5.2 b.y. or would cycle all of the upper 700 km of the mantle through a mid-ocean ridge melting regime in 0.8 to 1.7 b.y. Given these endmember limits on what portion of the mantle has been actually involved in melt production over time, the sub-oceanic mantle has been cycled, on average, ~1 to ~5 times through mid-ocean ridge melting regimes. This estimate might be low by a factor of three due to higher heat dissipation during the Archaen.

It is generally accepted that fractional melting of the sub-oceanic mantle occurs; this process produces very strong depletions in incompatible elements in the residual mantle. If the bulk D for an element is 0.01 (e.g., Cs, Rb, Ba. Th, U, K, La), 3% fractional melting will reduce the concentrations of these elements in the residue to $<5\%$ of their starting concentration. At 6% fractional melting, the abundances of these elements in the residual mantle decrease to $<0.3\%$ of their original mantle concentration.

Studies of Archaen to present-day basaltic and komatiitic magmas have shown that the volumetrically-abundant types of magmas were produced by $\sim$10–30% melting, possibly even higher percentages for some komatiites. Those magma types produced by smaller extents of melting (e.g., alkali olivine basalts, nephelinites, etc,) are volumetrically minor in the Earths magma budget.

Fractional melting of the mantle at percentages required to produce the volumetrically abundant magma types erupted throughout Earths history will have depleted the abundances of incompatible elements in the mantle to such low levels ($<0.1\%$ of starting composition) that it would not be possible to re-melt the mantle at a later time to produce more basaltic magmas with the abundances of incompatible elements found in present-day MORBs. Once the mantle has been melted by fractional processes to the stage where the total amount of melt produced is greater that a few percent, that mantle cannot re-melt to produce MORB levels of abundances unless the mantle is refertilized and the abundances of incompatible elements in the mantle increase by $5\times$–$100\times$.

Proposed model for the evolution of sub-oceanic mantle

On a continual basis, mantle has been processed through mid-ocean ridge melting regimes over time. The available evidence indicates that melting under present-day mid-ocean ridge spreading centers is fractional, with the individual melt fractions accumulating to form composite magmas that eventually erupt as MORBs, following mantle-melt interactions and magma chamber processes. The abundances of highly incompatible elements (bulk D <0.01) in the residual mantle following the passage of the mantle through the melting regime is $<0.05\times$ chondrites; the residual mantle is a harzburgite with $<2\%$ CPX. Seafloor spreading and eventual subduction re-introduces strongly depleted mantle and the enriched oceanic crust back into the mantle convective regime. If the strongly depleted mantle passes through a mid-ocean ridge melting regime, it will not melt. The potential for producing basaltic magmas depends, therefore, on the depleted mantle becoming refertilized.

Viewed in this perspective, variations in the composition of the sub-oceanic mantle are not directly related to variable extents of partial melting, but rather to the extent of refertilization of the strongly depleted mantle and the nature of the fertilizing agent. When this refertilized portion of the upper mantle later passes through a mid-ocean ridge melting regime, MORB primary magmas are again produced by fractional melting to leave a depleted harzburgite residual mantle.

It is suggested, therefore, that the compositions of composite primary MORB magmas are most strongly a result of the extent and nature of refertilization of the mantle. The roles of the extent of melting and the mean depth of melting are suggested to be only secondary effects on the compositions of composite primary MORBs.

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