How large is the mantle source of ocean island basalts?

S.L. Goldstein *Max-Planck-Institut für Chemie, Postfach 3060, D-55020 Mainz, Germany*
D.M. Miller *Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA*
C.H. Langmuir *Max-Planck-Institut für Chemie, Postfach 3060, D-55020 Mainz, Germany.*
A.W. Hofmann

Introduction

The differentiation of the silicate Earth has resulted in formation of a continental crust enriched in elements that preferentially partition into silicate liquids such as Rb, Th, U, and the light rare earths, and a 'residual' mantle which is depleted in these elements. There have been many attempts to carry out a mass balance between the continents and the residual mantle using Nd and Sr isotope ratios and elemental abundances, in order to estimate the mean age of mantle depletion and the size of the depleted and undifferentiated mantle (e.g. Galer *et al.* 1989 and references therein). Most attempts have assumed that the source of mid-ocean ridge basalts (MORB) reasonably approximates the depleted mantle complement to the continental crust, and that ocean island basalt (OIB) sources are an insignificant portion of the depleted mantle. These studies have been used, for example, as geochemical arguments in favor of convective separation of the upper and lower mantle. However, the OIB source has been ignored mainly due to difficulties in constraining its size and mean isotopic composition. If OIB sources comprise a significant portion of the residual mantle, many conclusions based on balancing the continents with the MORB source alone would be invalid, as would corresponding inferences about the gross structure and composition of the mantle. In this abstract we present a path to constrain the sizes of the OIB, MORB, and primitive mantle reservoirs.

Method

Our method uses the fractionation of Ce and Pb between the mantle and continental crust. Ce/Pb ratios in oceanic basalts are similar to their mantle sources, and both MORB and OIB have Ce/Pb ratios of ~ 25 (Hofmann *et al.* 1986, Newsom *et al.* 1986). In the bulk silicate Earth, Ce/Pb ≈ 11 (Miller *et al.* 1994), therefore the high Ce/Pb in MORB and OIB sources are balanced by low Ce/Pb in the continental crust. Because Ce/Pb ratios are the same in OIB and MORB, the mass balance between continent and mantle for Ce/Pb includes both mantle source reservoirs. This is not the case for previous models based on Nd isotopes.

For a given Ce/Pb ratio, Ce abundance, and mass of the continental crust, the mean Ce abundance and the mass of the 'residual" MORB plus OIB mantle can be calculated. This mean abundance is higher than the permissible range of Ce abundances of the MORB reservoir (Miller *et al.* 1994). The 'excess' Ce is removed from the residual mantle to achieve a appropriate concentration appropriate for MORB mantle sources. The OIB reservoir is made by mixing the excess Ce with some of the MORB mantle until the Ce abundance is appropriate for producing OIB magmas. The OIB source cannot be made by mixing the excess Ce with primitive mantle, because it would result in a Ce/Pb much lower than 25. The calculated size of the OIB source scales with its Ce content. Tighter constraints result from the inclusion of other elements, such as Rb, Th, La, Nd, Sm, Yb. Since the mass of the 'residual' MORB plus OIB mantle is defined by the Ce/Pb balance, to the extent that the concentrations of these elements in the continents are known, their concentrations in the residual mantle can be determined. Elements are partitioned into the MORB mantle so as to allow generation of reasonable trace element patterns in parental MORB magmas. Excesses which remain for all these elements are assumed to reside in the OIB source. Using a variety of elements with different distribution coefficients then leads to a set of credible models that are based on acceptable elemental abundances and ratios in the OIB source.

Clearly the results depend on the extent to which we know the continental crust and MORB mantle compositions. Those reported use the following inputs. Nd = 16–27 ppm in the continental crust. Abundances of other elements are based on their ratio to Nd in the average continental crust of Taylor and McLennan (1985). Ce/Pb = 3.8–5.0 in the continental crust, based on the range of literature estimates (Galer *et al.* 1989). Ce = 7.5 ppm in parental MORB (c.f. Sun and McDonough 1989), whose formation is approximated by batch partial melting with $D_{Ce} \approx 0.01$ and F ~0.1. The OIB source must have enough Ce to generate parental magmas with Ce = 18 ppm, about the lowest values in OIB (c.f. Hofmann *et al.* 1986). D_{Ce} and F are as in MORB. In order to generate reasonable OIB trace element patterns, primitive mantle normalized ratios of highly incompatible elements to La in the OIB source are greater than 0.5.

Certain qualitative considerations are evident. If parental OIB are derived by lower extents of melting, or have lower Ce contents, then the concentrations in the OIB reservoir decrease, and its size increases. Higher Ce or lower Ce/Pb in the continental crust result in a larger residual MORB plus OIB mantle. The residual mantle must be large enough to supply the lithophile elements to the continents, and leave enough behind to account for the MORB and OIB sources. Therefore the lower limit on the mass of the residual mantle is determined by the amount of highly lithophile elements like Rb and Th in the continental crust.

Quantitative results and implications

If all the constraints listed above are satisfied, the residual MORB plus OIB mantle can comprise between 44-80% of the whole mantle. While this appears to be a large range, the results have several important features and implications. The OIB mantle is about half the mass of the MORB mantle. It contains about twice the amount of highly lithophile elements, such as Rb and Th, as the MORB mantle, and about equal amounts of light rare earth elements. Clearly, in terms of both its mass and its inventory of elements, OIB-like sources constitute a major mantle reservoir.

The smallest residual mantle among our models, 44% of the whole mantle, is ~50% larger than many estimates based mainly on balancing Nd isotopes between the continents and MORB sources (e.g. Jacobsen and Wasserburg 1979, O'Nions *et al.* 1979, DePaolo 1981).

With a residual mantle of ~44% of the whole mantle, the mass of the MORB mantle would be ~30% of the whole mantle, about the size of the geophysical upper mantle to 670 km. However, even in this limiting case, the mass of OIB mantle is ~2.5 times the size of the D″ layer at the base of the lower mantle. Therefore the total residual mantle reservoir does not fit into simple geophysical mantle boxes. All other credible models require a mass of MORB-like mantle much larger than the geophysical upper mantle, and a mass of OIB mantle that is 2.5 to 5 times the size of the D″ layer, indicating that the bulk of OIB-like sources exist outside of this region, probably in the lower mantle and the continental lithospheric mantle.

Most credible models indicate existence of significant amounts of undifferentiated mantle. If convection in the lower mantle mixes MORB-like and OIB-like sources with undifferentiated mantle, then these mixtures have average Ce/Pb much lower than 25. Such sources are not observed in oceanic island basalts. Therefore, the spatial relationships of these sources in the lower mantle are as yet unclear.

We have shown that the size of the OIB reservoir can be estimated, that its mass is relatively large compared to MORB mantle, and that it contains a significant portion of the mantle inventory of incompatible trace elements. Its relative size can be quantified and therefore can be taken into account in models of the mass balance between mantle and crust. Once the sizes of reservoirs can be constrained, their physical distribution is obviously of great interest. The mass balance calculations suggest that MORB, OIB, and primitive mantle reservoirs are all important in the lower mantle. However, the primitive mantle mass is much smaller than that of the lower mantle, and larger than the D″ layer. Therefore, it might be expected on physical grounds that convective mixing would lead to the production of lower mantle with intermediate Ce/Pb ratios, which are not observed in oceanic basalts. The reconciliation of these geochemical reservoirs with physical locations in the mantle remains an intriguing problem.

References

DePaolo D.J. (1980) *Geochim. Cosmochim. Acta*, **44**, 1185–96.

Galer S.J.G., Goldstein S.L. and O'Nions R.K. (1989) *Chem. Geol.*, **75**, 257–90.

Hofmann A.W. *et al.* (1986) *Earth Planet. Sci. Lett.*, **79**, 33–45.

Jacobsen S.B. and Wasserburg G.J. (1979) *J. Geophys. Res.*, **84**, 7411–27.

Miller D.M., Goldstein S.L. and Langmuir C.H. (1994) *Nature*, **368**, 514–20.

Newsom H.E. *et al.* (1986) *Earth planet. Sci. Lett.*, **80**, 299–313.

O'Nions R.K., Evensen N.M. and Hamilton P.J. (1979) *J. Geophys. Res.*, **84**, 6091–101.

Sun S.-s. and McDonough W.F. (1989) In *Geol. Soc. (Lond.) Spec. Pub.*, **42**, 313–45.

Taylor S.R. and McLennan S.M. (1985) *The Continental Crust: Its Composition and Evolution.* Blackwell Scientific Publications, Oxford, 312 pp.