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Major and trace element composition of the depleted MORB mantle (DMM)

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Abstract

We derive an estimate for the chemical composition of the depleted MORB mantle (DMM), the source reservoir to mid-ocean ridge basalts (MORBs), which represents at least 30% the mass of the whole silicate Earth. A database for the chemical and physical properties of abyssal peridotites has become robust and complete enough to truly access a reference DMM. Using trace element depletion trends from the abyssal peridotites, it is possible to construct a large part of DMM's trace element pattern. Splicing this information with isotopic constraints (Sr–Nd–Pb–Hf) and canonical ratios (Ce/Pb, Nb/Ta, Nb/U, Ba/Rb, H_2O/Ce, CO_2/Nb and Cl/K), we can extend abundance estimates to all the incompatible elements including volatile content. The resulting trace element pattern for average DMM constrains parental MORB to be generated by 6% aggregated fractional melting, consistent with recent models for hydrous melting of the mantle [P.D. Asimow, J.E. Dixon, C.H. Langmuir, A hydrous melting and fractionation model for mid-ocean ridge basalts: application to the Mid-Atlantic Ridge near the Azores, Geochem. Geophys. Geosyst. 5 (2004) 10.1029/2003GC000568]. We show that DMM is roughly balanced by the continental crust and better balanced upon inclusion of ocean island basalt source and oceanic crust components. Compared to the primitive mantle, DMM has been depleted by 2–3% melt extraction and has only 15% the radiogenic heat production.

Keywords: DMM; major elements; trace elements; mid-ocean ridge basalts; mantle

1. Introduction

The trace element composition of the depleted upper mantle (DMM) is a fundamental parameter in modeling the generation of mid-ocean ridge basalts (MORBs), calculating the crust–mantle mass balance, and establishing the chemical and thermal evolution of the Earth. To date, all attempts to establish an average composition for the upper mantle, whether by parent/daughter derivations from isotopic systems [1–6] or by MORB trace element inversions [6–9], have centered on MORB liquids and included major

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assumptions about melt generation, melt transport, and differentiation processes that have affected these upper mantle melts. Unfortunately, it is just these processes that we are trying to understand, rather than assume a priori.

The most compelling evidence for upper mantle depletion comes from the heavy-element isotopic composition of MORBs. Although MORBs and their residues, abyssal peridotites, have some degree of heterogeneity in radiogenic isotope ratios (Sr–Nd–Pb–Hf), they are focused within a small range of values relative to ocean island basalts and are, with very few exceptions, depleted from bulk earth values in $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, and $^{176}Hf/^{177}Hf$, thus requiring a long-term history of low Rb/Sr, Hf/Lu, and Nd/Sm (i.e. incompatible element depletion). Direct evidence for upper mantle depletion came with the classic trace element studies of Johnson et al. [10] and Johnson and Dick [11] on abyssal peridotites, but most of the observed depletion in these peridotites is due to melt extraction during the latest spreading events, so that the composition of the general ambient upper mantle has been severely overprinted by this latest melting episode.

Ultimately, we know that this mantle, which has been estimated to comprise 30–70% by mass of the bulk silicate earth, has been depleted over time in the highly incompatible (lithophile) elements ([1,8], refs. therein). Most models ascribe the depletion of the upper mantle to the extraction of the enriched continental crust, a process that has removed up to 90% of the most incompatible elements, and 80–85% of the heat-producing elements (e.g. [8]). Some part of the depletion may also be created by the preservation of recycled oceanic crust that is currently sequestered in unknown regions of the mantle. It is possible the lower mantle (below 670 km) has also been depleted by such processes, but this question is highly controversial at present.

In place of assuming a set of bulk partition coefficients or a degree of melt extraction, we use in this paper the following constraints in deriving an average trace element composition of DMM: (1) trace element content of clinopyroxenes from abyssal peridotites, (2) isotopic evolution from primitive upper mantle (PUM), and (3) canonical trace element ratios in MORBs. Abyssal peridotite data from the literature, the backbone of this study, are treated in a way reminiscent of studies such as Loubet et al. [12], Hart and Zindler [13], and McDonough and Sun [14]. Abyssal peridotites, unlike basalts, are not modified by secondary processes such as fractional crystallization, magma mixing, and crustal assimilation [15], but may be subject to melt impregnation [16] and melt/rock reaction [17]. We show that melt impregnation can be recognized and therefore filtered from the abyssal peridotite data set and suggest that melt/rock reaction in the data set we have used has had more effect on major element chemistry than trace element chemistry. Overall, it seems that, for the moderately incompatible elements, abyssal peridotites more accurately record the trend of upper mantle depletion than do MORBs.

The average trace element content of DMM, as deduced here, generally shows a very smooth pattern with increasing trace element compatibility, which to first order mass-balances with the continental crust. The degree of depletion indicated in DMM represents 2–3% melt removal from the primitive upper mantle (PUM) of McDonough and Sun [14]; this means that DMM has only 15% the radiogenic heat production of PUM (from K, U, and Th). Present-day ocean crust (i.e. MORBs) can be modeled with 6% aggregated fractional melting of the deduced DMM.

2. Trace element composition of DMM

2.1. Abyssal peridotites

Abyssal peridotites have been shown to be residues of fractional or near-fractional melting that produces MORB (e.g. [10]). Although bulk trace element compositions of these peridotites are heavily modified by alteration on the seafloor, many workers have analyzed the trace element compositions (Sr, Zr, Ti, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, and Y) of relict, unaltered clinopyroxene grains as a means of chemical characterization [10,11,18–21]. Using such clinopyroxene compositions, bulk compositions ($C_{\mathrm{WholeRock}}$) of the peridotites can be calculated for each trace element with the following equation:

$$C_{\mathrm{WholeRock}} = C_{\mathrm{cpx}}\left(\frac{D_{\mathrm{bulk}}}{D_{\mathrm{cpx}}}\right) \tag{1}$$

Where the bulk partition coefficient (D_{bulk}) is determined from modal abundances (x_{mineral}) of olivine (ol), orthopyroxene (opx), clinopyroxene (cpx), and spinel