AN ESTIMATE OF THE MASS OF THE DEPLETED MANTLE Youxue Zhang, Department of Earth & Environmental Sciences, the University of Michigan, Ann Arbor, MI 48109-1005, USA <youxue@umich.edu>

Introduction: The mass of the depleted MORB mantle has been estimated numerous times but the range is large, from the upper mantle to almost the entire mantle [1-4]. Although Salters and Stracke [5] argued that the continental crust (CC) and depleted MORB mantle (DMM) do not seem to be complementary reservoirs, in this report, I reevaluate the mass balance by using all elemental concentrations in the bulk silicate Earth, DMM and CC. In the reevaluation, individual elements are examined to determine which elements agree with the mass balance, and which elements have difficulties to be reconciled, so that future research may explain the discrepancy. It will be shown that for most elements, CC and DMM are complementary and mixing them at some proportions would achieve BSE composition within errors. Based on the result, the mass of DMM is estimated.

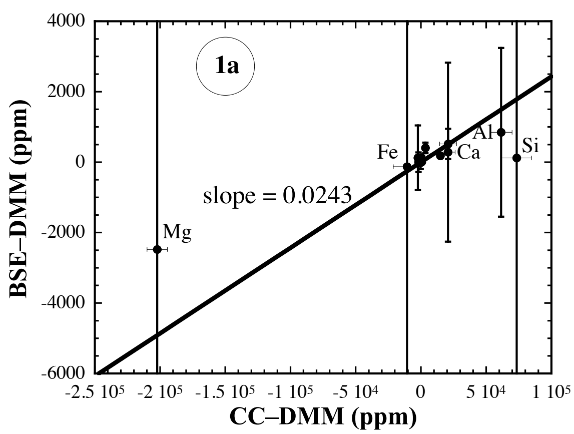
Mass Balance: The mass balance equation is:

$$C_{i,\mathrm{BSE}} = F_{\mathrm{CC}}C_{i,\mathrm{CC}} + (1\text{–}F_{\mathrm{CC}})C_{i,\mathrm{DMM}},$$

where $C_{i,\mathrm{BSE}}$, $C_{i,\mathrm{CC}}$, and $C_{i,\mathrm{DMM}}$ are the concentrations of element i in BSE [6], CC [7] (with relative errors assumed to be two times that for upper crust) and DMM [5], and F_{CC} is the mass fraction of CC and (1–F_{CC}) is the mass fraction of DMM to add up to BSE. Data are available for 52 elements. Hence, F_{CC} can be expressed as:

$$F_{\mathrm{CC}} = (C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}})/(C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}),$$

and calculated for every element i using the concentrations from literature with their estimated errors. Error propagation is used to estimate F_{CC} on every element, and the weighted average of F_{CC} is 0.0243±0.0017. How well individual elements satisfy the mass balance is examined by plotting ($C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}$) vs. ($C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}$), as in Figs. 1a-1d.



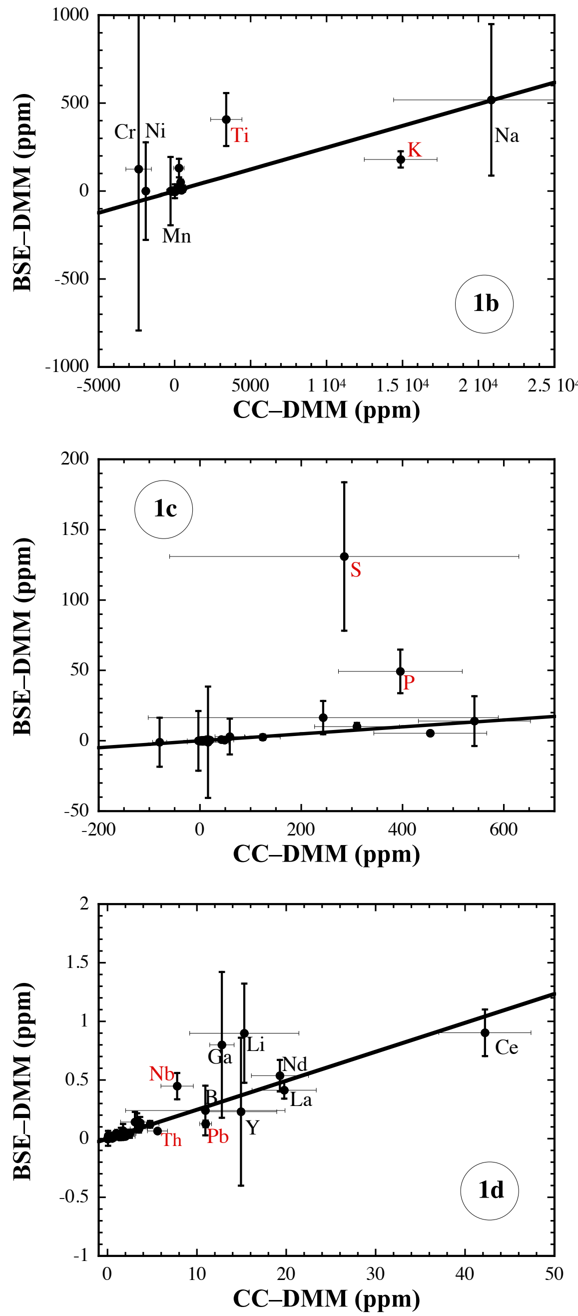


Fig. 1. ($C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}$) vs. ($C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}$), with increasing zooming-in for elements with low concentrations. The solid line is ($C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}$) = 0.0243($C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}$).

Figures 1a-1d reveal that major elements do not provide much constraint, and most trace elements are consistent with CC and DMM being complementary within error, but there are also exceptions, including P, S, Cl, K, Ti, Rb, Nb, Cd, Cs, Ba, Re, Tl, Pb, Bi, Th and U. Another way to view the data more clearly in a single diagram is to plot $\ln|C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}|$ vs. $\ln|C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}|$,

$$\ln|C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}| = \ln|C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}| + \ln F_{\mathrm{CC}},$$

as shown in Fig. 2. Absolute values of concentration differences are used because logarithm of a negative value is not real. If CC and DMM are complementary, the plot should be linear with a slope of 1 with intercept being $\ln F_{\mathrm{CC}}$. As can be seen in Fig. 2, this expectation is satisfied for most elements.

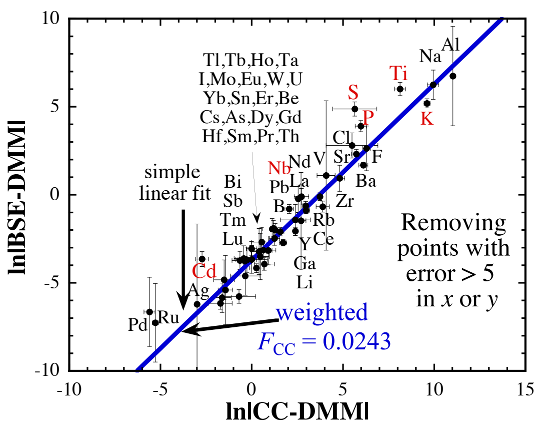


Fig. 2. $\ln|C_{i,\mathrm{BSE}} - C_{i,\mathrm{DMM}}|$ vs. $\ln|C_{i,\mathrm{CC}} - C_{i,\mathrm{DMM}}|$ to show the existence of a linear relation with a slope of 1.

Figures 1 and 2 demonstrate that although there are exceptions, the assumption that CC and DMM are complementary works well for most elements. Exceptions could be real or could be due to errors in estimating the specific concentrations.

Adopting the mass balance model, the mass ratio of CC to DMM is 0.0243:0.9757. Taking the mass of CC to be $(2.18\pm0.02)\times10^{22}$ kg [8], the mass of DMM with average composition in [5] is $(8.75\pm0.64)\times10^{23}$ kg. Adding the mass of CC and oceanic crust, the initial mass of DMM would be $(9.03\pm0.64)\times10^{23}$ kg. Hence, crust+DMM accounts for $(22.4\pm1.6)\%$ of BSE. The mass of crust+DMM corresponds to the mass from the surface to 550-560 km depth, which is somewhat surprising because most estimates would have DMM mass to be at least the upper mantle to 670 km depth. DMM in [9] is not used because fewer elements are assessed. Because DMM in [9] is more depleted, using it would imply an even smaller mass.

An Extraction Model: Although CC is not directly from the partial melting of the mantle, especially in terms of major elements, it is nonetheless interesting to examine whether trace elements in DMM can be related to BSE by treating DMM as mantle residue of partial melting of BSE using assessed partition coefficients of trace elements [9]. A batch melting model is used. If all melt in the partial melting model is extracted from the mantle, the residual mantle would be too depleted in the highly incompatible elements. However, by allowing a small fraction of the melt to be retained by the residual mantle,

$$C_{i,\mathrm{DMM}} = \frac{C_{i,\mathrm{BSE}}}{1-F_{\mathrm{melt}}+F_{\mathrm{kept}}}\left[\frac{F_{\mathrm{kept}}+D_i(1-F_{\mathrm{melt}})}{F_{\mathrm{melt}}+D_i(1-F_{\mathrm{melt}})}\right],$$

DMM composition can be roughly matched by a total degree of partial melting ($F_{\mathrm{melt}}+F_{\mathrm{kept}}$) of 2.8%, with about 0.5% (F_{kept}) retained in the mantle, meaning extraction of ~2.3% of melt (F_{melt}) from the mantle. These percentages vary with choices of mantle compositions and partition coefficients. The fractions of melt extraction to produce DMM and CC from two different methods (~2.3% vs 2.43±0.17%) are roughly consistent, suggesting self-consistency among the models although the results are somewhat surprising.

The Exceptions: Exceptions (those inconsistent with the mass balance model) include P, S, Cl, K, Ti, Rb, Nb, Cd, Cs, Ba, Re, Tl, Pb, Bi, Th and U. For P, S, Cl, Ti, Nb, and Cd, the concentrations in 0.0243(CC)+0.9757(DMM) are lower than that in BSE. For K, Rb, Cs, Ba, Tl, Pb, Bi, Th and U, the concentrations in 0.0243(CC)+0.9757(DMM) are higher than in BSE. Some of these are easy to explain. For example, Cl in the oceans would be able to reconcile this element. Some have been noted before (e.g., Hofmann et al., 1986; Saunders et al., 1988). Some might be due to errors in the estimations. Note that all heat-generating elements, K, Th and U, are not reconciled. Future research will shed light on the elements for which CC and DMM are not complementary.

Summary: Mixing CC and DMM at 0.0243: 0.9757 proportion would roughly produce the BSE. In addition, average DMM may be viewed to be produced from the upper mantle by 2.9% partial melting, of which 2.4% is extracted to eventually form the continental crust, and the remaining 0.5% melt and the residual solid phases forming DMM. The mass of DMM is about 83% of that of the upper mantle.

References: [1] Zindler & Hart, 1986, Annu. Rev. Earth Planet. Sci., 14, 493. [2] Zhang & Zindler, 1989, JGR, 94, 13719. [3] Zhang, 2014, Treatise on Geochem. (2nd ed), 6, 37. [4] Stracke, 2015, Encycl. Mar. Geosci., DOI 10.1007/978-94-007-6644-0_11-4. [5] Salters & Stracke, 2004, G^3, 5, Q05004. [6] McDonough & Sun, 1995, Chem. Geol., 120, 223. [7] Rudnick & Gao, 2014, Treatise on Geochem. (2nd ed), 4, 1. [8] Peterson & DePaolo, 2007, Mass and Composition of the Continental Crust Estimated Using the CRUST2.0 Model, AGU abstract. [9] Workman & Hart, 2005, EPSL, 231, 53. [10] Hofmann et al., 1986, EPSL, 79, 33. [11] Saunders et al., 1988, J. Petrol., 29, 415.