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Probing Chemical Heterogeneity of the Mantle Using Open System Isotopic Models of the Silicate Earth

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ABSTRACT
The layering and convection within the Earth's mantle plays a major role in the formation of continental crust as well as tectonic activities and the heat budget of the Earth. The mode of mantle convection (whole versus layered) is still debatable despite concerted geophysical and geochemical studies for the past several decades. This study is an exhaustive numerical approach to develop an open system geochemical model for the Earth comprising bulk continental crust (CC), depleted upper mantle (UM)–source of mid–ocean ridge basalts (MORB), a lower non-chondritic mantle (LM)–source of ocean island basalts (OIB), and an isolated reservoir (IR). The model is solved numerically using fourth-order Runge-Kutta method at 1 Ma time step over the age of the Earth, simulating the evolution of key radioactive isotope systems in terrestrial reservoirs. Coupled Rb–Sr, Sm–Nd, and U–Th–Pb isotope systematics will constrain various aspects related to the Earth's differentiation processes leading to chemical heterogeneity within the mantle. Various crustal growth scenarios (linear vs. non-linear, early vs. delayed, and continuous vs. episodic growth) and their effects on the evolution of isotope systematics in the silicate reservoirs have been evaluated. The most plausible model-derived solution is the one that produces the present–day concentrations as well as isotopic ratios in the terrestrial reservoirs, constrained from published data. Modeling results suggest that a whole mantle (compositionally similar to the present–day MORB) model fails to satisfy observational constraints. However, a layered mantle model, in which the present–day UM is ~ 60% of total mantle mass and the lower mantle is non–primitive produced the required isotopic ratios and abundances in the terrestrial reservoirs. Modeling also suggests that isotopic evolution in reservoirs is strongly affected by the mode of crustal growth. It is observed that Pb paradoxes result from open system evolution, which allows large-scale mass exchange between reservoirs.

Key words: Mantle convection, open system modeling, crustal growth pattern, Pb paradox.

INTRODUCTION

Several geochemical approaches have been adopted to study layering and convection in the mantle, which includes mass balance models (Jacobsen and Wasserburg, 1981; Turcotte et al., 2001), open system evolution models consisting both forward transport modeling and inverse approach (e.g., Kramers and Tolstikhin, 1997; Allègre et al., 1983; Paul et al., 2002; Kellogg et al., 2002 and 2007) . This study presents a four–reservoir open system evolution model of the Earth comprising a bulk continental crust (CC), a depleted upper mantle (UM) that is source of mid– Ocean ridge basalts (MORB), an enriched lower mantle (LM) that is source of plume– derived ocean island basalts (OIB), and a highly–enriched isolated reservoir (IR) at the base of the mantle where majority of the subducted lithospheric material is stored. The term "depleted and enriched" are used with reference to highly incompatible trace elements. Incorporating Rb–Sr, Sm–Nd, Lu-Hf and U–Th–Pb isotope systematics, isotopic evolution in terrestrial reservoirs is numerically simulated with time (age of the Earth) from an initial to its final state (t = 4.55 Ga; age of the Earth) that is constrained by the present–day compositions.

Further, the secular growth of the continental crust may have been largely affected the distribution of chemical heterogeneities within the mantle to the extent of producing chemically distinct layers. In other words, continuous production of crust, episodic production at certain time intervals, higher growth initially followed by negligible growth etc. as well as recycling of this crustal material at different times will affect the timing of depletion of highly incompatible radioactive parents in the mantle and consequential enrichment in the crust. This, in turn would affect the evolution of daughter isotopic compositions in the respective reservoirs. Therefore, growth of continental crust with time should be an important constraint in open system models. One of the key goals of this study is to understand the means and to quantify the mass transfer processes between different portions of the Earth through the geologic time in an open system isotope evolution model.

METHODOLOGY

In our model (schematics shown in Figure 1), the continental crust grows at the expense of magmatic fluxes from both the upper and lower mantle. Also the mass of

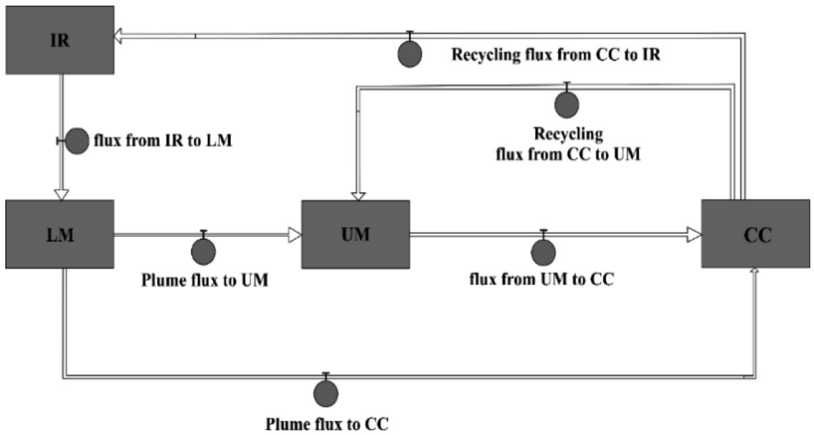

Figure 1. Open system mass transfer model considered in this study. Input and output flux to the reservoir is shown by arrows. UM– Depleted Upper Mantle; LM– Lower Mantle; CC–Bulk Continental Crust; IR-Isolated Reservoir.

UM is a function of input fluxes such as plume flux from LM, recycling flux from CC and the output flux from UM to the CC. Similarly, LM mass grows due to incoming flux from CC that is stored in the IR reservoir at first and then slowly mixed with the LM after a transit time of about one billion years. LM also contributes to the growth of UM and CC in the form of rising plume.

Mathematically, the rate of change of mass of the continental crust can be expressed as

$$\frac{dM_{CC}}{dt} = F_{LM\rightarrow CC} + F_{UM\rightarrow CC} - F^{R}_{CC\rightarrow D\ layer} - F^{R}_{CC\rightarrow UM}$$
$$= c_1 e^{\lambda(b-t)} f_{LM} + c_1 e^{\lambda(b-t)}(1 - f_{LM})$$
$$- c_2 M_C e^{\lambda(b-t)} f_C - c_2 M_C e^{\lambda(b-t)}(1 - f_C) \quad \text{(Eq. 1)}$$

where b and λ are constants and M_{CC} refers to the mass of the continental crust. Initially, $t = 0$, and for the present–day $t = b$, where b represents the age of the Earth. The parameters c_2 are adjusted in different scenarios such that the model must yield present–day mass of the continental crust (M_{CO}); c_1 is a function of c_2. The parameter λ is scaled according to the radiogenic heat generation in the mantle, which is directly proportional to the concentration of heat producing elements (HPE: U, Th and K) in the mantle. f_{LM} and f_C are fractional contributions of LM to the crust and crust to the LM (through IR), respectively. Hence, $1–f_{LM}$ is the fractional contribution of UM to the crust and $1–f_C$ is the fractional contribution of crust to UM. The first two terms on the R.H.S of equation (1) are additive as they are the growth terms (magmatic fluxes from LM and UM to the crust), whereas the other two terms are subtractive as it represents the recycling fluxes from crust to LM and UM. The rate of change of total amount i.e. moles of isotopic species in each reservoir can be specified in a very similar manner as that of the mass transfer. For a given species i (e.g. ^{87}Sr), the flux from reservoir a to reservoir b (F^{i}_{ab}), is a function of the mass flux $F_{a\rightarrow b}$, the concentration of i in reservoir a, and the mean enrichment factor for that species/element during the transfer between the reservoirs. Note that the mean enrichment factor essentially controls the extent of enrichment of the incompatible trace element in the crust, and is a variable parameter in our model.

The initial state of the model is assumed to be of homogeneous chondritic composition, which further differentiated into crust and mantle reservoirs. A set of differential equations fully constraining the Rb–Sr, Sm–Nd, U–Th–Pb isotope systems are solved repeatedly using Runge–Kutta numerical algorithm over the age of the Earth at 1 Ma time steps.

DISCUSSION AND CONCLUSIONS

The geochemical modeling explores how different continental crust extraction models (continuous versus episodic and early versus late and concave upward versus concave downward growths) modify the geochemical evolution of the silicate reservoirs. The objective was to reproduce the present–day isotopic ratios in the UM and crust (shown in Figure 2 as vertical bars in the right-hand side Y-axis), which are well–constrained values from global data bases. Our modeling results strongly favor exponential crustal growth (Brown, 1979). The temporal evolution of 87Sr/86Sr and Nd isotopic ratios (εNd), respectively are shown in Figure 2 for the exponential crustal growth case.

The failure of other crustal growth models (not shown here) in reproducing the present–day isotopic compositions in the CC and mantle reservoirs suggests that neither the production of the entire crust within the first 1 Ga nor the rapid growth in a single event where ~80% of crust formed by the end of Archean within 700 Ma period, are viable scenarios. Particularly, concave upward crustal growth models in which ~50% of crust was formed in the past 1 Ga failed to satisfy isotopic constraints. The simulations show it is possible to resolve the Pb paradox in an evolutionary

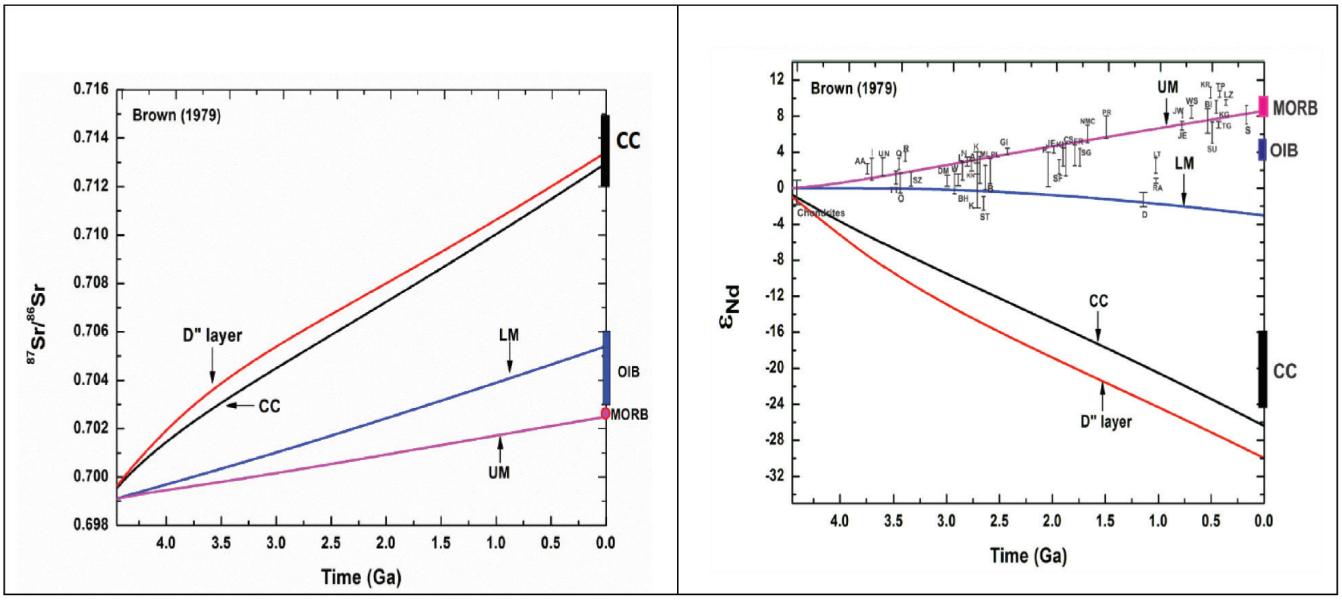

Figure 2. Evolution of Sr and Nd isotopic composition in terrestrial reservoirs in case of the exponential crustal growth model. The model–derived ε_{Nd} evolution pattern in UM is compared with the available initial ε_{Nd} values in mantle–derived products of known age, such as komatiites, other volcanics, granites and ophiolites, compiled by Galer et al., (1989).

model that also matches mass balance constraints. This study represents an important effort to better constrain the chemical and geodynamic evolution of the silicate Earth.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

REFERENCES

Allègre, C.J., Hart, S.R., Minster J.F., 1983. Chemical structure and evolution of the mantle and continents determined by inversion of Nd and Sr isotopic data, II. Numerical experiments and discussion, Earth and Planetary Science Letters, J.66, pp: 191-213.

Brown, G.C., 1979. The changing pattern of batholith emplacement during earth history, In: Atherton, M.P., Tarney, J., (Eds.), Origin of Granite Batholiths. Shiva, Nantwich, UK, pp: 106-115.

Galer, S.J.G., Goldstein, S.L., O'Nions, R.K., 1989. Limits on chemical convective isolation in the Earth's interior, Chemical Geology, v.75, pp: 257-290.

Jacobsen, S.B., Wasserburg, G.J., 1981. Transport models for crust and mantle evolution, Tectonophysics, v.75, pp: 163–179.

Kellogg, J.B., Jacobsen, S.B., O'Connell, R.J., 2002. Modeling the distribution of isotopic ratios in geochemical reservoirs, Earth and Planetary Science Letters. v.204, pp: 183-202.

Kellogg, J.B., Jacobsen, S.B., O'Connell, R.J., 2007. Modeling lead isotopic heterogeneity in mid–ocean ridge basalts, Earth and Planetary science Letters, v.262, pp: 328-342.

Kramers, J.D., Tolstikhin, I.N., 1997. Two terrestrial lead isotope paradoxes, forward transport modelling, core formation and the history of the continental crust, Chemical Geology, v.139, pp: 75-110.

Paul, D., White, W.M., Turcotte, D.L., 2002. Modelling the isotopic evolution of the Earth, Phil. Trans. Royal Society London., v.360, pp: 2433-2474.

Turcotte, D.L., Paul, D., White, W.M., 2001. Thorium–uranium systematics require layered

mantle convection, Journal of Geophysical Research, v.106, no. B3, pp: 4265-4276.

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