MIXING THE TERRESTRIAL MANTLE USING ^{142}Nd/^{144}Nd AS A TRACER AND IMPLICATIONS FOR THE EARTH AND THE MOON.

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Introduction: Modeling major silicate differentiation events and subsequent mixing and stirring of the produced reservoirs is useful for understanding the evolution of rocky planetary bodies such as Earth, the Moon, and Mars. In such an investigation, isotopic variations of certain systems can be used as geochemical tracers to map the extent of heterogeneity present in silicate reservoirs. The Sm-Nd system is one such set of geochemical tracers that is widely used, due to the lithophile behavior of both elements. In particular, the short-lived ^{146}Sm-^{142}Nd system, with a half-life of 68 [1] or 103 [e.g., 2] Ma, has been used in constraining early Earth differentiation events based on rocks formed as early as 3.8 Ga [3, 4]. In contrast, present day (<500 Ma) ^{142}Nd/^{144}Nd ratios of mantle-derived ocean island basalts and MORBs show almost no variation [e.g., 5, 6] at the current analytical precision (2σ = ± 5ppm) of the Themal Ionization Mass Spectrometer (TIMS).

The contrast in the heterogeneities observed as far back as 4 Ga versus none in the present suggests a close tie between the ^{146}Sm-^{142}Nd isotope evolution and the convection process of the terrestrial mantle. We use ^{142}Nd/^{144}Nd as a tracer for modeling mantle stirring as a stochastic process to infer the evolution of the terrestrial mantle. We use the results to understand the possible Giant Impact origin of the Moon and its relation to the early differentiated Earth.

Methods: We assume a terrestrial mantle differentiated into enriched and depleted reservoirs in an early magma ocean [7]. We assign the volume of the present day upper mantle and lower mantle to these two layers. The two reservoirs are stirred and sampled probabilistically [8].

The lower mantle reservoir is assumed to solidify before the upper mantle during the magma ocean solidification. We calculate the depletion or enrichment of Nd relative to the present day Nd abundance of the BSE [9] in each of the two reservoirs. We base calculations on the bulk partition coefficient of Nd for a solid lower mantle of a pyrolitic composition [10, 11] assuming equilibrium fractionation.

The two physical reservoirs throughout the history of the Earth experience mixing through stretching and thinning during convection, where the short length of each mantle reservoir exponentially decreases with time due to deformations of the initial reservoirs [12]:

$$l_t = l_0 e^{-\frac{t}{\tau_{stir}}} \qquad (1)$$

where τ_{stir} is the characteristic time scale of stirring.

We sample the heterogeneities in the whole mantle by placing a box whose side is a length of l_s, which we will refer to as the length scale of sampling. The box contains heterogeneities that are from both the upper (l_{t2}) and the lower mantle (l_{t3}) reservoirs, which are constantly evolving with time (equation 1). The heterogeneities from the two reservoirs are randomly distributed throughout the whole mantle sampling box. We sample the mantle multiple times by calculating the compositions of the sampling boxes for each 100-Ma time step. This procedure generates a set of synthetic Nd data simulating the coverage of μ^{142}Nd measurements that have been made.

Results: Using a stirring rate of 500 Ma [12], a length scale of 150 km and a sampling number of 10 per 100-Ma time step, we calclulated the distribution of μ^{142}Nd as a function of age. The results plotted in Fig. 1 to a first approximation are consistent with the available terrestrial data [e.g., 3–6, 13–17]. Multiple runs with sample sizes varying from 10 to 1000 predict very little ^{142}Nd/^{144}Nd heterogeneity (<1ppm) in the Earth's mantle after 2 Ga.

Implications for the Terrestrial Mantle and the Moon: In treating μ^{142}Nd in the upper and lower mantle reservoirs as free parameters, we find that an upper mantle μ^{142}Nd value of –40 ppm (compared to the terrestrial standard) and a lower mantle μ^{142}Nd value of 20 ppm combined with relative concentrations of Nd present in the upper and lower mantle reservoirs seem to adequately reproduce the pattern of μ^{142}Nd of Hadean rocks to those of the present. The upper and lower mantle μ^{142}Nd values are to be taken as preliminary reference points subject to further investigation. We aim to better constrain Sm/Nd ratios of the two reservoirs by exploring the relative Sm/Nd ratio of the upper mantle reservoir to that of the lower mantle by investigating the partitioning behavior of Sm relative to Nd in a crystallizing magma ocean.

Our results predict no μ^{142}Nd heterogeneities in samples that exceed 1 ppm after 2 Ga, while the current level of TIMS measurements is around 2σ = ± 5ppm. A better understanding the mixing processes of the terrestrial mantle requires higher precision ^{142}Nd/^{144}Nd data for modern terrestrial samples. Heterogeneities in modern samples that are smaller than the current level of instrumental precision and yet larger than the variations observed in our model may either imply sluggish convective mixing of the mantle or isolation of mantle regions from whole mantle convection.

Similarities in geochemical signatures such as oxygen isotopes between the Moon and Earth suggest that the Moon bears an isotopic resemblance to the Earth. If the earliest silicate mantle differentiation event on the Earth predates the giant Moon-forming impact, there is a possibility that the Moon might have retained isotopic signatures of potential layering on the proto-Earth. Current μ^{142}Nd measurements of the bulk Moon suggest a –7.3ppm [18] difference from the terrestrial standard. If a large proportion of the Moon were derived from the proto-Earth, we infer that the one of the early mantle reservoirs that has preferentially supplied material for the Moon must have had a largely negative μ^{142}Nd value as well.

3.8 Ga old Isua samples [3, 17] have been characterized by positive μ^{142}Nd anomalies and are thought to have been derived from the early depleted terrestrial mantle. If the Moon were derived from the enriched portion of the differentiated and layered proto-Earth, the source of the Isua samples and the terrestrial source material of the Moon may have not been identical.

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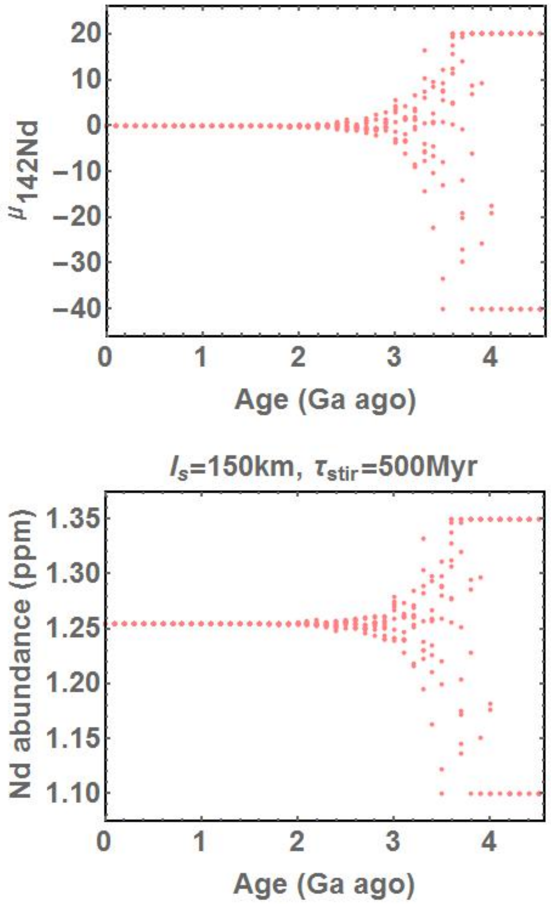

Figure 1: Modeled μ^{142}Nd values for the Earth (upper plot), assuming a lot of 10 samples for each time interval of 100 Ma over a 150 km-long length scale. The lower plot indicates the concentrations of Nd in each of the mantle reservoirs and their sampling throughout the mixing and stirring of the mantle.

$$\mu^{142}\text{Nd}: \frac{\left({}^{142}Nd/{}^{144}Nd_{sample} - {}^{142}Nd/{}^{144}Nd_{s\tan dard}\right)}{{}^{142}Nd/{}^{144}Nd_{s\tan dard}} \times 10^{6}$$