EXTINCT ISOTOPE HETEROGENEITIES IN THE MANTLES OF EARTH AND MARS: IMPLICATIONS FOR MANTLE STIRRING RATES.

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Introduction: Extinct isotope heterogeneity (such as ^{182}W and ^{142}Nd) in basalts from martian meteorites demonstrates the existence of very early geochemical heterogeneity in martian mantle. This heterogeneity is likely to be the consequence of accretion and core formation [1], solidification of magma ocean and/or other early mantle differentiation events [6]. In contrast, for the same extinct isotope systems, young terrestrial basalts show no detectable heterogeneity in spite of the data requiring these systems to be fractionated during the lifetime of their parent nuclides (^{182}Hf and ^{146}Sm) in the early Earth. For example, a core formation process in a deep magma ocean has been suggested for both Earth and Mars to explain siderophile element depletion in their mantles [2-5]. As a consequence of the “deep magma ocean” core formation process, [1] has argued both early Earth and Mars would have a very early two-mantle-reservoir structure with different W isotopic compositions.

Model constraints: Here we report results based on a stochastic model for mantle mixing or stirring and basalt sampling in Earth and Mars following the principles of [7]. We focus here on application to W isotopes but the principles are generally applicable to any other extinct isotope system. The primary constraint for Mars is the fact that two groups of martian meteorites W isotopic compositions: shergottites have a $\varepsilon_{W(CHUR)}$ of 2.23 ±0.21 and nakhlites+chassignites have a $\varepsilon_{W(CHUR)}$ of 5.15 ±0.50 [6]. These may represent distinct early martian upper and lower mantle, respectively, consistent with their formation during the deep magma ocean core formation process. A similar early mantle structure is likely to have been present in the early Earth but all young terrestrial basalts show a homogeneous W isotopic composition of $\varepsilon_{W(CHUR)} = 1.9 \pm 0.1$ and thus provide no direct evidence for this. As Mars is a smaller planet it must have cooled down faster than the Earth and convective mixing is not likely to have had as significant an effect in stirring the martian mantle compared to the Earth’s mantle. Thus, we will explore the relative constraints that the ^{182}Hf-^{182}W isotopic system places on the convective mixing rates of an early layered mantle structure for both Earth and Mars.

Model setup: The evolution of an initial layered mantle structure and its development into a heterogeneous mantle by mantle convection is modeled following the principles of [7]. The mantle heterogeneity scale l_h is exponentially decreasing over time (t) and described as:

$$l_h(t) = l_h(0)e^{-\frac{t}{\tau_{stir}}}$$

where τ_{stir} is the characteristic time scale of stirring. This is due to deformation and stretching of the initial reservoir structure in the turbulent regime. Here, we consider a simplified initial mantle heterogeneity, which only includes two-layer mantles with different W isotopic composition (**Fig. 1**), corresponding to the W isotopic compositions of shergottites and nakhlites+chassignites. This is the initial state expected to be produced by the core formation process in a deep magma ocean, but with a solid lower mantle [1]. After a certain time t, the shortest dimensions of the two mantle reservoirs become l_{2t} and l_{3t}(**Fig. 1**), which are critical to the sampling problem. As shown in **Fig. 1**, we modeled the mantle heterogeneity as a random distribution of cubes with lengths of l_{2t} and l_{3t} in the planetary mantles.

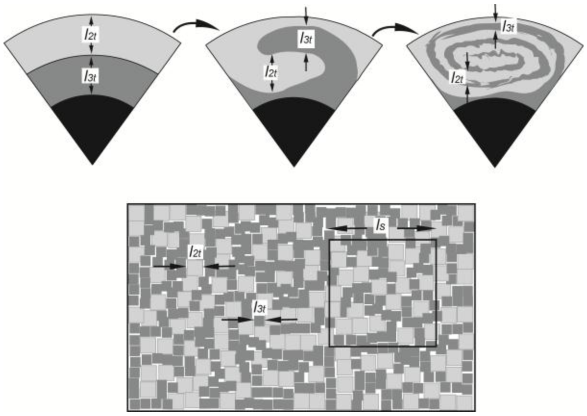

Fig. 1. Two-dimensional cartoon showing the mixing (upper part) and sampling (lower part) models.

The sampling function is first to randomly choose the sampling target (cubes) following a binomial distribution and then stochastically determine the sampling proportion of that target following a multinomial distribution or a poisson distribution depending on sampling size. The sampling results are then used to calculate the W isotopic composition of samples.

Results (Fig. 2): The distribution of the W isotopic composition of 1000 randomly selected mantle samples is solely determined by the ratio of l_s and l_t, where l_s is the sampling length scale of mantle-derived basalts and l_t is the smaller mantle heterogeneity scale of l_{2t} and l_{3t}. When the mantle heterogeneity scale is very small ($l_s/l_t \geq 20$), 95% of the samples show the average value of W isotopic compositions of two mantle reservoirs and the mantle heterogeneity cannot be observed despite it does exist (top panel of **Fig. 2**).

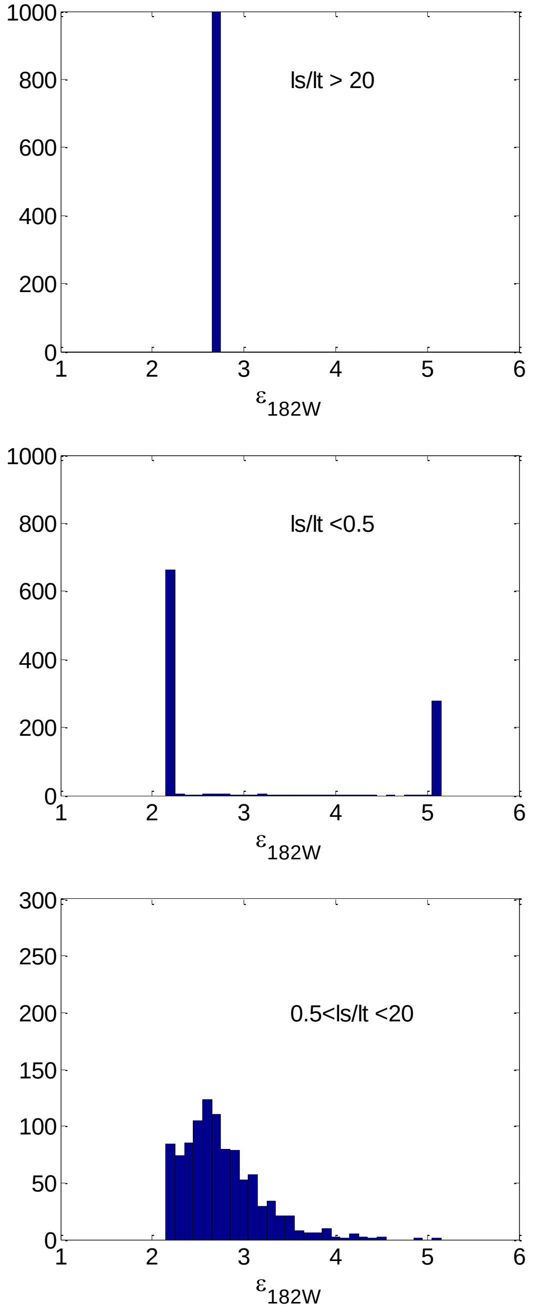

Fig. 2 Histograms of synthetic W isotope data (binned at 0.1 ϵ unit, for various ratios of l_s/l_t).

When the mantle heterogeneity scale is significantly larger ($l_s/l_t \leq 0.5$), 95% of the samples show W isotopic composition of either mantle reservoirs and demonstrate the original mantle heterogeneity (middle panel of Fig. 2).

Other cases between these two shows a mixing pattern of W isotopic compositions of two mantle reservoirs (lower panel of **Fig. 2**).

Based on the "deep magma ocean" core formation model, the initial mantle W isotope heterogeneity scale in both Earth and Mars are comparable (~780 km) [1, 8]. A sampling size of 30 km is assumed for both Earth and Mars. Then mantle stirring rate can be calculated to be τ_{stir} ≤730 Myr for $l_s/l_t \geq 20$ and τ_{stir} ≥1780 Myr for $l_s/l_t \leq 0.5$, corresponding to the cases for earth and Mars, respectively.

It has been shown by [7] that the present Earth mantle heterogeneities for the long-lived isotopic systems (^{87}Rb-^{87}Sr and ^{147}Sm-^{143}Nd) can be modeled with a 500 Myr stirring time and 30-100 km sampling size. These parameters imply a W isotopic heterogeneity scale of ~84 m in Earth's mantle today, and a homogeneous W isotopic composition for all modern terrestrial basalts. This is consistent with direct measurements of W isotopes in young terrestrial basalts.

In contrast, based on the measure W isotopic composition of martian rocks, we can constrain the mantle stirring rate (τ_{stir}) for Mars to be ≥1780 Myr, which corresponds to a at least 60 km W isotopic mantle heterogeneity in Mars, at least 700 times larger than that in the Earth. Modeling the long-lived isotopic systems (^{87}Rb-^{87}Sr and ^{147}Sm-^{143}Nd) for Mars we obtain a relatively consistent τ_{stir}-value in the range 2000 to 2500 Myr.

The parameters derived for the Earth also predict that mantle heterogeneity for extinct isotope systems (^{182}Hf-^{182}W and ^{146}Sm-^{142}Nd) should be present at the time of the oldest terrestrial crustal rocks at Isua west Greenland – consistent with observations.

Conclusions: On the basis of both extinct (^{182}Hf-^{182}W and ^{146}Sm-^{142}Nd) and long-lived (^{87}Rb-^{87}Sr and ^{147}Sm-^{143}Nd) isotope systems we have shown that the mantles of Earth and Mars exhibit substantially different mixing or stirring rates (τ_{stir}-values of ~500 Myr and 2000 Myr, respectively). This is consistent with the expectation that Mars cooled down faster than the Earth. It remains to use this new constrain in quantitative models for the thermal evolution of both planets.

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