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Effects of magma ocean crystallization and overturn on the development of ^{142}Nd and ^{182}W isotopic heterogeneities in the primordial mantle

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A B S T R A C T

One possible mechanism to explain the observed variability of the short-lived $^{146}Sm \rightarrow {}^{142}Nd$ and $^{182}Hf \rightarrow {}^{182}W$ systems recorded in some early Earth rocks is crystal–liquid fractionation and overturn in an early magma ocean. This process could also potentially explain the deviation between the ^{142}Nd isotopic composition of the accessible Earth and the chondritic average. To examine these effects, the magma ocean solidification code of Elkins-Tanton (2008) and a modified Monte Carlo algorithm, designed to randomly choose physically reasonable trace element partition coefficients in crystallizing mantle phases, are used to model the isotopic evolution of early Earth reservoirs. This model, also constrained by the ^{143}Nd composition of the accessible Earth, explores the effects of changing the amount of interstitial liquid trapped in cumulates, the half-life of ^{146}Sm, the magnitude of late accretion, and the simplified model of post-overturn reservoir mixing. Regardless of the parameters used, our results indicate the generation of early mantle reservoirs with isotopic characteristics consistent with observed anomalies is a likely outcome of magma ocean crystallization and overturn of shallow, enriched, and dense (i.e., gravitationally unstable) cumulates. The high-iron composition and density of a hypothesized, early-formed enriched mantle reservoir is compatible with seismic observations indicating large, low-shear velocity provinces (LLSVPs) (e.g., Trampert et al., 2004) present in the mantle today. Later melts of an enriched reservoir are likely to have remained isolated deep within the mantle (e.g., Thomas et al., 2012), consistent with the possibility that the presently observed LLSVPs could be partially or fully composed of remnants of an early enriched reservoir.

1. Introduction and motivation

The record of ^{142}Nd and ^{182}W variability. High precision isotopic measurements of extinct radionuclides have shed light on the formation and evolution of the early Earth (Caro et al., 2003; Boyet and Carlson, 2005; Willbold et al., 2011). For example, $^{146}Sm \rightarrow {}^{142}Nd$ (half-life = 103 Myr or 68 Myr) and $^{182}Hf \rightarrow {}^{182}W$ (half-life = 8.9 Myr) isotopic systematics are ideal for studying early magmatic processes because the parent isotopes became essentially extinct within 500 Myr and 60 Myr, respectively, of Solar System formation. The two systems are also complementary in that they behave differently from the standpoint of geochemical fractionation of parent and daughter elements: Hf, Sm, and Nd are strongly lithophile trace elements, while W is moderately siderophile. Hence, the study of the combined systems can potentially be used to distinguish between various, large-scale, early Earth processes.

Rocks from the lithologically diverse ∼3.8 Ga Isua Greenstone Belt (Caro et al., 2003; Willbold et al., 2011) and the ∼3.8 Ga or ∼4.4 Ga Nuvvuagittuq Greenstone Belt (O'Neil et al., 2008, 2012; Touboul et al., 2014) have resolvable excesses of 10–20 ppm in both ^{182}W and ^{142}Nd; the Nuvvuagittuq suite also preserves ^{142}Nd depletions. Isotopic anomalies for these systems are reported as μ values, which are the deviations from the terrestrial standard in parts per million (ppm). The ∼2.8 Ga komatiites from the Kostomuksha Greenstone Belt also have well resolvable excess μ^{182}W values of ∼14 ppm (Touboul et al., 2012) but a modern μ^{142}Nd value of 0 (Boyet and Carlson, 2006). By contrast,

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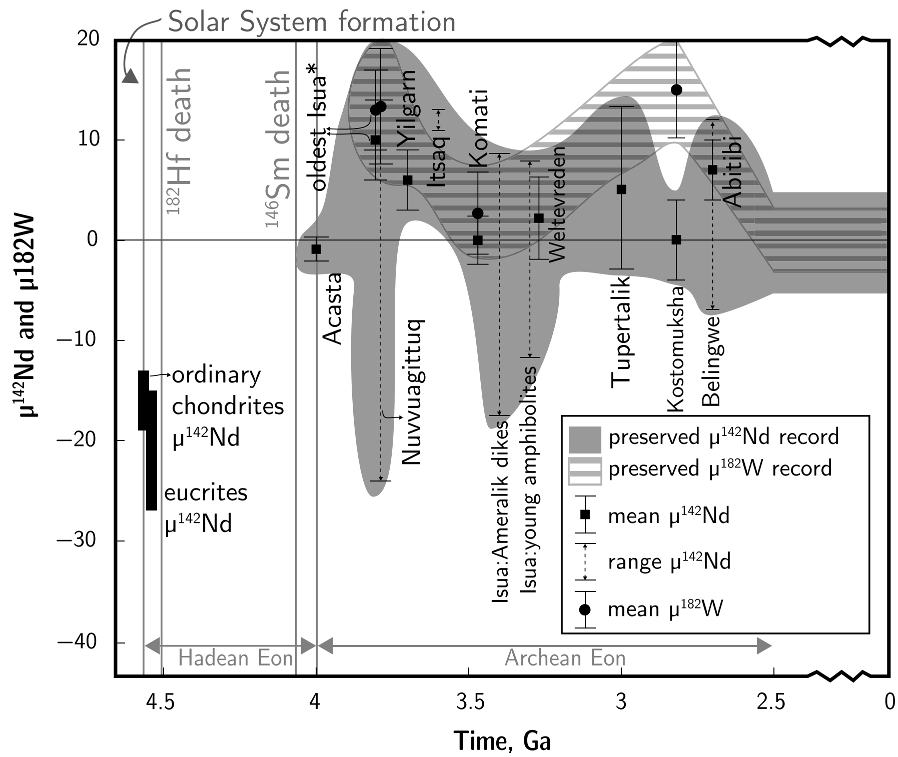

Fig. 1. Compilation of presently available short-lived radioisotopic signatures preserved in the rock record. If reported, a location-based average isotopic anomaly is plotted. Otherwise, a dashed line is plotted to span the range of data for a specific location. *The oldest Isua data are plotted slightly offset from the 3.8 Ga date to clearly distinguish the data from the Nuvvuagittuq data. The oldest Isua data are from Willbold et al. (2011) and Caro et al. (2006) because they report both μ^{142}Nd and μ^{182}W for the same Isua rock samples. However, the extended range reported by many other studies in similar and nearby rocks (e.g. the oldest Istaq complex samples from Bennett et al., 2007), up to +20 ppm, is reflected in the grey shading of μ^{142}Nd (the full compilation is given by Rizo et al., 2013). Data are from Caro et al. (2006), Boyet and Carlson (2006), Bennett et al. (2007), Carlson and Boyet (2008), Willbold et al. (2011), O'Neil et al. (2012), Rizo et al. (2012), Touboul et al. (2012), (2014), Puchtel et al. (2013), Rizo et al. (2013), Debaille et al. (2013). Chondrite and eucrite range taken from Carlson and Boyet (2008). The 68 Myr half-life of ^{146}Sm was used by Rizo et al. (2013) to calculate a 3.3 Ga Lu–Hf/Sm–Nd age of Isua: young amphibolites (the corresponding U–Pb age is 3.01 Ga). All other ages were determined using U–Pb, Pb–Pb, or Re–Os systematics. The Nuvvuagittuq data are plotted using the zircon date.

the ∼3.5 Ga Komati komatiites from the Barberton Greenstone Belt are characterized by a modern μ^{142}Nd value of 0 and also a μ^{182}W that is unresolved from modern ^{182}W (Touboul et al., 2012; Puchtel et al., 2013), which indicates that these isotopic anomalies were not uniformly distributed during early Earth history. Collectively, studies of ^{142}Nd in other early Earth rocks have shown a general, non-linear age trend (Fig. 1) of both positive and negative anomalies decreasing towards the present, which largely disappear by ∼2.7 Ga (e.g., Rizo et al., 2013). So far only the Isua Greenstone Belt samples appear to record variations in both ^{142}Nd and ^{182}W (Caro et al., 2003; Willbold et al., 2011), but open-system behavior (i.e., W mobility), mixing, or fractionation after ^{182}Hf was no longer extant but before ^{146}Sm became extinct, could have led to a decoupling of the two isotopic systems of the early Earth rocks or their mantle sources (Touboul et al., 2014).

Boyet and Carlson (2005) reported that modern terrestrial rocks have ∼20 ppm higher μ^{142}Nd values than the chondritic average. There are at least three possible explanations for this difference: (1) the Earth formed from primitive materials enriched in Sm, relative to Nd, compared to the chondritic average; (2) the Earth was constructed largely from materials enriched in *s*- and/or *p*-process isotopes (Carlson et al., 2007; Gannoun et al., 2011); (3) a low Sm/Nd reservoir with negative μ^{142}Nd formed early in the Earth or in precursor materials and was isolated (Boyet and Carlson, 2005; Labrosse et al., 2007) or collisionally eroded away (Caro et al., 2006; O'Neill and Palme, 2008).

Options (1) and (2) may be unlikely because those primitive materials are rare. Additionally, nucleosynthetic heterogeneity may not be sufficient to account for the offset (i.e., Carlson et al., 2007; Caro, 2011; Gannoun et al., 2011; Qin et al., 2011). Consequently, here we quantitatively explore whether option (3) is a viable process in light of the observed μ^{142}Nd and μ^{182}W variations in observed in early Earth rocks, but consider the consequences of (1) and (2).

Processes that control μ^{142}Nd and μ^{182}W after the Earth accreted. Variations in μ^{142}Nd can only be produced by crystal–liquid fractionation in the silicate Earth within the lifetime of ^{146}Sm; (1) and (2) from above cannot lead to variations in ^{142}Nd after accretion. However, additional processes must be considered as possible causes for ^{182}W variations in the mantle, such as:

1. Addition of late accreted materials with bulk chondritic compositions (μ^{182}W ∼ −200) to the mantle.
2. Addition of a core component (μ^{182}W ∼ −220) to the mantle.
3. Merging of a differentiated impactor's mantle with Earth's mantle.
4. Metal–silicate equilibration, while ^{182}Hf was extant, resulting in variable modification of Hf/W in the mantle during core-segregation.
5. Crystal–liquid fractionation in the silicate Earth occurring while ^{182}Hf was extant by either:
   (a) Partial melting of the mantle;
   (b) Magma ocean differentiation.

Late accretion and core–mantle interactions (processes 1 and 2) would cause the μ^{182}W value of normal mantle to decrease. A core-merging giant impact (process 3) could also potentially cause the μ^{182}W of the mantle to increase, but such a high-energy impact would also likely result in a new partial or full magma