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Differentiation mechanisms of the early Hadean mantle: Insights from combined ^{176}Hf-^{142,143}Nd signatures of Archean rocks from the Saglek Block

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Abstract

Positive ^{142}Nd anomalies in Eoarchean rocks provide evidence for early (4.40 ± 0.03 Ga; Morino et al., 2017) depletion of Earth's mantle. This model age lies within errors of the Pb-Pb "age of the Earth" (Connelly and Bizzarro, 2016), and is similar to model ages inferred for crystallization of the lunar mantle (McLeod et al., 2014), implying that this large-scale event may reflect crystallization of a magma ocean following the Moon-forming impact. However, differentiation mechanisms responsible for the formation of this early depleted mantle reservoir and the depth at which it formed cannot be constrained from the Sm-Nd isotope system alone, because the magnitude of Sm/Nd fractionation during partial melting or fractional crystallization shows little dependence on pressure-controlled changes in mantle mineralogy. In contrast, the Lu-Hf isotope system is highly dependent on mineralogy, notably the presence or absence of garnet, an upper mantle phase, and thus may be used to constrain the pressure of fractionation. This study provides the first ^{176}Lu-^{176}Hf isotopic results on mafic and ultramafic rocks belonging to the Eoarchean (Nulliak) and Mesoarchean suites of the Saglek Block (northern Labrador, 3.2–3.9 Ga). The ^{176}Lu-^{176}Hf dating confirms the distinction between these two groups of rocks and provides ages consistent with those obtained from ^{147}Sm-^{143}Nd dating. The whole rock ^{176}Lu-^{176}Hf errorchrons yield ages and initial epsilon values of 3766 ± 140 Ma, $\varepsilon^{176}Hf_i = 6.0 \pm 2.5$ and 3023 ± 390 Ma, $\varepsilon^{176}Hf_i = -0.3 \pm 2.5$ for the Nulliak suite and the Mesoarchean suite respectively. The time-integrated ^{176}Lu/^{177}Hf for the sources of the Nulliak and the Mesoarchean suites considering a time of differentiation at 4.40 ± 0.03 Ga are estimated to be 0.047 ± 0.005 and 0.033 ± 0.005, respectively. For the Mesoarchean samples, the combined ^{146,147}Sm-^{142,143}Nd and ^{176}Lu-^{176}Hf data are consistent with a near-chondritic mantle source. On the other hand, Nulliak ultramafic rocks were derived from a mantle reservoir with superchondritic Lu/Hf and Sm/Nd. The Nulliak parent reservoir, however, does not plot on the ε^{176}Hf-ε^{143}Nd mantle array defined by modern oceanic basalts. Instead, the Nulliak source more likely belongs to a distinct array defined by Eo- and Meso-Archean komatiites. These results are interpreted in the framework of a simple model of crystallization of a primordial magma ocean. It appears that the fractionation observed in the mantle source of Nulliak was most likely generated by crystallization of a garnet-bearing assemblage in the shallow mantle, above the transition zone rather than by perovskite fractionation in the lower mantle. To preserve this depleted reservoir from the rest of the hot and vigorously convecting mantle, the Nulliak mantle source may have been isolated either at the top of the mantle in a buoyant lithosphere or near the core-mantle boundary, with the latter setting being more consistent with the komatiitic nature of the erupted rocks. Given that the garnet signature argues for differentiation of the Nulliak source at relatively shallow depth (few hundred kilometers), its isolation in the deep mantle would require a cumulate overturn following crystallization of the magma ocean.

Keywords: ^{176}Hf-^{142,143}Nd; Magma ocean; Differentiation; Nulliak; Hadean

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1. INTRODUCTION

Models of planet formation indicate that the final stage of Earth's accretion was punctuated by highly energetic collisions with planetary embryos (Chambers and Wetherill, 1998), following their rapid growth from a swarm of planetesimals (Chambers, 2004; Morbidelli et al., 2012). The last of these collisions (Canup and Asphaug, 2001), likely the Moon-forming impact, is believed to have induced large-scale melting of the proto-Earth's mantle, generating a global magma ocean that may have extended down to the core-mantle boundary (CMB) (Canup, 2004). Magma ocean crystallization could potentially have resulted in gross chemical stratification of Earth's mantle (Ohtani, 1985), sequestration of a basal molten layer near the CMB (Labrosse et al., 2007; Coltice et al., 2011) and the extraction of a primordial crust by upward migration of residual melts (Caro et al., 2005; Bourdon and Caro, 2007). Nevertheless, the long-term consequences of this event on the structure and composition of Earth's mantle, as well as the ultimate fate of primordial silicate reservoirs remain speculative, obscured by 4.5 Gyr of geodynamic activity and complete rejuvenation of Earth's surface. Our understanding of primary differentiation processes thus mainly relies on indirect observations based on short-lived radioactive decay systems (Caro et al., 2003; Touboul et al., 2012; Mukhopadhyay, 2012; Caracausi et al., 2016; Rizo et al., 2016; Mundl et al., 2017; Peters et al., 2018), which provide temporal and compositional information on primordial silicate reservoirs. One of these observations is that positive ^{142}Nd anomalies (i.e. high ^{142}Nd/^{144}Nd compared to the homogeneous value of the present-day mantle) are present in Archean terranes of West Greenland and Northern Canada (Caro et al., 2006; Bennett et al., 2007; Debaille et al., 2013; Morino et al., 2017). Such anomalies were produced by decay of now extinct ^{146}Sm ($T_{1/2} = 103$ Myr) in a mantle reservoir that was depleted in incompatible elements near the end of terrestrial accretion, at 4.40 ± 0.03 Ga (Morino et al., 2017). This reservoir (hereafter referred to as Early Depleted Mantle or EDM) was episodically sampled by Archean magmatism at least until 2.7 Gyr ago (Debaille et al., 2013). Model age calculations using coupled ^{146,147}Sm-^{142,143}Nd chronometry indicate that the differentiation event responsible for the formation of the EDM predated late-stage crystallization of the lunar magma ocean by <50 Ma (Solomon and Longhi, 1977; Boyet and Carlson, 2007; Borg et al., 2011; Elkins-Tanton et al., 2011; McLeod et al., 2014). This time interval is consistent with slower cooling of the residual lunar magma ocean under the blanketing effect of a thick anorthositic crust (Elkins-Tanton et al., 2011). The ^{146,147}Sm-^{142,143}Nd age of the EDM also lies within error of the Pb-Pb age of the Earth, at ca. 4.42 ± 0.01 Ga (Connelly and Bizzarro, 2016), which was suggested to record Pb loss by devolatilization or by sequestration in the core during the giant impact phase of accretion (Oversby and Ringwood, 1971; Wood et al., 2006; Lagos et al., 2008; Wood et al., 2010; Connelly and Bizzarro, 2016). Collectively, these chronological constraints point towards a major differentiation event at ca. 4.40 Ga, possibly triggered by the Moon-forming impact, and ultimately resulting in global chemical differentiation of the mantle-crust system.

While the chronological aspects of early mantle differentiation are well established from coupled ^{146,147}Sm-^{142,143}Nd systematics, fundamental uncertainties still remain as to the physical process that produced the depleted reservoir carrying positive ^{142}Nd anomalies. Preservation of primordial mantle domains on a billion year timescale requires long-term isolation from the convective system (Morino et al., 2017). This observation is consistent with creation of positive ^{142}Nd anomalies in a chemically buoyant lithospheric mantle, which may have been preserved from rehomogenization as part of a long-lived Hadean stagnant lid (Debaille et al., 2013; Caro et al., 2017). Alternatively, the presence of positive ^{142}Nd anomalies in Eoarchean rocks may reflect entrainment within hot plumes of perovskitic cumulates formed by fractional crystallization of a basal magma ocean (Labrosse et al., 2007). The ^{146,147}Sm-^{142,143}Nd systems alone cannot provide definitive constraints on this issue because the magnitude of Sm/Nd fractionation during partial melting or fractional crystallization shows little dependence on pressure-controlled changes in mantle mineralogy, i.e., Sm is less incompatible than Nd throughout the mantle, so cumulates with moderately elevated Sm/Nd would be produced at all mantle depths. To circumvent this limitation, Caro et al. (2005) proposed an approach based on coupled ^{146,147}Sm-^{142,143}Nd and ^{176}Lu-^{176}Hf systematics, with the aim of fingerprinting the crystallization of Mg-perovskite (bridgmanite) at lower mantle pressures. Unlike Sm/Nd, Lu/Hf partitioning is strongly dependent on mantle mineralogy (e.g. Salters and White, 1998; Corgne and Wood, 2004). At upper mantle pressures pertaining to partial melting and/or fractional crystallization in the presence of garnet, Lu is less incompatible than Hf. Crystallization of a shallow (<660 km) magma ocean is thus expected to generate positively correlated Lu/Hf and Sm/Nd fractionations, provided that melt segregation proceeded faster than upward migration of the solidification front (Solomatov and Moresi, 1996; Solomatov and Louis, 2007). In contrast, at lower mantle pressures in the presence of bridgmanite, Hf becomes more compatible than Lu (Corgne et al., 2005), so that crystallization of a deep magma ocean is expected to produce negatively correlated Lu/Hf and Sm/Nd fractionations (Caro et al., 2005). The ^{176}Hf-^{143}Nd signatures of Eoarchean rocks carrying ^{142}Nd anomalies, which ultimately reflect the time-integrated Lu/Hf and Sm/Nd of their sources, thus have the potential to provide important constraints on the depth and processes pertaining to differentiation of the EDM.

The approach outlined above requires determination of both the Sm/Nd and Lu/Hf of the mantle reservoir hosting the positive ^{142}Nd anomaly. While the former can be precisely determined from coupled ^{146,147}Sm-^{142,143}Nd systematics (Caro et al., 2003; Caro et al., 2006; Bennett et al., 2007; Rizo et al., 2011; O'Neil et al., 2016), previous attempts to estimate $(Lu/Hf)_{EDM}$ from Eoarchean mafic rocks of the Isua Supracrustal Belt (ISB, West Greenland; 3.7–3.8 Ga) yielded conflicting results. Rizo et al. (2011) and Hoffmann et al. (2011) reported unradiogenic initial