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Chemical stratification in the post-magma ocean Earth inferred from coupled ^{146,147}Sm–^{142,143}Nd systematics in ultramafic rocks of the Saglek block (3.25–3.9 Ga; northern Labrador, Canada)

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ABSTRACT

The coupled ^{146,147}Sm–^{142,143}Nd chronometer has the potential to provide precise constraints on both the age and the composition of silicate reservoirs generated by magma ocean processes on accreting planets. Application of this chronometer to early Earth differentiation, however, is made difficult by the poor preservation and complex geological history of Eoarchean rocks hosting ^{142}Nd anomalies, which often prevents accurate determination of their initial ^{143}Nd/^{144}Nd ratios. In order to better constrain the chronological aspects of Earth's formation, we investigated the ^{146,147}Sm–^{142,143}Nd systematics of well-preserved mafic/ultramafic enclaves of the Archean Saglek block of northern Labrador (3.25–3.9 Ga). Our results show that two distinct ultramafic suites are present within the Hebron/Saglek fjords region. The first group of samples, with $\mu^{142}\text{Nd} = 1.6 \pm 2.8$ and $\varepsilon^{143}\text{Nd}_i = 0.4 \pm 0.4$, yields a whole-rock isochron age of 3365 ± 100 Ma and is tentatively suggested to be associated with the Mesoarchean Upernavik formation. The second group, with $\mu^{142}\text{Nd} = 8.6 \pm 3.3$ ppm and $\varepsilon^{143}\text{Nd}_i = 1.4 \pm 0.6$, yields an Eoarchean date of 3782 ± 93 Ma, and is assigned to the Nulliak assemblage. Application of coupled ^{146,147}Sm–^{142,143}Nd chronometry to the Nulliak suite yields a model age of differentiation of $4.40^{+0.05}_{-0.06}$ Ga, and a corresponding $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{source}}$ ratio of 0.211 ± 0.007 for the early depleted mantle. These estimates are remarkably similar to those obtained for a tholeiitic lava of the Abitibi greenstone belt (Theo's flow, 2.7 Ga) based on the ^{142,143}Nd dataset of Debaille et al. (2013). Viewed in conjunction with previous ^{142,143}Nd data, our results provide a precise estimate of the age of primordial differentiation of Earth's mantle, 160^{+30}_{-20} Myr after formation of the solar system. This chronological constraint, combined with evidence for late solidification of the lunar magma ocean, strongly supports a young age for the giant impact and the Earth–Moon system. Further, the similarity of ^{146,147}Sm–^{142,143}Nd model ages and $(\text{Sm}/\text{Nd})_{\text{source}}$ ratios inferred for Nulliak, Isua and Theo's flow suggests that their parent magmas were derived from a common mantle reservoir. This early depleted domain appears to have evolved as a closed-system on a multi-billion year timescale despite efficient mixing in the hot Hadean/Archean mantle. We thus propose that the occurrence of positive ^{142}Nd anomalies in the Archean rock record reflects episodic melting of a depleted reservoir otherwise isolated from the convective system, rather than progressive homogenization of a highly depleted Hadean mantle.

1. Introduction

Understanding Earth's evolution over time requires knowledge of the initial state created by the processes of accretion and primary differentiation. The earliest evolutionary stages of our planet, however, are enigmatic, obscured by the nearly complete absence of geological record prior to 4 Ga, and by the poor preservation of geochemical signals recorded in Earth's oldest rocks. Extinct radioactivities (e.g. ^{182}Hf–^{182}W, ^{129}I–^{129}Xe, ^{146}Sm–^{142}Nd) provide a way of circumventing these issues and establish precise chronological constraints on early planetary differentiation processes (e.g. Avice and Marty, 2014; Caro et al., 2003; Dauphas and Pourmand, 2011; Kleine et al., 2009). Together with models of planetary formation (e.g. Chambers, 2004), these studies show that after a period of rapid (10^6–10^7 yr) "runaway" accretion of chondritic material, the terrestrial planets accreted through collisions with differentiated embryos over a characteristic timescale of 10^8 yr. This giant impact phase of accretion set the stage for the formation of the Moon, mainly from debris ejected from the proto-

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Earth during a highly energetic collision with a Mars-sized impactor (Canup, 2012; Canup and Asphaug, 2001; Ćuk and Stewart, 2012). This Moon-forming event had dramatic consequences on the structure and composition of our planet. The kinetic energy released during impact induced vaporization and large scale melting of the silicate Earth (Canup, 2004), leading to the formation of a magma ocean extending deep into the lower mantle. Crystallization of this magma ocean would then have proceeded rapidly (1–10 Ma), from the bottom of the mantle upward (Abe, 1997; Sleep et al., 2014). Denser melts may also have accumulated at the core-mantle boundary (Labrosse et al., 2007), producing a deep primordial reservoir which may since then have remained largely isolated from the convective system (Caracausi et al., 2016; Coltice et al., 2011; Mukhopadhyay, 2012). The Moon-forming giant impact thus marks a fundamental transition in terrestrial evolution. However, the timing of this event is still under debate, with estimates ranging from 30 to 200 Ma after formation of the solar system (Avice and Marty, 2014; Borg et al., 2011; Touboul et al., 2007; Carlson et al., 2014; Barboni et al., 2017). Given the short crystallization time expected for the terrestrial magma ocean, the chronology of primordial mantle differentiation is relevant to determining the timing of the giant impact. However, conflicting age estimates spanning the first 130 Myr of Earth's history have been proposed for early mantle differentiation (Bennett et al., 2007; Boyet and Carlson, 2005; Caro et al., 2006; Touboul et al., 2012). This uncertainty prevents further assessment of the sequence of events that led to the formation of the Earth–Moon system.

The chronology of early mantle differentiation processes can be studied through the combined use of the long-lived ^{147}Sm–^{143}Nd ($T_{1/2} = 106$ Ga) and short-lived ^{146}Sm–^{142}Nd ($T_{1/2} = 0.103$ Ga) systems, which together provide high temporal resolution of early (>4.1 Ga) differentiation events (Bourdon and Caro, 2007; Caro, 2011; Harper and Jacobsen, 1992). Previous studies showed that Eoarchean rocks often exhibit small (±10 ppm) ^{142}Nd anomalies inherited from now-vanished Hadean (>3.85 Ga) crustal or mantle reservoirs (e.g. Bennett et al., 2007; Caro et al., 2016, 2006; Debaille et al., 2013; O'Neil et al., 2008; Rizo et al., 2012; Roth et al., 2014; Puchtel et al., 2016a). In contrast, the ^{142}Nd/^{144}Nd ratio of the present-day silicate Earth, as sampled by MORBs and OIBs, is remarkably homogeneous (Andreasen et al., 2008; Caro et al., 2006; Jackson and Carlson, 2012; Murphy et al., 2010). These observations are commonly interpreted to reflect global mantle differentiation near the end of terrestrial accretion, followed by progressive rehomogenization of early differentiated reservoirs (Bennett et al., 2007; Caro et al., 2006; Rizo et al., 2012; Roth et al., 2014), though the timescale and tectonic regime prevailing during this rehomogenization remain subject to debate (Debaille et al., 2013).

While the presence of ^{142}Nd anomalies in the Archean rock record provides unambiguous evidence of Hadean mantle differentiation, the timing of this event cannot be precisely constrained using ^{142}Nd alone, because the size of the anomaly depends on both the differentiation age and the extent of Sm/Nd fractionation (e.g. Caro, 2011). Coupled ^{146,147}Sm–^{142,143}Nd systematics provide a solution to this problem, and were successfully used to refine chronological constraints on early differentiation of the Moon and Mars (e.g. Bourdon et al., 2008; Brandon et al., 2009; Caro et al., 2008; Debaille et al., 2007; McLeod et al., 2014; Borg et al., 2016). Application of coupled ^{146,147}Sm–^{142,143}Nd chronometry to terrestrial samples, however, is in some ways more challenging, as the ^{147}Sm–^{143}Nd record of Eoarchean rocks is often perturbed by alteration or metamorphic overprinting, preventing accurate determination of their initial ^{143}Nd/^{144}Nd ratios (e.g. Gruau et al., 1996; Moorbath et al., 1997). For that reason, the first high-precision ^{142,143}Nd data were obtained from more evolved lithologies, namely i) mafic to intermediate metasediments (metapelites) of the 3.7–3.8 Ga Isua supracrustal belt (ISB) (Caro et al., 2006, 2003), and ii) tonalitic gneisses from Innersuatuut Island near Nuuk (3.85 Ga, West Greenland) (Bennett et al., 2007). While both studies reported relatively similar model ages at 4.46 ± 0.11 Ga and 4.51 ± 0.04 Ga, respectively, this agreement is only apparent, because ^{146,147}Sm–^{142,143}Nd model ages were calculated using different input parameters for the Bulk Silicate Earth (BSE); Caro et al. (2006) considered in their model a BSE with chondritic Sm/Nd ratio and a ^{142}Nd/^{144}Nd ratio equal to that of the modern "accessible" silicate Earth, while Bennett et al. (2007) used a BSE with a ^{142}Nd/^{144}Nd ratio identical to those of ordinary chondrites (i.e. 20 ppm lower than the terrestrial value (Boyet and Carlson, 2005)). When recalculated using the former set of parameters, the ^{142,143}Nd signal recorded in Innersuatuut tonalites yields a younger model age of 4.33 ± 0.03 Ga, which postdates formation of the oldest nuclei of continental crust (Harrison, 2009) and is therefore unlikely to reflect primary differentiation processes. More recent ^{142,143}Nd studies of mantle-derived rocks (amphibolites) of the ISB (O'Neil et al., 2016; Rizo et al., 2011) yielded results virtually identical to those reported by Caro et al. (2006), confirming previous age estimates for differentiation of the Isua mantle source. Nevertheless, the ^{147}Sm–^{143}Nd systematics of many of the ISB amphibolites have apparently been perturbed by metamorphism (e.g. Rizo et al., 2011), complicating their interpretation. Given the paucity of rocks suitable for application of coupled ^{146,147}Sm–^{142,143}Nd chronometry beyond the Isua and Innersuatuut localities, the significance of each of these model ages remains uncertain. In particular, it is unclear whether the Archean ^{142}Nd record truly reflects a single event near the end of terrestrial accretion or if more complex scenarios, involving continuous differentiation of the Hadean mantle, must also be considered.

Here we present new high precision ^{142}Nd and ^{147}Sm–^{143}Nd data for visually fresh ultramafic rocks collected in the Archean Saglek block of Northern Labrador. As these samples are likely derived from a deep mantle source, their isotopic compositions can be interpreted with less ambiguity than those from the more evolved lithologies studied in the past. We show how these results help refine the chronological constraints on primordial mantle differentiation, and provide new insights into the long-term evolution of silicate reservoirs generated in the aftermath of the Moon-forming giant impact.

2. Geological setting

Mafic and ultramafic samples from this study were collected during fieldwork in the Hebron/Saglek fjords region of the Saglek Block (northern Labrador, Canada). The geology of the region has been described in several previous studies (e.g. Bridgwater and Schiøtte, 1991; Komiya et al., 2015; Ryan and Martineau, 2012; Shimojo et al., 2016), to which the reader is referred for more detailed information. Briefly, the Saglek block in the north, together with the Hopedale block in the south, constitute the Archean terranes of Labrador and form the westernmost part of the North Atlantic Craton (Fig. 1). The Saglek Block is dominated by quartzofeldspathic gneisses, ranging in age from 3.25 to 3.9 Ga, intruded by a variety of post-tectonic granitoids (2.5–2.7 Ga) (Bridgwater and Schiøtte, 1991; Komiya et al., 2015; Shimojo et al., 2016). The volumetrically dominant Eoarchean tonalitic to granodioritic gneisses enclose numerous volcano-sedimentary units, ranging in size from tens of meters to several kilometers, and mainly composed of metamorphosed mafic and ultramafic rocks, of both intrusive and extrusive origin, associated with rocks derived from detrital and chemical sedimentary protoliths (Bridgwater and Schiøtte, 1991; Komiya et al., 2015; Nutman and Bridgwater, 1989; Ryan and Martineau, 2012). Like the rest of the Saglek block, the