Hadean geodynamics inferred from time-varying [142]Nd/[144]Nd in the early Earth rock record

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Abstract

Tracking the secular evolution of ^{142}Nd/^{144}Nd anomalies is important towards understanding the crust-mantle dynamics in the early Earth. Excessive scatter in the published data, however, precludes identifying the fine structure of ^{142}Nd/^{144}Nd evolution as the expected variability is on the order of few parts per million. We report ultra-high precision ^{142}Nd/^{144}Nd data for Eoarchean and Palaeoarchean rocks from the Isua Supracrustal Belt (SW Greenland) that show a well-resolved ^{142}Nd/^{144}Nd temporal variability suggesting progressive convective homogenisation of the Hadean Isua depleted mantle. This temporally decreasing ^{142}Nd/^{144}Nd signal provides a direct measure of early mantle dynamics, defining a stirring timescale of <250 Myr consistent with vigorous convective stirring in the early mantle. The ^{142}Nd/^{144}Nd evolution suggests protracted crustal residence times of ~1000-2000 Myr, inconsistent with modern-style plate tectonics in the Archean. In contrast, a stagnant-lid regime punctuated by episodes of mantle overturns accounts for the long life-time estimated here for the Hadean proto-crust.

Introduction

The short-lived ^{146}Sm-^{142}Nd decay system provides a powerful tool for studying the early evolution of silicate Earth. The presence of ^{142}Nd/^{144}Nd variations relative to bulk silicate Earth represent irrefutable evidence for mantle differentiation prior to 4.0 Ga. The most extensively studied terrain for ^{142}Nd/^{144}Nd heterogeneity is the Isua Supracrustal Belt (SW Greenland) that contains well-preserved Eoarchean rocks carrying the highest ^{142}Nd/^{144}Nd excesses reported so far (*e.g.*, Caro *et al.*, 2006). A decreasing trend in ^{142}Nd/^{144}Nd anomalies with time for the Greenland rocks, suggesting progressive convective homogenisation of fractionated mantle domains, has been proposed (Bennett *et al.*, 2007;

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Rizo *et al.*, 2013). However, the rate of homogenisation is not well-constrained due to the excessive scatter in the ^{142}Nd/^{144}Nd data. The extent of ^{142}Nd/^{144}Nd variability within a rock suite that has been assigned a single geological age is 2-5 times the analytical reproducibility, precluding identification of the exact course of ^{142}Nd evolution. Thus, highly precise ^{142}Nd/^{144}Nd data for Archean rocks of varying ages is necessary to constrain the tempo of survival of Hadean ^{142}Nd/^{144}Nd anomalies and, hence, gain insights into early Earth dynamics.

Results

We studied Eoarchean amphibolites (>3.8 Ga) and Amitsoq gneisses (3.8-3.7 Ga) as well as Palaeoarchean Ameralik dykes (~3.45 Ga) from the Isua Supracrustal Belt for their chemistry and Sm-Nd isotope systematics, the latter measured using an ultra-high precision protocol employing multiple collector inductively-coupled plasma source mass spectrometry (Saji *et al.,* 2016). The ^{142}Nd/^{144}Nd compositions are reported in the μ notation as parts per million deviations (ppm) from the standard (Fig. 1 and Table S-3). The Eoarchean amphibolites define a weighted mean μ^{142}Nd composition of 10.5 ± 0.7 (2σ; n = 7) indistinguishable from the mean composition of the Amitsoq gneisses, which is 11.4 ± 0.7 (2σ; n = 6). These results are similar to previous measurements of Eoarchean ISB rocks by thermal ionisation mass spectrometry but define a much narrower compositional range for both lithologies in our study (Fig. S-16). The gneisses from the northern terrane, for which zircon U-Pb analyses define an age of 3701 ± 2 Ma, record a μ^{142}Nd composition (~11 ppm) indistinguishable from that of the tectonically distinct southern terrane that yield zircon U-Pb ages of 3803 ± 3 Ma (Fig. S-14), in contrast to Bennett *et al.* (2007) that suggest a decrease in μ^{142}Nd from ~20 ppm at 3.85 Ga to ~15 ppm by 3.7 Ga. We conclude that the Eoarchean ~3.75 Ga crust in Isua has a homogeneous μ^{142}Nd composition of ~11 ppm inherited from a precursor mafic crust represented by the Isua amphibolites. The Palaeoarchean ~3.45 Ga metadoleritic Ameralik dykes carry a lower but well-resolved μ^{142}Nd excess of 4.9 ± 0.5 (2σ; n = 10), in contrast to an earlier study that measured variable μ^{142}Nd compositions as negative as –13 ppm in samples collected from similar localities as in this study (Rizo *et al.,* 2012). The excessive scatter in the μ^{142}Nd data of Rizo *et. al.* (2012) that span from $–13.3 \pm 3.6$ to $+5.4 \pm 3.2$ ppm is not present in our high precision data set and potentially reflects analytical artifacts (see Section 2.4 of Supplementary Information for details).

Discussion

Steady-stage coupled ^{142}Nd-^{143}Nd systematics of Eoarchean amphibolites constrain the formation age of Isua depleted mantle reservoir to 4390 ± 20 Myr (^{146}Sm $t_{1/2}$ = 103 Myr). Interestingly, the negative μ^{142}Nd anomalies measured in ~3.75 Ga tonalite-trondjemite-granodiorite (TTG) gneisses and Ujaraaluk unit amphibolites from Nuvvuagittuq Supracrustal Belt as well as the tholeiitic to enriched lavas from Ukaliq Supracrustal Belt (O'Neil *et al.*, 2008, 2012; Roth *et al.*, 2013; Caro *et al.*, 2017), both in the North Eastern Superior Province (Canada), define a single isochron as the Isua amphibolites corresponding to a large scale Hadean differentiation event forming Isua depleted mantle and complementary proto-crust at 4.39 Ga (Fig. 2). The model differentiation age is consistent

with the estimated ages (~4.35-4.40 Ga) for crystallisation of lunar magma ocean (Gaffney and Borg, 2014) and the oldest terrestrial zircons (~4.37 Ga; Whitehouse *et al.*, 2017). The correspondence between the timing of this Hadean differentiation event and crystallisation of the lunar magma ocean potentially suggests that the Isua depleted mantle reservoir represents a primordial mantle domain that formed following solidification of the terrestrial magma ocean after the Moon-forming impact (Canup, 2012; Carlson *et al.*, 2015; Caro *et al.*, 2017). The time-integrated $^{147}Sm/^{144}Nd$ ratio derived from the two stage model for the Isua depleted mantle is ~0.22 ± 0.01 and the complementary Hadean protocrust is basaltic ($^{147}Sm/^{144}Nd$ = ~0.17). Magma ocean crystallisation models for Earth-size planets predict the primordial crust to be of basaltic composition formed by decompression melting of portions of Hadean mantle after the primary mantle overturn (Elkins-Tanton, 2008).

The homogeneous $\mu^{142}Nd$ in mantle-derived modern terrestrial rocks compared to the $\mu^{142}Nd$ heterogeneity of Archean rocks is interpreted to reflect homogenisation by plate tectonic processes (*e.g.*, Bennett *et al.,* 2007). Thus, the subdued $\mu^{142}Nd$ anomaly in the Palaeoarchean Ameralik dykes compared to the Eoarchean Isua rock suites can be interpreted as reflecting progressive homogenisation of the Hadean Isua depleted mantle reservoir by convective stirring if both rock types were derived from the same mantle domain. Trace element characteristics of Ameralik dykes are consistent with derivation from a non-metasomatised depleted mantle source (see Section 2.1 of Supplementary Information). This source lacks the recycled crustal components characterising the source of Eoarchean volcanics, but do not contain any plume-like or shallow lithospheric components to suggest derivation from a heterogeneous mantle other than the Isua depleted mantle (Figs. S-7, S-8 and S-9). Petrogenetic indicators suggest melting under shallow upper mantle conditions in the garnet stability field for both rock suites (Figs. S-4 and S-5). The nearly identical initial $\epsilon^{143}Nd$ (2.0 ± 0.6 for Eoarchean amphibolites, Moorbath *et al.*, 1997; 3.0 ± 0.9 for Ameralik dykes, Rizo *et al.*, 2012) is also consistent with derivation of both rock suites from an Archean depleted mantle (Vervoort and Blichert-Toft, 1999). It is, therefore, conceivable that the Ameralik dykes were sourced from the convecting mantle beneath Isua that gave rise to the Eoarchean magmatism and carry the time-evolved $\mu^{142}Nd$ fingerprint of the Hadean Isua depleted mantle reservoir.

The $\mu^{142}Nd$ anomaly of 4.9 ± 0.7 ppm carried by the Ameralik dykes at ~3.4 Ga suggests survival of the Hadean Isua depleted mantle that formed 4.39 Ga for at least ~1 Gyr, with the reduction in $\mu^{142}Nd$ anomaly reflecting the pace of homogenisation in the Hadean-Archean mantle. We infer a mantle homogenisation timescale of 1.4 Gyr, given that the $\mu^{142}Nd$ anomaly would be reduced to modern accessible mantle compositions by ~3.0 Ga and that the age of differentiation cannot be older than ~4.45 Ga (Fig. 3 and Table S-5). Mantle homogenisation timescales close to 1.4 Gyr translate to a mantle stirring timescale of 250 Myr (see Section 2.5 of Supplementary Information). The estimated early Earth mantle stirring timescale is also consistent with the stirring time of 100-250 Myr inferred from the dispersion in the $\epsilon^{143}Nd$ of Archean rocks (Caro *et al.*, 2006). The stirring time inferred for upper mantle convection today from the isotopic dispersion in modern oceanic basalts is 250-750 Myr (Kellogg *et al.*, 2002). Given the intra-oceanic supra-subduction zone-like setting inferred for Isua Eoarchean volcanics from their arc-like geochemistry, we consider the homogenisation of Isua depleted mantle reservoir to occur at length scales comparable to

modern upper mantle convection. Thus, the shorter mantle stirring time of 250 Myr inferred for the Hadean-Archean mantle from the secular variation in the Isua μ^{142}Nd data suggests the vigorous pace of convective stirring in the Hadean-Archean mantle that leads to compositional heterogeneities being mixed away at a rate faster than today (Olson *et al.*, 1984). This observation agrees with models that show Archean mantle convection to proceed at faster rates due to the lower viscosity from higher mantle temperatures (Coltice and Schmalzl, 2006).

The secular evolution of mantle heterogeneity depends on whether the complementary crustal reservoir is introduced into the mantle convection cells *via* recycling. Stagnant-lid tectonics allows preservation of primordial mantle heterogeneities for timescales of several billion years (Debaille *et al.*, 2013). The relatively efficient homogenisation of μ^{142}Nd anomaly with time as seen in Isua rocks is consistent with a geodynamic regime that involves lithosphere recycling rather than stagnant-lid tectonics. Using a box model that considers material transport across continuously interacting crust and depleted mantle reservoirs, the observed evolution of Isua μ^{142}Nd anomaly is well-reproduced for crustal residence times between 1000-2000 Myr (Fig. 3). The μ^{142}Nd anomaly of ~7 ppm identified by Debaille *et al.* (2013) in 2.7 Ga Theo's Flow from the Abitibi Greenstone Belt also lies within error on the same evolution curve as Isua amphibolites but corresponds to crustal residence times of 2000-4000 Myr. Such long crustal residence timescales imply that the primordial mafic proto-crust, whose extraction between 4.45 Ga and 4.39 Ga created the Isua depleted mantle reservoir, survived complete recycling until the mid-Archean, allowing the positive mantle μ^{142}Nd signatures to be sampled by juvenile Archean magmatism. These long crustal residence timescales in the Archean contrast sharply with the short lifetime of oceanic crust today (~200 Myr) prior to recycling at subduction zones (Hawkesworth *et al.*, 2010), implying a tectonic regime in the early Earth different from modern plate tectonics. Numerical models show that flat slab subduction like that of today is less likely in the Archean and predict an intermittent drip-like subduction style reducing the efficiency of lithosphere recycling (van Hunen and van den Berg, 2008). Several models suggest the prevalence of a stagnant-lid regime punctuated by episodes of vertical tectonics under the influence of strong mantle overturns in the early Archean (Debaille *et al.*, 2013; Sizova *et al.*, 2015; Bédard, 2018). Mobile-lid tectonics involving long-lived subduction possibly did not begin until the mid-Archean as evidenced by an apparent inflexion in the rate of continental crust generation at ~3.0 Ga (Dhuime *et al.*, 2012), coinciding with the lifetime estimated here for the Hadean mafic proto-crust until 3.4-2.4 Ga. Although the preservation of primordial Hadean reservoirs for long timescales is consistent with a stagnant-lid tectonic regime, the rate of mantle homogenisation inferred from Isua ^{142}Nd data cannot be accounted for by simple stagnant-lid tectonics and requires some degree of recycling of complementary crustal reservoir into the convecting depleted mantle. The disparity in the crustal residence times defined by Isua amphibolites, Ameralik dykes and Theo's Flow possibly indicates the sporadic nature of mantle overturn-induced lithospheric recycling in the Archean and the subsequent variations in the rate of crustal recycling with time and between localities (Fig. 4). Identification of a transitional hybrid regime characterised by quiescent stagnant-lid intervals alternating with plate tectonic-like mantle overturns throughout most of the Archean lends credence to theoretical models (O'Neill *et al.*, 2016)

that suggest that plate tectonics as it operates today on Earth represents a transient phase in the evolution of planets.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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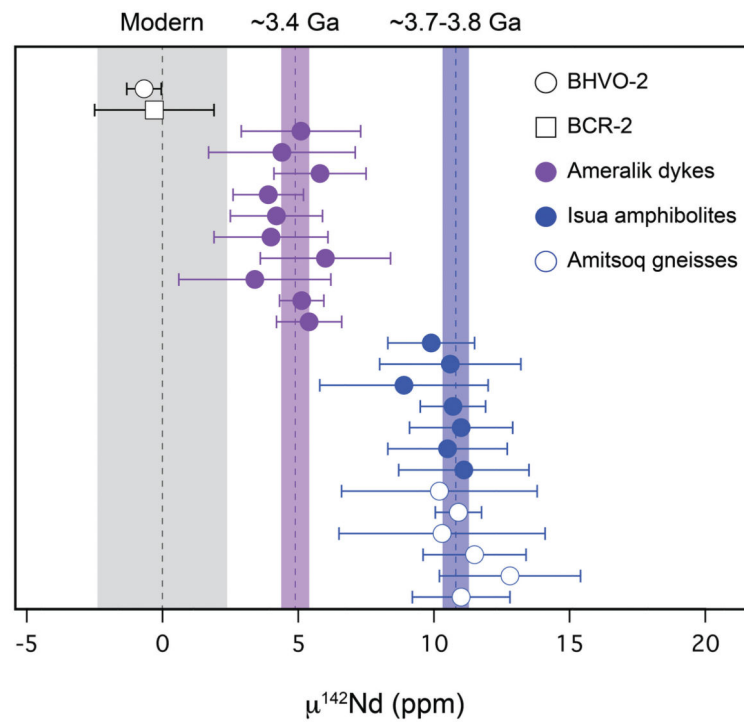
Figure 1.
The μ^{142}Nd composition relative to JNdi-1 for terrestrial rock standards and rocks from Isua Supracrustal Belt. Error bars for each sample indicate the internal errors (2 SE). The grey band for modern samples is the 2 SD external reproducibility (Saji *et al.*, 2016). The light purple band represents the weighted mean and 2σ uncertainty (MSWD = 0.9) of the Palaeoarchean (~3.4 Ga) samples whereas the light blue band represents the weighted mean and 2σ uncertainty (MSWD = 0.5) of the Eoarchean (3.7-3.8 Ga) samples.
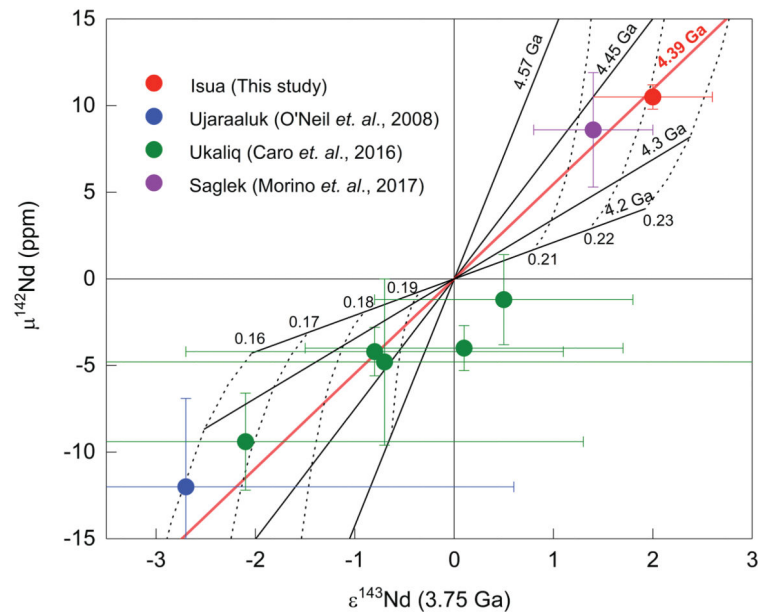
Figure 2.

Two stage coupled ^{147,146}Sm–^{142,143}Nd systematics for ~3.75 Ga Isua amphibolites. Solid black lines are loci of constant model ages calculated with bulk silicate Earth parameters of μ^{142}Nd = 0 and ^{147}Sm/^{144}Nd = 0.196. Dashed curves represent loci of constant time-integrated (^{147}Sm/^{144}Nd)$_{source}$ ratios. The red line is a linear regression for all samples and corresponds to a model age of 4390 ± 20 Ma. The Ujaraaluk data point is the mean of faux amphibolites from O'Neil *et al.* (2008). The Saglek data point is the mean of Eoarchean amphibolites from Morino *et al.* (2017). The Ukaliq data corresponds to enriched, boninitic and transitional mafic rocks as well as Voizel suite TTGs from Caro *et al.* (2017). The ϵ^{143}Nd (3.75 Ga) value for Isua amphibolites is from Moorbath *et al.* (1997).
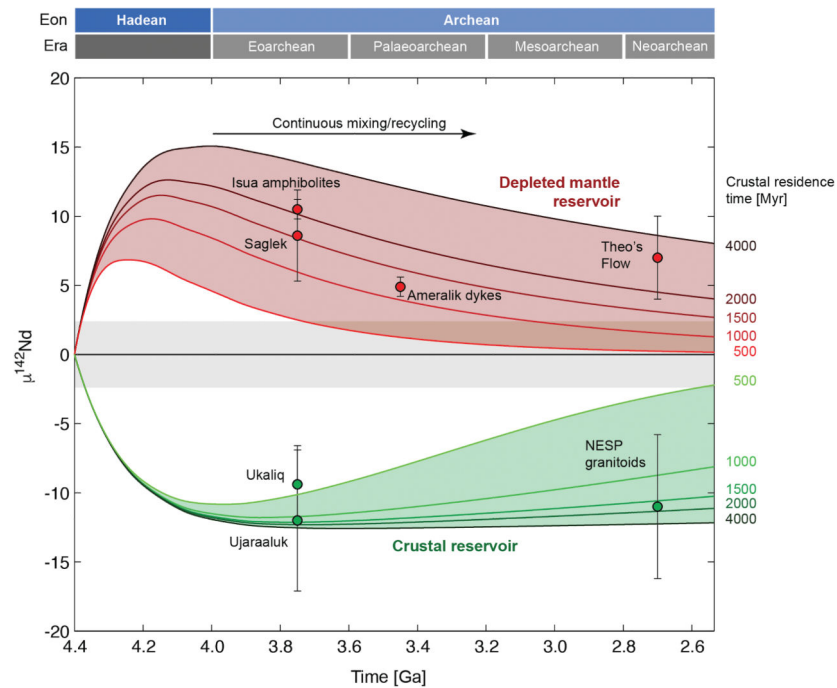
Figure 3.

μ^{142}Nd evolution of the depleted mantle and complementary crust as calculated by a continually interacting crust-mantle box model. The different coloured curves correspond to crustal residence times between 500 to 4000 Myr. The evolution of Isua μ^{142}Nd data is best fitted for residence times between 1000-2000 Myr. Sensitivity of the inferred residence times to model parameters is detailed in Table S-5. The Hadean crustal component identified in Eoarchean Ujaraaluk and Ukaliq units in Nuvvuagittuq Supracrustal Belt and Neoarchean North Easter Superior Province (NESP) granitoids are also in agreement with crustal residence time of 1000-2000 Myr (O'Neil *et al.*, 2012; Caro *et al.*, 2017; O'Neil and Carlson, 2017). Inferred crustal residence times are also consistent within error with the μ^{142}Nd data for Theo's Flow (Debaille *et al.*, 2013).
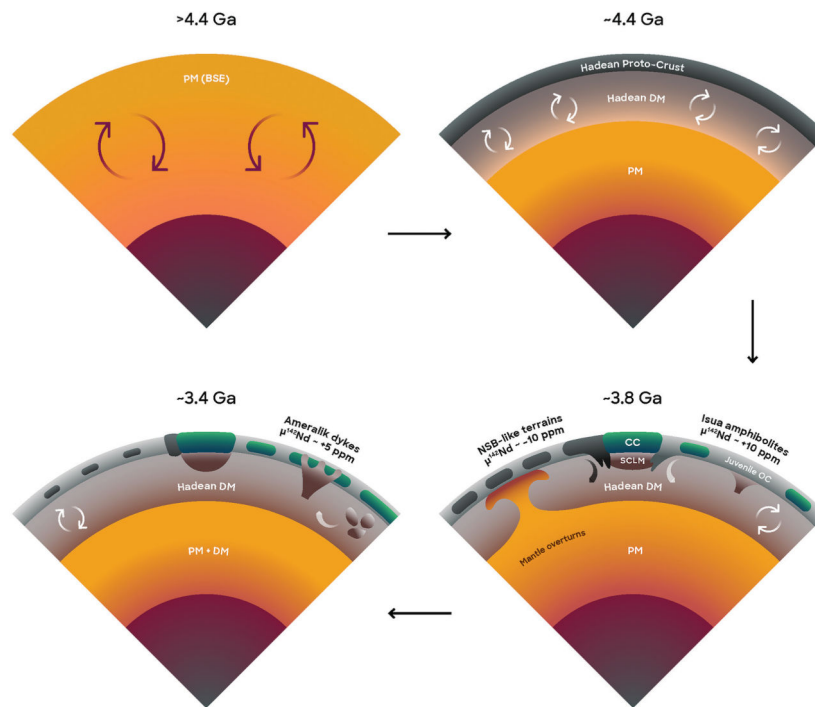
Figure 4.

A schematic diagram illustrating the evolution of Isua Hadean depleted mantle and proto-crust. The Hadean depleted mantle (DM) and proto-crust formed by primary differentiation at ~4.45-4.36 Ga following the Moon-forming event. The Hadean proto-crust acts as a stagnant-lid due to its buoyancy and is reworked and recycled into the mantle during large-scale deep mantle upwellings in a lid-overturn tectonic regime (Bédard, 2018). Basaltic magmatism thickens the oceanic crust (OC) and results in formation of continental crust (CC) by intra-crustal melting and ensures stabilisation of cratons with a depleted subcontinental lithospheric mantle (SCLM) keel. ISB amphibolites are derived in the Eoarchean from the convecting Hadean DM metasomatised by crust-derived fluids. The NSB rocks possibly formed during reworking of the Hadean proto-crust in mantle overturn episodes recycling portions of the crust into the mantle. Ameralik dykes form in the Palaeoarchean during a delamination episode triggering decompression melting of the Isua Hadean DM.