Geochemistry Geophysics Geosystems G3

Technical Brief
Volume 13, Number 6
14 June 2012
Q06011, doi:10.1029/2012GC004114
ISSN: 1525-2027

Published by AGU and the Geochemical Society

Homogeneous superchondritic $^{142}Nd/^{144}Nd$ in the mid-ocean ridge basalt and ocean island basalt mantle

Matthew G. Jackson
Department of Earth Sciences, Boston University, 675 Commonwealth Avenue, Boston, Massachusetts 02215, USA (jacksonm@bu.edu)

Richard W. Carlson
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA (rcarlson@dtm.edu)

[1] ^{146}Sm decays to ^{142}Nd with a relatively short half-life (~68 Ma). The $^{142}Nd/^{144}Nd$ of modern terrestrial mantle-derived lavas is 18 ± 5 ppm higher than the chondrite reservoir. The difference in $^{142}Nd/^{144}Nd$ between Earth and chondrites likely owes to Sm/Nd ratios 6% higher in the accessible Earth that arose within the first 30 million years following accretion. In order to constrain the early history of the mantle domains sampled by ocean island basalts (OIB) and mid-ocean ridge basalts (MORB), we present high-precision $^{142}Nd/^{144}Nd$ measurements on 11 different lavas from five hot spots, and one lava each from the Indian and Atlantic ridges. The lavas examined in this study bracket much of the known Sr-Nd-Pb-He isotopic variability the in mantle. These data complement existing high-precision $^{142}Nd/^{144}Nd$ data on MORB and OIB lavas. In agreement with previous studies, we find that MORB and OIB lavas examined for high-precision $^{142}Nd/^{144}Nd$ exhibit ratios that are indistinguishable from the terrestrial standard and are 15–20 ppm higher than the average obtained for ordinary and enstatite chondrites. The uniform, superchondritic $^{142}Nd/^{144}Nd$ data in OIB and MORB are consistent with derivation from a common, early formed (<30 Ma after accretion) progenitor reservoir with Sm/Nd ~6% higher than chondrites. If there exists any variability in $^{142}Nd/^{144}Nd$ in the OIBs and MORBs examined to date, it is too small to be resolved with the precision currently available.

Components: 7200 words, 2 figures, 2 tables.

Keywords: $^{142}Nd/^{144}Nd$; MORB; OIB; early Earth; mantle geochemistry; plume.

Index Terms: 1025 Geochemistry: Composition of the mantle; 1038 Geochemistry: Mantle processes (3621); 1040 Geochemistry: Radiogenic isotope geochemistry.

Received 21 February 2012; **Revised** 24 April 2012; **Accepted** 14 May 2012; **Published** 14 June 2012.

Jackson, M. G., and R. W. Carlson (2012), Homogeneous superchondritic $^{142}Nd/^{144}Nd$ in the mid-ocean ridge basalt and ocean island basalt mantle, *Geochem. Geophys. Geosyst.*, *13*, Q06011, doi:10.1029/2012GC004114.

1. Introduction

[2] The composition of the bulk silicate Earth (BSE)—the solid Earth minus the core—has long been assumed to be tied to chondrites: the refractory lithophile elements, like Sm and Nd, are thought to exist in chondritic relative abundances in the BSE [e.g., *Jagoutz et al.*, 1979; *Jacobsen and Wasserburg*, 1980; *Hart and Zindler*, 1986;

Table 1. Sample Locations and Justification for Analyzing $^{142}Nd/^{144}Nd$[a]

Sample ID	Location	Reason for $^{142}Nd/^{144}Nd$ Analysis[b]	Latitude	Longitude
2ΠD43 wr	MORB (popping rock)	MORB sample with $^{129}Xe/^{130}Xe$ anomaly relative to air.	13.5°N	45.0°W[c]
D113 wr	MORB, Indian Ocean	MORB sample previously analyzed for $^{142}Nd/^{144}Nd$.	23.343°S	74.942°E[c]
MAG-B-47 wr	Mangaia, Cook Islands	OIB lava with one of the most extreme HIMU (highest $^{206}Pb/^{204}Pb$, 21.784) globally.	21.93°S	157.93°W[c]
ALIA-115-21 wr	Savai'i, Samoa	OIB lava with the most extreme EM2 signature (highest $^{87}Sr/^{86}Sr$, 0.7205) globally.	14.090°S	172.898°W
ALIA-115-21 cpx	Savai'i, Samoa	OIB magmatic phenocrysts with an extreme EM2 signature ($^{87}Sr/^{86}Sr$, 0.7216).	14.090°S	172.898°W
ALIA-115-18 wr	Savai'i, Samoa	OIB lava with the second most extreme EM2 signature (second highest $^{87}Sr/^{86}Sr$, 0.7186) globally.	14.090°S	172.898°W
ALIA-115-18 cpx	Savai'i, Samoa	OIB magmatic phenocrysts with an extreme EM2 signature ($^{87}Sr/^{86}Sr$, 0.7202-0.7208).	14.090°S	172.898°W
78-1 cpx	Malumalu, Samoa	OIB lava with a high $^{87}Sr/^{86}Sr$ ratio (0.7089) hosting cpx with high $^{87}Sr/^{86}Sr$ ratios (0.7077-0.7083)	14.623°S	169.726°W
T54 wr	Ta'u, Samoa	OIB lava with one of the lowest $^{87}Sr/^{86}Sr$ ratios (0.7047) from Samoa.	14.265°S	169.497°W
Ofu-04-06 wr	Ofu, Samoa	OIB lava with one of the highest $^{3}He/^{4}He$ ratios (33.8 Ra) globally.	14.168°S	169.642°W[c]
NSK-97-214 wr	Fernandina, Galapagos	OIB lava with one of the highest $^{3}He/^{4}He$ ratios (30.3 Ra) globally.	0.300°S	91.628°W
70488-2 wr	Christmas Island[d]	OIB lava from a known EM1 hotspot.	11.625°S	103.682°E[c]
KK-18-8 wr	Loihi, Hawaii	OIB lava with one of the highest $^{3}He/^{4}He$ ratios (32.3 Ra) globally.	18.96°N	155.27°W[c]
KOO-8 wr	Koolau, Hawaii	OIB lava with one of the most enriched geochemical signatures (high $^{87}Sr/^{86}Sr$) from Hawaii	21.31°N	157.65°W[c]
KOO-30 wr	Koolau, Hawaii	OIB lava with one of the most enriched geochemical signatures (high $^{87}Sr/^{86}Sr$) from Hawaii	21.31°N	157.65°W[c]

[a]wr is whole rock analysis, cpx is clinopyroxene analysis.
[b]See text for references to original measurements.
[c]Locations are approximate as samples were taken before GPS availability and/or latitude and longitude were not reported in the original manuscript.
[d]The Christmas Island sample was actually dredged from Vening Meinesz Seamount, with a dredge depth of 1763 m.

McDonough and Sun, 1995; *Palme and O'Neill*, 2003, *Amelin and Rotenberg*, 2004; *Patchett et al.*, 2004]. Sm and Nd present two different radiogenic decay schemes that can be useful for evaluating the hypothesis that the Earth and chondrites have the same Sm/Nd ratios: ^{146}Sm decays to ^{142}Nd ($T_{1/2}$ = 68 Ma [*Kinoshita et al.*, 2012]) and ^{147}Sm decays to ^{143}Nd ($T_{1/2}$ = 106 Ga). If chondrites and BSE have the same Sm/Nd ratio, then they should have identical $^{142}Nd/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios.

[3] *Boyet and Carlson* [2005] measured small, but significant (18 ± 5 ppm) differences between chondrites and modern terrestrial lavas. If the $^{142}Nd/^{144}Nd$ anomaly in modern terrestrial lavas relative to chondrites is the result of radiogenic decay of ^{146}Sm and not initial Solar System nucleosynthetic heterogeneity [*Andreasen and Sharma*, 2006, 2007; *Carlson et al.*, 2007; *Qin et al.*, 2011], then all modern terrestrial rocks originate from an ancient reservoir that had Sm/Nd ratios ~6% higher than chondritic during the lifetime of ^{146}Sm. A 4.568 Ga reservoir with $^{147}Sm/^{144}Nd$ = 0.208 ± 0.002 (6% higher than chondritic) will today have $^{143}Nd/^{144}Nd$ = 0.5130 ± 0.0001. This $^{143}Nd/^{144}Nd$ value is significantly higher than chondritic (0.51263 [*Bouvier et al.*, 2008]), and only slightly lower than normal MORB (0.51313 [*Su*, 2003]). If the Earth is not chondritic, then the question arises as to whether any of the primitive (but not chondritic) BSE material has survived to the present-day. The range of superchondritic $^{143}Nd/^{144}Nd$ ratios predicted for a non-chondritic BSE brackets the lavas with the highest terrestrial mantle-derived $^{3}He/^{4}He$ signatures, providing evidence consistent with the highest $^{3}He/^{4}He$ mantle being parental to all mantle reservoirs that give rise to modern volcanism [*Boyet and Carlson*, 2006; *O'Neill and Palme*, 2008; *Caro et al.*, 2008; *Caro and Bourdon*, 2010; *Jackson et al.*, 2010].

[4] Alternatively, if the BSE is chondritic, then the high $^{3}He/^{4}He$ lavas sample surviving portions of an Early formed incompatible element Depleted Reservoir (EDR), that must be complemented by an Early formed Enriched Reservoir (EER) that has

not yet been sampled at Earth's surface. If this is the case, then mantle plumes, which are thought to derive from the deep mantle [*Morgan*, 1971; *Courtillot et al.*, 2003], may sample the EER. The EER is predicted to have ^{142}Nd/^{144}Nd 38–54 ppm lower than the terrestrial standard [*Carlson and Boyet*, 2008]. Therefore, if a component of the EER is entrained in mantle plumes and sampled by plume-fed hot spot lavas, then the extremely low ^{142}Nd/^{144}Nd of the EER would be expected to shift the ^{142}Nd/^{144}Nd of OIB lavas to lower values, even if it is sampled by the plume in diluted form.

[5] In this study we prospect for surviving mantle reservoirs that host anomalous ^{142}Nd/^{144}Nd ratios. We examine OIB and MORB lavas sampling the four canonical mantle end-members (DMM, depleted MORB mantle; EM1, enriched mantle 1; EM2, enriched mantle 2; HIMU, high 'μ', or high ^{238}U/^{204}Pb [*Zindler and Hart*, 1986]) and FOZO-C ('*Fo*cus *Zo*ne' or '*C*ommon' components, both with high ^{3}He/^{4}He [*Hart et al.*, 1992; *Hanan and Graham*, 1996]).

2. Sample Descriptions and Locations

[6] The following OIB and MORB samples were selected to better characterize the ^{142}Nd/^{144}Nd of the convecting mantle (Table 1). MAG-B-47 is a subaerial sample collected from Mangaia and has one of the most radiogenic Pb-isotopic (HIMU) compositions measured in an OIB [*Hauri and Hart*, 1993]. Samoan lavas ALIA-115-18 and ALIA-115-21 (and clinopyroxene separates from these samples), dredged from the flanks of the island of Savai', were selected for their extreme ^{87}Sr/^{86}Sr compositions (>0.721 [*Jackson et al.*, 2007a]). Two other Samoan lavas (Ta'u island sample T54 and clinopyroxene separates from Malulalu seamount sample AVON3-78-1) with less extreme ^{87}Sr/^{86}Sr compositions [*Workman et al.*, 2004; *Jackson et al.*, 2009] were also selected for ^{142}Nd/^{144}Nd measurement. The Hawaiian Koolau (KOO-8 and KOO-30) and Loihi (KK-18-18) samples were selected because they represent two extreme compositions in the Hawaiian mantle, where the Koolau location represents the most geochemically enriched extreme (highest ^{87}Sr/^{86}Sr and lowest ^{143}Nd/^{144}Nd [*Frey et al.*, 1994; *Roden et al.*, 1994]) in Hawaii, and Loihi seamount has the highest ^{3}He/^{4}He ratios (>30 Ra [*Kurz et al.*, 1982]). Lavas from Koolau and Loihi were previously examined for high-precision ^{142}Nd/^{144}Nd by *Murphy et al.* [2010]. In order to further characterize the high ^{3}He/^{4}He reservoir, we also measured ^{142}Nd/^{144}Nd on the highest ^{3}He/^{4}He (>30 Ra) lavas from Ofu island in Samoa (Ofu-04-06 [*Jackson et al.*, 2007b]) and Fernandina island in the Galapagos (NSK-97-214 [*Kurz and Geist*, 1999; *Saal et al.*, 2007; *Jackson et al.*, 2008]). A single sample from the Christmas Island (territory of Australia in the Indian Ocean) hot spot (70488–2) was selected for its EM1-type signature [e.g., *Hoernle et al.*, 2011]. Two MORB samples (2ΠD43 and D-113) were selected to better characterize the ^{142}Nd/^{144}Nd of this reservoir. D-113 is from the Mid-Indian Ocean Ridge [*Engel et al.*, 1965] and shows elevated ^{87}Sr/^{86}Sr (0.7032 [*Subbarao and Hedge*, 1973]) at high ϵ^{143}Nd (+10.6 [*Carlson et al.*, 1978]) typical of Indian Ocean MORB. D-113 was previously examined for high-precision ^{142}Nd/^{144}Nd by *Boyet and Carlson* [2006]. 2ΠD43, a "popping" rock from the Atlantic mid-ocean ridge (~14° N), exhibits a ^{129}Xe/^{130}Xe anomaly [e.g., *Moreira et al.*, 1998; *Staudacher et al.*, 1989]. While high precision ^{142}Nd/^{144}Nd measurements were previously made on Loihi, Koolau and the Indian MORB samples [*Murphy et al.*, 2010; *Boyet and Carlson*, 2006], we report the first high-precision ^{142}Nd/^{144}Nd measurements on the Samoa, Mangaia, Christmas Island and Galapagos hot spots.

3. Methods

[7] New ^{142}Nd/^{144}Nd data on the OIB and MORB samples are reported in Table 2. The analytical procedures for ^{142}Nd/^{144}Nd measurement in OIB and MORB samples are similar to those reported by *O'Neil et al.* [2008]. 100–200 mg of sample powder (whole rock basalt or clinopyroxene [cpx]) was dissolved in concentrated HF-HNO_3 and chemically separated following the procedures outlined in *Boyet and Carlson* [2005]. The procedure is designed to reduce interference from Sm and Ce isobars. For the samples studied here, the ^{147}Sm/^{146}Nd ratio is less than 3.2×10^{-6} for all sample runs (Table 2). The ^{140}Ce/^{146}Nd ratio is <7.8×10^{-5} for 17 of the 23 sample runs, and the remaining six of the runs have ^{140}Ce/^{146}Nd ratios between 1.0×10^{-4} and 8.1×10^{-4} (Table 2). Following correction for both Ce and Sm interferences all samples exhibit ^{142}Nd/^{144}Nd ratios that are indistinguishable from the terrestrial standard. The total lab blank for Nd is <20 pg, or <0.008% of the sample load, so no correction was made for blank contribution.

[8] Approximately 250–500 ng of Nd was loaded on a Re double filament and analyzed on the ThermoFinnigan Triton thermal ionization mass spectrometer at DTM following the mass spectrometric

10.1029/2012GC004114

Table 2 (Sample). $^{142}Nd/^{144}Nd$ of Standards and Samples (Including Replicate Runs) Reported in This Study[a] [The full Table [2] is available in the HTML version of this article]

Sample ID	Location	wr or cpx?	Barrell #	# Cycles	^{144}Nd Volts	$^{142}Nd/^{144}Nd$ Dynamic
STANDARDS:						
JNdi			218	520	3.0	1.1418329
JNdi			218	502	1.9	1.1418405
JNdi			218	502	3.2	1.1418393
JNdi			223	475	14.7	1.1418382
JNdi			223	498	3.1	1.1418396
JNdi			232	498	3.7	1.1418377
JNdi			232	495	3.3	1.1418407
JNdi			232	500	3.3	1.1418406
JNdi			232	500	2.5	1.1418313
JNdi			232	502	3.1	1.1418397
JNdi			233	343	3.1	1.1418412
JNdi			233	500	2.5	1.1418379
			Standard Mean			1.1418383
			2σ (ppm, std. dev.)			0.0000063
SAMPLES:						
2ΠD43	MORB (popping rock)	wr	218	201	1.9	1.1418403
D113	MORB, Indian Ocean	wr	232	495	3.1	1.1418423
MAG-B-47	Mangaia, Cook Islands	wr	232	497	4.1	1.1418381
MAG-B-47rep[b]	Mangaia, Cook Islands	wr	232	500	3.5	1.1418367
ALIA-115-21	Savai'i, Samoa	wr	218	497	3.0	1.1418292
ALIA-115-21rep[b]	Savai'i, Samoa	wr	218	494	2.6	1.1418320
ALIA-115-21rep[c]	Savai'i, Samoa	wr	223	441	3.4	1.1418360
ALIA-115-21rep[d]	Savai'i, Samoa	wr	232	339	4.2	1.1418392
ALIA-115-21rep[e]	Savai'i, Samoa	wr	232	497	4.2	1.1418421
ALIA-115-21	Savai'i, Samoa	cpx	232	498	3.1	1.1418368
ALIA-115-21rep[b]	Savai'i, Samoa	cpx	232	493	3.4	1.1418431
ALIA-115-18	Savai'i, Samoa	wr	232	503	2.6	1.1418382
ALIA-115-18	Savai'i, Samoa	cpx	232	501	4.3	1.1418340
ALIA-115-18rep[b]	Savai'i, Samoa	cpx	232	501	3.9	1.1418294
78-1	Malumalu, Samoa	cpx	232	298	3.4	1.1418392
T54	Ta'u, Samoa	wr	232	501	3.7	1.1418314
Ofu-04-06	Ofu, Samoa	wr	218	498	3.1	1.1418346
Ofu-04-06rep[b]	Ofu, Samoa	wr	218	203	2.2	1.1418440
NSK-97-214	Fernandina, Galapagos	wr	233	498	3.7	1.1418382
70488-2	Christmas Island	wr	233	501	5.4	1.1418341
KK-18-8	Loihi, Hawaii	wr	218	494	5.9	1.1418325
KOO-8	Koolau, Hawaii	wr	232	406	4.2	1.1418352
KOO-30	Koolau, Hawaii	wr	233	222	2.1	1.1418338
			Sample mean			1.1418365
			2σ (ppm, std. dev.)			0.0000084

[a]Abbreviations are as follows: whole rock (wr), clinopyroxene (cpx). The samples were not spiked, so the exact filament loads are not known (but should be between 250–500 ng of Nd). $\mu^{142}Nd = (^{142}Nd/^{144}Nd_{sample}/^{142}Nd/^{144}Nd_{standard} - 1)*10^6$, where $^{142}Nd/^{144}Nd_{standard}$ is the average of the standard values run in the study (1.1418383 ± 0.0000063, $\pm 2\sigma$ standard deviation, n = 12). Standard and sample data in this study were measured in four separate barrels: Barrel 218 (Aug 26–Sept 3, 2008), Barrel 223 (Sept 24–26, 2008), Barrel 232 (Oct 20–26, 2008), Barrell 233 (Oct 27–28, 2008). Data for ^{144}Nd is expressed in volts (10^{-11} amps). The $^{146}Nd/^{144}Nd$ is not corrected for fractionation. Data were corrected for mass fractionation using the exponential law and normalized to a $^{146}Nd/^{144}Nd$ of 0.7219. The $^{143}Nd/^{144}Nd$ of the whole rock and cpx separates are offset for samples ALIA-115-18 and ALIA-115-21. This is consistent with earlier observations of cpx-whole rock isotopic disequilibrium in Samoan lavas [*Jackson* et al., 2009]. A high precision $^{142}Nd/^{144}Nd$ measurement was made on the Indian MORB sample (D113 [*Boyet and Carlson*, 2006]) and is shown together with our new measurement of this sample in Figure 1.

[b]Rerun original load of the same filament.

[c]Rerun of the same batch of chemistry as the first run, but using a different filament.

[d]Rerun using a new (the second) batch of chemistry on the same powder, never run on another filament.

[e]Rerun using a new (the third) batch of chemistry on the same powder, never run on another filament.

procedures outlined in *Carlson et al.* [2007] and *O'Neil et al.* [2008]. A two-step dynamic routine was used to provide static measurements of all Nd isotope ratios and ^{140}Ce and ^{147}Sm, with a dynamic measurement of ^{142}Nd/^{144}Nd. Each sample or standard run on the Triton takes approximately 5 h, including the time required for 540 cycles (where two 8-s integrations are made for each cycle to obtain a dynamic ^{142}Nd/^{144}Nd measurement) and time for 30 s of baselines after each block of 30 cycles. We used amplifier rotation during measurement, and an amplifier gain calibration was made at the start of each day. Each separate analysis, including run lengths (expressed in number of cycles) and ^{144}Nd intensities, are shown in Table 2. Five samples were run twice on the same filament (denoted by the superscript "b" in Table 2: ALIA-115-21, MAG-B-47, ALIA-115-21cpx, ALIA-115-18cpx, Ofu-04-06). For one sample (ALIA-115-21), the Nd separated from the same batch of chemistry was loaded on another filament and run in a new barrel. The total chemistry (including sample dissolution on the same batch of powder) was repeated two more times on this sample, and the Nd separated was run on two additional filaments in yet another barrel. In all cases, replicates follow the basic conclusion of the study: oceanic lavas have ^{142}Nd/^{144}Nd that are indistinguishable from the terrestrial standard (Figure 1). The sample data show no correlation between dynamically measured ^{142}Nd/^{144}Nd and either statically measured ^{148}Nd/^{144}Nd or ^{150}Nd/^{144}Nd that would be suggestive of deviation from the exponential mass dependence that was used for mass fractionation correction in this study.

4. Results

[9] This study confirms and extends the observation that oceanic lavas hosting a wide variety of mantle components exhibit ^{142}Nd/^{144}Nd ratios that are identical to the terrestrial standard. Within analytical uncertainty, none of the modern OIB and MORB lavas reported here or in other studies [*Boyet and Carlson*, 2006; *Caro et al.*, 2006; *Andreasen et al.*, 2008; *Murphy et al.*, 2010] exhibit ^{142}Nd/^{144}Nd ratios different from the terrestrial standard (Figure 1 and Table 2). Data for lavas representing each of the mantle end-members—HIMU, EM2, EM1, MORB and FOZO (high ^{3}He/^{4}He)—are reported in this study. This is the first data demonstrating that lavas with radiogenic Pb-isotopic (HIMU) compositions (^{206}Pb/^{204}Pb > 21) have ^{142}Nd/^{144}Nd like all other modern terrestrial lavas. The ^{142}Nd/^{144}Nd result on extreme Samoan EM2 lavas is consistent with earlier measurements on less extreme EM2 lavas from the Societies [*Caro et al.*, 2006]. Additionally, we show that enriched Samoan lavas, including the high ^{3}He/^{4}He lava from Ofu (Ofu-04-06) and cpx separates from Malumalu seamount lava AVON3-78-1, have ^{142}Nd/^{144}Nd ratios indistinguishable from the terrestrial standard. The new data on Koolau and Christmas Island lavas support the observation that lavas hosting an EM1 signature, like lavas from Pitcairn [*Boyet and Carlson*, 2006; *Caro et al.*, 2006], have ^{142}Nd/^{144}Nd like all other modern terrestrial lavas. Together with measurements of Hawaiian and Icelandic lavas with high ^{3}He/^{4}He (Murphy *et al.*, 2010; Andreasen *et al.*, 2008), this study supports the contention that lavas with the highest ^{3}He/^{4}He (>30 Ra) from all the four hot spots with the highest ^{3}He/^{4}He (>30 Ra: Iceland, Hawaii, Galapagos, Samoa) exhibit ^{142}Nd/^{144}Nd that is identical to all other modern terrestrial lavas. Previous studies have shown that MORB lavas [*Boyet and Carlson*, 2006; *Caro et al.*, 2006] and abyssal peridotites [*Cipriani et al.*, 2011] have ^{142}Nd/^{144}Nd ratios that are indistinguishable from the terrestrial standard. We confirm these results with ^{142}Nd/^{144}Nd measurements on two different MORB lavas including sample 2ΠD43, a "popping" rock that exhibits a ^{129}Xe/^{130}Xe anomaly relative to the atmosphere [*Staudacher et al.*, 1989].

5. Discussion

5.1. Superchondritic ^{142}Nd/^{144}Nd in the Mantle Sampled by OIBs and MORBs

[10] Together with previously published results [*Boyet and Carlson*, 2006; *Caro et al.*, 2006; *Andreasen et al.*, 2008; *Murphy et al.*, 2010], our results show that all MORB and OIB lavas–from 5 different mid-ocean ridge locations and 9 different hot spots–host ^{142}Nd/^{144}Nd that is identical to the terrestrial standard (Figure 1 and Table 2). For several different reservoirs to evolve simultaneously in this brief time interval (<30 Ma) to have the exact same Sm/Nd (6% higher than chondrite) and ^{142}Nd/^{144}Nd (18 ± 5 ppm higher than chondrite) would be fortuitous. Therefore, we suggest that all measured modern terrestrial mantle reservoirs that contribute to OIB and MORB volcanism descend from a *single* early formed reservoir with a superchondritic Sm/Nd ratio (Figure 2).

[11] The origin of this progenitor reservoir is still unknown. The progenitor reservoir is either a nonchondritic BSE or the high Sm/Nd "depleted" reservoir (EDR) produced in an early differentiation event where an early enriched reservoir (EER) was

extracted from the mantle [*Boyet and Carlson*, 2005; *Caro et al.*, 2008; *O'Neill and Palme*, 2008; *Caro and Bourdon*, 2010; *Jackson et al.*, 2010]. The non-chondritic BSE and the EDR are geochemically identical entities, characterized by the same super-chondritic Sm/Nd (6% higher than chondrites), $^{143}Nd/^{144}Nd$ (0.5130) and $^{142}Nd/^{144}Nd$ (18 ± 5 ppm higher than chondritic). An EER is only needed if the BSE has chondritic relative abundances of refractory lithophile elements (Figure 2). This study and previous studies have identified no geochemical evidence that any surface rock has been derived from the EER [e.g., *Boyet and Carlson*, 2006; *Caro et al.*, 2006; *Andreasen et al.*, 2008; *Murphy et al.*, 2010]. Either the EER has been convectively isolated from participating in surface magmatism throughout Earth history, or there is no EER and the BSE does not have chondritic relative abundances of the refractory lithophile elements.

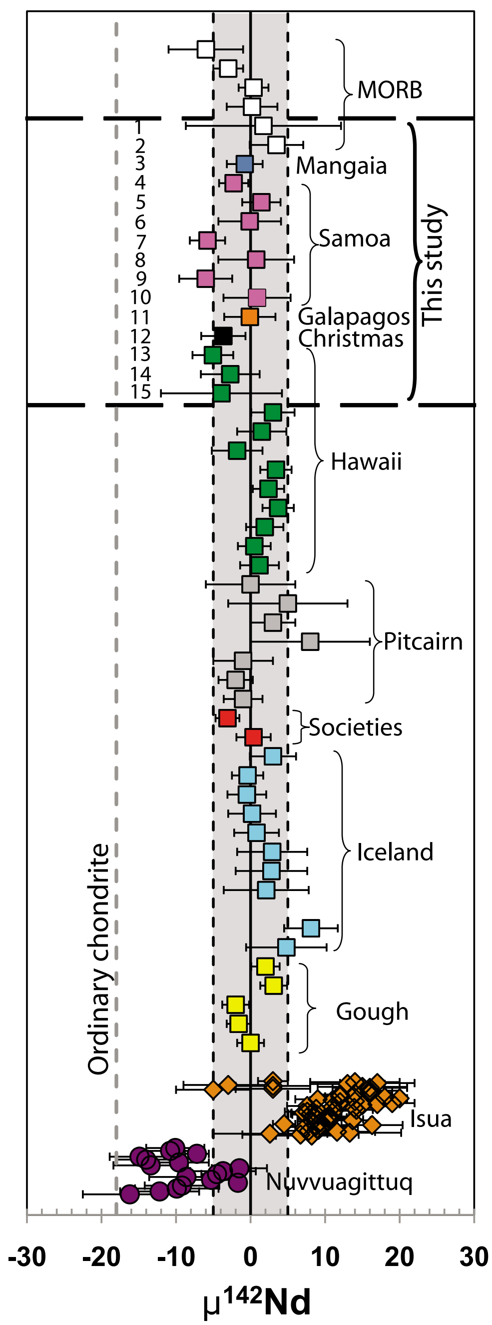

Figure 1. New high precision $^{142}Nd/^{144}Nd$ measurements on global MORB (Indian MORB and popping rock) and OIB (Mangaia, Samoa, Hawaii, Galapagos and Christmas Island) lavas. The new data are plotted with published MORB data and data from the Hawaii, Pitcairn, Societies, Iceland and Gough hostpots. The published data are from *Boyet and Carlson* [2006], *Caro et al.* [2006], *Andreasen et al.* [2008] and *Murphy et al.* [2010]. Error bars on each sample represent either the 2σ standard error of the mean or 2σ of the error on the mean for replicate analyses. All measured OIB and MORB samples are indistinguishable from the terrestrial standard at 5 ppm external precision (gray bar), and offset to higher $^{142}Nd/^{144}Nd$ ratios than ordinary chondrites. $^{142}Nd/^{144}Nd$ analyses from two localities with demonstrated anomalies are shown for context: Isua, Greenland [*Boyet and Carlson*, 2006; *Caro et al.*, 2006; *Bennett et al.*, 2007; *Rizo et al.*, 2011] and Nuvvuagittuq, Quebec [*O'Neil et al.*, 2008]. The numbers to the left of the samples represent the following samples measured as part of this study (the values in parenthesis indicate how many times a sample was measured, if measured more than once; see Table 2): 1 = 2ΠD43, 2 = D113, 3 = MAG-B-47 (n = 2), 4 = ALIA-115-21 whole rock (n = 5), 5 = ALIA-115-21cpx (n = 2), 6 = ALIA-115-18 whole rock, 7 = ALIA-115-18cpx (n = 2), 8 = 78–1cpx, 9 = T54, 10 = Ofu-04-06 (n = 2), 11 = NSK-97-214, 12 = 70448–2, 13 = KK-18-18, 14 = KOO-8, 15 = KOO-30.

[12] Two explanations that have been proposed for a BSE deficient in the more incompatible of the refractory lithophile elements are impact erosion of planetesimal crusts prior to accretion to Earth [*O'Neill and Palme*, 2008; *Caro et al.*, 2008] or volcanic ejection of partial melts from small planetesimals [*Warren*, 2008]. In modeling the trace element composition of the EDR/non-chondritic Earth [e.g., *Boyet and Carlson*, 2005; *Jackson et al.*, 2010; *Jackson and Carlson*, 2011] an important feature is the relative smoothness of the chondrite-normalized patterns when plotting the refractory incompatible elements according to their incompatibility during the relatively shallow mantle melting involved in the production of MORB or OIB [e.g., *Hofmann*, 1988]. The shape of the incompatible element pattern of the EDR/nonchondritic BSE thus is most consistent with the loss of a partial melt generated at relatively low pressure [*Boyet and Carlson*, 2005] such as might occur on small

planetesimals prior to their accretion to Earth. Alternatively, if this differentiation occurred on Earth, then a possible explanation of the EDR trace element pattern would be removal of an early formed terrestrial crust either through impact erosion or its subduction and permanent storage in the deep mantle. The timing of these early events—collision erosion or subduction of early crust—is not well known, but is likely to have happened well before 30 Ma, as suggested by recent modeling efforts [*Korenaga*, 2009] and the recent revision of the ^{146}Sm half-life from 103 Ma to 68 Ma [*Kinoshita et al.*, 2012].

[13] An important consequence of a non-chondritic BSE model is as follows: Because all modern terrestrial mantle reservoirs were derived from this non-chondritic BSE, a non-chondritic BSE becomes the standard for determining whether a reservoir is considered "enriched" (<0.5130) or "depleted" (>0.5130). For comparison, in a chondritic world, all reservoirs with ^{143}Nd/^{144}Nd > 0.51263 [*Bouvier et al.*, 2008] are considered depleted, and reservoirs with ^{143}Nd/^{144}Nd < 0.51263 are enriched. Therefore, it is the range of ^{143}Nd/^{144}Nd ratios from 0.51263 to 0.5130 that is affected by a change of reference frame: considered "depleted" in a non-chondritic world, lavas with ^{143}Nd/^{144}Nd ratios from 0.51263 to 0.5130 would be considered "enriched" in the non-chondritic BSE model. The importance of this subtle difference is illustrated with HIMU lavas. In the non-chondritic reference-frame, extreme HIMU lavas from Mangaia with ^{143}Nd/^{144}Nd of 0.51286 are considered enriched, not depleted. The non-chondritic BSE model suggests a history of incompatible element enrichment for the HIMU reservoir, instead of a history of incompatible element depletion. If HIMU forms from recycled oceanic crust [e.g., *Hofmann and White*, 1982], then the history of isotopic enrichment in HIMU, as implied by a

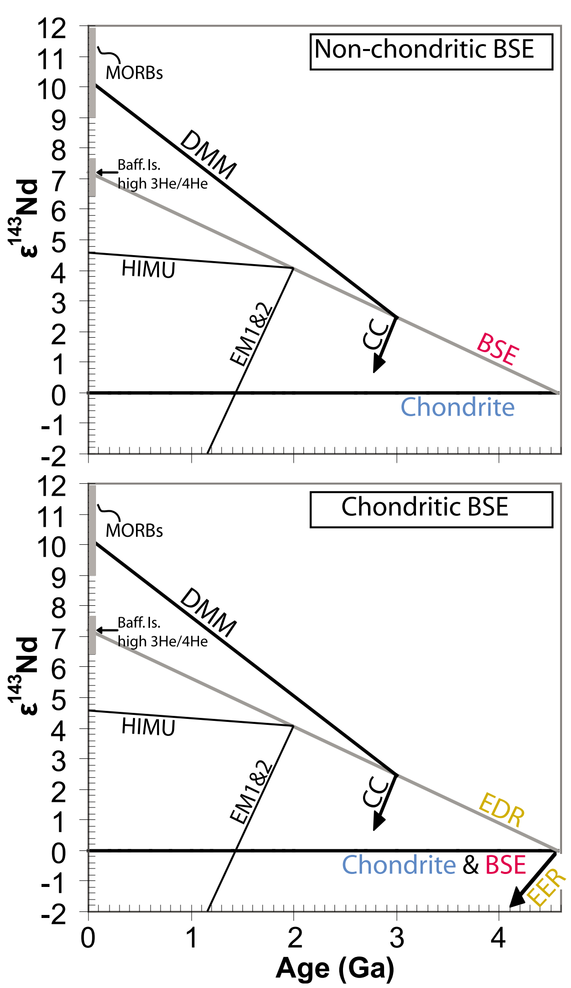

Figure 2. ^{143}Nd/^{144}Nd evolution of a chondritic and non-chondritic Earth. Both models are consistent with the observation that all accessible modern, mantle-derived terrestrial samples have ^{142}Nd/^{144}Nd 18 ± 5 ppm higher than chondrites, and were derived from an early formed (<30 Ma after accretion) precursor reservoir with Sm/Nd ~6% higher than chondrites. This precursor reservoir has a present-day ^{143}Nd/^{144}Nd of ~0.5130 (ε^{143}Nd = 7.2 [*Jackson and Carlson*, 2011]) and is (bottom) an EDR (early depleted reservoir) if BSE is chondritic (which implies the existence of an EER), or (top) a non-chondritic BSE. HIMU, EM1, EM2, DMM and most of the continental crust (excluding only a few, rare Archaean/Hadean terranes) were extracted from either the EDR (if the BSE is chondritic) or the BSE (if the BSE is not chondritic). In the chondritic Earth case (bottom), terrestrial samples with ε^{143}Nd < 0 (^{143}Nd/^{144}Nd < 0.51263) are considered enriched relative to BSE, and are considered depleted if ε^{143}Nd > 0 (^{143}Nd/^{144}Nd > 0.51263); in the non-chondritic Earth case (top), terrestrial samples with ε^{143}Nd < 7.2 (^{143}Nd/^{144}Nd < 0.5130) are considered enriched, and are considered depleted if ε^{143}Nd > 7.2 (^{143}Nd/^{144}Nd > 0.5130). The choice of reference frame is important, as the bulk of OIB ^{143}Nd/^{144}Nd measurements plot within a range of ^{143}Nd/^{144}Nd ratios of 0.51263 and 0.5130. The ε^{143}Nd of the highest ^{3}He/^{4}He Baffin Island lavas is also indicated [*Stuart et al.*, 2003; *Starkey et al.*, 2009], and coincides with the value of the EDR or the non-chondritic BSE. A ~2 Ga formation age of the EM and HIMU reservoirs is chosen to be consistent with the secondary isochron age of the mantle array in ^{207}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb isotopic space [e.g., *Zindler and Hart*, 1986]. A 3 Ga formation age of DMM is chosen to be consistent with *Workman and Hart* [2005]. The figure is adapted from *Jackson et al.* [2007b]. ε^{143}Nd = (^{143}Nd/^{144}Nd$_{sample}$/^{143}Nd/^{144}Nd$_{CHUR}$ − 1) × 10^{4}, where ^{143}Nd/^{144}Nd$_{CHUR}$ = 0.51263 [*Bouvier et al.*, 2008].

non-chondritic BSE, is consistent with the suggested origin of HIMU.

[14] Indeed, with the exception of lavas from Koolau, lavas erupted from the highest-flux mantle plume, Hawaii, generally have geochemically depleted $^{143}Nd/^{144}Nd$ ratios (>0.51263) relative to a chondritic Earth. This implies a history of depletion in the mantle source of Hawaiian lavas. However, if the Earth is not chondritic, the bulk of Hawaiian shield lavas are actually enriched ($^{143}Nd/^{144}Nd <$ 0.5130 [see *Jackson and Carlso*n, 2011]), which implies a history of geochemical enrichment for this plume relative to the bulk composition of the silicate Earth. Enrichment of the Hawaiian plume source is also consistent with its Pb isotopic composition that plots to the right of the Pb geochron, whereas a depleted source would be expected to plot to the left of the geochron. Therefore, the non-chondritic reference frame provides a view that is more consistent with the standard model for the origin of mantle plumes, which maintains that plumes are buoyantly upwelling regions of *enriched* crustal material that was subducted into the mantle in the geologic past [*Hofmann and White*, 1982; *White and Hofmann*, 1982]. Indeed, most of the global OIB database has $^{143}Nd/^{144}Nd$ that lies in the range of 0.51263 to 0.5130 (the median lies near 0.5130 [*Zindler and Hart*, 1986; *Jackson and Carlson*, 2011]), suggesting that, in a non-chondritic reference frame, most plume-derived lavas sampled geochemically enriched material relative to the BSE. By contrast, in a chondritic world, approximately 90% of OIB lavas are considered depleted ($^{143}Nd/^{144}Nd > 0.51263$) relative to BSE, which is not consistent with the hypothesis that plumes originate from recycling of ancient subducted enriched crustal materials.

[15] Whether any of the EDR (or non-chondritic BSE) has survived differentiation or mixing with recycled crust over Earth history to survive in the modern mantle is not clear. The $^{143}Nd/^{144}Nd$ predicted for the progenitor reservoir (0.5130) is similar to that measured in lavas with the highest terrestrial mantle $^{3}He/^{4}He$ ratios [*Boyet and Carlson*, 2006; *Caro et al.*, 2008; *Caro and Bourdon*, 2010; *Jackson et al.*, 2010]. The high $^{3}He/^{4}He$ mantle reservoir, including lavas with the highest $^{3}He/^{4}He$ (50 Ra) from Baffin Island [*de Leeuw et al.*, 2010], have $^{142}Nd/^{144}Nd$ identical to all other modern terrestrial lavas and 18 $\pm$ 5 ppm higher than chondrites. The highest $^{3}He/^{4}He$ Baffin Island lavas also have Pb-isotopic compositions that lie near the geochron, which is consistent with an ancient origin for this mantle reservoir [*Jackson et al.*, 2010].

5.2. Is the Hidden Early Enriched Reservoir Simply "Hidden" in the Measurement Precision?

[16] We cannot exclude the possibility that a hidden EER exists in the deep mantle, but if it exists, it is not efficiently entrained in mantle plumes and is thus not sampled at Earth's surface. Entrainment of basal mantle layers by plumes is the subject of significant discussion, and *Bourdon and Caro* [2007] review the limits on the amount of a basal layer than can be entrained. Here, we place limits on how much EER can be entrained without measurably modifying the Nd isotopic composition of the EDR. We model the minimum amount of EER mantle (that contributes to a melt) necessary to generate a clearly resolved $^{142}Nd/^{144}Nd$ anomaly relative to the terrestrial standard (i.e., -10 ppm relative to the terrestrial standard). We assume an EER composition from *Carlson and Boyet* [2008] ($^{142}Nd/^{144}Nd$ ranges from -38 to -54 ppm relative to the terrestrial standard, with Nd concentrations ranging from 2.2 to 8.9 ppm, respectively), and we assume that the EER mantle was diluted with mantle material with 1.0 ppm Nd (similar to the EDR composition of *Carlson and Boyet* [2008]) and $^{142}Nd/^{144}Nd$ identical to the terrestrial standard. This scenario requires that approximately 2–14% of the Nd in the mantle plume is from the EER to generate a $^{142}Nd/^{144}Nd$ anomaly of -10 ppm. A similar calculation, with similar results, notes that with one exception [*Upadhyay et al.*, 2009], there has been no variation in $^{142}Nd/^{144}Nd$ in mantle-derived rocks since 3.5 Ga [e.g., *Bennett et al.*, 2007]. Using the same EER and EDR concentrations mentioned above, the lack of a secular trend in $^{142}Nd/^{144}Nd$ in mantle-derived rocks since 3.5 Ga allows no more than the same 2 to 14 weight % entrainment of the EER into the EDR. The calculation shows that, given current measurement precision, 2 to 14 weight % of an EER may be entrained in plumes or into the EDR without generating a measurable difference $^{142}Nd/^{144}Nd$. This neither supports nor denies the presence on an EER, but does point out the relative insensitivity of the Nd system in resolving the presence of geochemical reservoirs left over from early Earth differentiation because of the limited fractionation of Sm and Nd and the low initial abundance of ^{146}Sm.

Acknowledgments

[17] We thank Tim Mock and Mary Horan for analytical assistance. We also thank Stan Hart, Mark Kurz, Nobu Shimizu and

Mark Javoy for supplying samples. Reviews by Bernard Bourdon and an unnamed reviewer are greatly appreciated.

References

Amelin, Y., and E. Rotenberg (2004), Sm–Nd systematics of chondrites, *Earth Planet. Sci. Lett.*, *223*, 267–282, doi:10.1016/j.epsl.2004.04.025.

Andreasen, R., and M. Sharma (2006), Solar nebula heterogeneity in p-process samarium and neodymium isotopes, *Science*, *314*, 806–809, doi:10.1126/science.1131708.

Andreasen, R., and M. Sharma (2007), Mixing and homogenization in the early solar system: Clues from Sr, Ba, Nd and Sm isotopes in meteorites, *Astrophys. J.*, *665*, 874–883, doi:10.1086/518819.

Andreasen, R., M. Sharma, K. V. Subbarao, and S. G. Viladkar (2008), Where on Earth is the enriched Hadean reservoir?, *Earth Planet. Sci. Lett.*, *266*, 14–28, doi:10.1016/j.epsl.2007.10.009.

Bennett, V. C., A. D. Brandon, and A. P. Nutman (2007), Coupled ^{142}Nd-^{143}Nd isotopic evidence for Hadean mantle dynamics, *Science*, *318*, 1907–1910.

Bourdon, B., and G. Caro (2007), The early terrestrial crust, *C. R. Geosci.*, *339*, 928–936, doi:10.1016/j.crte.2007.09.002.

Bouvier, A., J. D. Vervoort, and P. J. Patchett (2008), The Lu–Hf and Sm–Nd isotopic composition of CHUR: Constraints from unequilibrated chondrites and implications for the bulk composition of terrestrial planets, *Earth Planet. Sci. Lett.*, *273*, 48–57, doi:10.1016/j.epsl.2008.06.010.

Boyet, M., and R. W. Carlson (2005), ^{142}Nd evidence for early (>4.53 Ga) global differentiation of the silicate Earth, *Science*, *309*, 576–581, doi:10.1126/science.1113634.

Boyet, M., and R. W. Carlson (2006), A new geochemical model for the Earth's mantle inferred from ^{146}Sm–^{144}Nd systematics, *Earth Planet. Sci. Lett.*, *250*, 254–268, doi:10.1016/j.epsl.2006.07.046.

Carlson, R. W., and M. Boyet (2008), Composition of the Earth's interior: The importance of early events, *Philos. Trans. R. Soc. A*, *366*, 4077–4103, doi:10.1098/rsta.2008.0166.

Carlson, R. W., J. D. Macdougall, and G. W. Lugmair (1978), Differential Sm-Nd evolution in oceanic basalts, *Geophys. Res. Lett.*, *5*, 229–232, doi:10.1029/GL005i004p00229.

Carlson, R. W., M. Boyet, and M. Horan (2007), Chondrite barium, neodymium, and samarium isotopic heterogeneity and early Earth differentiation, *Science*, *316*, 1175–1178, doi:10.1126/science.1140189.

Caro, G., and B. Bourdon (2010), Non-chondritic Sm/Nd ratio in the terrestrial planets: Consequences for the geochemical evolution of the mantle–crust system, *Geochim. Cosmochim. Acta*, *74*, 3333–3349, doi:10.1016/j.gca.2010.02.025.

Caro, G., B. Bourdon, J. L. Birck, and S. Moorbath (2006), High-precision ^{142}Nd/^{144}Nd measurements in terrestrial rocks: Constraints on the early differentiation of the Earth's mantle, *Geochim. Cosmochim. Acta*, *70*, 164–191, doi:10.1016/j.gca.2005.08.015.

Caro, G., B. Bourdon, A. N. Halliday, and G. Quitte (2008), Super-chondritic Sm/Nd ratios in Mars, the Earth and the Moon, *Nature*, *452*, 336–339, doi:10.1038/nature06760.

Cipriani, A., E. Bonatti, and R. W. Carlson (2011), Non-chondritic ^{142}Nd in suboceanic mantle peridotites, *Geochem. Geophys. Geosyst.*, *12*, Q03006, doi:10.1029/2010GC003415.

Courtillot, V., A. Davaille, J. Besse, and J. Stock (2003), Three distinct types of hotspots in the Earth's mantle, *Earth Planet. Sci. Lett.*, *205*, 295–308, doi:10.1016/S0012-821X(02)01048-8.

de Leeuw, G. A. M., R. W. Carlson, R. M. Ellam, and F. M. Stuart (2010), Baffin Island picrites contain normal terrestrial ^{142}Nd/^{144}Nd: Implications for the source of high ^{3}He/^{4}He in deep Earth, *Geophys. Res. Abstr.*, *12*, 5321.

Engel, C. G., R. L. Fisher, and A. E. J. Engel (1965), Igneous rocks of the Indian Ocean floor, *Science*, *150*, 605–610, doi:10.1126/science.150.3696.605.

Frey, F. A., M. O. Garcia, and M. F. Roden (1994), Geochemical characteristics of Koolau Volcano: Implications of intershield geochemical differences among Hawaiian volcanoes, *Geochim. Cosmochim. Acta*, *58*, 1441–1462, doi:10.1016/0016-7037(94)90548-7.

Hanan, B. B., and D. W. Graham (1996), Lead and helium isotope evidence from oceanic basalts for a common deep source of mantle plumes, *Science*, *272*, 991–995, doi:10.1126/science.272.5264.991.

Hart, S. R., and A. Zindler (1986), In search of a bulk-Earth composition, *Chem. Geol.*, *57*, 247–267, doi:10.1016/0009-2541(86)90053-7.

Hart, S. R., E. H. Hauri, L. A. Oschmann, and J. A. Whitehead (1992), Mantle plumes and entrainment: Isotopic evidence, *Science*, *256*, 517–520, doi:10.1126/science.256.5056.517.

Hauri, E. H., and S. R. Hart (1993), Re-Os isotope systematics of HIMU and EMII oceanic island basalts from the south Pacific Ocean, *Earth Planet. Sci. Lett.*, *114*, 353–371, doi:10.1016/0012-821X(93)90036-9.

Hoernle, K., F. Hauff, R. Werner, P. van den Bogaard, A. D. Gibbons, S. Conrad, and R. D. Müller (2011), Origin of Indian Ocean Seamount Province by shallow recycling of continental lithosphere, *Nat. Geosci.*, *4*, 883–887, doi:10.1038/ngeo1331.

Hofmann, A. W. (1988), Chemical differentiation of the Earth: The relationship between mantle, continental crust, and oceanic crust, *Earth Planet. Sci. Lett.*, *90*, 297–314, doi:10.1016/0012-821X(88)90132-X.

Hofmann, A. W., and W. M. White (1982), Mantle plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.*, *57*, 421–436, doi:10.1016/0012-821X(82)90161-3.

Jackson, M. G., and R. Carlson (2011), An ancient recipe for flood basalt genesis, *Nature*, *476*, 316–319, doi:10.1038/nature10326.

Jackson, M. G., S. R. Hart, A. A. P. Koppers, H. Staudigel, J. Konter, J. Blusztajn, M. D. Kurz, and J. A. Russell (2007a), The return of subducted continental crust in Samoan lavas, *Nature*, *448*, 684–687, doi:10.1038/nature06048.

Jackson, M. G., M. D. Kurz, S. R. Hart, and R. W. Workman (2007b), New Samoan lavas from Ofu Island reveal a hemispherically heterogeneous high ^{3}He/^{4}He mantle, *Earth Planet. Sci. Lett.*, *264*, 360–374, doi:10.1016/j.epsl.2007.09.023.

Jackson, M. G., S. R. Hart, A. E. Saal, N. Shimizu, M. D. Kurz, J. S. Blusztajn, and A. C. Skovgaard (2008), Globally elevated titanium, tantalum, and niobium (TITAN) in ocean island basalts with high ^{3}He/^{4}He, *Geochem. Geophys. Geosyst.*, *9*, Q04027, doi:10.1029/2007GC001876.

Jackson, M. G., S. R. Hart, N. Shimizu, and J. Blusztajn (2009), The ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd disequilibrium between Polynesian hot spot lavas and the clinopyroxenes they host: Evidence complementing isotopic disequilibrium in melt inclusions, *Geochem. Geophys. Geosyst.*, *10*, Q03006, doi:10.1029/2008GC002324.

Jackson, M. G., R. W. Carlson, M. D. Kurz, P. D. Kempton, D. Francis, and J. Blusztajn (2010), Evidence for the survival of the oldest terrestrial mantle reservoir, *Nature*, *466*, 853–856, doi:10.1038/nature09287.

Jacobsen, S. B., and G. J. Wasserburg (1980), Sm–Nd isotopic evolution of chondrites, *Earth Planet. Sci. Lett.*, *50*, 139–155, doi:10.1016/0012-821X(80)90125-9.

Jagoutz, E., H. Palme, H. Baddenhausen, K. Blum, M. Cendales, G. Dreibus, B. Spettel, V. Lorenz, and H. Wänke (1979), The abundances of major, minor and trace elements in the Earth's mantle as derived from primitive ultramafic nodules, *Proc. Lunar Planet. Sci. Conf.*, *10th*, 2031–2050.

Kinoshita, N., et al. (2012), A shorter ^{146}Sm half-life measured and implications for ^{146}Sm-^{142}Nd chronology of the solar system, *Science*, *335*, 1614–1617, doi:10.1126/science.1215510.

Korenaga, J. (2009), A method to estimate the composition of the bulk silicate Earth in the presence of a hidden geochemical reservoir, *Geochim. Cosmochim. Acta*, *73*, 6952–6964, doi:10.1016/j.gca.2009.08.020.

Kurz, M. D., and D. J. Geist (1999), Dynamics of the Galapagos hotspot from helium isotope geochemistry, *Geochim. Cosmochim. Acta*, *63*, 4139–4156, doi:10.1016/S0016-7037(99)00314-2.

Kurz, M. D., W. J. Jenkins, and S. R. Hart (1982), Helium isotope systematics of oceanic island and mantle heterogeneity, *Nature*, *297*, 43–47, doi:10.1038/297043a0.

McDonough, W. F., and S. S. Sun (1995), The composition of the Earth, *Chem. Geol.*, *120*, 223–253, doi:10.1016/0009-2541(94)00140-4.

Moreira, M., J. Kunz, and C. Allègre (1998), Rare gas systematics in popping rock: Isotopic and elemental compositions in the upper mantle, *Science*, *279*, 1178–1181, doi:10.1126/science.279.5354.1178.

Morgan, W. J. (1971), Convection plumes in the lower mantle, *Nature*, *230*, 42–43, doi:10.1038/230042a0.

Murphy, D. T., A. D. Brandon, V. Debaille, R. Burgess, and C. Ballentine (2010), ^{142}Nd/^{144}Nd reservoir in the deep mantle: Implications for the Nd isotope systematics of the Earth, *Geochim. Cosmochim. Acta*, *74*, 738–750, doi:10.1016/j.gca.2009.10.005.

O'Neil, J., R. W. Carlson, D. Francis, and R. K. Stevenson (2008), Neodymium-142 evidence for Hadean mafic crust, *Science*, *321*, 1828–1831.

O'Neill, H. S. C., and H. Palme (2008), Collisional erosion and the non-chondritic composition of the terrestrial planets, *Philos. Trans. R. Soc. A*, *366*, 4205–4238, doi:10.1098/rsta.2008.0111.

Palme, H., and H. S. C. O'Neill (2003), Cosmochemical estimates of mantle composition, in *Treatrise on Geochemistry*, vol. 2, *The Mantle and Core*, edited by R. W. Carlson, pp. 1–38, Elsevier, Amsterdam.

Patchett, P. J., J. D. Vervoort, and U. Söderlund (2004), Lu–Hf and Sm–Nd isotopic systematics in chondrites and their constraints on the Lu–Hf properties of the earth, *Earth Planet. Sci. Lett.*, *222*, 29–41, doi:10.1016/j.epsl.2004.02.030.

Qin, L., R. W. Carlson, and C. M. O'D. Alexander (2011), Correlated nucleosynthetic isotopic variability in Cr, Sr, Ba, Sm, Nd and Hf in Murchison and QUE 97008, *Geochim. Cosmochim. Acta*, *75*, 7806–7828, doi:10.1016/j.gca.2011.10.009.

Rizo, H., M. Boyet, J. Blichert-Toft, and M. Rosing (2011), Combined Nd and Hf isotope evidence for deep-seated source of Isua lavas, *Earth Planet. Sci. Lett.*, *312*, 267–279, doi:10.1016/j.epsl.2011.10.014.

Roden, M. F., T. Trull, S. R. Hart, and F. A. Frey (1994), New He, Nd, Pb, and Sr isotopic constraints on the constitution of the Hawaiian plume: Results from Koolau Volcano, Oahu, Hawaii, USA, *Geochim. Cosmochim. Acta*, *58*, 1431–1440, doi:10.1016/0016-7037(94)90547-9.

Saal, A. E., M. D. Kurz, S. R. Hart, J. S. Blusztajn, J. Blichert-Toft, Y. Liang, and D. Geist (2007), The role of lithospheric gabbros on the composition of Galapagos lavas, *Earth Planet. Sci. Lett.*, *257*, 391–406, doi:10.1016/j.epsl.2007.02.040.

Starkey, N. A., F. M. Stuart, R. M. Ellam, J. G. Fitton, S. Basu, and L. M. Larsen (2009), Helium isotopes in early Iceland plume picrites: Constraints on the composition of high ^{3}He/^{4}Hemantle, *Earth Planet. Sci. Lett.*, *277*, 91–100, doi:10.1016/j.epsl.2008.10.007.

Staudacher, T., P. Sarda, S. H. Richardson, C. J. Allègre, I. Sagna, and L. V. Dmitriev (1989), Noble gases in basalt glasses from a Mid-Atlantic Ridge topographic high at 14°N: Geodynamic consequences, *Earth Planet. Sci. Lett.*, *96*, 119–133, doi:10.1016/0012-821X(89)90127-1.

Stuart, F. M., S. Lass-Evans, J. G. Fitton, and R. Ellam (2003), High ^{3}He/^{4}He ratios in picritic basalts from Baffin Island and the role of a mixed reservoir in mantle plumes, *Nature*, *424*, 57–59, doi:10.1038/nature01711.

Su, Y. (2003), Global MORB chemistry compilation at the segment scale, PhD thesis, Dep. of Earth and Environ. Sci., Columbia Univ., N. Y.

Subbarao, K. V., and C. E. Hedge (1973), K, Rb and ^{87}Sr/^{86}Sr in rocks from the Mid-Indian Oceanic Ridge, *Earth Planet. Sci. Lett.*, *18*, 223–228, doi:10.1016/0012-821X(73)90060-5.

Upadhyay, D., E. E. Scherer, and K. Mezger (2009), ^{142}Nd evidence for an enriched Hadean reservoir in cratonic roots, *Nature*, *459*, 1118–1121, doi:10.1038/nature08089.

Warren, P. H. (2008), A depleted, not ideally chondritic bulk Earth: The explosive-volcanic basalt loss hypothesis, *Geochim. Cosmochim. Acta*, *72*, 3562–3585, doi:10.1016/j.gca.2008.04.031.

White, W. M., and A. W. Hofmann (1982), Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution, *Nature*, *296*, 821–825, doi:10.1038/296821a0.

Workman, R. K., and S. R. Hart (2005), Major and trace element composition of the depleted MORB mantle (DMM), *Earth Planet. Sci. Lett.*, *231*, 53–72, doi:10.1016/j.epsl.2004.12.005.

Workman, R. K., S. R. Hart, M. G. Jackson, M. Regelous, K. A. Farley, J. Blusztajn, M. Kurz, and H. Staudigel (2004), Recycled metasomatized lithosphere as the origin of the Enriched Mantle II (EM2) end-member: Evidence form the Samoan Volcanic Chain, *Geochem. Geophys. Geosyst.*, *5*, Q04008, doi:10.1029/2003GC000623.

Zindler, A., and S. R. Hart (1986), Chemical geodynamics, *Annu. Rev. Earth Planet. Sci.*, *14*, 493–571, doi:10.1146/annurev.ea.14.050186.002425.