Earth and Planetary Science Letters xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^{3}He/^{4}He$ mantle

Matthew G. Jackson [a,*], Mark D. Kurz [b], Stanley R. Hart [b]

[a] Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington D.C., 20015, USA
[b] Woods Hole Oceanographic Institution, Woods Hole, MA, 02543, USA

ARTICLE INFO

Article history:
Received 19 May 2009
Received in revised form 29 August 2009
Accepted 31 August 2009
Available online xxxx

Editor: T.M. Harrison

Keywords:
$^{3}He/^{4}He$
neon isotopes
FOZO
PHEM
C
EM2
Samoa
OIB
mantle

ABSTRACT

We report the first neon isotope measurements on phenocrysts from subaerial and submarine Samoan lavas. These new data complement existing Ne-isotope data from Samoan peridotite xenoliths. Neon isotopes were measured in magmatic phenocrysts separated from nine shield-stage lavas from 5 Samoan volcanoes, including Ofu, Ta'u, Vailulu'u, Malumalu and Savai'i. Phenocrysts from subaerial Samoan lavas have higher $^{20}Ne/^{22}Ne$ than submarine phenocrysts, which may suggest different atmospheric contamination mechanisms for these two different eruptive environments. Olivine phenocrysts from a subaerial Ta'u lava exhibit the highest $^{20}Ne/^{22}Ne$ (11.3) value in this study. Two subaerial Samoan samples from Ofu Island with high $^{3}He/^{4}He$ ratios (Ofu-04-06 and Ofu-04-03; 34 and 24 Ra [ratio to atmosphere], respectively) also have elevated $^{20}Ne/^{22}Ne$ ratios relative to air, and in a three-isotope neon plot the Ofu samples are indistinguishable from measurements made on high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos. The similarity of helium and neon isotopes in Ofu and Hawaii–Iceland–Galapagos is remarkable given the distinctions in $^{87}Sr/^{86}Sr$ (0.70458 for Ofu vs. 0.70329–0.70368 for Hawaii–Iceland–Galapagos) and $^{143}Nd/^{144}Nd$ (Ofu's 0.51283 vs. 0.51294–0.51297 for Hawaii–Iceland–Galapagos) in high $^{3}He/^{4}He$ lavas from these localities. Thus, the occurrence of similar helium and neon isotope compositions in lavas from these 4 hotspots does not appear to be linked to their variable Sr and Nd isotope compositions, and demonstrates a complex relationship between the isotopes of noble gases and the more refractory radiogenic isotopes. Additionally, we observe strongly nucleogenic neon isotopes in one the most isotopically-enriched ($^{87}Sr/^{86}Sr>0.718$) Samoan lavas. This observation is consistent with the presence of recycled, continentally-derived marine sediment in the mantle source of the most enriched lavas from Samoa.

1. Introduction

The Samoan archipelago is an age-progressive hotspot located just north of the northern terminus of the Tonga subduction zone (Hart et al., 2004; Koppers et al., 2008). Based on measurements of radiogenic isotopes and trace elements, lavas erupted at the Samoan hotspot have long been known to sample a heterogeneous mantle (Hedge et al., 1972; White and Hofmann, 1982; Wright and White, 1986; Farley et al., 1992; Workman et al., 2004). Isotopically-enriched Samoan lavas-like the submarine samples from Savai'i Island—host an EM2 (enriched mantle 2; Zindler and Hart, 1986; Hofmann, 1997) component that suggests a role for recycled, continentally-derived marine sediment in the mantle upwelling beneath the Samoan hotspot (White and Hofmann; 1982; Jackson et al., 2007a; Workman et al., 2008). By contrast, some of the Samoan lavas with the most isotopically-depleted (high) $^{143}Nd/^{144}Nd$ ratios, like those erupted at Ofu Island, can exhibit high $^{3}He/^{4}He$ ratios (up to 33.8 Ra; Jackson et al., 2007b), and these lavas exhibit no evidence for an enriched recycled sediment component. High $^{3}He/^{4}He$ ratios of a similar magnitude have been observed only in Hawaii (Kurz et al., 1982; Honda et al., 1993; Valbracht et al., 1997), Iceland and the proto-Iceland plume (Kurz et al., 1985; Graham et al., 1998; Hilton et al., 1999; Trieloff et al., 2000; Stuart et al., 2003; MacPherson et al., 2005), and the Galapagos (Graham et al., 1993; Kurz and Geist, 1999; Saal et al., 2007). The high $^{3}He/^{4}He$ component sampled by these hotspots is thought to be an ancient, relatively undegassed, deep-seated mantle component (e.g., Kurz et al., 1982). Many studies have suggested that the high $^{3}He/^{4}He$ mantle reservoir is common to all other hotspots, and it has been variously referred to as FOZO (Focus Zone; Hart et al., 1992), PHEM (Primitive Helium Mantle; Farley et al., 1992) or C (Common; Hanan and Graham, 1996). The origin, lithology, location and long-term history of the high $^{3}He/^{4}He$ reservoir remain poorly known (e.g., Hart et al., 1992; Anderson, 1998; Parman et al., 2005; Class and Goldstein, 2005; Jackson et al., 2008; Albarède, 2008).

Neon isotopes provide an important constraint on the origin of the mantle hosting high $^{3}He/^{4}He$ signatures. The evolution of neon and helium isotopes are closely linked by their common parentage in the U

* Corresponding author.
E-mail address: mjackson@ciw.edu (M.G. Jackson).

0012-821X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2009.08.039

and Th decay systems: ^{4}He formed by the decay of U and Th decreases ^{3}He/^{4}He ratios, while ^{21}Ne is generated by nucleogenic reactions on Mg and O, where the nucleogenic reactions (e.g., ^{18}O(α,n)^{21}Ne) originate from U and Th decay. Therefore, the evolution of neon isotopes in the earth's mantle is controlled by long-term (U+Th)/Ne ratios, and the helium isotope system is governed by time-integrated (U+Th)/He ratios. Regions of the mantle with high ^{3}He/^{4}He should have low time-integrated (U+Th)/He and, owing to the similar behavior of helium and neon, low (U+Th)/Ne. This hypothesis is borne out by the observation that the mantle component sampled by the highest ^{3}He/^{4}He (>30 Ra) hotspots, Hawaii, Iceland and Galapagos, have less nucleogenic neon isotopes than low ^{3}He/^{4}He hotspots and MORBS (midocean ridge basalts) (e.g., Honda et al., 1991; Hiyagon et al., 1992; Honda et al., 1993; Dixon et al., 2000; Trieloff et al., 2000; Moreira et al., 2001; Kaneoka et al., 2002; Dixon, 2003; Kurz et al., 2009). Nonetheless, the high ^{3}He/^{4}He lavas sampled from different hotspots have been found to exhibit heterogeneous ^{21}Ne/^{22}Ne$_{extrap}$ values, where ^{21}Ne/^{22}Ne compositions are extrapolated to a constant ^{20}Ne/^{22}Ne value[1] to deconvolve the mantle and atmospheric components in lavas and xenoliths (the expression for calculating ^{21}Ne/^{22}Ne$_{extrap}$ is in the Fig. 4 caption). Galapagos lavas with the highest ^{3}He/^{4}He ratios also host ^{21}Ne/^{22}Ne$_{extrap}$ isotope compositions that are closer to solar values than Icelandic high ^{3}He/^{4}He lavas, and Loihi lavas in turn have even more nucleogenic Ne isotopes than Iceland (Kurz et al., 2009). The observation of variable neon isotope signatures in high ^{3}He/^{4}He lavas suggests some variation in time-integrated (U+Th)/Ne ratios in the high ^{3}He/^{4}He mantle, but some of the neon isotope variability may owe to fractionation of He from Ne during degassing with subsequent mixing of melts with variable He/Ne (e.g., Moreira and Sarda, 2000; Sarda and Moreira, 2002; Gonnermann and Mukhopadhyay, 2007). However, owing to the fact that the highest ^{3}He/^{4}He lavas from these three hotspots host somewhat different Sr and Nd isotopes, perhaps it is not surprising that their neon isotope compositions are also distinct.

Here we present the first neon isotope data from magmatic phenocrysts in Samoan lavas. These new data complement existing noble gas measurements from Samoan peridotite xenoliths, which revealed a range of neon isotope ratios in samples with a wide range of ^{3}He/^{4}He (11.5–21 Ra; Poreda and Farley, 1992). However, xenoliths can be residues of melt extraction and may host a contribution of relatively nucleogenic ^{21}Ne/^{22}Ne from the upper mantle from melting processes, residence in the mantle, or emplacement. In an attempt to characterize the neon isotopic composition of the Samoan source mantle, and avoid the upper mantle neon component found in some xenoliths, the strategy was to examine neon isotopes in olivine and clinopyroxene phenocrysts in lavas. Indeed, we find that Samoan lavas with a moderately high to high ^{3}He/^{4}He (13.3–33.8 Ra) exhibit a ^{21}Ne/^{22}Ne$_{extrap}$ ratios that are similar to the neon isotope values reported in high ^{3}He/^{4}He lavas from Fernandina (Galapagos), Loihi (Hawaii), and Iceland. This result is surprising, as high ^{3}He/^{4}He lavas from Samoa have distinctly more enriched Sr and Nd isotopes than Loihi, Galapagos and Icelandic high ^{3}He/^{4}He lavas. The result also suggests that the evolution of neon in the mantle, while generally coupled to helium, may not follow the evolution of Sr and Nd isotopes.

2. Samples and procedures

Neon isotope data are reported only for magmatic phenocrysts. The Sr–Nd–He isotopes for the nine lavas examined in this study were

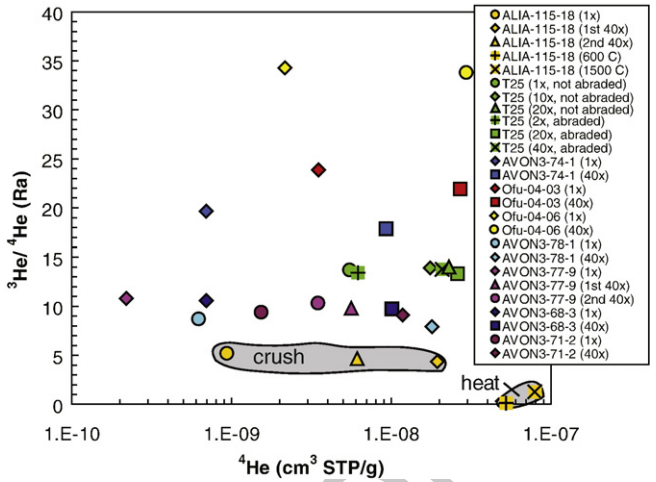

Fig. 1. Helium isotopes for all crushing and heating experiments are plotted against their respective gas concentrations. All measurements are made on phenocrysts of clinopyroxene (ALIA-115-18) or olivine (the other 8 samples). Crushing experiments yield similar ^{3}He/^{4}He for a particular sample over a range of concentrations. By comparison, a heating experiment made on one aliquot of clinopyroxene phenocrysts from sample ALIA-115-18 had higher ^{4}He and lower ^{3}He/^{4}He than crushes made on the same aliquot of phenocrysts.

reported elsewhere (Workman et al., 2004; Jackson et al., 2007a,b). All samples are alkaline basalts based on the classification of Macdonald and Katsura (1964). Six lavas were recovered by submarine dredging during the AVON3 cruise (see Workman et al., 2004) and the remaining samples (Ofu-04-03, Ofu-04-06 and T25) were collected on land. Based on the results of previous helium isotope work on Samoan lavas (Workman et al., 2004; Jackson et al., 2007b), samples with the most helium-rich phenocrysts were chosen for neon isotope measurement. Following whole-rock crushing and magnetic separation of phenocrysts, only the freshest material was chosen for neon isotope analysis. The clinopyroxene (Jackson et al., 2009) and olivine (Jackson, in prep) phenocrysts are compositionally magmatic, and show no overlap with the clinopyroxene and olivine compositions measured in Samoan xenolith olivines (Hauri and Hart, 1994). From six lavas, more than 1 g of olivine phenocrysts was separated for noble gas measurement. Less material was available for Ofu-04-06 (0.67 g of olivine), AVON3-71-2 (0.90 g of olivine) and ALIA-115-18 (0.54 g of clinopyroxene). All phenocrysts were ultrasonicated for 15 min in acetone before loading into ultra-high vacuum crushers. In order to efficiently remove surface coatings and adhering basalt, many of the mineral separates were abraded using pressurized air (in a stainless

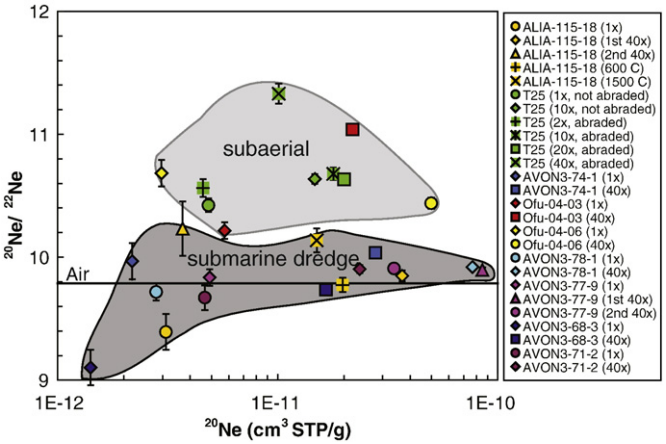

Fig. 2. Neon isotopes for all crushing and heating experiments are plotted against their respective gas concentrations. Neon measurements on magmatic phenocrysts from samples collected on land have higher ^{20}Ne/^{22}Ne than neon measurements made on phenocrysts recovered by deep-sea dredging. Error bars are 1σ (see Table 1).

[1] Neon is often extrapolated to either the solar ^{20}Ne/^{22}Ne value of 13.8, or to neon B (^{20}Ne/^{22}Ne of 12.5), where the latter represents an alternative starting composition for the earth that is found in meteorites (e.g., Black, 1972; Trieloff et al., 2000). We extrapolate to the solar neon component in this study, but extrapolating to the neon B component would not alter our conclusions.

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high ^{3}He/^{4}He mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

steel abrasion chamber), and then cleaned in weak (<10%) nitric acid. In order to test the effects of this cleaning procedure, neon isotopes were measured on two aliquots of olivines from sample T25: the first aliquot was not treated, and the second was subjected to air abrasion and nitric acid treatment. Helium and neon isotopes obtained on the air abraded and nitric acid-treated olivine phenocrysts were similar to the untreated olivines (see Figs. 1–3), suggesting that the abrasion and nitric acid treatment does not diminish gas contents or alter the proportion of the measured atmospheric neon component. The sample with the highest $^{20}Ne/^{22}Ne$ and $^{21}Ne/^{22}Ne$ was from a crushing experiment of abraded olivine from sample T25. Most samples reported in Table 1 were air abraded and cleaned in nitric acid before analysis.

Neon measurements were made on a MAP 215-50 mass spectrometer dedicated to high precision neon measurements. The procedures for neon extraction, purification and mass spectrometry follow those from Kurz et al. (2009). Helium was also measured on the MAP 215-50 mass spectrometer in order to obtain He/Ne ratios. Following each of a series of crushing steps *in vacuo* (for phenocrysts separated from 9 samples), helium and neon isotopes were measured in the mass spectrometer. In addition to an *in vacuo* crushing experiment, the powder remaining from sample ALIA-115-18 was also measured for neon after an initial heating step (at 600 °C) and again following fusion (at 1500 °C). Blanks during crushing and step-heating experiments were $<1\times10^{-11}$ cc STP ^{4}He and $<2\times10^{-12}$ cc STP ^{20}Ne. Interferences from $H_2^{18}O$ and HF are negligible and require no correction (Kurz et al., 2008). Interferences from doubly charged ^{40}Ar and CO_2 on the ^{20}Ne and ^{22}Ne peaks, respectively, are dealt with following the protocol in Kurz et al. (2009). It is difficult to estimate the error associated with corrections for these doubly-charged interferences, and neon measurements with low signal intensities (2000 cps on ^{20}Ne, or $<1\times10^{-11}$ cc in the mass spectrometer) that require large blank corrections (>3%), and doubly charged corrections greater than 3%, are not included in the interpretation and discussion that follows (Kurz et al., 2009). However, low intensity neon isotope measurements are included in Table 1 for completeness.

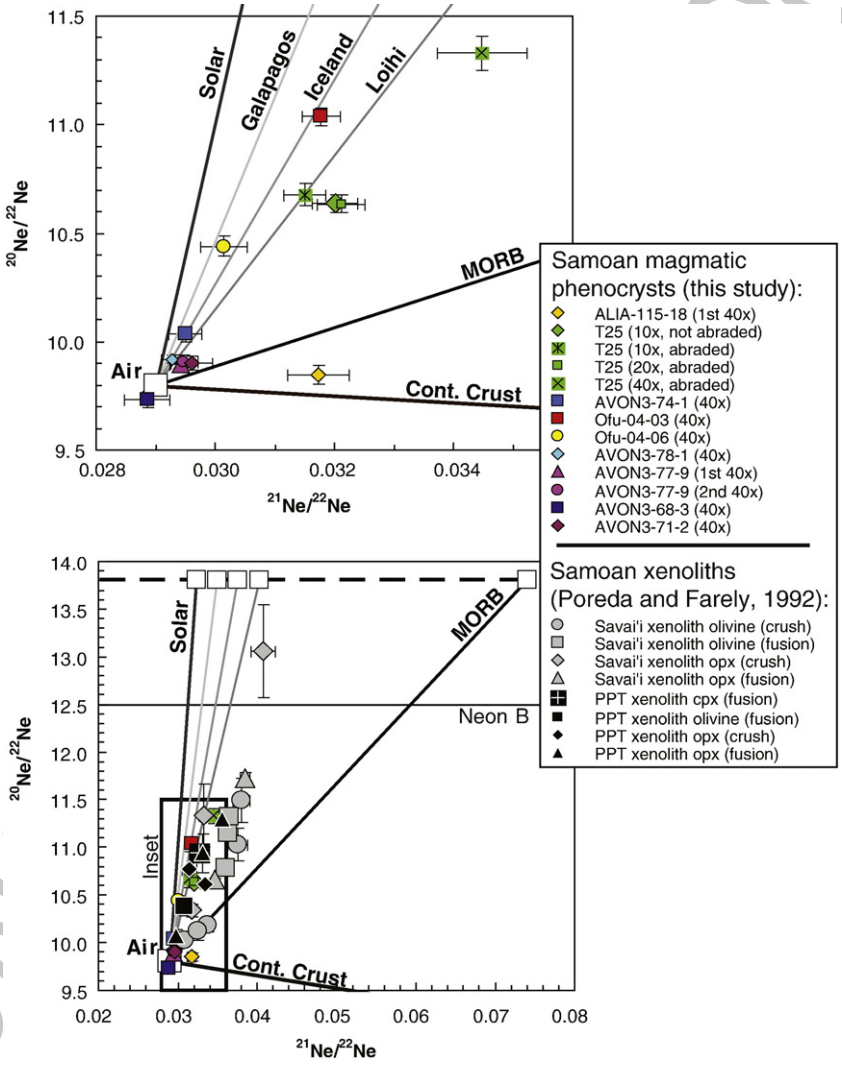

Fig. 3. Three-isotope neon plot, showing new Ne data from Samoan magmatic phenocrysts (upper panel, this study) and previously published Ne measurements from Samoan xenoliths (lower panel). Only individual crushing experiments with high signal intensities are plotted (>2000 cps on ^{20}Ne, or $>1\times10^{-11}$ cc ^{20}Ne in the mass spectrometer). Error bars on Samoan measurements are 1σ (see Table 1). Samoan xenolith measurements that are plotted include the data shown in Fig. 1 of Poreda and Farley (1992). The highest $^{3}He/^{4}He$ lavas (24 and 34 Ra) from Ofu Island, Samoa exhibit neon isotopes that are indistinguishable from high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos. The EM2 lava with high $^{87}Sr/^{86}Sr$ (0.7186) and low $^{143}Nd/^{144}Nd$ (0.5123) from Samoa, ALIA-115-18 (2nd 40×), plots between the continental crust and MORB lines, consistent with the hypothesis that the Samoan EM2 mantle hosts a component of recycled continental crust. References for the Iceland, Loihi and Galapagos lines are in Table 2. Data from Moreira et al. (1998) are used to define the MORB line. The horizontal dashed line represents the solar $^{21}Ne/^{22}Ne$ value, as measured in present-day solar wind (Benkert et al., 1993); the horizontal solid line marks the Neon B component, which is found in meteorites and is an alternative starting composition for the Earth (e.g., Black, 1972; Trieloff et al., 2000). The line for continental crust is from Ballentine and Burnard (2002) and Ballentine et al. (2005).

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^{3}He/^{4}He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

Table 1
Neon and helium data for magmatic phenocrysts (olivine and clinopyroxene) from Samoan lavas.

Sample ID	Location	Subaerial or submarine?	Phase analyzed	Abraded	Mass	^4He	^3He cm^3 STP/g	$^3He/^4He$	1σ	^{20}Ne	$^{20}Ne/^{22}Ne$	1σ	$^{21}Ne/^{22}Ne$	1σ	$^{21}Ne/^{22}Ne_{extrap}$
					(g)	(cm^3 STP/g)	(cm^3 STP/g)	(R/Ra)		(cm^3 STP/g)					
T25–1×[a]	Ta'u Island	Subaerial	Olivine	No		5.48E−09	5.42E−14	13.70	0.074	4.85E−12	10.42	0.06	0.0304	0.0005	0.038
T25–10×	Ta'u Island	Subaerial	Olivine	No		1.75E−08	1.76E−13	13.92	0.102	1.47E−11	10.64	0.04	0.0320	0.0004	0.043
T25–20×[b]	Ta'u Island	Subaerial	Olivine	No		2.25E−08	2.25E−13	13.87	0.116						
Total					1.85	4.55E−08	4.56E−13	13.87	0.106	1.96E−11	10.58	0.04	0.0316	0.0004	0.042
T25–2×[a]	Ta'u Island	Subaerial	Olivine	Yes		6.18E−09	5.99E−14	0.13	13.42	4.57E−12	10.56	0.07	0.0322	0.0007	0.046
T25–10×[c]	Ta'u Island	Subaerial	Olivine	Yes						1.79E−11	10.68	0.05	0.0315	0.0004	0.040
T25–20×	Ta'u Island	Subaerial	Olivine	Yes		2.60E−08	2.50E−13	13.33	0.18	2.00E−11	10.63	0.04	0.0321	0.0004	0.044
T25–40×	Ta'u Island	Subaerial	Olivine	Yes		2.08E−08	2.07E−13	13.77	0.18	1.01E−11	11.33	0.08	0.0345	0.0008	0.043
Total					1.37	5.30E−08	5.17E−13	13.52	0.17	5.26E−11	10.78	0.05	0.0324	0.0005	0.043
ALIA-115-18–1×[a]	Savai'i Island dredge	Submarine	Cpx	No[d]		9.35E−10	3.51E−15	5.20	0.09	3.11E−12	9.39	0.15	0.0289	0.0014	0.030
ALIA-115-18–40×(1st)	Savai'i Island dredge	Submarine	Cpx	No[d]		1.94E−08	6.10E−14	4.35	0.04	3.68E−11	9.85	0.04	0.0317	0.0005	0.254
ALIA-115-18–40×(2nd)[a]	Savai'i Island dredge	Submarine	Cpx	No[d]		6.12E−09	2.05E−14	4.65	0.04	3.70E−12	10.23	0.22	0.0352	0.0016	0.087
Total					0.54	2.65E−08	8.51E−14	4.45	0.04	4.36E−11	9.85	0.07	0.0318	0.0007	0.262
ALIA-115-18–600 C[a]	Savai'i Island dredge	Submarine	Cpx	No[d]		5.23E−08	4.80E−15	0.13	0.00	1.97E−11	9.77	0.06	0.0297	0.0011	−0.077
ALIA-115-18–1500 C[a]	Savai'i Island dredge	Submarine	Cpx	No[d]		7.93E−08	7.27E−14	1.27	0.01	1.50E−11	10.14	0.10	0.0367	0.0013	0.120
Total					0.30	1.32E−07	7.75E−14	0.81	0.01	3.47E−11	9.93	0.08	0.0327	0.0012	0.142
Ofu-04-03–1×[a]	Ofu Island	Subaerial	Olivine	Yes		3.50E−09	6.04E−14	23.87	0.19	5.74E−12	10.22	0.07	0.0303	0.0006	0.042
Ofu-04-03–40×	Ofu Island	Subaerial	Olivine	Yes		2.70E−08	4.28E−13	21.92	0.33	2.19E−11	11.04	0.04	0.0318	0.0003	0.038
Total					1.62	3.06E−08	4.89E−13	22.14	0.32	2.76E−11	10.87	0.05	0.0315	0.0004	0.038
AVON3-78-1–1×[a]	Malumalu Seamount dredge	Submarine	Olivine	Yes		6.22E−10	3.91E−15	8.71	0.09	2.80E−12	9.72	0.07	0.0295	0.0006	0.005
AVON3-78-1–40×	Malumalu Seamount dredge	Submarine	Olivine	Yes		1.80E−08	1.03E−13	7.92	0.08	7.67E−11	9.92	0.02	0.0293	0.0002	0.038
Total					2.13	1.86E−08	1.07E−13	7.94	0.08	7.96E−11	9.91	0.02	0.0293	0.0002	0.039
AVON3-68-3–1×[a]	Vailulu'u Seamount dredge	Submarine	Olivine	Yes		6.94E−10	5.31E−15	10.58	0.07	1.41E−12	9.10	0.14	0.0269	0.0010	0.041
AVON3-68-3–40×	Vailulu'u Seamount dredge	Submarine	Olivine	Yes		1.01E−08	7.09E−14	9.73	0.07	1.66E−11	9.73	0.04	0.0289	0.0004	0.037
Total					1.70	1.08E−08	7.62E−14	9.78	0.07	1.80E−11	9.68	0.05	0.0287	0.0004	0.039
Ofu-04-06–1×[a]	Ofu Island	Subaerial	Olivine	Yes		2.19E−09	5.43E−14	34.30	0.17	2.97E−12	10.68	0.11	0.0323	0.0012	0.044
Ofu-04-06–40×	Ofu Island	Subaerial	Olivine	Yes		2.99E−08	7.31E−13	33.82	0.16	4.98E−11	10.44	0.05	0.0301	0.0004	0.036
Total					0.67	3.21E−08	7.85E−13	33.86	0.16	5.28E−11	10.45	0.05	0.0303	0.0004	0.037
AVON3-71-2–1×[a]	Vailulu'u Seamount dredge	Submarine	Olivine	Yes		1.53E−09	1.04E−14	9.40	0.06	4.67E−12	9.67	0.10	0.0273	0.0007	0.081
AVON3-71-2–40×	Vailulu'u Seamount dredge	Submarine	Olivine	Yes		1.18E−08	7.74E−14	9.10	0.05	2.36E−11	9.90	0.03	0.0296	0.0004	0.052
Total					0.90	1.33E−08	8.78E−14	9.14	0.05	2.83E−11	9.86	0.04	0.0292	0.0004	0.043
AVON3-74-1–1×[a]	Ta'u Island dredge	Submarine	Olivine	Yes		6.94E−10	9.85E−15	19.66	0.16	2.18E−12	9.97	0.15	0.0305	0.0014	0.065
AVON3-74-1–40×	Ta'u Island dredge	Submarine	Olivine	Yes		9.28E−09	1.20E−13	17.86	0.09	2.78E−11	10.04	0.03	0.0295	0.0003	0.037
Total					1.14	9.97E−09	1.30E−13	17.98	0.10	3.00E−11	10.03	0.04	0.0296	0.0004	0.039
AVON3-77-9–1×[a]	Vailulu'u Seamount dredge	Submarine	Olivine	No		2.19E−10	1.71E−15	10.81	0.09	4.91E−12	9.83	0.07	0.0299	0.0008	0.131
AVON3-77-9–40× (1st)	Vailulu'u Seamount dredge	Submarine	Olivine	No		5.61E−09	3.97E−14	9.80	0.10	8.51E−11	9.90	0.02	0.0294	0.0002	0.047
AVON3-77-9–40× (2nd)	Vailulu'u Seamount dredge	Submarine	Olivine	No		3.47E−09	2.59E−14	10.33	0.07	3.38E−11	9.91	0.03	0.0295	0.0002	0.046
Total					1.32	9.30E−09	6.74E−14	10.02	0.09	1.24E−10	9.90	0.03	0.0295	0.0002	0.048

Errors on individual measurements are propagated from in-run statistics. Clinopyroxene is abbreviated as cpx.
[a] Corrections for blank and interferences from doubly charged CO_2 and ^{40}Ar exceeded 3%.
[b] Neon lost.
[c] Helium lost.
[d] Phenocrysts were not abraded, but they were cleaned in nitric acid, followed by rinsing in water and acetone.

3. Results and discussion

Neon isotope measurements in ocean island basalts reflect a mixture of a mantle and air components (Sarda et al., 1988). Owing to very low concentrations of neon, it is extremely difficult to measure neon isotopes in magmatic phenocrysts. We employed a series of crushing and measurement steps on each sample, with the strategy of obtaining enhanced mantle signatures with further crushing; variable degrees of crushing of a single sample often yield variable proportions of mantle and atmospheric neon signatures. Nonetheless, many of the samples in this study with the highest neon concentrations exhibited neon isotope signatures that are similar to or indistinguishable from atmospheric neon.

3.1. Helium measurements on Samoan magmatic phenocrysts

The variation of $^3He/^4He$ as a function of ^4He concentrations in the crushing and heating experiments is shown in Fig. 1 and Table 1. The $^3He/^4He$ ratios for the crushing experiments are similar to the previously published ratios on these same lavas (Workman et al., 2004; Jackson et al., 2007a,b). As mentioned above, the abrasion experiment on sample T25 yielded similar $^3He/^4He$ and ^4He concentrations compared to the unabraded olivines. ALIA-115-18 phenocrysts were the only samples to undergo both heating and crushing experiments, and the heating experiment yielded total ^4He concentrations ~5 times higher than the crushing experiment. The high Th and U contents in the basaltic host lava (Th = 10.74 ppm and U = 1.84 ppm; Jackson et al., 2007a) suggest that implantation of ^4He into the clinopyroxene, due to *in situ* decay of U and Th in the groundmass, may be responsible for the lower $^3He/^4He$ (~5 times lower) and higher ^4He in the heating experiments. This hypothesis is supported by the lower $^3He/^4He$ in the heating steps. However, we cannot exclude the possibility that some of the radiogenic helium in the heating experiments derives from melt inclusions, or from decay of Th and U hosted in the clinopyroxene. Assuming that the U and Th concentrations in the clinopyroxenes are 0.06 and 0.6 ppm, respectively (values somewhat higher than measured in OIB-hosted clinopyroxenes by Hanyu and Nakamura (2000)), the clinopyroxenes will have generated 1.3×10^{-7} cm^3 ^4He STP/g since eruption at 5.29 Ma (see $^{40}Ar/^{39}Ar$ age in Koppers et al., 2008). This ^4He value is similar to the total ^4He released during the heating experiments, and is consistent with a post-eruptive radiogenic ingrowth origin for most of the ^4He obtained by crushing. It is unclear if some component of the post-erupted radiogenic ingrowth, as detected in the heating experiments, has influenced (i.e., lowered) the $^3He/^4He$ obtained by crushing. If so, then the $^3He/^4He$ of the crushing experiments (4.35–5.20 Ra) may represent a lower limit to the $^3He/^4He$ in the host mantle that gave rise to the ALIA-115-18 melt.

By contrast, all of the other samples analyzed in this study are from the eastern Samoan volcanic province, the youngest portion of the hotspot. (Ages for the eastern province volcanoes are inferred to be <1 Ma, based on plate reconstruction using a Pacific plate velocity of 7 mm/yr and adopting Vailulu'u seamount as the current location of the Samoan plume). Their young age, along with the relatively helium-rich character of the olivines analyzed, ensures that post-eruptive radiogenic ingrowth has minimally affected their $^3He/^4He$.

3.2. New neon isotope measurements on Samoan magmatic phenocrysts

Table 1 shows that there are clear $^{21}Ne/^{22}Ne$ anomalies relative to atmosphere, but there does not appear to be a relationship between $^{21}Ne/^{22}Ne$-anomalies and neon concentrations. Of particular importance are the large $^{21}Ne/^{22}Ne$ anomalies observed in the crushing and heating experiments from ALIA-115-18. The combined crushing experiments for this sample show slightly higher concentrations of Ne than the combined heating experiments, and the crushing experiments also yielded higher $^3He/^4He$ (~4.4 Ra) and lower ^4He than the heating experiments. While the neon given off in the most gas-rich crushing step (ALIA-115-18—1st 40×) could have inherited elevated $^{21}Ne/^{22}Ne$ by ingrowth of ^{21}Ne since eruption, this is not indicated by the lower ^4He concentrations and higher $^3He/^4He$ compared to the heating experiments. Correcting the $^{21}Ne/^{22}Ne$ ratios for post-eruptive nucleogenic ingrowth of ^{21}Ne (assuming that all of the ^4He is produced by radiogenic ingrowth and assuming a $^4He/^{21}Ne$ production ratio of 2.2×10^7; Yatsevich and Honda, 1997) shows that ingrowth is responsible for <10% of the total $^{21}Ne/^{22}Ne$ anomaly in experiment ALIA-115-18—1st 40×. Due to low $^4He/^{21}Ne$ ratios in this Ne-rich crushing experiment, the correction is relatively small, suggesting that the large $^{21}Ne/^{22}Ne$ anomaly in this experiment represents a mantle signature. We consider the 40× crushing step to be the most reliable neon isotopic determination. By contrast, the magnitude of the $^{21}Ne/^{22}Ne$ anomaly in the heating experiment with the largest $^{21}Ne/^{22}Ne$ anomaly (ALIA-115-18 1500 °C) could be reduced by ~30% when corrected for post-eruptive ^{21}Ne ingrowth, owing to high $^4He/^{21}Ne$ ratios in the heating experiments. However, even after correction for post-eruptive nucleogenic ^{21}Ne ingrowth, there is still a measurable $^{21}Ne/^{22}Ne$ anomaly in the 1500 °C heating experiment. It is possible that crushing experiments release helium and neon signatures indicative of the mantle values, while heating experiments may yield helium and neon isotope signatures that host a non-trivial component of post-eruptive radiogenic (nucleogenic) ingrowth. We note that there are still relatively few neon data on this unusual sample and no equivalent data in the literature with which to compare. Additional work on similar lavas will be needed to confirm the nucleogenic $^{21}Ne/^{22}Ne$ observed in the ALIA-115-18 lava.

The data given in Table 1 and presented in Fig. 2 show that phenocrysts from all three subaerial lavas have the highest $^{20}Ne/^{22}Ne$ ratios. Compared to phenocrysts from subaerial samples, phenocrysts from the six submarine samples span a wider range (both higher and lower) of neon concentrations. Nonetheless, at any given neon concentration, phenocrysts from the submarine samples exhibit lower $^{20}Ne/^{22}Ne$ ratios. For comparative purposes, sample T25 and AVON3-74-1 were collected from the same island, Ta'u. There are no equivalent data sets, and it is unclear if phenocrysts from submarine samples are generally more air contaminated compared to phenocrysts from samples collected on land. The air contamination mechanisms for basaltic phenocrysts are difficult to quantify (Farley and Craig, 1994). However, it is counter-intuitive that the more rapidly quenched Samoan submarine lavas would be more affected by air contamination, perhaps suggesting that the contamination process is pre- or syn-eruptive.

Data with high signal intensities (>2000 cps of ^{20}Ne, or $>1\times10^{-11}$ cc ^{20}Ne in the mass spectrometer) obtained by crushing *in vacuo* are presented in a neon three-isotope plot in Fig. 3. Most samples (AVON3-74-1, AVON3-78-1, AVON3-77-9, AVON3-68-3, AVON3-71-2) exhibit neon isotope ratios that are similar to the atmospheric value and are not included in the following discussion. Crushes of olivine phenocrysts from the two high $^3He/^4He$ lavas from Ofu Island, Ofu-04-06 (40×) and Ofu-04-03 (40×), yielded sufficient neon (4.98×10^{-11} cc ^{20}Ne STP and 2.19×10^{-11} cc ^{20}Ne STP, respectively) for relatively reliable measurement. At 34 and 24 Ra, respectively, phenocrysts from the two Ofu lavas have the lowest $^{21}Ne/^{22}Ne_{extrap}$ values in this study, and also exhibit $^{21}Ne/^{22}Ne_{extrap}$ ratios that are as low as the least nucleogenic values obtained on Samoan xenoliths (see Fig. 3) (Poreda and Farley, 1992). In a three-isotope neon plot, both Ofu measurements plot between the Galapagos, Iceland and Loihi lines, overlapping with all three at the 2σ level. Due to the small sample sizes, the resulting uncertainties make it difficult to distinguish the Ofu mantle neon isotopic composition from those of Iceland, Galapagos or Loihi. Ofu-04-06, the Samoan sample with the highest $^3He/^4He$ (~34 Ra), plots between the Iceland and Galapagos lines.

The neon isotope measurements from Ta'u Island sample T25 exhibit clear mantle signatures, and one crushing experiment yielded the highest $^{20}Ne/^{22}Ne$ in this study (11.33 ± 0.08). Olivine phenocrysts

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^3He/^4He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

from this sample have lower $^{3}He/^{4}He$ ratios (~13 Ra) than the Ofu samples, and exhibit correspondingly higher $^{21}Ne/^{22}Ne_{extrap}$ values. In a three-isotope neon plot, the Loihi-line appears to roughly divide the data from sample T25 from the two Ofu lavas. However, owing to measurement uncertainty, it is difficult to discriminate between the Ofu and Ta'u data.

The Samoan lava with the lowest $^{3}He/^{4}He$ obtained by crushing (4.35 Ra), sample ALIA-115-18 (2nd 40×), has nucleogenic $^{21}Ne/^{22}Ne$ and plots below the MORB line in a three-isotope neon plot. In fact, neon data for this crushing experiment plot closer to the continental crust line than the MORB line. This sample exhibits Sr, Nd and Pb isotope ratios similar to the EM2 endmember, and has a whole rock $^{87}Sr/^{86}Sr$ ratio of 0.7186 (up to 0.7202 in clinopyroxene separates), among the highest ever observed in an ocean island basalt (OIB) (Jackson et al., 2007a). The elevated $^{21}Ne/^{22}Ne$ ratio for the most Ne-rich experiment, ALIA-115-18 (2nd 40×), does not appear to be a result of post-eruptive nucleogenic ingrowth of ^{21}Ne based on the neon and helium concentrations, and the $^{4}He/^{21}Ne$ production ratio. However, measurement uncertainties for this sample and other samples in this study are large, owing to low neon concentrations in magmatic phenocrysts, and further work on high $^{87}Sr/^{86}Sr$ Samoan samples will be required to substantiate the nucleogenic neon in the EM2 mantle.

3.3. Relationship between He, Ne and Nd isotopes in Samoan lavas

The relationship between helium and neon isotopes in Samoan lavas is illustrated in Fig. 4. More radiogenic helium isotopes in Samoan magmatic phenocrysts are associated with more nucleogenic $^{21}Ne/^{22}Ne$ values, as expected from their common production from Th and U decays. The correlation between He and Ne isotopes has been observed in other OIB data sets (e.g., Moreira et al., 2001; Graham, 2002). The Samoa trend is bracketed on one end by the lowest $^{4}He/^{3}He$ (highest $^{3}He/^{4}He$), which plots in the same region of He–Ne isotope space as the high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos (see Table 2 for summary of He, Ne and lithophile radiogenic isotope data on lavas from other hotspots). The Ta'u lava with moderately radiogenic $^{3}He/^{4}He$ (~13 Ra) plots in the field defined by lavas from Reunion, Kerguelen (Heard Island) and the Azores (Terciera Island), which also host moderately radiogenic helium isotopes (11–18 Ra). Although there are only a few data points, Ofu and Ta'u lavas form a trend in He–Ne isotope space toward a mantle component with radiogenic helium and nucleogenic neon (Fig. 4). Noble gas data alone do not clearly indicate which mantle component is an appropriate mixing endmember. However, it is clear from He and Ne data obtained on basaltic glasses from Pitcairn—the archetypal EMI (or enriched mantle 1) locality—that EM1 does not bracket the high $^{4}He/^{3}He$ and high $^{21}Ne/^{22}Ne_{extrap}$ portion of the Ofu–Ta'u array (Honda and Woodhead, 2005). Helium and neon isotopes obtained on magmatic phenocrysts from Mangaia (Parai et al., 2008), an island with quintessential HIMU (high $^{235}U/^{204}Pb$, or "hi-μ") geochemical characteristics, lies on an extension of the array formed by the Ofu and Ta'u noble gas data, as does MORB. Given the fact that Samoa hosts the strongest EM2 component observed in the OIB mantle, this component would be an obvious choice for an endmember. However, noble gas data obtained on the Samoan EM2 lava, ALIA-115-18 (2nd 40×), do not permit simple calculation of a $^{21}Ne/^{22}Ne_{extrap}$ value, owing to the fact that, at the 2 sigma level, the $^{20}Ne/^{22}Ne$ ratio for this experiment may be lower than the value for air. Nonetheless, this sample clearly has coupled radiogenic He and nucleogenic Ne and we cannot exclude it as a possible mixing endmember for the Ofu–Ta'u array.

Other isotopes can help constrain appropriate endmembers with radiogenic He and nucleogenic Ne that anchor the Ofu–Ta'u array. In an attempt to resolve the various mantle components, Fig. 5 shows available global Ne data (obtained from glasses and phenocrysts) and $^{143}Nd/^{144}Nd$ data, including data from high $^{3}He/^{4}He$ and moderately high $^{3}He/^{4}He$ hotspots (see Table 2 for Ne and Nd isotope compilation). A salient feature of the plot is that, when compared to high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos, the high $^{3}He/^{4}He$ Ofu lavas are offset to lower (more enriched) $^{143}Nd/^{144}Nd$ ratios. In spite of this offset in $^{143}Nd/^{144}Nd$, Ofu-04-06 has a $^{21}Ne/^{22}Ne_{extrap}$ value that falls squarely in the range of the Hawaii, Iceland and Galapagos data. While this Ofu lava also anchors the low $^{21}Ne/^{22}Ne_{extrap}$ portion of the trend formed by the Ofu and Ta'u lavas, it is clear that EM1, HIMU and MORB all fail to plot on an extension of the Ofu–Ta'u data trend. However, the composition of the Samoan EM2 lava does have nucleogenic neon-isotope values coupled with unradiogenic $^{143}Nd/^{144}Nd$, and is a candidate for the endmember anchoring the low $^{143}Nd/^{144}Nd$ portion Ofu–Ta'u trend.

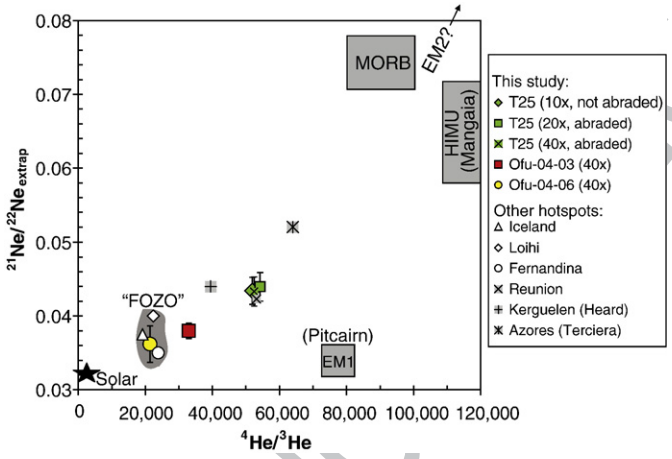

Fig. 4. $^{4}He/^{3}He$ vs. $^{21}Ne/^{22}Ne_{extrap}$ measured in Samoan magmatic phenocrysts. Only data with high signal intensities (>2000 cps of ^{20}Ne, or $>1\times10^{-11}$ cc ^{20}Ne in the mass spectrometer) and neon isotopes with clear mantle signatures ($^{20}Ne/^{22}Ne>10$ or $^{20}Ne/^{22}Ne>0.03$ at the 2σ level) are plotted, except for neon data for ALIA-115-18, which are too nucleogenic to yield meaningful $^{21}Ne/^{22}Ne_{extrap}$ values. Previously reported neon compositions for the mantle endmembers—HIMU (Parai et al., 2008), EM1 (Honda and Woodhead, 2005), and MORB (e.g., Sarda et al., 1988)—are unsuitable as mixing endmembers for the Ofu–Ta'u trend. Neon and helium data from other hotspots (e.g., Iceland, Galapagos, Samoa, Reunion, etc.) are obtained by measurements of glasses or magmatic phenocrysts (see Tables 1 and 2 for values plotted). FOZO is defined by the highest $^{3}He/^{4}He$ lavas from Hawaii, Iceland, Galapagos and Samoa. $^{21}Ne/^{22}Ne_{extrap}$ values are provided by the following expression:

$$^{21}Ne/^{22}Ne_{extrap} = (^{21}Ne/^{22}Ne_{M} - 0.029) / ((^{20}Ne/^{22}Ne_{M} - 9.8) / (13.8 - 9.8)) + 0.029,$$

where M signifies "measured", 13.8 is the solar $^{20}Ne/^{22}Ne$ ratio, and 0.029 and 9.8 are the atmospheric ratios for $^{21}Ne/^{22}Ne$ and $^{20}Ne/^{22}Ne$, respectively (Graham, 2002).

4.1. Recycled sediment in the Samoan EM2 mantle?

Samoan sample ALIA-115-18 has Sr, Nd and Pb isotope ratios that, together with other lavas from the same submarine dredge, define the EM2 endmember. Due to the extreme isotopic enrichment and unique trace element signatures, this lava was suggested to be a melt of a mantle source that hosts 5–6% recycled, continentally-derived marine sediment (Jackson et al., 2007a; Workman et al., 2008).

The ALIA-115-18 lava has nucleogenic neon and unradiogenic $^{143}Nd/^{144}Nd$ compositions, a combination not observed in EM1, HIMU and MORB, but a feature that is typical of the continental crust. Thus, the nucleogenic neon in the extreme Samoan EM2 lava is consistent with a sediment component in the Samoan mantle. In a three-isotope neon plot, the ALIA lava plots closer to the "continent line" than the line defined by MORB lavas. Subduction zones may act as a barrier to the lighter noble gases (Staudacher and Allègre, 1988), and sediment, which is rich in Th and U, may be poor in He and Ne after subduction zone processing. The high (Th+U)/He and (Th+U)/Ne ratios in recycled sediment will thus contribute extremely radiogenic helium and nucleogenic neon to the Samoan EM2 mantle. Further noble gas

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^{3}He/^{4}He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

Table 2
Estimated Ne, He, Sr, Nd and Pb isotopic compositions for high and moderately high $^3He/^4He$ OIB lavas, EM1, HIMU and MORB.

Location	$^{21}Ne/^{22}Ne_{ext}$	$^3He/^4He$ (Ra)	$^4He/^3He$	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
High $^3He/^{4He}$ (>30 Ra; FOZO) compositions								
Samoa (Ofu)	0.038	33.8	21,377	0.70458	0.51283	19.19	15.57	39.20
Galapagos (Fernandina)	0.035	30.3	23,846	0.70329	0.51294	19.08	15.54	38.71
Hawaii (Loihi)	0.040	32.3	22,370	0.70368	0.51295	18.45	15.48	38.19
Iceland	0.038	37.7	19,166	0.70347	0.51297	18.65	15.47	38.45
Moderately high $^3He/^4He$ (11–18 Ra) compositions								
Reunion	0.042	13.6	53,128	0.70413	0.51284	18.88	15.59	38.96
Kerguelen (Heard)	0.044	18.3	39,483	0.70486	0.51271	18.78	15.59	39.17
Azores (Terciera)	0.052	11.3	63,942	0.70352	0.51296	19.88	15.63	39.31
Low $^3He/^4He$ (<10 Ra) compositions								
MORB	0.075	8	90,318	0.70283	0.51309	18.39	15.51	38.03
Pitcairn (EM1)	0.034	9.3	77,693	0.70519	0.51248	17.45	15.46	38.99
Samoa (Savai'i shield—EM2)	See footnote[a]	4.4	166,102	0.71859	0.51231	18.96	15.64	39.40
Mangaia (HIMU)	0.065	6.3	114,236	0.70284	0.51290	21.65	15.82	40.54

Xenolith data are not included, as the table shows magmatic phenocryst and glass data only.

[a] Estimates in this table are based on sample suites where neon isotope data was obtained on magmatic glasses and phenocrysts. Sample suites where neon isotope data are obtained on xenoliths are not considered here, owing to possible neon contamination from the depleted upper mantle. The Sr, Nd, Pb and He isotopic compositions of Samoa, Galapagos, Hawaii, Iceland, Reunion, Kerguelen and Azores are for lavas with the highest $^3He/^4He$ from each location, and are taken from the compilation of Jackson et al. (2007b). The Neon isotope data for Samoa are from this study, and use the $^{21}Ne/^{22}Ne_{extrap}$ value of Ofu-04-03 (40×), owing to its smaller measurement error and stronger mantle neon signature than Ofu-04-06. The $^{21}Ne/^{22}Ne_{extrap}$ for the Galapagos is based on data from Fernandina lavas form Kurz et al. (2009). The $^{21}Ne/^{22}Ne_{extrap}$ for Hawaii is based on Loihi data (see text for references). The $^{21}Ne/^{22}Ne_{extrap}$ for Iceland is based on the lava suites with the most unradiogenic Ne (see text for references), which also tend to have the least radiogenic helium. The $^{21}Ne/^{22}Ne_{extrap}$ for Reunion is based on measurements from Hanyu et al. (2001); this data is supported by noble gas work on xenoliths as outlined in Hopp and Trieloff (2005), Trielof et al. (2002), and Staudacher et al. (1990). Reunion has relatively homogeneous He-isotope compositions. The $^{21}Ne/^{22}Ne_{extrap}$ for Kerguelen is based on the Ne-isotope measurements of high $^3He/^4He$ lavas from Heard (Doucet et al., 2005). The $^{21}Ne/^{22}Ne_{extrap}$ value for the Azores is based on measurements of lavas from Terciera, and the $^{21}Ne/^{22}Ne_{extrap}$ value is as suggested in Madureira et al. (2005).The Ne, Sr, Nd and Pb isotope data for Pitcairn are for sample 52-DS-1 from Honda and Woodhead (2005). 52-DS-1 has Sr, Nd and Pb isotopes typical of the EM1 mantle endmember, and exhibits extremely unradioenic Ne. Sr isotopes exhibit a negative correlation with $^{21}Ne/^{22}Ne_{extrap}$ in Pitcairn (Honda and Woodhead, 2005), supporting the contention that EM1 hosts extremely unradiogenic Ne isotopes. The He isotopes measured on this sample are quite radiogenic (<2 Ra), which may owe to radiogenic ingrowth and low 4He concentrations in the glass analyzed. However, Pitcairn sample 49-DS-1 has similar Sr, Nd and Pb ratios, but higher $^3He/^4He$ and 4He compared to 52-DS-1. Thus, the $^3He/^4He$ ratio of 49-DS-1 is adopted for the EM1 endmember. Higher $^3He/^4He$ ratios were reported in Pitcairn lavas (Honda and Woodhead, 2005; Farley and Neroda, 1998), but these lavas have Sr–Nd–Pb isotopes that are less enriched than 52-DS-1 and plot farther from the EM1 endmember. The helium and neon isotopic compositions of the Mangaia suite are from Parai et al., (2009); the Sr, Nd and Pb compositions are an average of Mangaia data from Hauri and Hart (1993) and Woodhead (1996), and are similar to the composition for the HIMU mantle endmember. The $^{21}Ne/^{22}Ne_{extrap}$ ratios exhibit a positive correlation with Pb-isotopes in the Cook–Australs (Parai et al., 2008), supporting the contention that HIMU has nucleogenic Ne isotopes that are similar to (but slightly less nucleogenic than) MORB. The Sr, Nd and Pb isotope composition of MORB is from the compilation of Su (2003), and is the average for all MORB segments. The Sr, Nd, Pb and He isotope composition of the Samoan submarine shield lava (ALIA-115-18) is from Jackson et al. (2007a), and its composition is similar to the EM2 endmember; the neon isotope data for the Samoan EM2 sample is more nucleogenic than MORB, and simple calculation of $^{21}Ne/^{22}Ne_{extrap}$ is not possible (and has little physical meaning) for this sample.

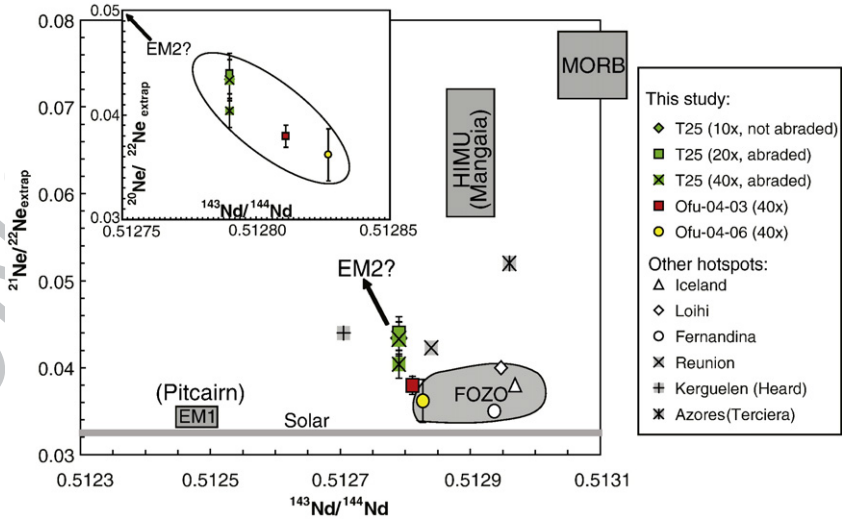

Fig. 5. $^{143}Nd/^{144}Nd$ is plotted against $^{21}Ne/^{22}Ne_{extrap}$ in Samoan magmatic phenocrysts. Only data with high signal intensities (>2000 cps of ^{20}Ne, or $>1\times10^{-11}$ cc ^{20}Ne in the mass spectrometer) and neon isotopes with clear mantle signatures ($^{20}Ne/^{22}Ne>10.4$) are plotted. Samoan neon data were obtained on magmatic phenocrysts, and $^{143}Nd/^{144}Nd$ data were obtained on leached whole rocks powders. The solar $^{21}Ne/^{22}Ne$ value is plotted on the margin of the figure, but its $^{143}Nd/^{144}Nd$ is not specified. See Tables 1 and 2 for values plotted. Data from other hotspots are the same as in Fig. 4. FOZO is defined by the highest $^3He/^4He$ lavas from Hawaii, Iceland, Galapagos and Samoa.

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^3He/^4He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

work on high $^{87}Sr/^{86}Sr$ Samoan samples will be necessary to constrain the evolution of the EM2 mantle.

4.2. Relationship between Ne and Sr–Nd isotope systematics: Implications for the evolution of the high $^{3}He/^{4}He$ mantle reservoir

Samoan high $^{3}He/^{4}He$ lavas from Ofu Island (up to 33.8 Ra) exhibit $^{87}Sr/^{86}Sr$ (not shown) and $^{143}Nd/^{144}Nd$ enrichment relative to the highest $^{3}He/^{4}He$ lavas from Hawaii (32.3 Ra), Iceland (37.7 Ra) and Galapagos (30.3 Ra) (Fig. 5). Given the relatively large differences in Sr and Nd isotopes ratios between Ofu and high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos, it is surprising that Ofu has $^{21}Ne/^{22}Ne_{extrap}$ values that are indistinguishable from the high $^{3}He/^{4}He$ lavas from the other three hotspots. This result suggests that the evolution of helium and neon in the high $^{3}He/^{4}He$ mantle (i.e., FOZO) may not be coupled to the evolution of Sr and Nd isotopes. Although this observation is based on very few measurements globally, it is worth exploring the implications.

Any model for the Samoan He and Ne isotope data must explain the relatively "enriched" Sr and Nd isotopes of the Ofu mantle (compared to high $^{3}He/^{4}He$ mantle sample by lavas from Hawaii–Iceland–Galapagos), coupled with relatively low time-integrated $(\widehat{Th}+U)/He$ and $(\widehat{U}+Th)/Ne$ ratios. Short-cycling of sediment into the Samoan mantle from the nearby Tonga-trench has been suggested as an explanation for the enriched $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope signatures in the Samoan mantle (Farley, 1995). Over sufficiently short timescales, the short-cycled sediment would not contribute significant quantities of radiogenic ^{4}He or nucleogenic ^{21}Ne to the mantle beneath Ofu. One problem with this model is that trace elements in high $^{3}He/^{4}He$ Samoan lavas show no more evidence for a sediment component than do high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos (Jackson et al., 2007b). Pb isotopes are also inconsistent with a local sediment component in the Ofu mantle (Jackson et al., 2007b). While the presence of ancient (not short cycled; see Jackson et al., 2007a) recycled sediment is clear in the Samoan mantle sampled by enriched, low $^{3}He/^{4}He$ EM2 lavas, it is not present in many Samoan lavas, including the highest $^{3}He/^{4}He$ samples from Ofu.

The "standard model" for the high $^{3}He/^{4}He$, low $^{21}Ne/^{22}Ne_{extrap}$ reservoirs in the earth holds that the low time-integrated $(\widehat{Th}+U)/He$ and $(\widehat{U}+Th)/Ne$ relate to primitive, relatively undegassed reservoirs deep in the earth that were left over from early planetary formation processes. However, it is well known that lavas with high $^{3}He/^{4}He$ ratios have $^{143}Nd/^{144}Nd$ and Pb-isotope ratios that are far from putative "primitive" chondritic bulk earth values, and the standard model has fallen out of favor (Hart et al., 1992; Class and Goldstein, 2005, Parman et al., 2005; Gonnermann and Mukhopadhyay, 2009).

However, the recent discovery that chondrites exhibit $^{142}Nd/^{144}Nd$ ~20 ppm higher than all measured modern terrestrial rocks (including high $^{3}He/^{4}He$ lavas; Andreasen et al., 2008) suggest that modern terrestrial rocks originate from a reservoir that had superchronditic Sm/Nd during the lifetime of ^{146}Sm (first few hundred million years after accretion) (Boyet and Carlson, 2005). The implications for the evolution of the high $^{3}He/^{4}He$ reservoir depend on whether or not the superchondritic Sm/Nd ratio is a characteristic of the entire planet (i.e., bulk silicate earth [BSE] is not chondritic) or simply a feature of a depleted reservoir that is the residue of early terrestrial differentiation of a chondritic earth (Carlson and Boyet, 2009). Owing to the observation that high $^{3}He/^{4}He$ lavas from Iceland, like all other modern terrestrial lavas, appear to have $^{142}Nd/^{144}Nd$ ratios that are higher than chondrites (Andreasen et al., 2008), the high $^{3}He/^{4}He$ reservoir was also derived from a high Sm/Nd reservoir. If BSE has elevated Sm/Nd relative to chondrites, then the high $^{3}He/^{4}He$ mantle may in fact be undifferentiated and primitive, as suggested by Kurz et al. (1982). Alternatively, if BSE has chondritic Sm/Nd ratios, then the difference in $^{142}Nd/^{144}Nd$ between chondrites and modern terrestrial rocks suggests that all measured terrestrial rocks (including high $^{3}He/^{4}He$ lavas) originated from an early depleted reservoir with superchronditic Sm/Nd, and that this reservoir could have been formed as a depleted residue of an early, global terrestrial differentiation event within 30 Myr of accretion (Boyet and Carlson, 2005; Boyet and Carlson, 2006).

If Samoa and the other high $^{3}He/^{4}He$ OIB data are to be explained by either model (an initially chondritic earth or nonchondritic earth), some process is required to modify Sr, Nd and Pb isotopes, without altering He and Ne, i.e. to explain Samoa. It is possible that Sr, Nd, and Pb isotopes in a deep, relatively undegassed reservoir are modified by recycling processes (Brandon et al., 2007; Jackson et al., 2008), while the $(\widehat{Th}+U)/He$ and $(\widehat{U}+Th)/Ne$ are low enough to be unaffected by recycled material. For example, an eclogite processed in a subduction will lose much of its He and Ne, and may become depleted in the He and Ne-producing elements, U and Th. Such material might be incorporated into a high $^{3}He/^{4}He$, low $^{21}\widehat{Ne}/^{22}Ne_{extrap}$ reservoir without producing enough ^{4}He and ^{21}Ne to alter the isotopic compositions. An advantage of this model is that recent incorporation of recycled material might also explain why high $^{3}He/^{4}He$ lavas plot off the terrestrial Pb-isotope geochron.

5. Conclusions

The most isotopically-enriched ($^{87}Sr/^{86}Sr>0.718$) Samoan lava (ALIA-115-18) has nucleogenic neon and the most radiogenic helium in Samoan lavas (4.45 Ra). In a three-isotope neon plot, the enriched Samoan lava plots between the lines defining the MORB and continental crust reservoirs. This observation is consistent with the presence of recycled, continentally-derived marine sediment in the mantle source of the most enriched lavas from Samoa.

By contrast, the lavas from Ofu have the highest $^{3}He/^{4}He$ in Samoa. The Ofu lavas have less depleted Sr and Nd isotopes than their counterparts from Hawaii, Iceland and Galapagos, yet they exhibit $^{21}Ne/^{22}Ne_{extrap}$ values that are similar to those measured in highest $^{3}He/^{4}He$ lavas from the other intraplate volcanic provinces. This suggests that there is some decoupling between the isotopes of noble gases and the more refractory radiogenic isotopes. The mechanism for this decoupling is unknown, but may owe to recycling of subduction zone processes, He and Ne-poor (eclogitic?) material into the high $^{3}He/^{4}He$ mantle.

Whether or not bulk silicate earth has chondritic Sm/Nd ratios has profound implications for the formation of the high $^{3}He/^{4}He$, low $^{21}Ne/^{22}Ne_{extrap}$ reservoir in the Earth's mantle. If BSE has chondritic Sm/Nd, $^{142}Nd/^{144}Nd$ measurements indicate that the accessible mantle is the residue of an early depletion event, and that the high $^{3}He/^{4}He$, low $^{21}Ne/^{22}Ne_{extrap}$ reservoir is derived from this depleted reservoir. However, if BSE is not chondritic, constraints from $^{142}Nd/^{144}Nd$ may suggest that the high $^{3}He/^{4}He$, low $^{21}Ne/^{22}Ne_{extrap}$ mantle is a largely primitive and undifferentiated reservoir that hosts a small contribution of recycled material.

6. Uncited reference

Caro et al., 2008

Acknowledgements

We would like to thank Joshua Curtice for his unfailing assistance in sample preparation and mass spectrometry. We also acknowledge two helpful reviews from David Graham and Sujoy Mukhopadhyay, and we thank T. Mark Harrison for editorial handling. Helium and neon measurements were supported by NSF grants OCE 0727044 and OCE 05-25864 to MDK. Sample collections were supported by NSF-EAR 0125917 and NSF-OCE 0351437 to SRH.

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^{3}He/^{4}He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

References

Anderson, D.L., 1998. A model to explain the various paradoxes associated with mantle noble gas geochemistry. Proc. Natl. Acad. Sci. U. S. A. 95, 9087–9092. doi:10.1073/pnas.95.16.9087.

Andreasen, R., Sharma, M., Subbarao, K.V., Viladkar, S.G., 2008. Where on Earth is the enriched Hadean reservoir? Earth Planet. Sci. Lett. 266, 14–28.

Albarède, F., 2008. Rogue mantle helium and neon. Science 319, 943–945.

Ballentine, C.J., Burnard, P.G., 2002. Production, release and transport of noble gases in the continental crust. Rev. Min. Geochem 47, 481–538.

Ballentine, C.J., Marty, B., Sherwood Lollar, B., Martin Cassidy, M., 2005. Neon isotopes constrain convection and volatile origin in the Earth's mantle. Nature 433, 33–38.

Benkert, J.P., Baur, H., Signer, P.,Wieler, R.,1993. He, Ne and Ar from the solar wind and solar energetic particles in lunar ilmenites and pyroxenes. J. Geophys. Res. 98 (no. E7) 13,147-13,162.

Black, D.C., 1972. On the origins of trapped helium, neon and argon isotopic variations in meteorites I. Gas-rich meteorites, lunar soil and breccia. Geochim. Cosmochim. Acta 36, 347–375.

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

Boyet, M., Carlson, R.W., 2006. A new geochemical model for the Earth's mantle inferred from ^{146}Sm–^{142}Nd systematics. Earth Planet. Sci. Lett. 250, 254–268.

Brandon, A.D., Graham, D.W., Waight, T., Gautason, B., 2007. ^{186}Os and ^{187}Os enrichments and high ^{3}He/^{4}He sources in the Earth's mantle: evidence from Icelandic picrites. Geochim. Cosmochim. Acta 71, 4570–4591. doi:10.1016/j.gca.2007.07.015.

Carlson, R.W., Boyet, M., 2009. Short-lived radionuclides as monitors of early crust–mantle differentiation on the terrestrial planets. Earth Planet. Sci. Lett. 279, 147–156.

Class, C., Goldstein, S.L., 2005. Evolution of helium isotopes in the Earth's mantle. Nature 436, 1107–1112. doi:10.1038/nature03930.

Caro, G., Bourdon, B., Halliday, A.N., Quitté, G., 2008. Super-chondritic Sm/Nd ratios in Mars, the Earth and the Moon. Nature 452, 336–339.

Dixon, E.T., Honda, M., McDougall, I.H., 2000. Preservation of near-solar neon isotopic ratios in Icelandic basalts. Earth Planet. Sci. Lett. 180, 309–324.

Dixon, E.T., 2003. Interpretation of helium and neon isotopic heterogeneity in Icelandic basalts. Earth Planet. Sci. Lett. 206, 83–99.

Doucet, S., Moreira, M., Weis, D., Scoates, J.S., Giret, A., Allègre, C., 2005. Primitive neon and helium isotopic compositions of high-MgO basalts from the Kerguelen Archipelago. Indian Ocean. Earth Planet. Sci. Lett. 241, 65–79.

Farley, K.A., 1995. Rapid cycling of subducted sediments into the Samoan mantle plume. Geology 23, 531–534.

Farley, K.A., Craig, H., 1994. Atmospheric argon contamination of ocean island basalt olivine phenocrysts. Geochem. Cosmochim. Acta 58, 2509–2517.

Farley, K.A., Natland, J.H., Craig, H., 1992. Binary mixing of enriched and undegassed (primitive?) mantle components (He, Sr, Nd, Pb) in Samoan lavas. Earth Planet. Sci. Lett. 111, 183–199.

Farley, K.A., Neroda, E., 1998. Noble gases in the Earth's mantle. Annu. Rev. Earth Planet. Sci. 26, 189–218.

Gonnermann, H.M., Mukhopadhyay, S., 2007. Non-equilibrium degassing and a primordial source for helium in ocean–island volcanism. Nature 449, 1037–1040.

Graham, D.W., Larsen, L.M., Hanan, B.B., Storey, M., Pedersen, A.K., Lupton, J.E., 1998. Helium isotope composition of the early Iceland mantle plume inferred from the Tertiary picrites of West Greenland. Earth Planet. Sci. Lett. 160, 241–255.

Graham, D.W., 2002. Noble gas isotope geochemistry of mid-ocean ridge and ocean island basalts; characterization of mantle source reservoirs. In: Porcelli, D., Ballentine, C.J., Wieler, R. (Eds.), Noble gases in geochemistry and cosmochemistry: Reviews in Mineralogy and Geochemistry, vol. 47, pp. 247–318.

Graham, D.W., Christie, D.M., Harpp, K.S., Lupton, J.E., 1993. Mantle plume helium in submarine basalts from the Galapagos platform. Science 262, 2023–2026.

Hanan, B.B., Graham, D.W., 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.

Hanyu, T., Dunai, T.J., Davies, G.R., Kaneoka, I., Nohda, S., Uto, K., 2001. Noble gas study of the Reunion hotspot: evidence for distinct less-degassed mantle sources. Earth Planet. Sci. Lett. 193, 83–98.

Hart, S.R., Coetzee, M., Workman, R.K., Blusztajn, J., Johnson, K.T.M., Sinton, J.M., 2004. Genesis of the Western Samoan seamount province: age, geochemical fingerprint and tectonics. Earth Planet Sci. Lett. 227, 37–56.

Hart, S.R., Hauri, E.H., Oschmann, L.A., Whitehead, J.A., 1992. Mantle plumes and entrainment: isotopic evidence. Science 256, 517–520.

Hauri, E.H., Hart, S.R., 1993. Re–Os isotope systematics of HIMU and EMII oceanic island basalts from the south Pacific Ocean. Earth Planet. Sci. Lett. 114, 353–371.

Hauri, E.H., Hart, S.R., 1994. Constraints on melt migration from mantle plumes: a trace element study of peridotite xenoliths from Savai'i, Western Samoa. J. Geophys. Res. 99, 24,301–24,321.

Hedge, C.E., Peterman, Z.E., Dickinson, W.R., 1972. Petrogenesis of lavas from Western Samoa. Geol. Soc. Am. Bull. 83, 2709–2714.

Hilton, D.R., Grönvold, K., Macpherson, C.G., Castillo, P.R., 1999. Extreme ^{3}He/^{4}He ratios in northwest Iceland: constraining the common component in mantle plumes. Earth Planet. Sci. Lett. 173, 53–60.

Hiyagon, H., Sakai, H., Ozima, M., Marty, B., Zashu, S., 1992. Noble gases in submarine glasses from mid-oceanic ridges and Loihi seamount: constraints on the early history of the Earth. Geochim. Cosmochim. Acta 56, 1301–1316.

Hofmann, A.W., 1997. Mantle geochemistry: the message from oceanic volcanism. Nature 385, 219–229.

Honda, M., McDougall, I., Patterson, D.B., Doulgeris, A., Clague, D.A., 1991. Possible solar noble-gas component in Hawaiian basalts. Nature 349, 149–151.

Honda, M., McDougall, I., Patterson, D.B., Doulgers, A., Clague, D.A., 1993. Noble gases in submarine pillow glasses from Loihi and Kilauea, Hawaii: a solar component in the Earth. Geochim. Cosmochim. Acta. 57, 859–874.

Honda, M., Woodhead, J.D., 2005. A primordial solar-neon enriched component in the source of EM-I-type ocean island basalts from the Pitcairn Seamounts. Polynesia. Earth Planet. Sci. Lett. 236, 597–612.

Hopp, J., Trieloff, M., 2005. Refining the noble gas record of the Réunion mantle plume source: implications on mantle geochemistry. Earth Planet. Sci. Lett. 240, 573–588.

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

Jackson, M.G., Kurz, M.D., Hart, S.R., Workman, R.K., 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., Hart, S.R., Saal, A.E., Shimizu, N., Kurz, M.D., Blusztajn, J.S., et al., 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., Hart, S.R., Shimizu, N., Blusztajn, J.S., 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.

Kaneoka, L., Hanyu, T., Yamamoto, J., Miura, N.Y., 2002. Noble gas systematics of the Hawaiian volcanoes based on the analysis of Loihi, Kilauea and Koolau submarine rocks. In: Takahashi, E., Llpman, P.W., Garcia, M.O., Naka, J., Aramaki, S. (Eds.), Hawaiian Volcanoes: Deep Underwater Perspectives: AGU Geophysical Monograph, vol. 128, pp. 373–389.

Koppers, A.A.P., Russell, J.A., Jackson, M.G., Konter, J., Staudigel, H., Hart, S.R., 2008. Samoa reinstated as a primary hotspot trail. Geology 36, 435–438.

Kurz, M.D., Curtice, J., Fornari, D., Geist, D., Moreira, M., 2009. Primitive neon from the Galapagos hotspot. Submitted to Earth Planet. Sci. Lett.

Kurz, M.D., Geist, D.J., 1999. Dynamics of the Galapagos hotspot from helium isotope geochemistry. Geochim. Cosmochim. Acta 63, 4139–4156.

Kurz, M.D., Jenkins, W.J., Hart, S.R., 1982. Helium isotope systematics of oceanic island and mantle heterogeneity. Nature 297, 43–47.

Kurz, M.D., Meyer, P.S., Sigurdsson, H., 1985. Helium isotopic systematics within the neovolcanic zones of Iceland. Earth Planet. Sci. Lett. 74, 291–305.

Macdonald, G.A., Katsura, T., 1964. Chemical composition of the Hawaiian lavas. J. Pet. 5, 83–133.

Macpherson, C.G., Hilton, D.R., Day, J.M.D., Lowry, D., Grönvold, K., 2005. High-^{3}He/^{4}He, depleted mantle and low δ^{18}O, recycled oceanic lithosphere in the source of central Iceland magmatism. Earth Planet. Sci. Lett. 233, 411–427. doi:10.1016/j.epsl.2005.02.037.

Madureira, P., Moreira, M., Matac, J., Allègre, C.J., 2005. Primitive neon isotopes in Terceira Island (Azores archipelago). Earth Planet. Sci. Lett. 233, 429–440.

Moreira, M., Kunz, J., Allegre, C., 1998. Rare gas systematics in popping rock: isotopic and elemental compositions in the upper mantle. Science 279, 1178–1181.

Moreira, M., Breddam, K., Curtice, J., Kurz, M.D., 2001. Solar neon in the Icelandic mantle: new evidence for an undegassed lower mantle. Earth Planet. Sci. Lett. 185, 15–23.

Moreira, M., Sarda, P., 2000. Noble gas constraints on degassing processes. Earth Planet. Sci. Lett. 176, 375–386.

Gonnermann, H.M., Mukhopadhyay, S., 2009. Preserving noble gases in a convecting mantle. Nature 459, 560–564.

Parai, R., Mukhopadhyay, S., Lassiter, J.C., 2008. New constraints on the HIMU mantle from neon and helium isotopic compositions of basalts from the Cook–Austral Islands. Earth Planet. Sci. Lett. 277, 253–261.

Parman, S.W., Kurz, M.D., Hart, S.R., Grove, T.L., 2005. Helium solubility in olivine and implications for high ^{3}He/^{4}He in ocean island basalts. Nature 437, 1140–1143.

Poreda, R.J., Farley, K.A., 1992. Rare gases in Samoan xenoliths. Earth Planet. Sci. Lett. 113, 129–144.

Saal, A.E., Kurz, M.D., Hart, S.R., Blusztajn, J.S., Blichert-Toft, J., Liang, Y., et al., 2007. The role of lithospheric gabbros on the composition of Galapagos lavas. Earth Planet. Sci. Lett. 257, 391–406.

Sarda, P., Moreira, M., 2002. Vesiculation and vesicle loss in mid-ocean ridge basalt glasses: He, Ne Ar elemental fractionation and pressure influence. Geochim. Cosmochim. Acta 66, 1449–1458.

Sarda, P., Staudacher, T., Allègre, C.J., 1988. Neon isotopes in submarine basalts. Earth. Planet. Sci. Lett. 91, 73–88.

Staudacher, T., Allègre, C.J., 1988. Recycling of oceanic crust and sediments: the noble gas subduction barrier. Earth Planet. Sci. Lett. 89, 173–183.

Staudacher, T., Sarda, P., Allègre, C.J., 1990. Noble gas systematics of Reunion Island, Indian Ocean. Chem. Geol. 89, 1–17.

Stuart, F.M., Lass-Evans, S., Fitton, J.G., Ellam, R.M., 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.

Su, Y., 2003. Global MORB chemistry compilation at the segment scale. PhD, Columbia University (available at http://petdb.ldeo.columbia.edu/documentation/morbcompilation/).

Trielof, M., Kunz, J., Allègre, C.J., 2002. Noble gas systematics of the Reunion mantle plume source and the origin of primordial noble gases in Earth's mantle. Earth Planet. Sci. Lett. 200, 297–313.

Trieloff, M., Kunz, J., Clague, D.A., Harrison, D., Allègre, C.J., 2000. The nature of pristine noble gases in mantle plumes. Science 288, 1036–1038.

Valbracht, P.J., Staudacher, T., Malahoff, A., Allègre, C.J., 1997. Noble gas systematics of deep rift zone glasses from Loihi Seamount, Hawaii. Earth Planet. Sci. Lett. 150, 399–411.

White, W.M., Hofmann, A.W., 1982. Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution. Nature 296, 821–825.

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high ^{3}He/^{4}He mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039

Woodhead, J.D., 1996. Extreme HIMU in an oceanic setting: the geochemistry of Mangaia Island (Polynesia), and temporal evolution of the Cook–Austral hotspot. J. Volc. Geotherm. Res. 72, 1–19.
Workman, R.K., Eiler, J.M., Hart, S.R., Jackson, M.G., 2008. Oxygen isotopes in Samoan lavas: confirmation of continent recycling. Geology 36, 551–554.
Workman, R.K., Hart, S.R., Jackson, M.G., Regelous, M., Farley, K.A., Blusztajn, J., 2004. Recycled metasomatized lithosphere as the origin of the Enriched Mantle II (EM2) end-member: evidence from the Samoan Volcanic Chain. Geochem., Geophys., Geosystem 5. doi:10.1029/2003GC000623.
Wright, E., White, W.M., 1986. The origin of Samoa: new evidence from Sr, Nd, and Pb isotopes. Earth Planet. Sci. Lett. 81, 151–162. doi:10.1016/0012-821X(87)90152-X.
Yatsevich, I., Honda, M., 1997. Production of nucleogenic neon in the earth from natural radioactive decay. J. Geophys. Res. 102 (B5), 10291–10298.
Zindler, A., Hart, S.R., 1986. Chemical geodynamics. Ann. Rev. Earth Planet. Sci. 14, 493–571.

Please cite this article as: Jackson, M.G., et al., Helium and neon isotopes in phenocrysts from Samoan lavas: Evidence for heterogeneity in the terrestrial high $^{3}He/^{4}He$ mantle, Earth Planet. Sci. Lett. (2009), doi:10.1016/j.epsl.2009.08.039