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New Samoan lavas from Ofu Island reveal a hemispherically heterogeneous high $^{3}He/^{4}He$ mantle

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Abstract

New measurements of high $^{3}He/^{4}He$ ratios in Samoan lavas from Ofu Island (19.5–33.8 times atmospheric) extend the known range for $^{3}He/^{4}He$ in the southern hemisphere mantle. The Ofu data suggest that the high $^{3}He/^{4}He$ mantle component thought to be common to all oceanic hotspots, called FOZO (*Fo*cus *Zo*ne), is not homogeneous. Sr, Nd and Pb isotopes in Ofu lavas indicate that the Samoan high $^{3}He/^{4}He$ component is isotopically distinct from the high $^{3}He/^{4}He$ lavas from Hawaii, Iceland and Galapagos. Along with Samoa, the highest $^{3}He/^{4}He$ sample from each southern hemisphere high $^{3}He/^{4}He$ hotspot exhibits lower $^{143}Nd/^{144}Nd$ ratios than their counterparts in the northern hemisphere (excluding lavas erupted in continental, back-arc, and submarine ridge environments). The observation of a large-scale isotopic enrichment (generally higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$) in the FOZO-A (austral) high $^{3}He/^{4}He$ mantle compared to the FOZO-B (boreal) high $^{3}He/^{4}He$ mantle is similar to the DUPAL anomaly, a globe-encircling feature of isotopic enrichment observed primarily in southern hemisphere ocean island basalts. Additionally, the recent discovery that terrestrial samples have $^{142}Nd/^{144}Nd$ ratios higher than chrondrites has potentially important implications for the origin of the FOZO reservoirs, and suggest that the high $^{3}He/^{4}He$ mantle has been re-enriched.

Keywords: Samoa; FOZO; PHEM; C; 3He/4He; mantle; basalt; geochemistry; DUPAL; hotspot

1. Introduction

Oceanic lavas with high $^{3}He/^{4}He$ signatures are rare, and derive from ancient reservoirs in the earth's mantle. Volcanically active hotspots with high $^{3}He/^{4}He$ lavas, such as Samoa and Hawaii, sample melts of buoyantly upwelling regions of the deep mantle where the high $^{3}He/^{4}He$ reservoir is thought to reside (Kurz et al., 1982; Hart et al., 1992; Class and Goldstein, 2005). Consequently, ocean island basalts (OIBs) erupted at hotspots provide a unique tool for probing the composition and history of the deep mantle. Radiogenic isotopes in OIBs are commonly used as tracers for the various mantle components revealed at hotspots, and show a diverse range of compositions, or endmembers, including DMM (depleted mid-ocean ridge basalt [MORB] mantle), HIMU (high 'μ', or $^{238}U/^{204}Pb$ mantle), EM1 and EM2 (enriched mantle 1 and 2) (Zindler and Hart, 1986).

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Emerging from this taxonomic diversity, a unifying theory in mantle geochemistry maintains that a single mantle component exists that is common to all hotspots (Hart et al., 1992): Mixing arrays from individual ocean islands originate near the mantle endmembers in various radiogenic isotope spaces and converge on a region characterized by depleted isotope ratios that is distinct from normal MORB (Hart et al., 1992). Lavas plotting in this region of convergence often exhibit elevated $^{3}He/^{4}He$ ratios, and are suggested to sample a component in the mantle common to all hotspots. Variably called FOZO (Hart et al., 1992), PHEM (*P*rimitive *He*lium *M*antle; Farley et al., 1992), or C (*C*ommon; Hanan and Graham, 1996), the high $^{3}He/^{4}He$ common component is thought to be a relatively less degassed region of the (lower?) mantle (Kurz et al., 1982; Class and Goldstein, 2005).

New geochemical data from the Samoan hotspot are not entirely consistent with this view of the mantle. The new $^{3}He/^{4}He$ ratios (up to 33.8±0.2 Ra, ratio to atmosphere) from the Samoan Island of Ofu are the highest yet recorded in the southern hemisphere, and are significantly higher than $^{3}He/^{4}He$ ratios previously measured (25.8 Ra) in Samoan basalts and xenoliths (Farley et al., 1992; Poreda and Farley, 1992; Workman et al., 2004). The new helium isotope data from Samoa extend the range of observed $^{3}He/^{4}He$ up to values comparable to those found in Hawaii (32.3 Ra; Kurz et al., 1982), Iceland (37.7 Ra; Hilton et al., 1999) and the Galapagos (30.3 Ra; Kurz and Geist, 1999; Saal et al., 2007), referred to here as HIG. The Ofu lavas are isotopically more enriched (higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$) than the high $^{3}He/^{4}He$ samples from HIG and exhibit elevated incompatible trace element concentrations. Due to this isotopic and trace element enrichment relative to HIG lavas, the new data from Samoan high $^{3}He/^{4}He$ lavas are inconsistent with recent models that describe the evolution of the high $^{3}He/^{4}He$ mantle, and the Ofu data suggest that the high $^{3}He/^{4}He$ mantle domain is isotopically heterogeneous.

2. Methods and results

2.1. Sample location and state of preservation

Ofu Island is located in the eastern province of the Samoan archipelago, an age-progressive hotspot track (Hart et al., 2004; Koppers et al., submitted for publication) located just north of the northern terminus of the Tonga subduction zone. The samples were collected at various locations on the perimeter of Ofu and Olosega islands (Ofu hereafter; sample location map is available in the supplementary data in the Appendix). Tholeiitic lavas in Samoa are rare (Natland, 1980; Workman et al., 2004), and with the exception of a cumulate (OFU-04-14) and a gabbro (OFU-04-17), the Ofu lavas presented in this study are alkali basalts (Table 1). The Ofu samples are generally quite fresh. With the exception of sample OFU-04-12, which has a Th/U ratio of 4.8 (and may indicate U-loss during subaerial weathering), the range of Th/U ratios in the Ofu sample suite is 4.0–4.4. The Ba/Rb ratios for Ofu samples (9.1 ± 1.1 at 1σ) are similar to the values for young Samoan basalts reported previously (Workman et al., 2004), and somewhat lower than the canonical value of ~12 for fresh OIB lavas (Hofmann and White, 1983). Excluding the cumulate sample OFU-04-14, which has a Rb/Cs ratio of 280, the range of Rb/Cs values from the Ofu samples (from 73 to 137) is close to the canonical range of 85–95 (Hofmann and White, 1983). These weathering proxies indicate that elements equally or less mobile than U, Rb and Cs yield useful petrogenetic information.

2.2. He, Sr, Nd and Pb isotopes in Ofu lavas

New $^{3}He/^{4}He$ values (19.5 to 33.8 Ra) were measured at Woods Hole Oceanographic Institution on olivine and clinopyroxene (cpx) phenocrysts separated from 12 hand samples (Table 1). Measurements were made by crushing and fusion *in vacuo*, following the protocol reported in (Kurz et al., 2004). The sample with the highest $^{3}He/^{4}He$ value, OFU-04-06, was taken from an ankaramite dike exposed at 2 m depth in a recent road cut. Olivines from this sample are relatively gas rich (67.5×10^{-9} cm^3 STP g^{-1}, the sum of crushing and fusion) and yielded similar $^{3}He/^{4}He$ ratios on two separate crushes of the same olivine separate (OFU-04-06cr1 followed by OFU-04-06cr2). Following the crushing experiments, a fusion extraction of the resulting olivine powder (OFU-04-06fus) yielded lower $^{3}He/^{4}He$, indicating the presence of ingrown radiogenic helium, probably implanted from the Th and U-rich matrix. Two different olivine populations (lighter and darker olivines) separated from sample OFU-04-06 yielded similar $^{3}He/^{4}He$ ratios (33.4 and 33.6 Ra). These fusion and crushing experiments, coupled with sampling depths, preclude the influence of cosmogenic helium for this important sample. The lava with the second highest $^{3}He/^{4}He$ value measured by crushing–sample OFU-04-15–also yielded lower $^{3}He/^{4}He$ ratios upon fusion (OFU-04-15fus) of the crushed olivine powder. Additionally, crushing experiments of sample OFU-04-03 (OFU-04-03cr1 followed by OFU-04-03cr2) yielded