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Silicon isotopes reveal recycled altered oceanic crust in the mantle sources of Ocean Island Basalts

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Abstract

The study of silicon (Si) isotopes in Ocean Island Basalts (OIB) has the potential to discern between different models for the origins of geochemical heterogeneities in the mantle. Relatively large (~several per mil per atomic mass unit) Si isotope fractionation occurs in low-temperature environments during biochemical and geochemical precipitation of dissolved Si, where the precipitate is preferentially enriched in the lighter isotopes relative to the dissolved Si. In contrast, only a limited range (~tenths of a per mil) of Si isotope fractionation has been observed from high-temperature igneous processes. Therefore, Si isotopes may be useful as tracers for the presence of crustal material within OIB mantle source regions that experienced relatively low-temperature surface processes in a manner similar to other stable isotope systems, such as oxygen. Characterizing the isotopic composition of the mantle is also of central importance to the use of the Si isotope system as a basis for comparisons with other planetary bodies (e.g., Moon, Mars, asteroids).

Here we present the first comprehensive suite of high-precision Si isotope data obtained by MC-ICP-MS for a diverse suite of OIB. Samples originate from ocean islands in the Pacific, Atlantic, and Indian Ocean basins and include representative end-members for the EM-1, EM-2, and HIMU mantle components. On average, δ^{30}Si values for OIB (-0.32 ± 0.09‰, 2 sd) are in general agreement with previous estimates for the δ^{30}Si value of Bulk Silicate Earth (-0.29 ± 0.07‰, 2 sd; Savage et al., 2014). Nonetheless, some small systematic variations are present; specifically, most HIMU-type (Mangaia; Cape Verde; La Palma, Canary Islands) and Iceland OIB are enriched in the lighter isotopes of Si (δ^{30}Si values lower than MORB), consistent with recycled altered oceanic crust and lithospheric mantle in their mantle sources.

Keywords: Silicon isotopes; Ocean Island Basalts; Mantle heterogeneity; Recycling

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1. INTRODUCTION

Knowledge of Earth's internal structure and composition has primarily been obtained through complimentary approaches of geophysical and geochemical investigation.

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However, debate still persists about the mechanisms responsible for generating the chemical and physical characteristics of Earth's mantle observed today, as well as their evolution through time. The large-scale composition of the mantle may be inferred in part from mantle-derived melts erupted at or near the Earth's surface, including Mid-Ocean Ridge Basalts (MORB) and Ocean Island Basalts (OIB). Therefore, analyses of oceanic basalts remain a key component in understanding the geochemical complexities of the mantle.

Trace element ratios, radiogenic isotope variations (e.g., Sr, Nd, Hf, Os, Pb), and noble gas systematics have traditionally been studied in mantle-derived samples to better understand the chemical composition and physical processes occurring within the mantle throughout Earth history (e.g., Zindler and Hart, 1986; Hofmann, 2003; Stracke et al., 2005). Ocean Island Basalts exhibit systematic differences in isotopic compositions when compared with MORB; this has generally been attributed to mantle heterogeneities arising from the recycling of various materials into OIB mantle source regions (e.g., Hofmann and White, 1982; Hauri and Hart, 1993; Hofmann, 1997; Graham, 2002; Jackson and Dasgupta, 2008; Day et al., 2009). Various different mantle endmembers have been proposed to explain the variable Sr, Nd, and Pb isotope ratios, in that each plume samples chemically distinct mantle sources (Zindler and Hart, 1986); this has been recently extended to Hf (e.g., Stracke, 2012) and Os isotopes (e.g., Day, 2013). The main compositional mantle endmembers include DMM (Depleted MORB Mantle), EM-1 (Enriched Mantle 1), EM-2 (Enriched Mantle 2), and HIMU ("high-μ", where μ is defined as the time-integrated $^{238}U/^{204}Pb$). Each endmember is defined in terms of their relative radiogenic Sr and Pb isotope characteristics: DMM displays low $^{87}Sr/^{86}Sr$ and relatively unradiogenic Pb, EM-1 has intermediate $^{87}Sr/^{86}Sr$ and low $^{206}Pb/^{204}Pb$, EM-2 shows high $^{87}Sr/^{86}Sr$ and intermediate $^{206}Pb/^{204}Pb$, and HIMU is defined by low $^{87}Sr/^{86}Sr$ and high $^{206}Pb/^{204}Pb$ (Zindler and Hart, 1986; Hofmann, 2003). These geochemical characteristics are thought to be a reflection of specific lithologies present as a component of the source: EM-1 may incorporate recycled lower continental crust material or pelagic sediments (Woodhead and McCulloch, 1989; Willbold and Stracke, 2010; Garapic et al., 2015) or delaminated subcontinental lithosphere (McKenzie and O'Nions, 1983; Mahoney et al., 1991), EM-2 may arise from the recycling of continental-derived sediments (White and Hofmann, 1982; Jackson et al., 2007a), and HIMU may involve recycled oceanic crust and lithospheric mantle (Hofmann and White, 1982; Chauvel et al., 1992; Hauri and Hart, 1993; Moreira and Kurz, 2001; Day et al., 2010; Cabral et al., 2013). It has even been proposed that an ancient marine carbonate component may exist in the HIMU mantle source (Castillo, 2015). The traditional mantle endmembers represent extremes in terms of isotopic composition, with each OIB location potentially representing a unique mixture of mantle components. However, linking observations of chemical heterogeneity of OIB with the mechanisms responsible for generating such variations is currently a major challenge in mantle geochemistry.

In contrast to radiogenic isotope systems, the mantle end-members are less well defined by stable isotope variations; although O, Mg, and Ca show possible recycled signatures (e.g., Eiler, 2001; Huang et al., 2011; Wang et al., 2016), generally it is assumed that the mantle is homogeneous with respect to most stable isotope systems. To date, this has been the case for silicon isotopes. For example, samples of and from the shallow mantle (peridotites and MORB) are assumed to be representative of the Si isotope composition of Bulk Silicate Earth (BSE), with any Si isotope heterogeneity being obliterated through convective mantle mixing (Savage et al., 2010). However, a systematic study of the Si isotope composition of OIB has not previously been performed; only a limited number of high-precision analyses are present in the literature (see Savage et al., 2014 for a recent review). Given the implications of possible mantle heterogeneities on a wide variety of mantle processes and the importance of an accurate characterization of the isotopic composition of BSE for geo- and cosmo-chemical comparison purposes, a dedicated investigation of potential Si isotope variations in OIB is warranted.

The Si isotope system is a potentially useful tool with which to investigate recycling of terrestrial surface materials within the mantle. Silicon is a key element in silicate minerals and is composed of three stable isotopes: ^{28}Si (92.23%), ^{29}Si (4.68%), and ^{30}Si (3.09%). Relatively large Si isotope fractionations have been observed as the result of low-temperature bio- and geo-chemical surficial/supergene processes, with the light Si isotopes becoming preferentially enriched in precipitated silica phases compared to dissolved Si in the fluid phase (Basile-Doelsch, 2006). Previous studies of the Si isotope systematics in low-temperature environments, including chert formation (Robert and Chaussidon, 2006; van den Boorn et al., 2007; Tatzel et al., 2015), diatom formation (De La Rocha et al., 1997; Hendry et al., 2010), and silicate weathering (Ziegler et al., 2005; Opfergelt et al., 2012), have shown that Si isotope variations can range over several per mil in surface environments. In contrast, high-temperature igneous processes typically result in relatively small fractionations; terrestrial igneous materials display only a limited range (~0.2 per mil on the $^{30}Si/^{28}Si$ ratio) of Si isotope compositions (Georg et al., 2007; Fitoussi et al., 2009; Chakrabarti and Jacobsen, 2010; Savage et al., 2010, 2011, 2013a,b; Armytage et al., 2011; Zambardi et al., 2013; Poitrasson and Zambardi, 2015), with the Bulk Silicate Earth being relatively homogeneous ($\delta^{30}Si = -0.29 \pm 0.07‰$, 2 sd; Savage et al. 2014). Partial mantle melting to form basaltic melts does not appear to generate large Si isotope fractionations (Savage et al., 2010; Savage et al., 2011) compared to low-temperature processes, so incorporation of recycled surface materials in the mantle could produce Si isotope variations that may be observed in OIB.

Here we present high-precision Si isotope data obtained by Multi-Collector Inductively-Coupled-Plasma Mass-Spectrometry (MC-ICP-MS) for a suite of OIB, including samples representative of the EM-1, EM-2, and HIMU mantle endmembers, to quantify potential Si isotope variations in the mantle and assess the processes that may generate Si isotope variability.