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The stable strontium isotopic composition of ocean island basalts, mid-ocean ridge basalts, and komatiites

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ABSTRACT

The radiogenic ^{87}Rb - ^{87}Sr system has been widely applied to the study of geological and planetary processes. In contrast, the stable Sr isotopic composition of the bulk silicate Earth (BSE) and the effects of igneous differentiation on stable Sr isotopes are not well-established. Here we report the stable Sr isotope ($^{88}\text{Sr}/^{86}\text{Sr}$, reported as $\delta^{88/86}\text{Sr}$, in parts per mil relative to NIST SRM 987) compositions for ocean islands basalts (OIB), mid-ocean ridge basalts (MORB) and komatiites from a variety of locations. Stable Sr isotopes display limited fractionation in a OIB sample suite from the Kilauea Iki lava lake suggesting that igneous processes have limited effect on stable Sr isotope fractionation ($\pm 0.12\text{‰}$ over 20% MgO variation; 2sd). In addition, OIB ($\delta^{88/86}\text{Sr} = 0.16\text{--}0.46\text{‰}$; average $0.28 \pm 0.17\text{‰}$), MORB ($\delta^{88/86}\text{Sr} = 0.27\text{--}0.34\text{‰}$; average $0.31 \pm 0.05\text{‰}$) and komatiites ($\delta^{88/86}\text{Sr} = 0.20\text{--}0.97\text{‰}$; average $0.41 \pm 0.16\text{‰}$) from global localities exhibit broadly similar Sr stable isotopic compositions. Heavy stable Sr isotope compositions ($\delta^{88/86}\text{Sr} > 0.5\text{‰}$) in some Barberton Greenstone belt komatiites may reflect Archean seawater alteration or metamorphic processes and preferential removal of the lighter isotopes of Sr. To first order, the similarity among OIBs from three different ocean basins suggests homogeneity of stable Sr isotopes in the mantle. Earth's mantle stable Sr isotopic composition is established from the data on OIB, MORB and komatiites to be $\delta^{88/86}\text{Sr} = 0.30 \pm 0.02\text{‰}$ (2sd). The BSE $\delta^{88/86}\text{Sr}$ value is identical, within uncertainties, to the composition of carbonaceous chondrites ($\delta^{88/86}\text{Sr} = 0.29 \pm 0.06\text{‰}$; 2sd) measured in this study.

1. Introduction

Strontium is an alkaline earth metal and refractory lithophile element, with a 50% condensation temperature (T_c) of 1464 K (Lodders, 2003). It has three stable isotopes - ^{84}Sr (0.56%), ^{86}Sr (9.86%), ^{88}Sr (82.58%) - and a long-lived radiogenic isotope, ^{87}Sr (7.00%), a daughter product of ^{87}Rb ($T_{1/2} = 49.75 \times 10^9$ years, Nebel et al., 2011). Due to differences in volatility and partitioning behaviour during igneous processes of Rb and Sr, the ^{87}Rb - ^{87}Sr system has seen wide application as a chronometer and tracer in geochemistry and cosmochemistry (e.g., Papanastassiou and Wasserburg, 1969; Birck and Allègre, 1973). In general, for Rb-Sr isotope chronology, the $^{88}\text{Sr}/^{86}\text{Sr}$ ratio is used as a normalization ratio to correct for instrumental mass-dependent effects using either thermal-ionization (TIMS) or multi-collector inductively-coupled-plasma (MC-ICP-MS) mass-spectrometry.

Utilizing non-traditional stable isotopes to understand a range of geological processes (e.g., Teng et al., 2017) has led to proliferation of high-precision stable isotopic measurements of Sr by either double-spike methods using TIMS (e.g., Parkinson et al., 2007; Pearce et al., 2015; Stevenson et al., 2014; Charlier et al., 2017) or MC-ICP-MS (e.g., Shalev et al., 2013), or by sample-standard bracketing with MC-ICP-MS (e.g., Halicz et al., 2008; Moynier et al., 2010; De Souza et al., 2010). Such studies have shown that biogenic and inorganic Ca-carbonates tend to be enriched in the lighter isotopes of Sr, while seawater is enriched in the heavier isotopes compared to the NIST SRM987 standard, which is a highly purified and homogenized Sr carbonate (Ohno and Hirata, 2007; Krabbenhöft et al., 2010; Raddatz et al., 2013). Stable isotopes of Sr are also used as tracers of continental weathering (e.g., Wei et al., 2013; Stevenson et al., 2016), and are proxies for paleo-temperature (Stevenson et al., 2014; Fietzke and Eisenhauer, 2006;

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Vollstaedt et al., 2014).

Studies of extra-terrestrial materials have found that chondrules and calcium aluminium-rich inclusions (CAIs) of the carbonaceous chondrite Allende are enriched in the lighter isotopes of Sr relative to the bulk rock, while terrestrial and extra-terrestrial materials have similar $^{88}\text{Sr}/^{86}\text{Sr}$ ratios within ~ 50 ppm (Patchett, 1980; Moynier et al., 2010; Charlier et al., 2012). Moynier et al. (2010) proposed that the isotopically light CAIs (down to $\sim -1.7\text{‰}$ for $^{88}\text{Sr}/^{86}\text{Sr}$ ratios compared to bulk meteorites) resulted from electromagnetic sorting of ionized heavy Sr from neutral Sr in the early Solar System, while Patchett (1980) suggested that CAIs were isotopically fractionated during volatilization processes.

Given the applications described above, advancing our knowledge of Sr isotopic variability in terrestrial igneous rocks is fundamental for two principle reasons. First, the interpretation of Sr isotope applied to understand weathering processes relies on the fact that the high-temperature fractionation of Sr isotopes is well-understood and that isotopic variations in weathering products do not reflect this important process. Second, the extent of Sr isotopic fractionation during igneous processes, as well as the estimation of the isotopic composition of the Earth's mantle and of the bulk silicate Earth (BSE), are central to any inter-planetary comparisons. However, the isotopic composition of the BSE has only been estimated from a limited number of terrestrial igneous rocks, including < 20 basalts (mostly from Hawaii, including many replicates of BHVO-2), a large set of rhyolites and several granites and andesites (Charlier et al., 2012, 2017, Moynier et al., 2010). While the Sr isotopic composition of the basalts, granites, and andesites cluster around the same value, several rhyolite glasses were reported to be enriched in the lighter Sr isotopes and it was suggested that igneous differentiation may cause Sr isotopic fractionation (Charlier et al., 2012). It is therefore possible that basalts may not be representative of their mantle source due to the effects of igneous fractionation on stable Sr isotopes.

To precisely determine the behavior of Sr isotopes during magmatic differentiation and establish the composition of BSE, it is necessary to investigate natural terrestrial samples from a common source. Kilauea Iki (KI) lava lake is well-suited to test the effects of fractional crystallization because these samples were formed in a closed system and have experienced extensive fractional crystallization, with MgO contents ranging from 26.9 to 2.4 wt% (Helz et al., 1994; 2012). They have therefore been used widely to study stable isotopic fractionation during igneous processes (e.g., Zn: Chen et al., 2013; Ga: Kato et al., 2017; Fe: Teng et al., 2008; Mg: Teng et al., 2010; Sn: Badullovich et al., 2017; Li: Tomascak et al., 1999). To evaluate the Sr isotopic composition of BSE we report data to test the effect of igneous differentiation on a series of Kilauea Iki lava lake samples, and to evaluate the spatial and temporal heterogeneity of Sr stable isotope compositions in the terrestrial mantle using basaltic rocks from different settings (ocean island basalts [OIB], mid ocean ridge basalts [MORB], continental flood basalts [CFB], and komatiites). We also report data for a variety of chondritic meteorites for comparison with the estimated BSE Sr isotopic composition.

2. Materials and methods

2.1. Samples

A set of forty-five basalts were selected for stable Sr isotopic analysis, including thirty-seven OIB, seven MORB from the Pacific, Atlantic and Indian Oceans, and one CFB (BCR-2). One of the MORB samples (EW9309-20D) comes from the Shona ridge anomaly, where there is evidence of plume-ridge interaction (Moreira et al., 1995). For the OIB, we selected samples covering a large range of compositions (Table 1). For example, St. Helena is classified as HIMU-like based on its radiogenic isotopes, and has low $^3\text{He}/^4\text{He}$ (Graham et al., 1992; Hanyu and Kaneoka, 1997). Seven samples from the Canary Islands, including the islands of La Palma, El Hierro, Gran Canaria, and Fuerteventura, are

considered to contain variable and distinct proportions of recycled oceanic crust and lithosphere as evidenced from He-O-Sr-Nd-Os-Pb isotopes (e.g., Day et al., 2009, 2010; Day and Hilton, 2011). Three samples from volcanic complexes in the Northern Rift Zone in Iceland have depleted tholeiitic compositions. OIB samples from Iceland have attracted many studies because of the association between an oceanic ridge and a mantle plume (Rickers et al., 2013). It has been suggested, based on unradiogenic He and Ne, that the source of these samples is deep, undegassed mantle (Breddam et al., 2000; Moreira et al., 2001). The remaining samples come from several ocean island localities in the Pacific, Indian and Atlantic ocean basins and have been previously characterized for major- and trace-elements, radiogenic isotopes, and Si and Ga stable isotopic compositions (LeRoex, 1985; Albarède and Tamagnan, 1988; Breddam et al., 2000; Claude-Ivanaj et al., 2001; Breddam, 2002; Workman et al., 2004; Geist et al., 2006; Jackson et al., 2007a, 2007b; Millet et al., 2008; Kurz et al., 2009; Day et al., 2010; Kawabata et al., 2011; Hart and Jackson, 2014; Garapić et al., 2015; Pringle et al., 2016, Peters & Day, 2017; Kato et al., 2017).

Samples that we analyzed from the Kilauea Iki lava lake were erupted in 1959 to form a 135 m deep lava lake. Drilling of the lava lake has afforded the opportunity to study the entire igneous sequence preserved during cooling and crystallization (Helz, 2012). The Kilauea Iki lava lake was formed from picritic lava with an average MgO content of ~ 15.4 wt% (Wright, 1973). The chemical evolution of the lava is controlled mainly by the olivine content with a range from olivine-rich cumulates, through olivine tholeiites, ferro-diabases and andesites (Helz and Thornber, 1987). We selected eight drill core and two surface outcrop samples (Iki-22, Iki-58). The MgO contents of these samples vary from 25.8 to 2.4 wt%, and the SiO_2 content from 44.6 to 57.1 wt% (Helz et al., 1994; Helz, 2012). The Li, Mg, Fe, Zn, Cu and Ga isotopic compositions for these samples have also previously been reported (see Tomascak et al., 1999; Teng et al., 2007, 2008, 2010, 2011, Chen et al., 2013; Savage et al., 2015; Kato et al., 2017).

We analyzed 2.69 Ga komatiites from the Belingwe Greenstone Belt in Zimbabwe (TN17, TN18, TN19, ZV10). These are drill core and surface outcrop samples reported previously by Puchtel et al. (2009) for Pt-Re-Os and Sm-Nd isotopes, and for their HSE (highly siderophile elements) and REE (rare earth elements) abundance systematics. The 2.41 Ga komatiite samples 01001, 01104, 01105 from the Victoria's Lava Lake from the Vetryny Belt, Fennoscandia, are olivine cumulates studied by Greber et al. (2015) for Mo stable isotopic composition, and by Puchtel et al. (2016) for Pt-Re-Os, ^{142}Nd , ^{182}W , and HSE abundance systematics. These komatiites are known to have assimilated $\sim 4\%$ of upper crustal material (Puchtel et al., 2016). Komatiites from the Barberton Greenstone belt in South Africa were analyzed, including 3.48 Ga Komati formation samples (BV03, BV10, BV13, BV15 from the lower to the upper part of the surface outcrop), and a single sample from the 3.27 Ga Weltevreden formation (501-1) previously studied by Puchtel et al. (2013, 2014) and Greber et al. (2015). Since komatiites are produced by high degrees (25–40%) of partial melting (e.g., Herzberg, 1992), and Sr behaves as an incompatible element, komatiite melts quantitatively extract Sr from the mantle sources, which permits assessment of the temporal and spatial Sr isotopic heterogeneity of Earth's mantle and possible fractionation during partial melting between komatiites, OIB and MORB.

Eight chondrite samples were studied for comparison with terrestrial samples. These included six carbonaceous chondrites - Vigarano (CV3), Felix (CO3), Isna (CO3), Cold Bokkeveld (CM2), Jbilet Winselwan (CM2) and Maralinga (CK4), one ordinary chondrite, Krymka (LL3), and one enstatite chondrite, Abee (EH4).

2.2. Sample purification

Between 7 and 100 mg of un-leached sample powder was dissolved in a 3:1 mixture of HF and HNO_3 in Teflon bombs. The bombs were placed on a hot plate for 2 days at 120 °C. The samples were evaporated

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