Extreme incompatibility of helium during mantle melting: Evidence from undegassed mid-ocean ridge basalts

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ABSTRACT

We report total helium concentrations (vesicles + glass) for a suite of thirteen ultradepleted mid-ocean ridge basalts (UD-MORBs) that were previously studied for volatile contents (CO_2, H_2O) plus major and trace elements. The selected basalts are undersaturated in $CO_2 + H_2O$ at their depths of eruption and represent rare cases of undegassed MORBs. Sample localities from the Atlantic (2), Indian (1) and Pacific (7) Oceans collectively show excellent linear correlations ($r^2 = 0.75$–0.92) between the concentrations of helium and the highly incompatible elements C, K, Rb, Ba, Nb, Th and U. Three basalts from Gakkel Ridge in the Arctic were also studied but show anomalous behavior marked by excess lithophile trace element abundances.

In the Atlantic–Pacific–Indian suite, incompatible element concentrations vary by factors of 3–4.3, while helium concentration varies by a factor of 13. The strong correlations between the concentrations of helium and incompatible elements are explained by helium behavior as the most incompatible element during mantle melting. Partial melting of an ultradepleted mantle source, formed as a residue of earlier melt extraction, accounts for the observed concentrations. The earlier melting event involved removal of a small degree melt ($\sim$1%) at low but non-zero porosity (0.01–0.5%), leading to a small amount of melt retention that strongly leveraged the incompatible element budget of the ultradepleted mantle source. Equilibrium melting models that produce the range of trace element and helium concentrations from this source require a bulk solid/melt distribution coefficient for helium that is lower than that for other incompatible elements by about a factor of ten. Alternatively, the bulk solid/melt distribution coefficient for helium could be similar to or even larger than that for other incompatible elements, but the much larger diffusivity of helium in peridotite leads to its more effective incompatibility and efficient extraction from a larger volume of mantle during melting. In either case, partial melting leaves a mantle residue with elevated $(U + Th)/^3He$. Consequently, peridotite residues of mantle melting cannot be the source of high $^3He/^4He$ observed at ocean island hotspots such as Hawaii and Iceland.

The extreme effective incompatibility of helium entails that high $^3He/^4He$ mantle sources, isolated before 4.45 Ga based on Xe and W isotopes, have not experienced any melt extraction since they were isolated from convecting portions of the mantle.

1. Introduction

Helium isotope variations in oceanic basalts have been of central importance to the field of chemical geodynamics. High $^3He/^4He$ ratios observed at localities such as Hawaii and Iceland are a key line of evidence for the existence of mantle plumes (Kurz et al., 1982). The high $^3He/^4He$ ratios (up to 50 R_A, where R_A is the ratio in air) compared to those in mid-ocean ridge basalts (MORBs), which typically have $^3He/^4He = 6$–10 R_A) require a mantle source region with a lower time-integrated $(U + Th)/^3He$ ratio. These hotspot or plume source regions must have remained effectively isolated over Earth's history, probably because they are located deeper and are less degassed than the upper mantle source region for MORBs (e.g., Porcelli and Elliott, 2008). Ne–Ar–Xe isotopic systematics in oceanic basalts are fully consistent with this inferred mantle structure (e.g., Marty, 2012; Mukhopadhyay, 2012; Moreira, 2013).

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Other geochemical evidence complicates this simple and coherent picture from the noble gases. High ^{3}He/^{4}He ratios at ocean island hotspots are often associated with "isotopically depleted" compositions of Nd, Sr and Pb that approach those seen in MORBs (Class and Goldstein, 2005). This complex behavior might arise through melt extraction and trace element depletion that affected the whole mantle. According to this model, deep island sources today would have retained a higher ^{3}He/(U + Th) ratio during ancient melting events when that mantle ascended beneath a mid-ocean ridge. The higher ^{3}He/(U + Th) might result either from a small amount of melt retention in the residue (Davies, 2010), or through elemental fractionation during the partial melting process. For example, Albarède (1998) suggested that recycled, depleted oceanic lithosphere in the mantle source region of ocean islands could lead to elevated ^{3}He/^{4}He because He behaves as a less incompatible element compared to U and Th during melt depletion events.

The behavior of U and Th during partial melting of spinel peridotite is dominated by the presence of clinopyroxene, which has a range of experimentally determined mineral/melt partition coefficients (k) that depend on pressure, temperature, mineral composition and oxygen fugacity. Values of k_U and k_{Th} in clinopyroxene range from 3.4×10^{-3} to 1.8×10^{-2} and 8×10^{-3} to 3.6×10^{-2}, respectively (LaTourrette and Burnett, 1992; Beattie, 1993a; Blundy and Wood, 2003; McDade et al., 2003). Values of k_U and k_{Th} in garnet are approximately 9×10^{-3} to 1.8×10^{-2} and 1.5×10^{-3} to 3.3×10^{-3} (LaTourrette et al., 1993; Beattie, 1993b).

There is also a long history of experimental determinations of helium partition coefficients relevant to mantle melting (Hiyagon and Ozima, 1986; Brooker et al., 2003; Parman et al., 2005; Heber et al., 2007; Jackson et al., 2013). These measurements have many complications and have sometimes provided conflicting interpretations. Numerical values for noble gas partitioning are sometimes argued to be maxima even when factors such as the presence of bubbles have been reduced or eliminated. While earlier estimates (e.g., Parman et al., 2005) were notably above 10^{-3}, recent determinations indicate a median helium partition coefficient of $\sim 2 \times 10^{-4}$ between peridotitic phases (olivine, clinopyroxene, orthopyroxene) and basaltic melt at mantle conditions (Heber et al., 2007; Jackson et al., 2013). Marty and Lussiez (1993) and Kurz (1993) used paired analyses of coexisting olivine and basalt glass of Atlantic MORBs to estimate the olivine–melt partition coefficient for helium and obtained values of 6 to 8×10^{-3}. These natural values represent upper limits because the olivines contained melt inclusions and the basalt glasses were partially degassed. The recent studies of Heber et al. (2007) and Jackson et al. (2013) suggest He is similar to or more incompatible than U and Th during early partial melting (e.g., of lherzolite), but perhaps He is more compatible at more advanced stages of melting (e.g., of harzburgite or dunite). This latter possibility would imply that depleted residues of ancient mantle melting might have high ^{3}He/(U + Th) and could ultimately be the source for high ^{3}He/^{4}He ratios at ocean island hotspots.

In principle, the bulk solid/melt distribution coefficient (K_{He}) for helium during mantle melting can also be estimated from concentration measurements in naturally occurring basalts. The extent of melting needs to be known and adjustment must be made for crystal fractionation; the choice of a melting model also influences the estimate and leads to some ambiguities. With highly incompatible elements that can only be fractionated from each other at very low extents of partial melting, a common approach is to estimate the source elemental ratios for a suite of variably depleted lavas and then determine the relative incompatibility of several elements. For volatile elements such as helium this is complicated by the fact that virtually all submarine basalts are oversaturated in their major volatiles ($CO_2 + H_2O$) and consequently they will have lost an unknown amount of helium by degassing. Although

degassing corrections can be made in favorable cases, for example using the ^{4}He/^{40}Ar* ratio, estimates of parental magma helium concentrations and source ratios of helium to other trace elements are uncertain. In this study we use a suite of mid-ocean ridge basalts that are undersaturated in major volatiles at their eruption depth (Michael and Graham, 2015). This sample suite allows a basic test of the behavior of helium during partial melting relative to other incompatible elements (U, Th, K, Rb, Nb, Ba and C). Our results indicate that helium effectively behaves as the most incompatible element during upper mantle melting. Two important conclusions stemming from this result are that peridotitic melting residues are not the origin of high ^{3}He/^{4}He ratios at ocean island hotspots, and that retention of helium in convecting mantle over Earth history is extremely unlikely, lending further support for the isolation of relatively primitive material deep in the planet.

2. Material and methods

The samples for this study are a suite of undegassed mid-ocean ridge basalt glasses previously studied for major volatiles ($CO_2 + H_2O$), and major and trace elements (Michael and Graham, 2015). Major elements were determined by electron microprobe analysis or published values have been used. Trace elements were determined by laser ablation ICP-MS (inductively coupled plasma mass spectrometry). Vesicle He contents and ^{3}He/^{4}He were measured by mass spectrometry and CO_2 contents were determined by capacitance manometry, following *in vacuo* crushing of approximately 250–400 mg of glass chips (typically one to four mm-size pieces). All samples had <3 ppm vesicle CO_2 as expected for their undersaturated nature and the general absence of vesicles. Helium amounts released by crushing were also low, between 1.6×10^{-8} and 9.2×10^{-7} ccSTP/g, and comprised 1–8% of the total helium released by melting glass chips (see below). Dissolved CO_2 and H_2O were determined by FTIR spectroscopy. Detailed descriptions of the sample locations are reported in Michael and Graham (2015). The lavas are all relatively primitive and have Mg# between 61 and 71. Trace element contents are very low, in keeping with the primitive and depleted nature of these magmas; [Nb] varies from 0.2 to 1.3 ppm, [K] from 90 to 625 ppm, and [La] from 0.9 to 2 ppm. Sample collection depths are close to their eruption depths based on knowledge of the dredge locations. All samples are volatile undersaturated based on comparison to the computed saturation concentrations using VolatileCalc (Newman and Lowenstern, 2002).

In this study, millimeter size glass chips ranging in weight from $\sim$60 to $\sim$100 mg were loaded into a stainless steel carousel that allowed samples to be sequentially dropped into a high temperature resistively-heated vacuum furnace. Glasses were melted at 1450 °C, the released gases were processed through a series of SAES getters to remove active gases, and the noble gases were cryo-sorbed onto activated charcoal at 10 K. Helium was selectively released from the cryogenic trap at 45 K and admitted to the mass spectrometer. Analyses were carried out as described previously in Graham et al. (2014). Furnace hot blanks, routinely analyzed before and after each sample, averaged $1.2 \pm 0.3 \times 10^{-10}$ ccSTP ^{4}He and were always <0.1% of the sample size.

3. Results

Analytical results are reported in the Supplementary Table S1.

3.1. Incompatible trace element variations

Trace element concentrations are very low. While the moderately incompatible elements (La through Lu) overlap with canonical values for normal mid-ocean ridge basalts (N-MORB), the highly incompatible elements (Cs, Rb, Ba, Th, U, Nb, Ta, K) are