Absence of a high time-integrated ^{3}He/(U+Th) source in the mantle beneath continents

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ABSTRACT

Volcanic rocks from ocean island and continental flood basalt provinces can exhibit ^{3}He/^{4}He ratios greatly in excess of those of mid-oceanic-ridge basalts (MORB). High ^{3}He/^{4}He ratios must indicate derivation from a mantle source with high time-integrated ^{3}He/(U+Th) relative to depleted MORB-source mantle. The location of the high ^{3}He/^{4}He mantle reservoir is a poorly resolved but important issue because of the constraints it places upon the structure and convective style of Earth's mantle. It has been proposed that the high ^{3}He/^{4}He reservoir resides in the upper mantle, rather than the lower mantle, because Earth should be volatile poor and highly differentiated, with incompatible elements (such as He) concentrated in the upper mantle and crust. This hypothesis can be tested using continental intraplate alkaline volcanics (CIAV) that are generated at or near the boundary between the conducting lithospheric and convecting asthenospheric mantle. Olivine and clinopyroxene phenocrysts from Cretaceous to Miocene CIAV from Canada, South Africa, and Uganda have ^{3}He/^{4}He ratios more radiogenic than MORB, strongly arguing against a widespread high ^{3}He/^{4}He source in the continental lithosphere or the underlying convecting upper mantle. Combined with a global data set of CIAV and continental lithosphere mantle xenoliths, these results provide no evidence for high ^{3}He/^{4}He in any samples known to originate from this environment. Therefore, volcanic rocks with ^{3}He/^{4}He greater than MORB ^{3}He/^{4}He are likely to sample a mantle source with high time-integrated ^{3}He/(U+Th) that cannot exist within or below the continents. This reservoir is also unlikely to exist within the upper mantle as defined by the ^{3}He/^{4}He distribution in MORB.

Keywords: helium, isotopes, mantle, continental, intraplate, volcanics.

INTRODUCTION

The helium isotope systematics of ocean island basalt (OIB), continental flood basalt (CFB), and mid-oceanic-ridge basalt (MORB) provide important constraints on the evolution and heterogeneity of Earth's mantle (Kurz et al., 1982; Van Keken et al., 2002; Graham, 2002). Helium isotope ratios (^{3}He/^{4}He) of phenocrysts and/or submarine glasses from OIB and CFB provinces are generally higher (up to 49.5R_A, where R_A = air ^{3}He/^{4}He; Stuart et al., 2003) compared with MORB (in this contribution, we employ the MORB ^{3}He/^{4}He average = 8 ± 1R_A; Farley and Neroda, 1998; Hilton and Porcelli, 2003), which are considered to sample the depleted MORB source mantle (DMM), in the convecting upper mantle. This distinction in helium isotopic compositions between tectonic settings indicates that a source with high time-integrated ^{3}He/(U+Th) is common in many intraplate OIB and CFB provinces, but is lacking, diluted, or obscured in MORB petrogenesis. The exact location of this source remains the subject of considerable controversy.

MODELS FOR HIGH TIME-INTEGRATED ^{3}He/(U+Th) MANTLE

Two distinct classes of model have been proposed to account for mantle sources with time-integrated ^{3}He/(U+Th) higher than the DMM. The first calls for a deep mantle reservoir characterized by a relatively high proportion of primordial helium. The location of this reservoir has been ascribed to either the entire mantle below the 670 km seismic discontinuity, i.e., the lower mantle (e.g., Craig and Lupton, 1976; Kurz et al., 1983), or to discrete domains within the lowermost mantle (e.g., Kellogg et al., 1999). However, the inability of the 670 km phase change to prevent large-scale mantle mixing (Van Keken and Ballentine, 1999) and tomographic images of seismically fast structures passing into the lower mantle from present-day subduction zones (van der Hilst et al., 1997) are difficult to reconcile with isolation between DMM and a lower mantle reservoir. An additional variant of these deep mantle models invokes the core-mantle boundary or the core (Macpherson et al., 1998; Porcelli and Halliday, 2001) as the reservoir hosting high ^{3}He/^{4}He ratios: in either case, mass transfer of high ^{3}He/^{4}He material must occur through the lower mantle.

The alternative class of model suggests that the high time-integrated ^{3}He/(U+Th) reservoir resides in the shallow mantle. In such models there is a shallow and relatively volatile-rich mantle characterized by low U and Th relative to DMM, due to ancient melt extraction events (Anderson, 1998). This shallow mantle contains He-rich mineral phases that have captured and preserved high ^{3}He/^{4}He fluids over extended periods ($>1 \times 10^9$ yr; Meibom et al., 2003). The essential prerequisites for this class of model are that the source maintains (1) low (LO) ^{238}U/^{3}He (NU) for a given U/Th ratio, i.e., the LONU component (Anderson, 1998), resulting in low ^{4}He production and consequent preservation of high ^{3}He/^{4}He, and (2) residence in the shallow mantle where it would be effectively sampled by low-degree partial melts formed through incipient rifting of continents (e.g., Anderson, 1995, 1998, 2000). LONU mantle can be envisaged as residual and refractory mantle (Anderson, 1998), existing within the ''perisphere,'' a hypothesized shallow mantle reservoir between the lithosphere and asthenosphere (Anderson, 1995, 2000). Such a model predicts shallow origins for both CFBs (e.g., King and Anderson, 1995) and OIBs that have high ^{3}He/^{4}He signatures.

Discriminating between shallow and deep mantle origins for high ^{3}He/^{4}He measured in volcanic rocks is of fundamental importance to understanding the evolution and differentiation of Earth. A deep mantle origin for high ^{3}He/^{4}He implies some degree of mantle stratification and periodic interaction between shallow and deep mantle reservoirs. A shallow mantle origin for high ^{3}He/^{4}He ratios would require sub-

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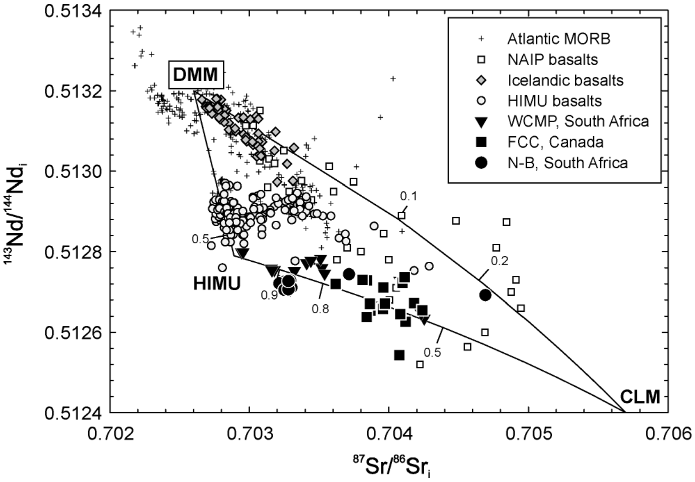

Figure 1. $^{87}Sr/^{86}Sr_i$ **vs.** $^{143}Nd/^{144}Nd_i$ **for Western Cape Melilitite Province (WCMP; Janney et al., 2002), Namaqualand-Bushmanland melilitites (N-B; Janney et al., 2003), and Freemans Cove Complex (FCC; Day, 2004), with published data for HIMU ocean island basalt, North Atlantic Igneous Province (NAIP), and Icelandic basalts. Atlantic mid-oceanic-ridge basalt (MORB) are between 55°S and 52°N; references and data are available upon request. End-member compositions are from Chauvel et al. (1992—depleted MORB source mantle [DMM], HIMU), and Hawkesworth et al. (1990—continental lithosphere mantle, CLM). Binary mixing trajectories with fractional, solid-source mixing are shown. This diagram illustrates that continental intraplate alkaline volcanics (CIAV) comprise mixtures of HIMU-DMM-CLM and that there are Sr and Nd isotope differences between CIAV and high-degree partial melts such as continental flood basalts or Icelandic basalts.**

TABLE 1. MINERAL He ISOTOPE AND ABUNDANCES RESULTS FOR CONTINENTAL INTRAPLATE ALKALINE VOLCANICS

Sample	Phase and mass (g)	$^3He/^4He$ (R/R_A)	(±2s)	^4He (10^{-9} cm^3 STP g^{-1})	(±2s)
Nephelinites and basanites, Freemans Cove Complex, Nunavut, Canada (55.7–56.3 Ma)*					
C246149	Ol 0.43	5.62	0.20	152	7
	Px 0.59	5.64	0.17	166	6
KIA99 BI-5	Ol 1.07	3.11	0.10	27.4	0.5
KIA99 BI-10-B	Ol 1.13	6.46	0.17	30.3	0.5
KIA99 BI-4-1	Ol 1.40	4.66	0.13	13.1	0.2
KIA99 BI-8	Ol 1.18	6.20	0.16	11.9	0.2
KIA99 BI-10-C	Ol 1.08	6.62	0.17	36.4	0.7
KIA99 BI-10-E	Ol 1.40	6.43	0.12	46.3	0.7
KIA99 BI-11-F	Ol 0.97	2.36	0.12	3.8	0.1
Alkali basalts, Freemans Cove Complex, Nunavut, Canada (55.7–56.3 Ma)*					
KIA99 BI-10-G	Ol 0.99	6.69	0.17	43.5	0.9
KIA99 BI-12	Ol 0.86	3.08	0.14	5.7	0.1
Ugandite, Uganda, East African Rift (<12 Ma)*					
PHN 2902A	Ol 1.09	7.11	0.16	6.9	0.1
	Px 0.41	6.87	0.16	24.2	1.2
Olivine melilitites, Western Cape Melilitite Province, South Africa (63.7–75.8 Ma)*					
KSV-256	Ol 0.76	3.07	0.14	33.4	0.9
KSV-266	Ol 0.65	6.12	0.16	130	4
SPK-1	Ol 0.20	5.28	0.13	571	59
SPK-3	Ol 0.33	5.53	0.15	286	17
Olivine melilitites, Namaqualand-Bushmanland, South Africa (72–80 Ma)*					
ZW-1	Ol 0.53	5.29	0.19	206	8
WK-1	Ol 0.27	5.16	0.17	154	12
HO-5	Ol 0.55	5.27	0.17	49.3	1.8
SP-4	Ol 0.27	3.85	0.19	33.4	2.5

Note: Helium was extracted by in vacuo crushing of 0.2–1.4 g purified separates of olivine or pyroxene and analyzed at Scripps Institution of Oceanography using procedures reported previously (Hilton et al., 2000b). Crush times were limited to 150 s (~70 beats per min), to help avoid release of radiogenic or cosmogenic lattice-based He. $^3He/^4He$ ratios of samples (R) are normalized to the atmospheric $^3He/^4He$ ratio (1.39×10^{-6}) and corrected for blanks. Raw helium isotope ratios were normalized using standard aliquots from Murdering Mudpots, Yellowstone National Park (= $16.45R_A$) and air collected from Scripps Institution of Oceanography Pier (= $1R_A$). Blanks averaged $<1.58 \times 10^{-10}$ cm^3 STP ^4He and ^3He blanks were always <4.5% of the measured ^3He. Correction for atmospheric He on the basis of Ne abundances is insignificant for all samples (<2%).

*Ages are provided from ^{40}Ar-^{39}Ar analyses of Freemans Cove Complex lavas (Day, 2004), from Pasteels et al. (1989) for the East African Rift lava, and from K-Ar and ^{40}Ar-^{39}Ar analyses of South African CIAV by Duncan et al. (1978), Moore and Verwoerd (1985), and G. Kiviets (2000, personal commun.).

stantial revision of concepts regarding mantle dynamics (e.g., Porcelli and Ballentine, 2002), models of volatile capture during planetary accretion (e.g., Pepin and Porcelli, 2002), and the partitioning behavior of helium, uranium, and thorium during mantle melting (e.g., Carroll and Draper, 1994).

Continental intraplate alkaline volcanics (CIAV) provide a means to test for the presence of a high $^3He/^4He$ reservoir in the shallow mantle. Although the trace element and isotopic geochemistry of CIAV is diverse (Fig. 1; Brooks et al., 1976; Hawkesworth et al., 1990; Janney et al., 2002, 2003), experimental data on a variety of compositions constrain their depth of generation close to the subcontinental boundary layer, at the transition between the convecting and conducting mantle (Green, 1970; Brey, 1978; Foley, 1992). The LONU source is hypothesized to reside in this region of the mantle (Anderson, 2000).

$^3He/^4He$ AND [He] DATA FOR NORTH AMERICAN AND AFRICAN CIAV

New $^3He/^4He$ data for olivine and clinopyroxene phenocrysts from 19 Cretaceous to Miocene CIAV, including melilitites, nephelinites, basanites, and alkali basalts, are reported in Table 1. CIAV from these locations were selected because their trace element and Sr-Nd-Os-Pb isotope compositions (Mitchell and Platt, 1983; Janney et al., 2002, 2003; Day, 2004) indicate that they have undergone minimal crustal contamination, and that their source regions contain contributions from asthenospheric and lithospheric mantle (e.g., Fig. 1).

The $^3He/^4He$ isotopic ratios of olivine in CIAV range from 3.1 to $6.1R_A$ for South African melilitites, 2.4 to $6.7R_A$ for Canadian CIAV, and 6.9 to $7.1R_A$ for a single ''ugandite'' (12 Ma) from the East African Rift. The most striking feature of these results is that despite more than two orders of magnitude variation in He abundance, the CIAV $^3He/^4He$ ratios all fall within a relatively narrow range that is lower (i.e., more radiogenic) than MORB (Fig. 2). These ratios have not been affected by posteruptive contamination with either radiogenic ^4He, or cosmogenic ^3He, which are produced in situ. First, this is because short crushing times were employed, which release only inclusion-sited (i.e., magmatic) volatiles and not those contained in crystal lattice sites (Hilton et al., 1993). Second, comagmatic pyroxenes and olivines from a Freemans Cove olivine melilitite and the East African Rift lava have indistinguishable $^3He/^4He$, which is inconsistent with modification after eruption (Hilton et al., 2000b). Therefore, we conclude that the age of the CIAV is not the controlling factor in establishing $^3He/^4He$ variations within and between the different CIAV provinces.

The $^3He/^4He$ ratios of magma that has undergone shallow-level degassing of a He-bearing CO_2 phase prior to eruption can be lowered by addition of radiogenic helium (Hilton et al., 1993, 1995, 2000a). Such contamination is most readily observed in samples with low helium concentrations (Hilton et al., 1995). Five of the new data have low $^3He/^4He$ (R/R_A) and low [He] compared to other samples from the same location (X in Fig. 2). There is no evidence of crustal contributions to these samples from elemental or Sr-Nd-Os-Pb isotope constraints (Janney et al., 2002, 2003; Day, 2004), highlighting the extreme sensitivity of He to record crustal contamination processes (Hilton et al., 1993). The remaining 14 samples show higher and less variable $^3He/^4He$ at each location (Fig. 2), so do not appear to have been modified by crustal He addition. We conclude that these $^3He/^4He$ values are characteristic of their mantle sources.

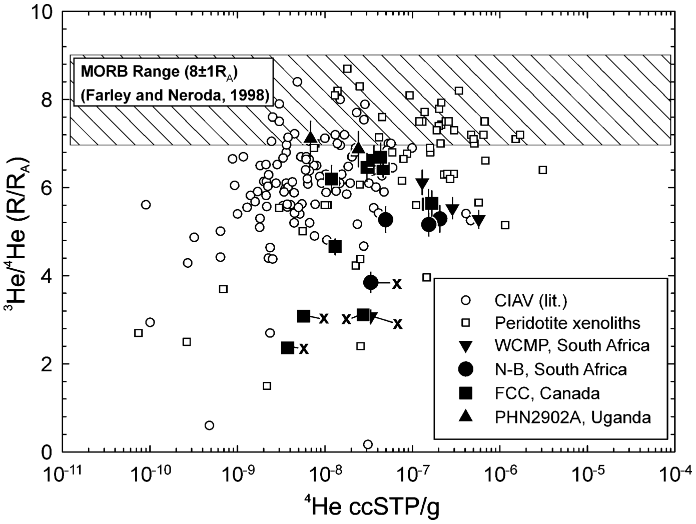

Figure 2. Plot of olivine and clinopyroxene ^{3}He/^{4}He ratios (R/R$_A$ notation) vs. helium concentration ([He]) for continental intraplate alkaline volcanics (CIAV) and continental lithospheric mantle (CLM) peridotite xenoliths. Only samples processed by crushing in vacuo are included. Samples from this study suspected to have primary magmatic ^{3}He/^{4}He signatures modified by radiogenic crustal He are marked (X). Published samples that are suspected of radiogenic or cosmogenic additions have also been excluded from compilation (e.g., Porcelli et al., 1987). Primary ^{3}He/^{4}He signatures for CIAV and CLM xenoliths are consistently more radiogenic than mid-oceanic-ridge basalt (MORB). Data do not indicate existence of a reservoir with high time-integrated ^{3}He/(U+Th) beneath the continents. Abbreviations as in Figure 1. Published CIAV and peridotite xenolith data compiled from Gautheron and Moriera (2002), Graham (2002), Dunai and Porcelli (2002), Hilton and Porcelli (2003), and references therein.

^{3}He/^{4}He OF CIAV AND CONTINENTAL LITHOSPHERIC MANTLE WORLDWIDE

If we exclude the five samples that are interpreted to have been modified by He contamination in our data set (X in Fig. 2), the average ^{3}He/^{4}He ratio for our CIAV data is 6.0 ± 0.7 (1σ, $n = 15$). Canadian and South African CIAV have ^{3}He/^{4}He ratios of 6.2 ± 0.4 (1σ, $n = 7$) and 5.4 ± 0.4 (1σ, $n = 6$), respectively. Exclusion of the lowest ^{3}He/^{4}He samples provides an estimate of the maximum helium isotope ratio in the sources of CIAV. Despite the simple explanation that ^{3}He/^{4}He values below the mode in each suite result from contamination in the crust, we cannot discount the possibility that the CIAV sources may be heterogeneous with respect to He and contain domains with ^{3}He/^{4}He $\leq 6R_A$. Regardless of location, lithology, or age, all ^{3}He/^{4}He ratios for CIAV are less than the canonical average MORB value of 8 ± 1R$_A$.

In Figure 2 we include published ^{3}He/^{4}He results for other CIAV and for CLM peridotite xenoliths entrained in CIAV. In the figure we do not consider CIAV that have temporal or spatial association with CFB or alkaline magmatic rocks located on ocean islands: therefore only volcanic rocks originating from low-degree partial melting and eruption through CLM have been included in the CIAV data set. The average ^{3}He/^{4}He ratio of the compiled CIAV database is 5.9 ± 1.2R$_A$ (1σ, $n = 121$), identical to results obtained here for the North American and African CIAV. We conclude that CIAV ^{3}He/^{4}He ratios show no indication that mantle with high time-integrated ^{3}He/(U+Th) participates in their petrogenesis. Rather, melilitites, nephelinites, basanites, and basalts from localities in southern Africa, Canada, and the western branch of the East African Rift, along with other CIAV worldwide, exhibit ^{3}He/^{4}He lower than is typical of MORB, suggesting derivation from a mantle source with time-integrated ^{3}He/(U+Th) lower than DMM.

The CIAV ^{3}He/^{4}He data are similar to those of CLM peridotite xenoliths (6.4 ± 1.6R$_A$, 1σ, $n = 59$) (Fig. 2). Since helium is highly mobile in the presence of magma or precursor CO$_2$-rich metasomatic fluids, the He isotope signature of the lithospheric mantle will be strongly influenced or dominated by the underlying shallow convecting mantle. Hence, while Sr-Nd-Pb-Os isotopes of CIAV reflect varying contributions from CLM and asthenosphere (Fig. 1), He isotope ratios are more likely to reflect the signature of the shallow convecting mantle. Wherever ^{3}He/^{4}He ratios have been measured in CLM peridotite xenoliths, high ^{3}He/^{4}He signatures have been conspicuous by their absence (Dunai and Porcelli, 2002).

LOCATION AND NATURE OF A HIGH TIME-INTEGRATED ^{3}He/(U+Th) SOURCE

Shallow mantle beneath the lithosphere with LONU characteristics has been proposed to account for the extreme ^{3}He/^{4}He characteristics of OIB and CFB (Anderson, 2000). Farley (1993) and Stuart (1994) argued against the hypothesis that high ^{3}He/^{4}He may originate from subduction of high-^{3}He extraterrestrial material (Anderson, 1993; Allègre et al., 1993). This has resulted in the notion that the LONU or ''perisphere'' layer must represent a residual and refractory upper mantle source (Anderson, 1998). This hypothesis has been difficult to reconcile with the elevated ^{3}He/^{4}He measured in oceanic hotspot volcanism (Graham, 2002).

The LONU hypothesis does not easily explain elevated ^{3}He/^{4}He because the LONU source is only likely to be sampled during the earliest stages of rifting. It is unlikely to exist in mature ocean basins, and therefore appears to be exhaustible and transient (Anderson, 2000). CIAV samples analyzed in this study are products of incipient rifting of ancient continental lithosphere and clearly indicate that a high ^{3}He/^{4}He reservoir is not sampled in either the lithospheric mantle or the uppermost convecting mantle beneath continents. Our results reinforce He isotope studies of CLM peridotite xenoliths that show that the continental lithosphere represents a source with low time-integrated ^{3}He/(U+Th) (Dunai and Porcelli, 2002).

We suggest that a source with high time-integrated ^{3}He/(U+Th) cannot exist in the upper mantle beneath continents. This is because CIAV or CLM consistently show ^{3}He/^{4}He ratios lower than MORB, yet such samples should have the highest ^{3}He/^{4}He according to the LONU model. Therefore, the high ^{3}He/^{4}He found in OIB and CFB originate from a high time-integrated ^{3}He/(U+Th) reservoir that exists in mantle rarely tapped by MORB and not sampled at all by CIAV.

IMPLICATIONS FOR ABSENCE OF HIGH ^{3}He/^{4}He UPPER MANTLE SOURCES

The absence of a high ^{3}He/^{4}He shallow mantle reservoir means that the relationship of extreme ^{3}He/^{4}He ratios measured in CFB and OIB (up to 49.5R$_A$; Stuart et al., 2003) and the lower ^{3}He/^{4}He measured in MORB (8 ± 1R$_A$; Farley and Neroda, 1998) has profound implications for mantle geodynamics. This is because helium isotope signatures appear to trace source components in CFB and OIB that retain parts of Earth's initial volatile inventory (Clarke et al., 1969). The absence of a reservoir with high time-integrated ^{3}He/(U+Th) in the upper mantle but the generation of OIB and CFB magmatism such as Hawaii (e.g., Kurz et al., 1983) and the Siberian or Deccan Traps (Basu et al., 1993, 1995) that have high ^{3}He/^{4}He implies that a proportion of the noble gas inventory present in OIB and CFB magmas originates from the deeper (lower) mantle.

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