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 $^4$He/$^3$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 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 $4.9R_A$, where $R_A = \text{air}^4$He/$^3$He; Stuart et al., 2003) compared with MORB (in this contribution, we employ the MORB $^4$He/$^3$He average = 8 ± 1$R_A$; 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) $^3$He/$^4$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 hypoth-
Table 1. Mineral He Isotope and Abundances Results for Continental Intraplate Alkaline Volcanics

<table>
<thead>
<tr>
<th>Sample</th>
<th>Phase and mass (g)</th>
<th>$^{3}$He/$^{4}$He (R/R$_A$)</th>
<th>$^{3}$He (10^{-12} cm$^2$ STP g$^{-1}$)</th>
<th>$^{4}$He (10^{-12} cm$^2$ STP g$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest America</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C246149</td>
<td>O1 0.43</td>
<td>5.62</td>
<td>0.20</td>
<td>152</td>
</tr>
<tr>
<td>KIA99 Bl-S</td>
<td>Px 0.59</td>
<td>5.64</td>
<td>0.17</td>
<td>166</td>
</tr>
<tr>
<td>KIA99 Bl-10-B</td>
<td>O1 1.13</td>
<td>6.46</td>
<td>0.17</td>
<td>303</td>
</tr>
<tr>
<td>KIA99 Bl-4-1</td>
<td>O1 1.40</td>
<td>6.46</td>
<td>0.13</td>
<td>13.1</td>
</tr>
<tr>
<td>KIA99 Bl-9</td>
<td>O1 1.18</td>
<td>6.20</td>
<td>0.16</td>
<td>11.9</td>
</tr>
<tr>
<td>KIA99 Bl-10-C</td>
<td>O1 1.08</td>
<td>6.62</td>
<td>0.17</td>
<td>36.4</td>
</tr>
<tr>
<td>KIA99 Bl-10-E</td>
<td>O1 1.40</td>
<td>6.43</td>
<td>0.12</td>
<td>46.3</td>
</tr>
<tr>
<td>KIA99 Bl-11-F</td>
<td>O1 0.97</td>
<td>2.36</td>
<td>0.12</td>
<td>3.8</td>
</tr>
<tr>
<td>Alkali basalts, Freemans Cove Complex, Nunavut, Canada (55.7–56.3 Ma)*</td>
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<td></td>
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<tr>
<td>KIA99 Bl-10-G</td>
<td>O1 0.99</td>
<td>6.69</td>
<td>0.17</td>
<td>43.5</td>
</tr>
<tr>
<td>KIA99 Bl-12</td>
<td>O1 0.86</td>
<td>3.08</td>
<td>0.14</td>
<td>5.7</td>
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<td>Uganda, Uganda, East African Rift (&lt;12 Ma)*</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>PHN 2902A</td>
<td>O1 1.09</td>
<td>7.11</td>
<td>0.16</td>
<td>6.9</td>
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<tr>
<td>KSV-256</td>
<td>O1 0.76</td>
<td>3.07</td>
<td>0.14</td>
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<tr>
<td>HO-5</td>
<td>O1 0.35</td>
<td>5.27</td>
<td>0.17</td>
<td>51.3</td>
</tr>
<tr>
<td>SP-4</td>
<td>O1 0.27</td>
<td>3.85</td>
<td>0.19</td>
<td>33.4</td>
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<td>Alkali melilitites, Namaqualand-Bushmanland, South Africa (72±80 Ma)*</td>
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<td>ZW-1</td>
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<td>5.29</td>
<td>0.19</td>
<td>206</td>
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<tr>
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<td>3.85</td>
<td>0.19</td>
<td>33.4</td>
</tr>
</tbody>
</table>

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 argon from the samples. Corrections were applied to the measured $^{4}$He abundance (1.39 x 10^{-10}) and corrected for all isotopes. Raw helium isotope ratios were normalized using standard aliquots from Murdering Mudpots, Yellowstone National Park (<1.45 R$_A$) and air collected from Scripps Institution of Oceanography Pier (<1 R$_A$). R$_A$ is the ratio of 4 He to 3 He in the Earth’s atmosphere. Variations in the He abundance of the world’s atmosphere are not significant 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 CAV by Duncan et al. (1978), Moore and Verwoerd (1985), and G. Kiviets (2000, personal commun.).
The CIAV $^3\text{He}/^4\text{He}$ 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 CO₂-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 $^3\text{He}/^4\text{He}$ ratios have been measured in CLM peridotite xenoliths, high $^3\text{He}/^4\text{He}$ signatures have been conspicuous by their absence (Dunai and Porcelli, 2002).

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

Shallow mantle beneath the lithosphere with LONU characteristics has been proposed to account for the extreme $^3\text{He}/^4\text{He}$ characteristics of OIB and CFB (Anderson, 2000). Farley (1993) and Stuart (1994) argued against the hypothesis that high $^3\text{He}/^4\text{He}$ may originate from subduction of high-$^3\text{He}$ 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 $^3\text{He}/^4\text{He}$ measured in ocean hotspot volcanism (Graham, 2002).

The LONU hypothesis does not easily explain elevated $^3\text{He}/^4\text{He}$ because the LONU source is likely to be sampled during the earliest stages of rifting. It is unlikely to exist in mature ocean basins, and therefore appears to be exhaustive 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 $^3\text{He}/^4\text{He}$ reservoir is not sampled in either the lithospheric mantle or the uppermost convecting mantle beneath continents. Our results reinforce the idea that the LONU is a transient source that has not yet been sampled, and we therefore 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 therefore appears to be exhaustible and transient (Anderson, 2000).

**IMPLICATIONS FOR ABSENCE OF HIGH $^3\text{He}/^4\text{He}$ UPPER MantLE SOURCES**

The absence of a high $^3\text{He}/^4\text{He}$ shallow mantle reservoir means that the relationship of extreme $^3\text{He}/^4\text{He}$ ratios measured in CFB and OIB (up to 49.5R_A; Stuart et al., 2003) and the lower $^3\text{He}/^4\text{He}$ 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 $^3\text{He}/(\text{U+Th})$ 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 $^3\text{He}/^4\text{He}$ implies that a proportion of the noble gas inventory present in OIB and CFB magmas originates from the deeper (lower) mantle.

**ACKNOWLEDGMENTS**

We thank C.J. Harrison for provision of sample C246-149 and the Polar Continental Shelf project for providing logistical and helicopter support for field studies of the Freeman's Cove Complex, Bathurst Island. We also thank Chris Ballentine and two anonymous reviewers for insightful comments that have significantly improved the arguments made in this manuscript. This work was...


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