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A “high $^{4}\text{He}/^{3}\text{He}$” mantle material detected under the East Pacific Rise (15°4′N)

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Abstract

We investigate in details helium isotope data reported in Mougel et al. (2014) for 14 basaltic samples collected on the East Pacific Rise by submersible (15°4′N) where the ridge interacts with the Mathematician seamounts. Samples locations are separated by only few hundred meters across a 15 km along-axis profile. The data reveal a strong geochemical variability that has never been observed at such high spatial resolution for helium isotope compositions. Moreover, they reveal an unusually high $^{4}\text{He}/^{3}\text{He}$ mantle component also characterized by unradiogenic lead, atypical in oceanic basalts. He–Pb systematics suggests a mixture between a nonradiogenic lead and radiogenic helium pyroxenitic component, recycled from the deep continental lithosphere and the ambient peridotitic mantle. The He isotope difference between these two end-members can be interpreted as a time evolution of two distinct mantle sources after a slight $(\text{U}+\text{Th})/^{3}\text{He}$ fractionation, likely due to some ancient degassing during the formation of deep continental pyroxenites.

1. Introduction

Helium ($\text{He}$) isotopes, coupled with heavy radiogenic isotopes, have been utilized for decades in order to explore the nature, structure, and evolution of the Earth's mantle. While $^{4}\text{He}$ comes mostly from the radioactive decay of uranium ($^{235}\text{U}$, $^{238}\text{U}$) and thorium ($^{232}\text{Th}$), $^{3}\text{He}$ is considered primordial. The preferred materials for analyzing $\text{He}$ isotopes are the quenched glassy rims of pillow lavas, as well as melt and fluid inclusions in minerals because they are less sensitive to degassing. Global compilation of the $\text{He}$ isotopic data in oceanic basalts has revealed that most ocean island basalts (OIB) have low and variable $^{4}\text{He}/^{3}\text{He}$ ratios (or high $R/Ra$ where $R$ is the $^{3}\text{He}/^{4}\text{He}$ ratio normalized to air), whereas most mid-ocean ridge basalts (MORB) have higher and more homogeneous $^{4}\text{He}/^{3}\text{He}$ ratios with a mean value of $90,000 \pm 10,000$ ($R/Ra = 8 \pm 1$) [Allègre et al., 1995]. MORB and OIB are therefore interpreted as sampling two different mantle reservoirs. OIB sample a more primitive (enriched in $^{3}\text{He}$) deep mantle reservoir, while MORB tap the degassed upper mantle [Kurz et al., 1982; Allègre et al., 1983; Kaneoka, 1983]. Nevertheless, higher than MORB $^{4}\text{He}/^{3}\text{He}$ (e.g., $>120,000$; $R/Ra < 6$) are also reported in oceanic basalts. Such samples can be found on St. Helena, Tristan da Cunha, Sao Miguel Islands, or in HIMU-Type OIB [e.g., Moreira et al., 1999; Graham et al., 1993; Moreira et al., 2012; Hanyu and Kaneoka, 1997; Class et al., 2005; Barfod et al., 1999], but this peculiar radiogenic helium signature is not common in MORB, especially when posteroptivatic radiogenic production is excluded. These “high $^{4}\text{He}/^{3}\text{He}$ hot spots” reflect either the presence of recycled materials [Hanyu and Kaneoka, 1997] or isotopic perturbations induced by late and shallow processes [Hilton et al., 1999]. The coupling of $\text{He}$ isotopes with other isotopic tracers, therefore, provides insight into the origin and nature of radiogenic $\text{He}$ materials in the mantle. Furthermore, studying $\text{He}$ isotope variability at various spatial scales in erupted lavas along oceanic spreading centers is also fundamental in order to understand the length scale(s) of mantle heterogeneities and the preservation of their signature at the surface. Despite apparent $\text{He}$ isotopes homogeneity in worldwide MORB from the entire ridge system, some local variations between single ridge segments exist [Georgen et al., 2003]. These may reflect the presence of mantle heterogeneities (e.g., petrological anomalies such as fertile recycled vein material or small mantle plumes) propagating through the upper mantle and melting beneath or close to ridges.

This paper represents one of the highest spatial resolutions for $\text{He}$ isotopic studies attempted on a single ridge segment. Fourteen basaltic samples were collected during submersible dives around 15°4′N along the East Pacific Rise (EPR) (Figure 1) where the Mathematician hot spot track intersects the ridge and were analyzed for their $\text{He}$ and lead (Pb) isotope compositions. Our results show an atypical straight correlation between these two isotope systems suggesting the mixture of two distinct mantle components. They also...
suggest the existence of a radiogenic He mantle heterogeneity beneath this area already marked by a highly unradiogenic Pb composition. The strong isotopic variability in this spatially restricted area is another important and unexpected characteristic of this 20 km² zone along a ridge segment. In this study, we investigate the origin of this “high \(^{4}\)He/\(^{3}\)He” mantle source and its He isotopic divergence from ambient mantle value.

2. Geologic Outline of the Study Area

The northern part of the EPR separates the Pacific and Cocos plates with a full spreading rate of ~85 mm/yr [Carbotte et al., 1998]. Between Rivera and Orozco Fracture zones (FZ), the ridge is offset by two discontinuities...
that have divided the ridge into three segments, which have axial morphologies that are drastically different from one another. This study focuses on the southern segment (Figure 1), located on the northern side of Orozco FZ. It is 115 km long, and is 400 m shallower (~2200 m) and twice as wide (~10 km wide) as the rest of the EPR [e.g., Scheirer and Macdonald, 1993; Weiland and Macdonald, 1996; Carbotte et al., 2000]. The ridge axis is intercepted perpendicularly on its western side by a prominent seamount chain named “P1545” [Macdonald et al., 1992; Weiland and Macdonald, 1996; Carlut et al., 2004]. Previous studies attributed this singular morphology to a remarkably high magmatic supply due to the presence of a hot spot [e.g., Scheirer and Macdonald, 1995; Weiland and Macdonald, 1996; Carbotte et al., 2000; Shah and Buck, 2006; Le Saout et al., 2014] named “Mathematician hot spot” [Le Saout et al., 2014; Mougel et al., 2014] which may also be responsible for the two-step western segment migration during the last 300 ka [Carbotte et al., 2000]. The geochemical composition of basaltic samples from this area is also quite notable [Mougel et al., 2014] as it displays a geochemical variability that has never been observed along a ridge at such a small spatial scale (~20 km of ridge axis), including a non-mantle signature (Unradiogenic Lead Component; ULC) related to the hot spot [Mougel et al., 2014]. The range of isotopic compositions of these basaltic samples is commensurate to that of the entire EPR and can be accounted for by a mixture of three main components representative of the hot spot heterogeneity and its interaction with the ridge. The particularity of ULC-influenced basaltic samples is a very unradiogenic Pb signature (208Pb/204Pb = 36.83, 207Pb/204Pb = 15.46, and 206Pb/204Pb = 17.49) associated with mostly enriched Sr, Nd, and Hf isotopic compositions (87Sr/86Sr = 0.70303, 143Nd/144Nd = 0.51303, and 176Hf/177Hf = 0.28302), which is different from any known mantle end-members. An ancient (>2 Ga) lower continental origin for this material has been formerly proposed [Mougel et al., 2014], with the involvement of other end-members in order to explain the unradiogenic Pb compositions. The current preferred model suggested by trace element and isotopic compositions is the recycling and sequestration within the upper mantle of sulfur-deep-sea pyroxenites coming from a continental arc root [Mougel et al., 2014]. Finally, the melting of the heterogeneous hot spot source and its connection with the ridge system then enables rapid and abundant melt transfer toward the ridge [Mittelstaedt et al., 2011], preserving the signatures of the heterogeneities in the MORB despite efficient mixing.

3. Samples and Methods

Samples of basaltic glass were collected “in situ” with the French submersible Nautil during the PARISUB cruise (R/V L’Atalante March–April 2010) along the EPR axis, between 15°37′N and 15°46′N [Gente et al., 2010]. The combination of high precision bathymetric data (Autonomous Underwater Vehicle acquisitions) and the use of the submersible allowed very accurate positioning of each sample. Volcanic glass chips were handpicked under a microscope and ultrasonically cleaned in ultra pure water and ethanol. Sample locations are given in Figure 1.

For He data acquisition, glass fragments (<4 mm) were melted under vacuum and gas was extracted, purified, and transferred to the mass spectrometer using the automated line connected to the Noblesse® mass spectrometer at Institut de Physique du Globe de Paris (IPGP). The 4He blank was ~2 x 10^-10 ccSTP (Cubic Centimeter Standard Temperature Pressure) during the course of the measurements. The detailed procedure on Noblesse is given in Moreira et al. [2011]. Pb isotope data were obtained from HF-HNO3 dissolution of ~500 mg of sample (after HCl leaching) following the protocol described in Blichert-Toft et al. [2005] and Agranier et al. [2005]. Isotopic compositions were analyzed using the Thermo Neptune Multiple Collector-Inductively Coupled Plasma-Mass Spectrometer (MC-ICP-MS) of Ifremer Brest. Values used for mass bias fractionation corrections are 205Tl/203Tl = 2.388. Those used for standard bracketing are those from Tott et al. [1996]. These isotopic data have been previously reported in the supporting information of a former paper [Mougel et al., 2014]. We now add the He concentrations of the samples.

4. Results

He and Pb data are given in Table 1. The 4He/3He ratios vary from 103,818 to 126,762 (R/Ra between 5.70 and 6.96). These data represent much more radiogenic compositions than “regular” MORB value (~90,000; R/Ra ~8) [Allègre et al., 1995; Graham, 2002] and are therefore not typical of a major hot spot signature such as Hawaii [Kurz et al., 1983, 1987], Iceland [Graham et al., 1998; Hilton et al., 1999], or Galapagos [Kurz et al., 2009], which show low 4He/3He (high R/Ra) ratios compared to MORB (down to 15,000) [Stuart et al., 2003]. He concentrations in our samples are also typical of MORB ranging from 1.0 × 10^-5 to 1.9 × 10^-5 ccSTP/g.
Table 1. Helium and Lead Isotopic Compositions of the Studied Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Weight (g)</th>
<th>4He (cc/STP/g)</th>
<th>4He/3He</th>
<th>206Pb/204Pb</th>
<th>207Pb/204Pb</th>
<th>208Pb/204Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>10PUB16-05</td>
<td>-105.429</td>
<td>15.722</td>
<td>0.021</td>
<td>1.2 x 10^-5</td>
<td>12.247</td>
<td>2.008</td>
<td>6.00</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB22-10</td>
<td>-105.430</td>
<td>15.725</td>
<td>0.034</td>
<td>1.9 x 10^-5</td>
<td>11.196</td>
<td>2.090</td>
<td>6.44</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB22-13</td>
<td>-105.431</td>
<td>15.732</td>
<td>0.022</td>
<td>1.2 x 10^-5</td>
<td>12.672</td>
<td>2.224</td>
<td>5.70</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB16-10</td>
<td>-105.432</td>
<td>15.739</td>
<td>0.031</td>
<td>1.4 x 10^-5</td>
<td>12.042</td>
<td>2.008</td>
<td>6.00</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB16-03</td>
<td>-105.430</td>
<td>15.719</td>
<td>0.025</td>
<td>1.5 x 10^-5</td>
<td>12.508</td>
<td>2.162</td>
<td>5.78</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB16-06</td>
<td>-105.429</td>
<td>15.725</td>
<td>0.029</td>
<td>1.4 x 10^-5</td>
<td>11.219</td>
<td>1.742</td>
<td>6.44</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB22-08</td>
<td>-105.429</td>
<td>15.722</td>
<td>0.027</td>
<td>1.2 x 10^-5</td>
<td>12.039</td>
<td>2.096</td>
<td>5.87</td>
<td>0.10</td>
</tr>
<tr>
<td>10PUB21-01</td>
<td>-105.421</td>
<td>15.675</td>
<td>0.027</td>
<td>1.1 x 10^-5</td>
<td>11.916</td>
<td>2.090</td>
<td>6.44</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB20-02</td>
<td>-105.415</td>
<td>15.655</td>
<td>0.033</td>
<td>1.5 x 10^-5</td>
<td>10.625</td>
<td>1.876</td>
<td>6.80</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB15-04</td>
<td>-105.427</td>
<td>15.716</td>
<td>0.029</td>
<td>1.5 x 10^-5</td>
<td>10.790</td>
<td>1.858</td>
<td>6.83</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB14-06</td>
<td>-105.410</td>
<td>15.623</td>
<td>0.025</td>
<td>1.5 x 10^-5</td>
<td>10.841</td>
<td>1.790</td>
<td>6.96</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB24-07</td>
<td>-105.432</td>
<td>15.753</td>
<td>0.027</td>
<td>1.0 x 10^-5</td>
<td>10.672</td>
<td>1.892</td>
<td>6.77</td>
<td>0.12</td>
</tr>
<tr>
<td>10PUB24-10</td>
<td>-105.435</td>
<td>15.760</td>
<td>0.036</td>
<td>1.6 x 10^-5</td>
<td>10.963</td>
<td>2.094</td>
<td>6.95</td>
<td>0.14</td>
</tr>
<tr>
<td>10PUB19-12</td>
<td>-105.432</td>
<td>15.691</td>
<td>0.029</td>
<td>1.1 x 10^-5</td>
<td>10.716</td>
<td>1.822</td>
<td>6.90</td>
<td>0.12</td>
</tr>
</tbody>
</table>

σ is the He/4He atmospheric ratio (= 1.384 x 10^-6).
Hamelin et al. silicates [processes in the mantle and/or crust acting as an averaging mechanism, and/or (3) the rapid diffusion of He in of geochemical studies dedicated to very small-scale area with submersible sampling approach, (2) mixing more than 300 to 50 km), especially in hot spot-ridge interaction systems. Reasons for this could be (1) the lack isotopic heterogeneities were easily identified at first and second orders of segmentation along ridges (from more than 300 to 50 km), especially in hot spot-ridge interaction systems. Reasons for this could be (1) the lack of geochemical studies dedicated to very small-scale area with submersible sampling approach, (2) mixing processes in the mantle and/or crust acting as an averaging mechanism, and/or (3) the rapid diffusion of He in silicates [Hanyu and Kaneoka, 1997; Hart et al., 2008] (from 3 to 7 orders of magnitude faster than Sr, Nd, and Pb), which prevent from He isotope heterogeneities preservation on scales smaller than tens of meters, and particularly for long-term mantle in growth of \(^4\)He [Hart et al., 2008]. Therefore, very small veins or layers become chemically undetectable after long-term diffusion and eruptive melt processing.

One of the most glaring example of a high-resolution study recording important He isotopic variability is the 120 km\(^2\) off-axis flow field of the EPR around 14°S, for which the \(^4\)He/\(^3\)He ratio of six samples range from 8.55 to 9.22 Ra [Geshi et al., 2007]. The mid-Atlantic ridge between 25°7’S and 26°5’S is also well documented by 14 samples that range from 7.3 to 7.7 Ra [Graham et al., 1996]. Finally, Gregg et al. [2000] also compared two samples separated by approximately 250 m along the EPR around 9°50’N but found no differences between them. The same observation has been made for the basalts from the Lucky Strike segment in the North Atlantic where the \(^4\)He/\(^3\)He ratio of 33 samples along this single ridge segment show a variation of only 1.2% (1σ) [Moreira et al., 2011].

In this study, we present the He isotope compositions of 14 samples covering a single 15 km along-axis profile of an EPR segment influenced by the mathematicians hot spot, with a sampling space of 3 km to less than 100,000

![Figure 2. Binary plot representing helium isotope compositions \(^4\)He/\(^3\)He versus \(^206\)Pb/\(^204\)Pb. Basalts from this study are represented as red circles and are compared to basalts from Atlantic (black), Pacific (green), and Indian (blue) oceanic domains [Kurz et al., 1982; Graham et al., 1992; Dasso et al., 1993; Mahoney et al., 1994; Dasso et al., 1999; Gautheron, 2002; Moreira and Allègre, 2002; Kurz et al., 2005; Meyzen et al., 2007; Moreira et al., 2008; Hamelin et al., 2011]. Error bars are smaller than the size of the symbols.](image)
50 m between 15°37′N and 15°46′N. R/Ra values range from 5.7 to 7 and therefore illustrate the preservation of moderate-amplitude He isotopic anomalies at very small spatial scale in the upper mantle. In our case, the sampling of this radiogenic He anomaly in EPR MORB is related to the presence of the Mathematician hot spot, which considerably boosts the magmatic budget of the fast-spreading ridge.

Such multi-isotopic variability and preservation are even more remarkable that they are recorded on a fast-spreading ridge system. Indeed, high degrees of partial melting would be expected to homogenize at medium and large spatial scale the mantle geochemical variability observed in MORB. However, high magmatic supply related to fast-spreading ridge system and/or a significant hot spot magma increment should, on the other hand, encourage rapid melt transfer toward the surface and incomplete mixing, which can preserved locally at small spatial scale the mantle heterogeneities. Therefore, we suggest that the most radiogenic He (i.e., ULC-influenced) basalts have sampled a component of the Mathematicians hot spot source. According to this radiogenic He signature and the limited impact of this short seamount chain on the morphology and structure of the ridge (compared to what is observed in primary, deep-rooted hot spot system), this hot spot might be more likely a fertile upper mantle heterogeneity rather than deep mantle plume.

The size of the Mathematicians mantle heterogeneity is difficult to estimate, but according to the morphological and geochemical comparison of the study segment with the adjacent segments, it seems at most limited by the Orozco FZ (15°25′N) and the 16°20′N overlapping spreading centers (~115 km). This heterogeneity is thus likely big enough to be preserved despite long-term diffusion, whereas mesoscales He heterogeneities are rapidly homogenized with the ambient upper mantle, as suggested by the coupled diffusion-production model of Hart et al. [2008]. Therefore, the He isotopic difference between ULC (4He/3He ~ 130,000) and ambient mantle (4He/3HeHe ~ 100,000) components may more likely reflect the time-integrated evolution of two separated mantle reservoirs. This difference can easily be expressed in a simple mantle evolution model that considers He degassing and radiogenic production. Pb isotopes suggest that the source of ULC is ancient, with a minimum age of 2 Ga (i.e., when the production rate of 207Pb was still higher than that of the 206Pb). Evolution of the number of moles of 4He and 3He with age τ can be described by the following equations:

\[
\frac{d^3\text{He}}{d\tau} + \frac{d^4\text{He}}{d\tau} = \phi^4\text{He} - 8\lambda_5 \times 238\text{U}_p e^{-\lambda_5 \tau} - 7\lambda_5 \times 235\text{U}_p e^{-\lambda_5 \tau} - 6\lambda_2 \times 232\text{Th}_p e^{-\lambda_2 \tau}
\]

(1)

Where \(\Delta(\tau)^3\text{He}\) represents the degassing flux of 3He at mid-ocean ridge, \(\lambda_5, \lambda_2\) are the decay constants of 238U, 235U, and 232Th, respectively; 238U-p, 235U-p, and 232Th-p are the present-day concentration and \(\phi\) is the degassing constant of the upper mantle (UM) ~2.2 × 10^{-10} yr^{-1} calculated for 3He = 10^{-10} cc/g in the MORB source, \(\Delta(\tau)^3\text{He}\) = 1000 moles/yr, \(m_{\text{UM}} = 10^{27}\) g, and \(V_m^{\text{He}} = 22,414\) cc/mol. We also assume here that only the upper mantle is degassing. Here as \(\tau\) represents age relative to present and not time, the radioactive production terms are preceded by a minus sign, and the degassing term is positive, whereas it would be the opposite if these equations were written as functions of time.

The evolution of 4He/3He over time \(R(\tau)\) can therefore be written as

\[
R(\tau) = R_p - \frac{8 \times \lambda_5}{\lambda_5 - \phi} \times 238\text{U}_p \left[ e^{(\lambda_5 - \phi)\tau} - 1 \right] + 7 \times \frac{\lambda_5}{\lambda_5 - \phi} \times 235\text{U}_p \left[ e^{(\lambda_5 - \phi)\tau} - 1 \right] + 6 \times \frac{\lambda_2}{\lambda_2 - \phi} \times 232\text{Th}_p \left[ e^{(\lambda_2 - \phi)\tau} - 1 \right]
\]

(2)

\[
R(\tau) - R_p = \left[ 8 \times \frac{\lambda_5}{\lambda_5 - \phi} \left[ e^{(\lambda_5 - \phi)\tau} - 1 \right] + 7 \times \frac{\lambda_5}{\lambda_5 - \phi} \times 137.88 \left[ e^{(\lambda_5 - \phi)\tau} - 1 \right] + 6 \times \frac{\lambda_2}{\lambda_2 - \phi} \left[ e^{(\lambda_2 - \phi)\tau} - 1 \right] \right]
\]

(3)

\[
\frac{U}{(4\text{He}))_p} = \frac{U}{(3\text{He})_p}
\]

where \(R_p\) is the present-day He isotopic ratio.

Based on Mougel et al. [2014] trace element data, the U content was estimated at ~12 ppb for both ULC and AM, considering 20% and 10% partial melting for pyroxenitic ULC and peridotitic AM, respectively. The mean K ratio (Th/U) in AM-influenced samples is 3.0 and that in ULC-influenced basalts is 2.7. The
results of this modeling presented in Figure 3 suggest that the most radiogenic He mantle (ULC) was likely more degassed by a factor of 1.72. Note that this is a minimum value. Indeed, as we do not have access to the true compositions of these two end-members, we approximate them by using the extreme values of the mixing line defined by our data set (For example, f value would increase by 0.027 by % of ULC increase). However, this hypothesis seems, therefore, compatible with the recycling of ancient lower crust material (i.e., sulfide-bearing pyroxenites) already suggested for ULC’s origin by Mougel et al. [2014]. In agreement with this scenario, we speculate that this fractionation may have occurred during the formation of pyroxenites in the deepest part of mature continental magmatic arc [Lee et al., 2012]. Since cumulates of the lower continental crust are affected by metamorphic processes during the thickening of the root, they are likely degassed during their transformation into pyroxenites, thus increasing the U/3He ratio. Moreover, as Pb is chalcophile but not U, the formation and recycling of these sulfide-rich metamorphic rocks will also affect the Pb composition of ULC (U/Pb decrease). The model presented here is capable of reproducing a difference of 30,000 in the 4He/3He ratio of heterogeneous upper mantle material sampled by EPR. This is achieved by early (~2 Ga) fractionation of U/3He and U/Pb ratios (induced by pyroxenites formation) followed by a continuous degassing of the upper mantle and radiogenic isotope production. This model is also consistent with the negative correlation between Pb and He isotopes observed in our data. Huang et al. [2014] have recently suggested that such cumulates would be more likely characterized by unradiogenic He. Indeed, they have proposed that He would be soluble enough in sulfide melts and trapped as inclusion in cumulates that would therefore end up enriched in He (relative to U and Th, supposed insoluble in sulfides), forming a low 4He/3He reservoir associated with unradiogenic Pb. Nevertheless, the negative correlation between He and Pb isotope ratios in our data indicates that such continental material could be, on contrary, radiogenic in helium, suggesting that it has a high U/3He ratio. Therefore, analyzing the geochemical composition of such sulfide inclusions and continental cumulates is both valuable and necessary to understand and estimate its impact on mantle-derived melts.

6. Conclusion

Despite large melting and mixing processes induced by the high spreading rate of the ridge, MORB from along a 15 km along EPR between 15°37’N and 15°46’N reflect a particularly heterogeneous mantle domain. This segment is affected by the Mathematician seamount source, which increases the ridge’s magmatic activity as well as its MORB geochemical diversity. In conjunction with Pb isotope data, He isotopes define an atypical trend for oceanic basalts. 4He/3He ratio correlates negatively with Pb isotope ratios, in opposition to what is observed in both the Pacific and Atlantic oceans. Furthermore, samples are characterized by radiogenic He associated with unexpectedly unradiogenic Pb that reveals the existence of an atypical high 4He/3He mantle heterogeneity below the EPR. The disparity in He isotopic compositions between the ambient upper mantle and this radiogenic component can be explained by a 2 Ga time-integrated evolution of the two distinct mantle reservoirs, after a slight (U + Th)/3He fractionation, most likely due to the degassing of deep continental arc material.
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