Trace element evidence from seamounts for recycled oceanic crust in the Eastern Pacific mantle

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Abstract

We present trace element data for 80 samples from about 50 seamounts in the east equatorial Pacific near the East Pacific Rise. These data indicate that the heterogeneous mantle source that supplies the seamounts consists of two components: (1) an extremely depleted component, much more depleted than estimates of the source of depleted MORB; and (2) an enriched component even more enriched than average OIB. The depleted component shows large variations in Zr/Hf, Nb/Ta, Rb/Cs, Ce/Pb, and Th/U that are correlated with each other and with La/Sm, indicating that these paired elements do fractionate from each other in some oceanic basalts. The order of incompatibility of trace elements we find differs slightly from that found elsewhere. For example, for seamounts, we find that D_{Nb} < D_{Th} < D_{Ta} < D_{U}. In comparison with Th and U, the enriched component shows anomalous enrichments of Ta and Nb. Since such fractionations are characteristic of subduction zones, we suggest that the most likely ultimate source of the enriched component is recycled ocean crust.

Keywords: seamounts; East Pacific Rise; basalts; trace elements; mantle source heterogeneity; oceanic crust recycling

1. Introduction

Isotopic and trace element studies of oceanic basalts provide fundamental constraints for models of earth’s differentiation and convection processes (e.g. [1–7]). It is generally thought that mid-ocean ridge basalts (MORB) are derived from a mantle source that was depleted early in earth history to produce the continental crust. Hofmann and colleagues [3,8] argue that this early differentiation event resulted in a relatively homogeneous mantle, from which the depleted source for MORB and the more enriched source of Ocean Island Basalt (OIB) were then produced over a long period, principally by the subduction of oceanic crust [9].

Data from oceanic basalts have led to the identification of several distinct mantle reservoirs and components [1], whose origin and significance is actively debated [5,10,11]. In addition to lavas from mid-ocean ridges and large hotspot volcanoes, samples from small seamounts near the East Pacific Rise have previously provided useful windows to the sub-oceanic mantle (e.g. [12–14]). These studies, and others, have shown that near-axis seamounts are geochemically more diverse than basalts erupted at the axis. Despite the greater diversity of seamount lavas, reflecting heterogeneity of the mantle source, the mean composition of seamount lavas is very...
similar to axial MORB, after considering the fact that seamount lavas are generally more primitive, with higher abundances of MgO [15].

In this paper, we present new trace element data for about 50 near-ridge seamounts near the East Pacific Rise between 5° and 15°N. The samples are a subset of those previously studied [15]. Our results confirm that seamount lavas in this part of the Pacific are extremely heterogeneous but can be readily explained by melting of a mantle source consisting of two components, one enriched in incompatible elements and the other depleted in incompatible elements. The geochemical consequence of melting such a source is to produce the apparent mixing relationships in the melts between the two components.
### Table 2

Major and trace element analyses of glass samples from near-Ridge seamounts, 5°N–15°N EPR

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>Lat/Lon</th>
<th>Sampling Depth</th>
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<th>Type</th>
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<th>Elements</th>
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<td>LI</td>
<td>XRF</td>
<td>Mg, Fe, Mn</td>
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<td>140°</td>
<td>235</td>
<td>R17</td>
<td>LI</td>
<td>XRF</td>
<td>Mg, Fe, Mn</td>
<td>473</td>
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<tr>
<td>5°N</td>
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<td>Mg, Fe, Mn</td>
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<tr>
<td>15°N</td>
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<td>175°</td>
<td>266</td>
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<td>XRF</td>
<td>Mg, Fe, Mn</td>
<td>473</td>
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</table>

**Note:** The table includes major and trace element analyses of glass samples from near-Ridge seamounts, with locations ranging from 5°N to 15°N EPR. The sampling depths vary from 200 to 266 meters, and the analytical methods used are XRF (X-ray fluorescence) for Mg, Fe, and Mn. The concentrations are recorded in parts per million (ppm).
Table 2 (continued)

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Electron microprobe analyses (wt. %)

| Anal. | Component | Mass %
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<tr>
<td>FeO</td>
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<tr>
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<td>MnO</td>
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</tr>
<tr>
<td>P2O5</td>
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<tr>
<td>Total</td>
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kg

1.03

1.04

471–483
Table 2 (continued)

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<th>R71-2</th>
<th>R72-2</th>
<th>R73-1</th>
<th>R74-6</th>
<th>R75-2</th>
<th>R76-2</th>
<th>R77-9</th>
<th>R80-1</th>
<th>R81-1</th>
<th>R82-1</th>
<th>R83-1</th>
<th>R84-8</th>
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<td>103.85</td>
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<td>103.64</td>
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Discouraged.
Sample locations are Lat. latitude in degrees north; long. longitude in degrees west; and depth in meters below sea level. Major element analyses were done using the electron microprobe at the University of Hawaii analyst: Y. Niu; all these data were normalized to a Smithsonian MORB glass reference standard VG-2, whose working values SiO$_2$, 50.57 wt%; TiO$_2$, 1.85%; Al$_2$O$_3$, 14.06%; FeOt, 11.59%; MnO, 0.22%; CaO, 11.12%; Na$_2$O, 2.63%; K$_2$O, 0.19%; and P$_2$O$_5$, 0.20%) were agreed upon by Jill Karsten, Emily Klein, and Yaoling Niu in 1993. FeOt is total Fe expressed as Fe$^{3+}$. Mg$^{2+}$ = Mg/100 with 10% total Fe as Fe$^{3+}$. Trace element analyses were done using a PQ2 Inductively-coupled Mass Spectrometer at The University of Queensland analyst: Y. Niu. The samples are fresh glass chips of 0.5±1.0 mm size hand picked under a binocular microscope. See the notes to Table 1 for sample preparation procedures and run conditions.
[12, 16–18], which may be termed melting-induced mixing [18]. We place constraints on the nature of the two components: (1) an extremely depleted component, exhibiting highly variable but correlated differences in Zr/Hf, Nb/Ta, Th/U, Rb/Cs and other ratios that generally show little variation between
MORB and OIB; and (2) an enriched component with relative enrichments of high-field strength elements (HFSE), such as Nb, Ta, Zr, and Ti. We argue that the enriched component is derived from subducted and recycled oceanic crust [6]. Cousens [19] has recently made a similar proposal to explain the enriched component present in the mantle below the northeast Pacific. Our data show that, at least in this part of the Pacific mantle, even the most depleted seamount and EPR MORB samples are affected by this enrichment process because the depleted end-member is much more depleted than any available lava samples.

2. Data and methods

We analyzed 80 seamount basalt glasses, rock standards, and blanks for trace elements by ICP–MS. Table 1 gives data for the standards and blanks and describes our sample preparation and analytical procedures. Table 2 gives major and trace element analyses of our samples. Major elements were determined on fresh glasses by electron microprobe [15] and trace elements were determined by ICP–MS at the University of Queensland.

3. Results

Fig. 1 shows sample locations and Fig. 2 shows a plot of the trace element data normalized to primitive mantle [3,5]. Also shown are estimates of average continental crust [20], OIB, and both normal (N-type) and enriched (E-type) MORB [5]. The samples exhibit a huge range of variation, from OIB-like lavas to extremely depleted samples. The depleted samples are similar to the most depleted MORB recovered from the EPR (e.g. [21]) and are more depleted than samples from the Lamont Seamounts near 10°N [14].

![Diagram](image_url)
The order of incompatibility shown in Fig. 2 differs slightly from the order conventionally used by others [3,5]. To determine the order, we used ratio-element plots of the type shown in Fig. 3. Plots such as these can confidently be used to infer which element of the plotted pair is more incompatible [8,22]. The fact that we find a slightly different order of incompatibility is perhaps not surprising, because

As found previously, both enriched and depleted samples may occur on the same seamount and we find no systematics to the geographic distribution of enriched and depleted samples. Enriched samples occur on seamounts as close as 4 km from the axis of the EPR.

Fig. 3. Plots of Zr/Hf vs. Zr and Nb/Ta vs. Nb for the seamount data. Note that these data indicate that $D_{Zr} < D_{Hf}$ and $D_{Nb} < D_{Ta}$. Similar plots were used to determine the order of incompatibility shown in Fig. 2. Note the wide variation of element ratios, these generally show very limited variation (shaded band) in oceanic basalts.

Fig. 4. Plots of various highly and moderately incompatible element pairs (Ta/Ho vs. Li/U; Ta/Hf vs. Ho/Th; Nb/Hf vs. P/Pr; Nb/Sm vs. Zr/Rb) to show that the seamount lavas can be explained by melting-induced two-component mixing; that is, the consequence of melting a two-component mantle source [12,13,16–18]. Note that the hyperbolae are not synonymous with binary mixing of two singular melts [23,24], since the seamounts are geographically dispersed. These hyperbolic plots constrain the nature of the mixing end-members. The depleted end-member is more depleted than previously proposed compositions of depleted MORB mantle. The enriched end-member cannot be average continental crust. We suggest that it is recycled ocean crust with a prior history of subduction-related melting [6].
this order is expected to vary with tectonic setting, differences in mantle sources and differences in the melting process [5]. The most significant differences we find in the order of incompatibility are in the relative incompatibility of Nb, Th, Ta, and U. We find that, in this part of the Pacific mantle, $D_{Nb} < D_{Th} < D_{Ta} ≈ D_{U}$. Note that the patterns in Fig. 2 are quite smooth, showing that the order of incompatibility that we use is indeed appropriate for this sample set.

As shown in Fig. 4, the trace element variations are apparently the result of melting-induced two-component mixing. We have made plots using dozens of different ratios and all are consistent with such two-component mixing. The mixing curves can be linear or hyperbolic [23, 24] on ratio–ratio diagrams, depending on the differences in relative incompatibility between the two elements in the numerator and in the denominator. The hyperbolic plots, however, constrain the nature of the mixing end-members. The depleted component is extremely depleted. A conservative estimate gives: $Zr/Hf ≤ 25$, $Nb/Ta ≤ 10$, $Th/U ≤ 1.5$, $Nb/U ≤ 20$, $Rb/Cs ≤ 20$ and $Ce/Pb ≤ 15$. On the other hand, the enriched end-member is more enriched than average OIB and resembles average continental crust (CC) in many ways. However, it is clear from Fig. 4 and other plots involving Ta and Nb, that CC cannot be the enriched end-member, being far too depleted in these elements.

Fig. 2 shows that the negative anomalies of Ta, Nb, Zr and other HFSE seen in CC are matched by positive anomalies in our samples. This is especially clear for Ta and Nb. Further, the positive anomalies grow larger with progressive enrichment. This is also shown in Fig. 5, indicating qualitatively that the Ta and Nb missing from continental crust may reside in the mantle source of oceanic basalts [4–6], particularly in an enriched component.

As shown in Fig. 3, our samples show relatively large variations in $Zr/Hf$ (28–49). This is also true for $Nb/Ta$ (10–18), $Rb/Cs$ (8–98), $Ce/Pb$ (10–44), $Th/U$ (1.4–3.8) and other element ratios (Fig. 6) that are generally constant for oceanic basalts [8, 22, 25–28]. Variations of this type were found previously in intraplate basaltic rocks [29]. Further, variations in these ratios show good correlations with each other ($R = 0.7–0.8$) and with $La/Sm$. This finding indicates that these element pairs have fractionated from each other, either during formation or modification of the depleted mantle source, or during melting to produce seamount magmas.

To gain insight into the nature of this process, we plot the variability of each element for seamount and EPR axis basalts. Fig. 7 shows that the relative variability of the elements varies rather smoothly with their order of incompatibility, as previously found for other suites [8, 30]. Furthermore, the patterns are the same for seamount and axial lavas. This observation provides strong evidence that the process leading to the observed correlated fractionations in $Zr/Hf$, $Nb/Ta$, $Rb/Cs$, $Ce/Pb$, $Th/U$, $La/Sm$ and other ratios is a melting process [30]. Additional evidence for this comes from a plot of our data similar to Fig. 2, but with the data normalized to the most depleted seamount sample. This plot (not shown) indicates very smooth and regular increases in incompatible element abundances in progressively enriched samples.

4. Discussion and conclusions

The data presented above shows that the mantle sampled by near-EPR seamounts in the east Equato-
Material Pacific consists of two end-members: an extremely depleted one, much more depleted than estimates of the depleted MORB mantle [1,2,5,7], and a highly enriched component derived from a source with anomalous enrichments of Nb and Ta relative to Th and U. These end-members are mixed in various proportions prior to or during melting to produce seamount magmas. Physically, these heterogeneous mantle domains must be rather small, perhaps on the order of several hundred meters, in order to explain the great diversity seen in the lavas of single seamounts. It seems reasonable that the enriched component represents highly localized dikes or veins, as previously proposed (e.g. [11,13,16,31]).

Important clues about the origin of the enriched component are its enriched nature and its enrichments of Nb and Ta relative to Th and U. It is widely believed that fractionation of Nb and Ta from Th and U occurs only in subduction zones, although the mechanism is controversial [6,32–34]. There appears to be wide agreement that, whatever the reason for the relative HFSE-depletion of arc magmas, it is likely that there is a complementary enrichment in other reservoirs, such as subducted hydrous ocean.
Fig. 7. Relative variability of trace element abundances in seamount samples (this study) and nearby axial samples from the East Pacific Rise (Niu and Batiza, unpubl. data for EPR samples from 9°–10°N, 11°–20°N, and 13°–14°N) plotted against their order of incompatibility, as in [8, 30] (Fig. 2). Relative variability is essentially a measure of the mixing contribution from the enriched and depleted end-members. Note the smooth variation for seamount samples and the similar trend shown by the axial samples. We interpret this smooth variation as indicating that element fractionations such as those seen in Fig. 5 are the result of a magmatic (melting) process.

If so, then one possibility is that this enriched material has simply been mixed into the upper mantle below the east Equatorial Pacific by convective processes (e.g. [35]). Once mixed with depleted mantle, upwelling could cause small amounts of melting and these melts could be dispersed as highly mobile, metasomatic fluids (e.g. [18]), possibly in the low-velocity asthenosphere [36]. We favor this scenario because recent mantle convection models favor only episodic mixing between the upper and lower mantle (e.g. [37]) and because the apparent absence of other enriched components in the east Equatorial Pacific does not suggest a well-stirred, multi-component blend [7]. In addition, the small size scale of the heterogeneities and the absence of larger-scale geographic gradients in trace element abundances in the area both suggest wide, but ‘spotty’ dispersal, consistent with a metasomatic or low-degree melt origin.

In conclusion, the new trace element data we present provide strong evidence for the involvement of recycled ocean crust in the east Equatorial Pacific mantle source of seamount lavas. These data also provide additional evidence [6] that the missing Nb and Ta in continental crust reside in the mantle source of oceanic basalts.

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References

[5] S.-s. Sun, W.F. McDonough, Chemical and isotopic system-


