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Extreme Mantle Source Heterogeneities Beneath the Northern East Pacific Rise Ñ Trace Element Evidence From Near-Ridge Seamounts

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Abstract

In this paper the authors summarize the results of their trace element study of lavas from 50 near-ridge seamounts on the flanks of the East Pacific Rise (EPR) between 5ûN and 15ûN. These seamount lavas are dominated by depleted N-type mid-ocean ridge basalts (MORB) with variably enriched E-type MORB and some extremely enriched ones resembling average compositions of ocean island basalts (OIB). This large compositional variation reflects with great fidelity the mantle source heterogeneity that is masked in lavas erupted at the EPR axis. In terms of incompatible trace element abundances, this source heterogeneity can be readily envisioned as being due to the presence of enriched domains of variable size and unevenly distributed within the ambient depleted mantle. The geochemical consequence of melting such a heterogeneous source is to produce apparent mixing relationships in the lavas. The enriched domains may be dikes or veins resulting from low-degree melt metasomatism. The low degree melts may be genetically related to eastward asthenospheric flow of Hawaii plume materials towards the EPR, as suggested by mantle tomographic studies. Trace element data suggest that the enriched materials (hence Hawaii plume materials) are ultimately derived from recycled oceanic crust.

Keywords: seamounts, East Pacific Rise, basalt, trace elements, mantle source heterogeneity

INTRODUCTION

Plate tectonics theory has established that mid-ocean ridges are mostly a passive feature in the sense that mantle upwelling beneath ridges is caused by plate separation [1-3]. Mid-ocean ridge basalts (MORB), which represent an end product of pressure-release melting of the upwelling mantle, thus record the geochemical signatures of the uppermost mantle. In comparison with basalts from elsewhere in the oceanic or continental volcanic provinces, MORB as a whole show remarkably small geochemical variations characterized by low abundances of incompatible elements, low radiogenic Sr and Pb, and high radiogenic Nd [4-8]. These observations have led to the notion that oceanic upper mantle is relatively uniformly depleted in incompatible elements; it has been designated as depleted MORB mantle (DMM) [5]. Nevertheless, the DMM is by no means compositionally uniform [9], even from ridges thermally unaffected by any known hotspots such as the East Pacific Rise (EPR) [10-19]. In fact, studies of near EPR seamounts revealed small scale yet large

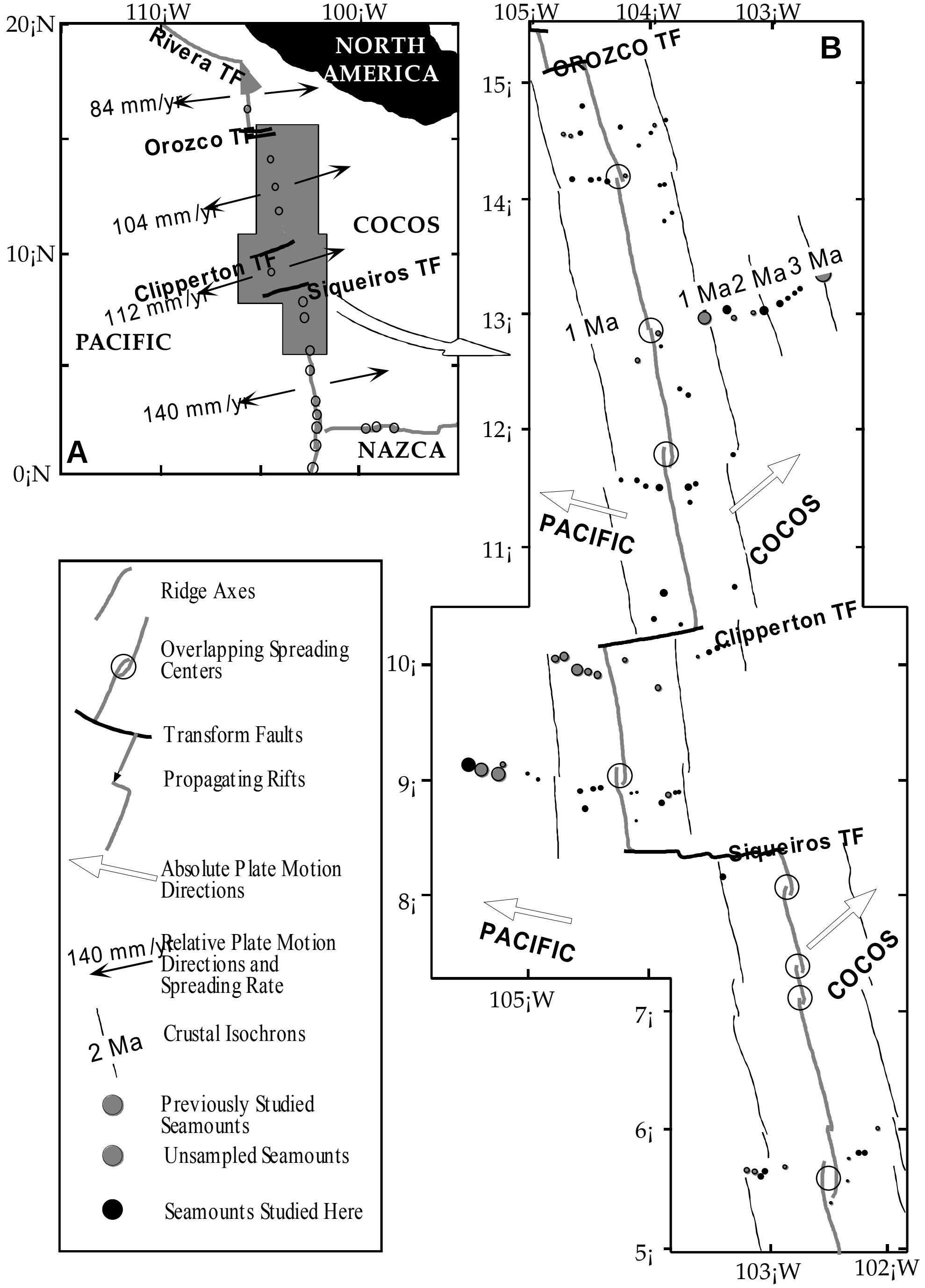

Figure 1. (a) The general tectonic framework of the northern East Pacific Rise and the vicinity. (b) A simplified map of the study area showing the locations of the near-ridge seamounts we studied.

amplitude compositional variations in the sub-EPR mantle [20-24]. In this paper we extended these studies based on our newly available trace element data on lavas from 50 near-EPR seamounts between 5ûN to 15ûN on both the Pacific and Cocos plates (Fig. 1). We first show that these seamount lavas span extreme compositional variations with extents of depletion and enrichment surpassing the known range of lavas from the seafloor. We then discuss the implications of the data in the context of mantle convection and ocean ridge dynamics.

RESULTS

Figure 2 shows chondrite-normalized rare-earth element (REE) abundances of the seamount lavas. The average continental crust (CC), ocean island basalts (OIB), and both enriched E-type and depleted N-type MORB are plotted for comparison. Clearly, these seamount lavas display a considerably large range of variations from extremely light-rare-earth-element (LREE) depleted samples to highly LREE-enriched basalts resembling the average OIB. Except for the few highly evolved samples (MgO < 6 wt. %; the dashed lines), the majority of the samples define a fairly simple fan-shaped pattern with more depleted samples being more depleted in the more incompatible elements and the more enriched samples having higher abundances of the more incompatible elements. The depleted samples are more depleted than samples from the Lamont Seamount chain near the 10ûN (Fig. 1) [24]. No doubt, such a huge variation can only be explained by melting a mantle that is extremely heterogeneous. Figure 3 plots $[La/Sm]_{CN}$, a useful measure of the extent of source depletion or enrichment, as a function of latitude (top) and longitude (bottom) of sample locations (Fig. 1) to show that mantle source enrichment/depletion has no geographic systematics. In fact, both enriched and depleted samples can be found on the same seamounts. This indicates that the scale of the

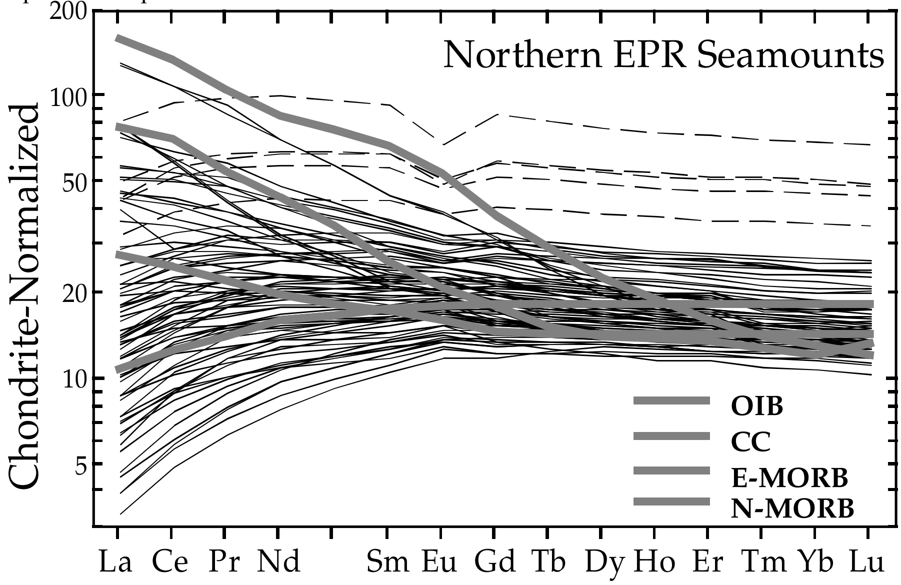

Figure 2. Chondrite-normalized rare-earth element abundances of seamount samples. Also shown are average compositions of Ocean Island Basalt (OIB), enriched E-MORB, depleted N-MORB [8], and continental crust (CC) [63] for comparison.

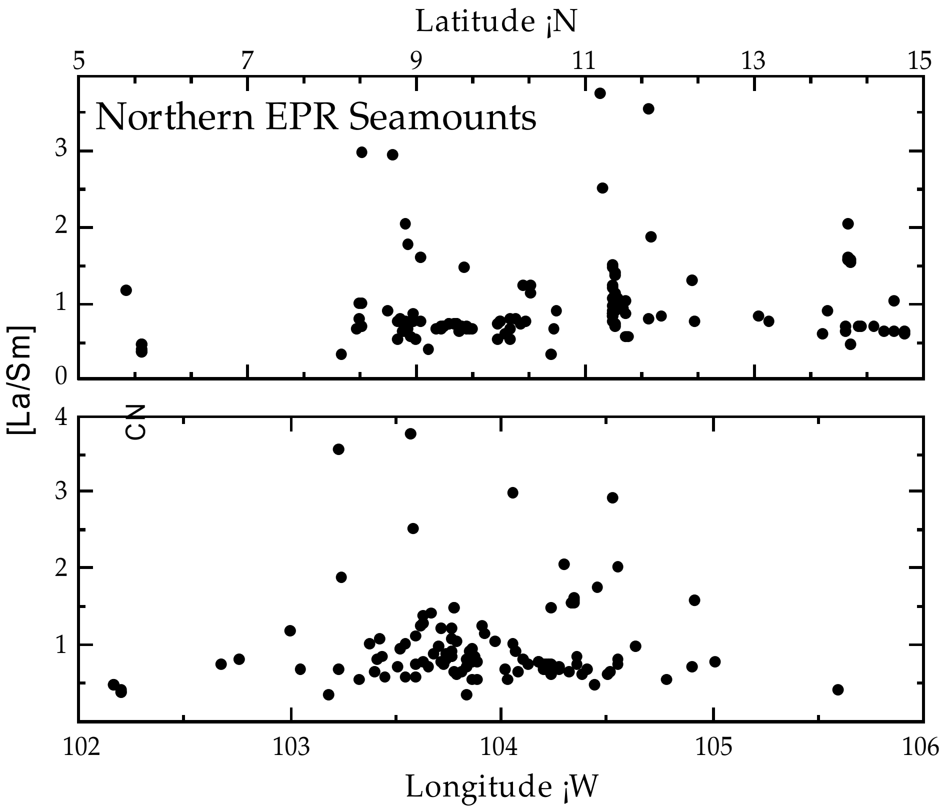

Figure 3. Chondrite-normalized [La/Sm]$_{CN}$ ratio of seamount samples are plotted as a function of latitude (top) and longitude (bottom) of seamounts studied. Clearly, the lack of systematic geographic variation, and the fact that both highly depleted and enriched lavas can be found within small areas or even single seamounts, indicates that the scales of source heterogeneities are quite small and that their distribution is spatially not uniform.

heterogeneities may be very small, perhaps on the order of 100Õs of meters or even smaller.

Figure 4 shows the relative variability [6] of each element for the seamount lavas. The decreasing variability is in fact consistent with decreasing relative incompatibility (or increasing bulk distribution coefficient, D) of these elements determined by the simple relationship shown in the inset [25]. This indicates that the large compositional variation in these lavas as well as the inferred source variation are the result of magmatic processes. The processes leading to such small scale yet large amplitude variation in the mantle source region may be examined closely through incompatible element ratio-ratio diagrams such as those in Figure 5. These hyperbolic curves are consistent with a binary mixing [26-27], and are also qualitatively consistent with various extents of melting given the relative incompatibility of these paired elements (Fig. 4). That is, qualitatively, samples plotting in the upper left corner represent the lowest extents of melting whereas samples in the lower right corner represent the highest extents of melting in these diagrams. It is important to note, however, that melting of a compositionally uniform source, alone, cannot explain the large amplitude variations. Further, this mixing cannot be simple binary mixing of melts because the lavas are from 50

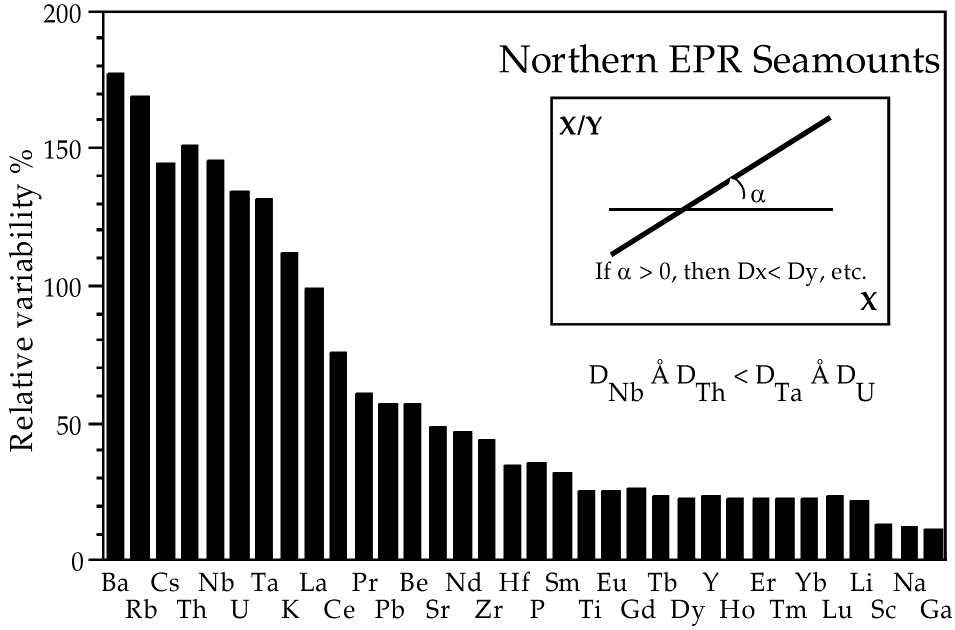

Figure 4. Relative variability of trace element abundances in seamount lavas plotted against their order of incompatibility determined by the simple relationship in the inset [25] to show the excellent correspondence between the variability and the incompatibility of elements. This indicates that the process leading to the observed trace element variations are partial melting.

different seamounts of varying ages and it is difficult to imagine the physical mixing of two singular melts over such a wide spatial and temporal interval. The curved trends in Figure 5 can be readily explained by melting a mantle that is compositionally heterogeneous via melting-induced mixing [28]. Enriched materials have lower melting temperature and thus tend to enter the melt first upon melting [21,29]. With progressive melting, the amount of the enriched material in the melt decreases as a result of dilution. Therefore, the geochemical consequence of melting of a heterogeneous mantle source is to produce the apparent mixing relationships seen in Figure 5. The important message here is that the apparently complex source heterogeneity reflected by the seamount lavas is in fact rather simple and can be explained by the presence of incompatible element enriched domains of variable size distributed widely but unevenly in the ambient depleted MORB mantle.

DISCUSSION

Why do near-ridge seamount lavas show larger geochemical variations than MORB lavas from the ridge axis?

The geochemical variations of northern EPR axial lavas have been well documented [10-19, 28, 30-32]. These variations are significantly smaller in amplitude than those seen in the nearby seamounts (Fig. 2). This difference can be explained by the action of two well-documented mixing processes that occur beneath the ridge axis but not under seamounts. First, MORB from the ridge axis represents melting of a large volume in the mantle. Melt

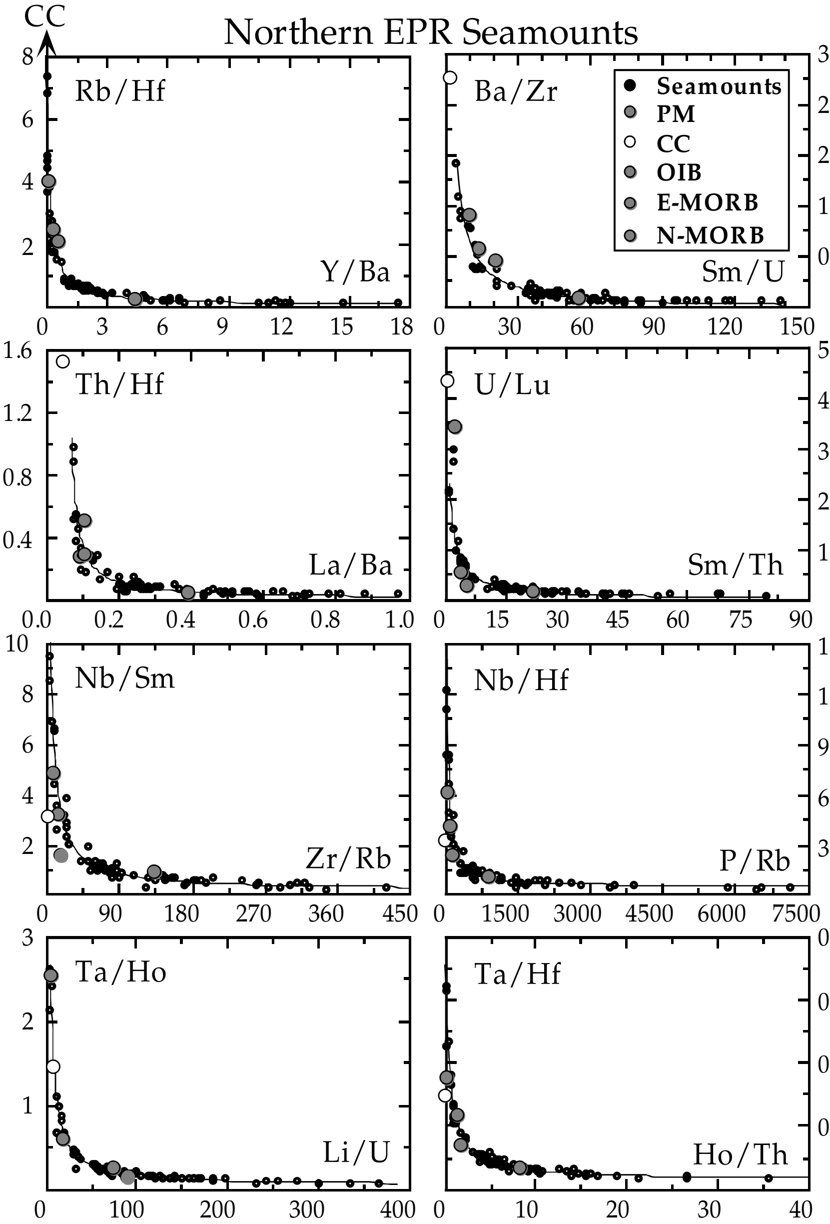

Figure 5. Plots of various highly and moderately incompatible element pairs to show that the seamount data can be explained by melting a source that has two reasonably uniform components: an enriched component and a depleted endmember. The hyperbola are due to melting-induced mixing, not mixing of two melts. For comparison, average continental crust (CC) [63], primitive mantle (PM), OIB, and both E- and N-MORB [8] are also plotted.

migration and focussing towards the very narrow (1-2 km) axial accretion zone [33] are an important mixing process that homoginizes melts moving upwards and laterally towards the axis. Secondly, additional mixing occurs in axial magma chambers that exist along much of the EPR axis [33-35] further homoginizing the melt prior to eruption [20-21, 23, 28, 30, 32]. In contrast, off-axis seamounts represent much smaller melt volumes tapped locally [20-21, 23, 28, 30, 32, 36-37], and lack steady-state magma chambers. Because they are much less efficiently mixed, seamount lavas reflect with greater fidelity than axial lavas the actual mantle source heterogeneity beneath the EPR.

Characteristic of the enriched heterogeneity

The above observations place three limits on the enriched heterogeneities: (1) the observed mixing is a melting-induced mixing, i.e., the enriched heterogeneities exist as physically distinct domains in the ambient depleted mantle prior to the major melting events (Fig. 5); (2) the sizes of the enriched heterogeneities must be variably small, and their distribution is not uniform (Fig. 3); and (3) the enriched heterogeneities must be of low-degree melt origin because the enriched samples have higher abundances of more incompatible elements (Fig. 2) and the relative abundance variability of trace elements is proportional to their relative incompatibility (Fig. 4). These observations, taken together, suggest that the enriched heterogeneities exist in the immediate source region in the form of small dikes or veins [28, 38-39]. The small sizes of the enriched heterogeneities are required to explain the coexistence of both depleted and enriched lavas within geographically small areas (Fig. 3) such as single seamounts [20-24, 28, 36-37]. The question yet to be answered is the origin of the low-degree melts that we suggest to occur in the form of dikes or veins. From trace elements alone (Figs. 2 and 5), it is obvious that the enriched component is broadly similar to the source for OIB, but the apparent absence of any known hotspots in the northern EPR region requires another mantle process, in addition to simple passive upwelling, to effectively transport plume materials to the sub-ridge mantle beneath the northern EPR.

Where does the plume material come from and why are the enriched heterogeneities beneath the EPR of wide but spotty dispersal?

The presence of enriched plume-like material beneath the northern EPR region has been puzzling because there are no known hotspots in this broad EPR region. However, recent mantle tomographic studies [40-41] show that lateral asthenospheric flow of plume materials towards ocean ridges is likely to be a wide-spread phenomenon. Figure 6 shows that indeed there is an obvious low-velocity layer at ~ 100 to 250 km depth beneath Hawaii that extends laterally towards the northern EPR. While the large distance (~ 5500 km) between Hawaii and the northern EPR makes such a link seem doubtful at first glance, large scale lateral flow of asthenosphere (even counter-flow) is apparently required to explain some geoid anomalies [41-42]. If the Hawaiian plume is, in fact, the source of the enriched component in the area of the northern EPR, the great distance of transport helps to explain both the spotty dispersal of the enriched heterogeneities and the absence of any thermal effects of the plume, as seen at ridges located nearer active plumes [43-47]. While large scale melting of plume material may not take place in the course of lateral asthenospheric flow because of little or limited decompression, very low-degree melts of low-melting point components must inevitably form and metasomatize the ambient depleted mantle. We propose that it may be this process that explains the enriched component of the seamount lavas.

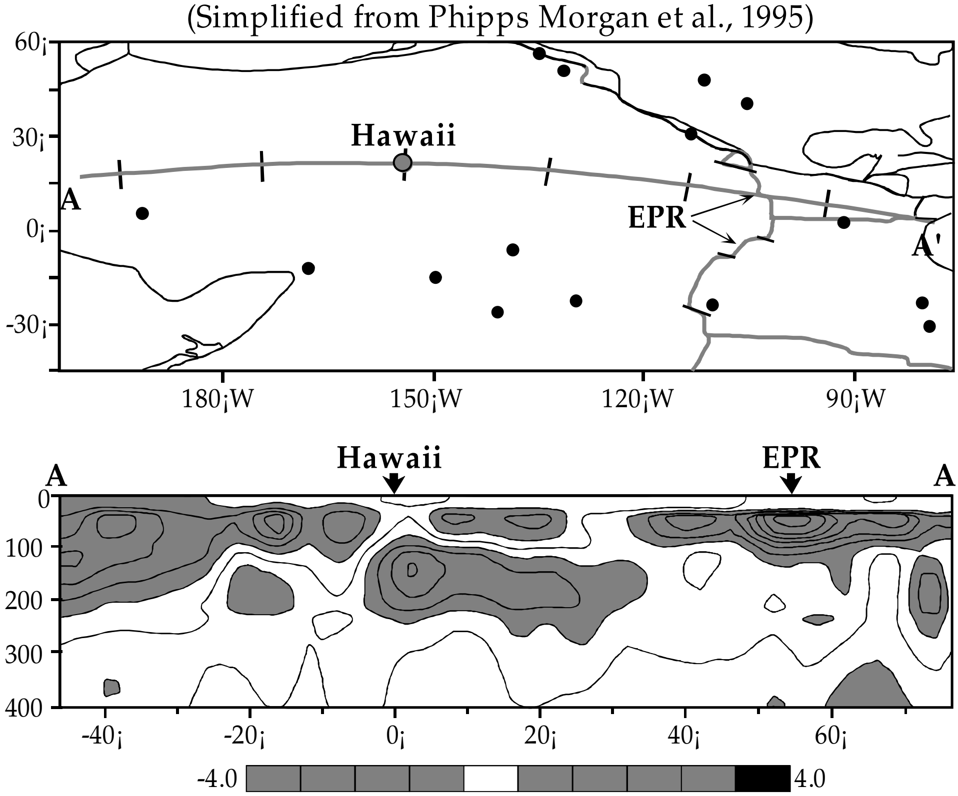

Figure 6. The top panel shows a portion of the global hotspot distribution (solid circles) and below is a vertical cross section of seismic shear velocity anomalies along a great circle path that connects the Hawaii hotspot and the EPR (profile A-A'). Note that there exists a clear low velocity layer at ~ 100 - 250 km depth beneath Hawaii that extends towards the East Pacific Rise to the east. Total velocity variation is ± 4%. Contour lines are at half the shading interval. Taken from [41].

The ultimate source of the enriched component or Hawaiian plume material

It is generally agreed that mantle convection and crustal recycling are the primary mechanisms for creating enriched heterogeneities [48-52] in the deep mantle that rise as plume sources to supply OIB. However the exact location of these OIB reservoirs remains open to debate [5, 25, 53-57]. A curious question is whether our data have sufficient resolution to decipher the ultimate source of the enriched component beneath the northern EPR. A potential clue is provided by the fact that, for seamounts, we find D_{Nb} Å D_{Th} < D_{Ta} Å D_{U} (Fig. 4). That is, mantle melting beneath seamounts (and also the EPR) does not fractionate Nb from Th, nor Ta from U; any Ta and Nb anomalies in lavas must, therefore, be a source signature inherited from previous events. Figure 7 shows that the mantle sources for the seamount lavas possess excess Ta and Nb. Despite the scatter, the data define a significant trend with generally more enriched lavas having higher excess Ta and Nb than depleted lavas. Several important implications of Figure 7 are (1) the missing Nb and Ta in the continental crust clearly must reside in the mantle source for oceanic basalts, and there is

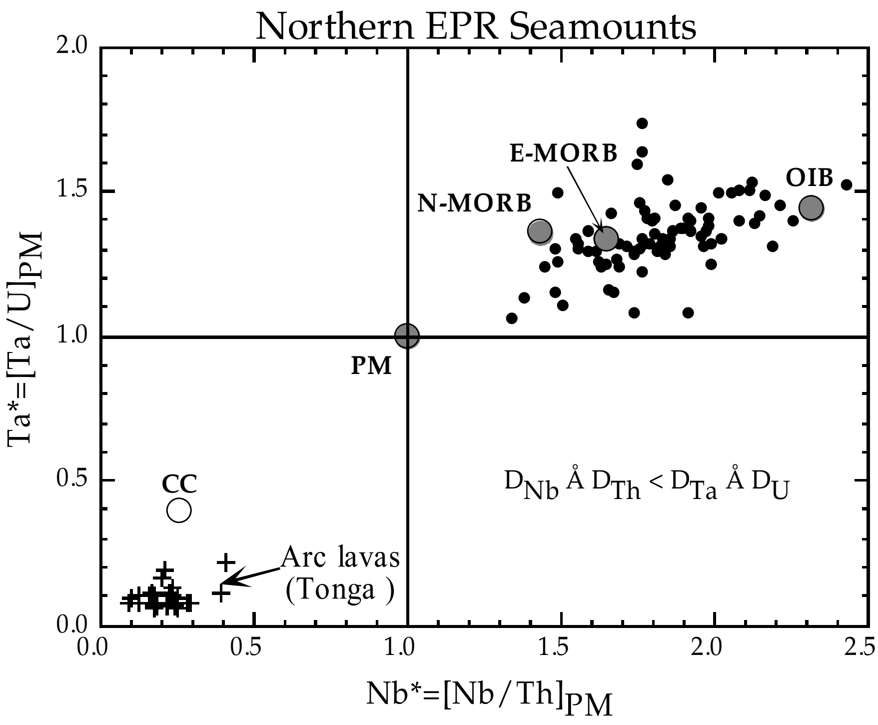

Figure 7. Ta* versus Nb* for the near-EPR seamount lavas. Average continental crust (CC) [63], primitive mantle (PM), OIB, and both E- and N-MORB [8], and unpublished Tonga arc lava data of A. Ewart are also plotted for comparison. Given the D_{Nb} Å D_{Th} < D_{Ta} Å D_U relationship during mantle melting beneath the ridge, the excess Ta and Nb in oceanic basalts are inherited from their sources.

no need to invoke a hidden Nb-Ta rich reservoir deep in the mantle [7,58]; (2) recycled continental crust material is unlikely to be significant in the source region of the oceanic basalts, being too depleted in Nb and Ta; (3) as subduction zone related arc magma genesis is the only known process that fractionates Nb from Th, and Ta from U (e.g., see Tonga arc lavas), it appears clear that subduction-zone processes must also be responsible for the excess Ta and Nb in the source region of oceanic basalts; and (4) recycled oceanic crust is, therefore, most likely the ultimate source of Hawaiian plume material (e.g., the Koolau volcanics, which also possess excess Nb relative to Th [59-60]) as proposed previously [6-7, 61], and hence the enriched component beneath the northern EPR. Nb and Ta may not partition into aqueous fluid removed from the down-going slab as effectively as the low field strength elements, resulting in their relative enrichments in subducted materials [7-8, 58, 62].

CONCLUSIONS

Near-EPR seamount lavas are compositionally quite variable, reflecting with great fidelity of mantle source heterogeneity that is not so obvious in the nearby EPR axial lavas. This heterogeneity is characterized by the presence of incompatible element enriched domains of variably small size non-uniformly distributed within the ambient depleted mantle. The enriched domains most likely exist as dikes or veins resulting from low-degree melt "metasomatism". These low-degree melts may have been derived from Hawaiian plume materials that flow at the asthenospheric level towards the northern EPR. The remote distance between Hawaii and the EPR explains both normal (thermally unaffected) EPR topography and the wide but spotty dispersal of the enriched heterogeneities present beneath the EPR. The observation that D_{Nb} Å $D_{Th} < D_{Ta}$ Å D_U and the excess Nb-Ta relative to Th-U in the seamount lavas suggest that the ultimate source of the enriched material (i.e., the source of Hawaii plume) is likely to be recycled oceanic crust.

Acknowledgments

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