Hf-Nd isotope variation in Mariana Trough basalts: The importance of "ambient mantle" in the interpretation of subduction zone magmas

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ABSTRACT

In the study of geochemical mass balances at subduction zones, the composition of the mantle wedge prior to additions from the slab is a critically important yet poorly constrained parameter. Deconvolving the influence of ancient versus modern enrichments is particularly difficult, especially when considering elements that are highly mobile. Here we provide an alternative approach, using less mobile elements, and a filter to remove the effects of recent slab additions. We provide new Hf isotope data for 30 Mariana Trough (MT) backarc basin lavas. Once filtered, Hf and Nd isotope ratios are highly correlated, of Indian mid-oceanic ridge basalt character, and display variations similar to ocean ridges of comparable lengths. The isotopic variability observed in this "ambient mantle" provides a new paradigm for the interpretation of the varied volcanic products of the arc. Thus, shoshonites associated with the northern termination of the backarc basin rift axis reflect the interaction of a subducted sediment melt with an isotopically enriched mantle source. In contrast, the large volcanoes of the Central Island province have a consistent offset in Nd isotope compositions from the MT array resulting from fluid addition. Existing data for smaller edifices in the submarine portion of the arc have larger variations resulting from fluid addition on a more local scale. We suggest that the similar characterization of ambient mantle elsewhere may help to resolve many conflicting geochemical observations in arc lavas worldwide.

INTRODUCTION

The Mariana Arc has long been lauded as an archetypal intraoceanic subduction system far removed from continental influences, with the implication that these magmas should better reveal subduction zone processes. Nevertheless, this subduction system has a protracted history that, although reasonably well understood, is far from simple (e.g., Stern et al., 2003), and complicates the understanding of modern volcanic products.

There is one essential prerequisite for interpreting the chemistry of subduction zone magmas: knowledge of the composition of the underlying "ambient mantle" (Todd et al., 2011) as it existed before modification by fluids or melts from the slab. Ambient mantle should reflect the composition of convecting asthenosphere, similar to that responsible for producing mid-oceanic ridge basalt (MORB) beneath mid-ocean ridges. A MORB-type source nonetheless encompasses a wide compositional range over several scales, from more to less depleted, and from Pacific to Indian type. Similarly, the natural variability of ambient mantle must be understood if realistic and useful models are to be generated. We have demonstrated previously that comparing individual arc chemistries with global MORB databases can fail to identify many of the subtleties of the subduction zone phenomenon (Woodhead et al., 2001). A better estimate of the ambient mantle should come from backarc basin magmatism as this may provide the best opportunity to characterize the local mantle wedge "baseline" upon which subsequent processes operate. High field strength elements (HFSEs) lend themselves to such study, the element Hf being particularly useful. Here we provide new Hf isotope data for a suite of samples from the Mariana Trough (MT), the active backarc basin associated with the Mariana Arc, and use these results to "see through" the effects of modern subduction influences and to define the compositional variability of this "ambient mantle". See the GSA Data Repository[1] for full details of the samples studied and analytical methodologies.

PEERING THROUGH THE SUBDUCTION VEIL

Geochemical Filters

Increasingly, evidence suggests that components derived from the subducting slab often influence the chemistry of melting products in backarc basin seafloor spreading regimes. This phenomenon has been well documented for the MT (e.g., Stolper and Newman, 1994; Gribble et al., 1996) but also appears to be an important process in all backarc basins characterized by seafloor spreading (e.g., Taylor and Martinez, 2003). These signatures are observed in magmas erupted in areas remote from older, rifted, arc lithosphere and thus appear to be linked to present-day subduction fluxes (e.g., Gribble et al., 1996).

Studies of MT magmas (e.g., Gribble et al., 1996, 1998; Kelley et al., 2006) suggest that the mantle source has been pervasively influenced by subduction zone fluids carrying, at least, the large ion lithophile elements such as Ba. The evidence for melts of subducted sediments, carrying nominally fluid-immobile incompatible trace elements, such as Th, is more limited. In this study we apply two geochemical filters to the MT data set, employing the Pearce et al. (2005) elemental proxies for subduction influences. The first removes all but those samples that formed by true seafloor spreading (i.e., all but those south of 20°N. This is equivalent to applying a Th/Ta filter (only retaining samples <3) to remove all basalts exhibiting a deep subduction influence (sediment melts; see the Data Repository). We then apply a further filter based upon the Ba/Nb ratio that Pearce et al. (2005) identify as a proxy for a "total subduction component" (i.e., slab-derived fluid plus deep slab melts). We retain all samples with Ba/Nb < 7, a value that should encompass most normal MORB (N-MORB), enriched MORB (E-MORB), and oceanic-island basalt (OIB)–like melts (using Ba/Nb criteria from Sun and McDonough, 1989). We stress that the samples remaining after this process do retain some trace element characteristics of subduction zone magmas (only two lavas ever recovered from the MT approximate true MORB). However, since we have applied a stringent filter based upon a highly mobile element (Ba), this effectively removes samples containing any significant trace of modern slab-related Nd and Hf, which are far less mobile in this environment, leaving isotope data reflecting solely ambient mantle sources.

Mariana Trough Ambient Mantle

Applying these two successive filters significantly reduces the isotopic variability observed in MT lavas (Fig. 1A). The filtered data set defines a coherent trend with highly correlated

[1]GSA Data Repository item 2012156, Table DR1, samples, and methods, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

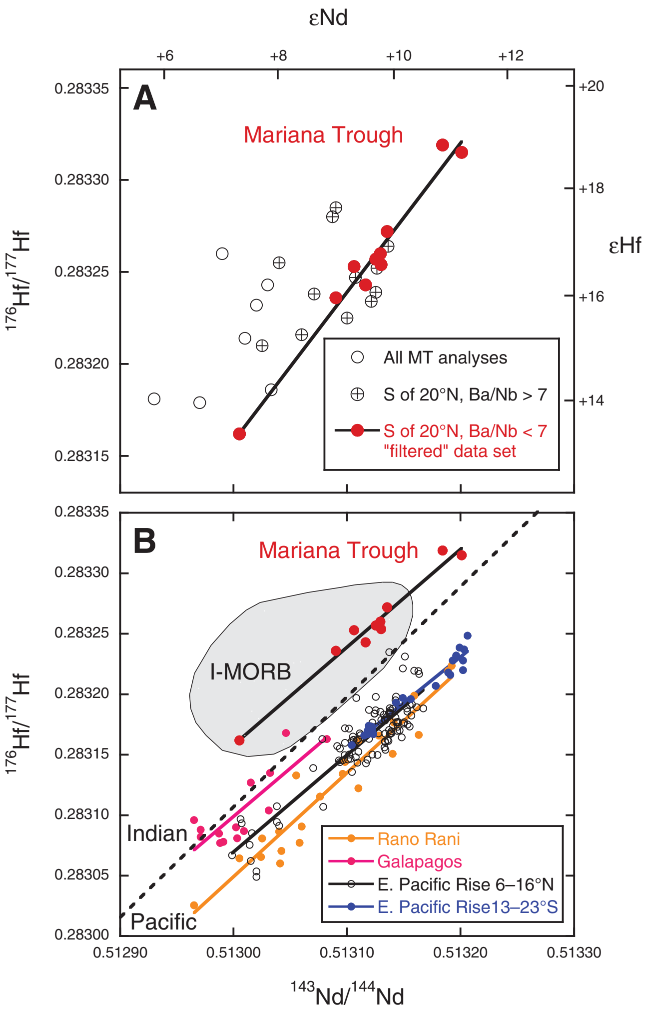

Figure 1. A: Mariana Trough (MT) samples (all circles), from the rifting environment north of 20°N (open circles), and the seafloor spreading environment south of 20°N with (1) Ba/Nb > 7 (crossed circles) and (2) Ba/Nb < 7 (red filled circles). The latter form the final data set filtered for the effects of modern subduction processes and used in subsequent diagrams and discussion. B: MT ambient mantle array compared with several mid-ocean ridge (MOR) segments (Salters et al., 2011). The isotopic variability in the MT mantle array scales with the MOR data. Also shown are a shaded field for Indian mid-oceanic-ridge basalt (I-MORB) samples (Chauvel and Blichert-Toft, 2001) and the Indian-Pacific mantle discriminant boundary (dashed line) for western Pacific arcs (Pearce et al., 1998).

Hf and Nd isotope ratios. Although the ends of the isotope array are defined by one or two analyses, the total range in filtered MT backarc basin isotopic variation is similar to that observed in different mid-ocean ridge segments, and the trajectories are broadly subparallel (Fig. 1B) (Salters et al., 2011). Similar Hf isotope variations have been observed in other backarc basins (e.g., East Scotia Sea, Barry et al., 2006; Havre Trough, Todd et al., 2011). It is also clear that the MT mantle source is of Indian MORB character, confirming previous observations (e.g., Hickey-Vargas et al., 1995). Note that the most depleted end of our MT mantle array (highest ε_{Nd} and ε_{Hf}) is represented by samples from Dredge 84 of Gribble et al. (1996). These were previously thought to best approximate the local mantle source for Mariana magmatism (Woodhead et al., 2001), a conclusion that no longer seems justified. Based on the natural isotopic variability in MORB, and the possibility that this is in itself inherited from ancient recycling processes (e.g., Rehkämper and Hofmann, 1997), it is unsurprising that the sub–Mariana Arc mantle, with the protracted subduction history in this region, should display similar levels of isotopic heterogeneity. Thus, we propose that the filtered data set illustrated in Figure 1A is a realistic representation of the sub-MT mantle isotopic variability, prior to any modern Nd or Hf additions from the slab, and that, on average, this is more isotopically enriched than the value that has been employed previously. We also stress that, although displaying considerable isotopic variability, the MT basalts, and hence their source, are not characterized by significant Nd and Hf elemental variation.

IMPLICATIONS FOR ARC MAGMATISM

Modeling the Effects of Slab Additions to an Ambient Mantle Wedge

Most attempts to model the effects of slab additions to the subarc mantle utilize a single mantle end-member composition. Moreover, in the case of Nd-Hf isotope studies in the Mariana Arc, this has been unavoidable as, prior to this study, only a single Hf isotope analysis of MT basalt has been reported (Woodhead et al., 2001). We can now evaluate Mariana Arc magmatism in the light of the newly defined ambient mantle array. For this purpose, we consider three geochemically diverse products of the arc front: lavas from large subaerial volcanoes of the Central Island province (CIP) between 16°N and 21°N, shoshonitic eruptives from the Alkalic Volcano province (AVP) between 23°N and 25°N, and rare depleted arc tholeiites from Poyo seamount. Together these encompass the compositional spectrum of melts produced in the arc system, and are shown in Figure 2A, together with a hypothetical mixing curve between the most depleted mantle end member from our ambient mantle array (equivalent to the Dredge 84 composition used previously) and a model bulk subducted sediment, chosen to best represent the data (see Data Repository).

In this simple model, it is possible to construct a single mixing curve (illustrated in Fig. 2A) that joins our depleted mantle end member with a hypothetical bulk sediment, passing through the majority of the subaerial arc, Poyo seamount, and shoshonite data. Although the structure of such a curve can explain the arc Hf-Nd isotopic compositions, the high proportions of bulk sediment required by the model are improbable. In particular, the LREE-depleted nature of the Poyo tholeiites limits the potential involvement of bulk sediment (e.g., the model requiring ~1% sediment addition would produce La/Yb well in excess of that observed). Similarly, oxygen isotope data for the AVP shoshonites (e.g., Ito et al., 2003) indicate that the involvement of bulk sediment is constrained to <3%. In addition, it is widely recognized that trace element parameters such as high Ba/La and Sr/Nd also require a substantial role for slab-derived fluids in the genesis of many CIP lavas (Elliott et al., 1997). Mixing trajectories with such fluids on ε_{Nd}-ε_{Hf} plots are likely to be subhorizontal (Nd being slightly mobile and Hf being less so) and are not easily accommodated into the bulk-mixing model of Figure 2A. We conclude therefore that the depleted MT lavas, as sampled in Dredge 84 and utilized in Woodhead et al. (2001), can no longer be considered appropriate end members for modeling the genesis of most Mariana Arc magmas. More reasonable models can be established using other compositions along the ambient mantle array, particularly employing the intermediate compositions represented by the majority of the filtered data of Figure 1A.

For example, if we assume that LREE-depleted tholeiites from Poyo seamount are derived from a source that was modified by slab-derived fluid with minimal, if any, sediment contribution (a reasonable assumption given their chemistry—see above), a simple fluid addition vector can be constructed from the ambient mantle that we have defined here (Fig. 2B). The CIP Nd-Hf array passes to the left of the MT array, also consistent with addition of fluids. Furthermore, the proportions of sediment melt involved in this new model are reasonable and in

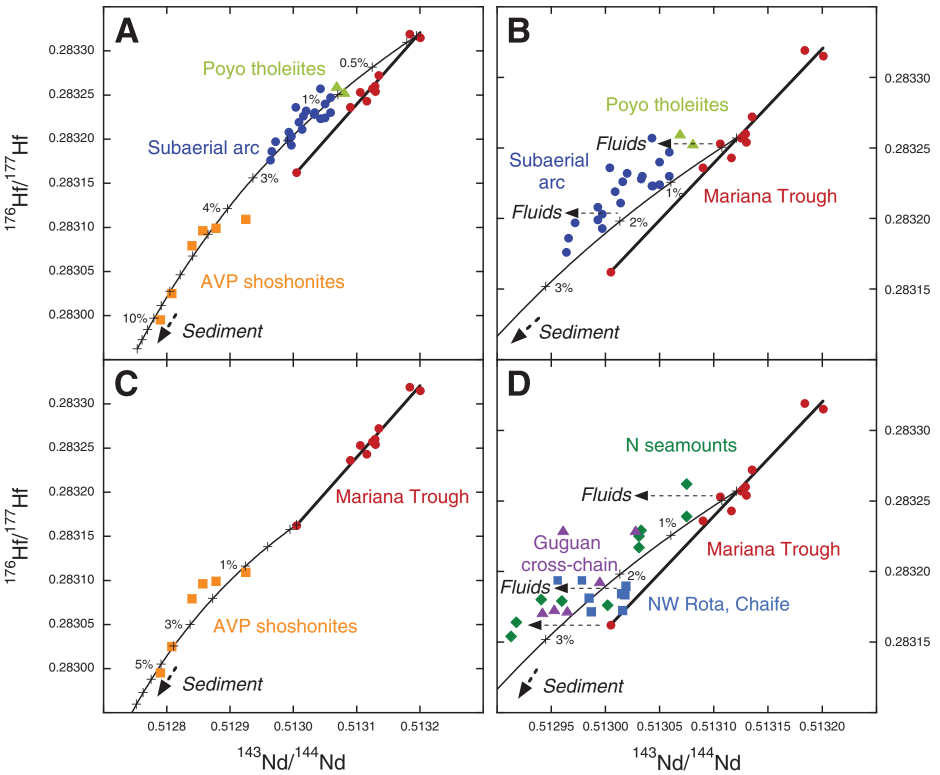

Figure 2. Mixing models. A: A single generic mixing model to explain the Hf-Nd isotopic composition of Mariana Arc lavas. In this case we plot a simple two-component mixture between the most depleted Mariana Trough (MT) samples (Dredge 84) and a bulk subducting sediment comprising a mixture of 40% pelagic clay and 60% volcanogenic sediment (see the Data Repository [see footnote 1]). Although the mixing curve reasonably fits the entire data set, the mixing proportions are incompatible with other geochemical constraints. Better-fit models can be established by utilizing the same bulk sediment composition but different MT mixing end members from the "ambient mantle" array. These are depicted in B (subaerial arc and Poyo tholeiites), C (Alkalic Volcano province [AVP] shoshonites), and D (Northern seamounts, Northwest Rota, Chaife seamounts, Guguan cross-arc chain). See text for further discussion.

keeping with estimates from other isotope and trace element systems (e.g., Wade et al., 2005).

AVP shoshonites likely require another isotopically distinct mantle end member—one at the unradiogenic Hf-Nd end of the MT array (Fig. 2C). In this case we can reproduce the AVP suite with between 0.5% and 5% bulk sediment admixture and little, if any, fluid involvement. These two products (tholeiites and shoshonites) define two end members in the spectrum of magmatic products from the arc, one dominated by fluid, the other by sediment melt. Most subaerial arc lavas are influenced by both processes, but we believe that the composition of the mantle end member itself must also vary. The apparent availability of heterogeneous mantle compositions might explain the origin of other volcanic products. For example, Stern et al. (2006) conclude that compositional variations in the Guguan cross-chain seamounts are difficult to reconcile with a subduction component carried as a sediment melt, yet these samples have Nd and Hf variations almost as large as the rest of the subaerial arc (Fig. 2D). These compositional differences can, however, be modeled by fluid addition to a mantle of variable isotopic character, as defined by the MT ambient mantle array.

Note that all models illustrated in Figure 2 require the involvement of both pelagic clay and volcanogenic sedimentary components. We do not suggest that such a composition remains fixed in space and time, and clearly this is only one end member of many plausible models (we have not, for example, appealed to any residual phases that might fractionate the Nd/Hf of the slab component; e.g., Tollstrup and Gill, 2005). Even so, the dominant volcanogenic input in the composition used here (a 60:40 mix of volcanogenic:pelagic sediments) may reconcile the requirement for a slightly greater sediment contribution (up to ~5% in the shoshonites) with the oxygen isotope constraints (<3%; Ito et al., 2003). This is because an admixture of volcanogenic material will likely lower the $\delta^{18}O$ of the sediment end member, a point made by Tollstrup and Gill (2005).

HFSE Mobility and the Thermal Structure of the Subducting Slab

Our new Hf isotope data also bear on the continuing debate over the mobility of HFSEs in subduction systems. In recent years, opinions have diverged on this point with some authors favoring limited Hf mobility (e.g., Pearce et al., 1999) and others suggesting "non-conservative" behavior (e.g., Woodhead et al., 2001; Yogodzinski et al., 2010). Importantly, the isotopically variable mantle array defined above allows a model accommodating *both* types of behavior for the Mariana Arc. In extreme cases, our data indicate that Hf may be essentially immobile (as in the case of Poyo tholeiites) or highly mobile (AVP shoshonites), depending on whether fluids or melts are involved. Distinguishing between these two end members would not be possible using a single mantle composition such as the Dredge 84 sample because all arc magmas would require Hf mobility in such a scenario.

It is tempting to speculate that these contrasting styles of magmatic process—as revealed in Hf-Nd isotope space—could reflect the thermal state of the subducting slab. Shoshonitic volcanism may represent the earliest stages of arc magmatism associated with a propagating backarc rift (Bloomer et al., 1989; Lin et al., 1990). Here volcanism is dominated by sediment melts that mask any fluid component in Nd-Hf isotope space (Fig. 2C). Perhaps oblique convergence in this region allows slower descent of the downgoing plate and thus a higher temperature and more melting at the slab-mantle interface. Perhaps, also, this melt component is greater than expected because it has accumulated in the subarc lithosphere over a period of time before being reactivated by melting during the recent rifting event (Pearce et al., 2005).

In the large, mature CIP volcanoes, the old, cold subducting Pacific plate has reached thermal equilibrium. Here fluid involvement is well established and appears to have achieved a "steady state" resulting in a relatively consistent offset in Nd isotope ratios between the ambient mantle array and the arc lavas (Fig. 2B). In this region, the dominant influence on isotopic variability appears to be sediment melt addition, causing movement parallel to the MT array. Notable exceptions include the smaller submarine edifices such as NW Rota-1 (Tamura et al., 2011) and Chaife (Kohut et al., 2006) seamounts, where slab dewatering and fluid involvement processes appear highly variable on a local scale (Fig. 2D).

CONCLUSIONS

New data for MT basalts, when filtered to remove components added during recent subduction processes, form a remarkably coherent array in Hf-Nd isotope space that can be used to define the composition of "ambient mantle" in the region. This mantle is of Indian MORB character and has isotopic variability similar to ridge segments of comparable length. This array provides an improved reference for interpreting the volcanic products of the Mariana Arc in terms of Hf and Nd behavior in subduction zone melts and fluids. This general result can be applied to understanding all convergent margin magmatic systems, although the nature of ambient mantle for a given arc must be established independently.

Hf can be mobile or immobile, depending on the agent of mass transfer between slab and mantle wedge. Shoshonites from the AVP likely represent the products of mixing between a relatively isotopically-enriched mantle and sediment melts, the latter derived from both clay and volcanogenic sedimentary components. Significant fluid additions cannot be distinguished here and may be a consequence of oblique convergence raising the temperature of the subducting slab in this region. Magmas of the mature CIP arc volcanoes are dominated by mantle sources that experience steady fluid addition. This is superimposed upon isotopic variability resulting from different proportions of sediment melt. Some smaller edifices appear to reflect unusually variable fluid additions.

In contrast to previous studies, which have utilized a single, isotopically depleted mantle end member, the newly identified MT ambient mantle array helps reconcile conflicting constraints on sediment and fluid involvement based upon a variety of trace element and isotopic parameters.

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