Isotopically ultradepleted domains in the convecting upper mantle: Implications for MORB petrogenesis

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ABSTRACT

Mid-oceanic-ridge basalts (MORB) form by partial melting of material in the convecting upper mantle. The range in isotopic compositions observed in MORB is inconsistent with the ultradepleted isotopic compositions observed in many abyssal peridotites. These results have called into question the prevailing hypothesis that abyssal peridotites (APs) are simple residues of recent MORB melting, which should result in the two reservoirs having the same range in isotopic compositions. We examined xenoliths that, based on their chemical features (e.g., light rare earth element depleted, fertile major element compositions, Sr-Nd-Pb isotopes similar to estimates for depleted MORB mantle), are interpreted to be derived from the convecting upper mantle, in order to evaluate the potential for isotopically ultradepleted domains to contribute significantly to MORB petrogenesis. Our data support the idea that isotopically ultradepleted peridotite is widely distributed in the upper mantle, and we demonstrate that ultradepleted domains are capable of contributing to MORB petrogenesis. An isotopically enriched component, such as recycled oceanic crust, in the MORB source mantle can account for the lack of MORB with ultradepleted isotopic compositions.

INTRODUCTION

Several recent studies have revealed a mismatch in the isotopic compositions of mid-oceanic-ridge basalts (MORBs) and abyssal peridotites (APs), with many APs having extremely depleted isotopic compositions not observed in MORB. Although earlier studies (e.g., Snow et al., 1994) found clinopyroxene hosted in AP to have Sr and Nd isotopic compositions similar to that of MORB, recent results show that Nd and Hf isotopes in AP extend toward more depleted (radiogenic) compositions (Cipriani et al., 2004; Salters and Dick, 2002; Stracke et al., 2011; Warren et al., 2009), well beyond the range observed in MORB (Fig. 1). Ultradepleted mantle domains are thought to be residues of ancient melt depletion that are not rehomogenized before being brought up again beneath a mid-ocean ridge (Liu et al., 2008; Rampone and Hofmann, 2012; Stracke et al., 2011). Herein ultradepleted refers to isotopic compositions that extend beyond the range observed in MORB (less radiogenic Sr, more radiogenic Nd and Hf) as a result of the time-integrated effect of incompatible trace element depletion. We use the term refractory to refer to peridotites with major element compositions that reflect significant melt removal (i.e., low Al and Ca). The abundance, composition, and distribution of ultradepleted domains in the mantle have major implications for current models for the composition of the convecting mantle and mechanisms for MORB melt generation.

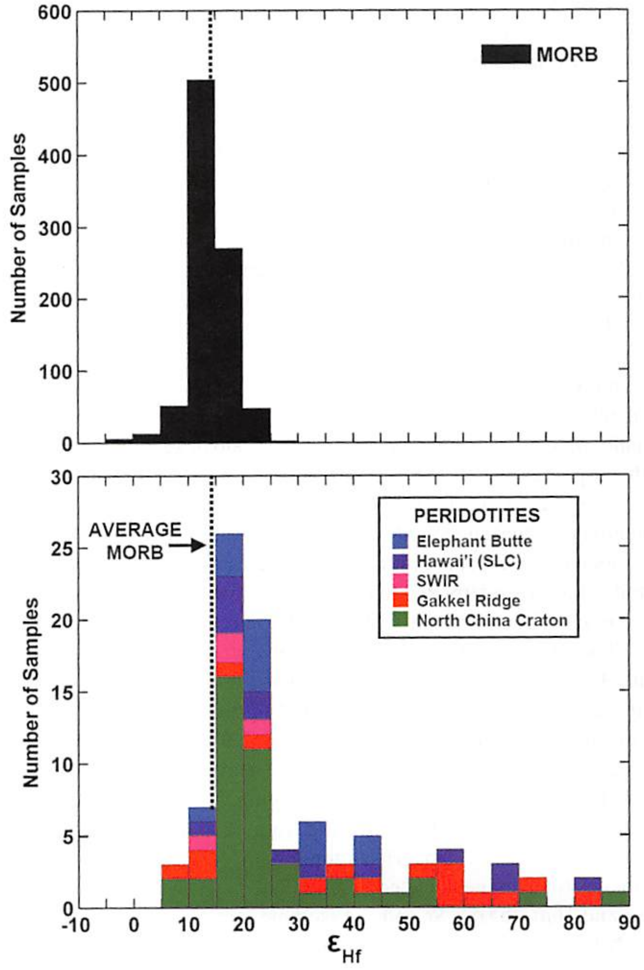

Figure 1. Distribution of Hf isotopes in mid-oceanic ridge basalt (MORB, upper panel) that are restricted to ε_{Hf} <~25. However, abyssal peridotites from Gakkel Ridge (eastern Arctic Ocean; data from Salters et al., 2011; Stracke et al., 2011) have been observed with ε_{Hf} > 100. Also shown are other peridotites (Elephant Butte, New Mexico, USA, this study; Salt Lake Crater, Hawai'i, data from Bizimis et al., 2007; South West Indian Ridge, SWIR, data from Stracke et al., 2011; North China craton, data from Chu et al., 2009; Wu et al., 2006; Zhang et al., 2012) that sample convecting upper mantle that extend to highly depleted Hf isotopic compositions.

Three hypotheses are immediately apparent to explain the mismatch between MORB and AP isotopic compositions: (1) ultradepleted domains in the upper mantle are volumetrically minor, but are oversampled by AP, possibly due to their low density, and so are not representative of MORB source mantle (the "slag" hypothesis); (2) ultradepleted domains are common in the convecting upper mantle, but have refractory major element compositions, prohibiting these domains from participating significantly in melt generation beneath mid-ocean ridges (the "ghost" hypothesis); or (3) MORBs are generated by mixing of two or more isotopically distinct components. Melts from ultradepleted material mix with melts from isotopically enriched components to generate MORB with intermediate isotopic compositions (the "hybrid" hypothesis).

SAMPLES

We test these hypotheses using available data from ocean island xenoliths and APs, plus new data from a suite of asthenosphere-derived xenoliths from Elephant Butte, New Mexico (southwestern United States). Because APs may have undergone recent melt depletion, making it difficult to establish their original composition, we examined major element, trace element, and isotopic compositions of a suite of asthenosphere-derived xenoliths from the Rio Grande Rift to constrain the fertility and

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range in isotopic compositions of convecting upper mantle in an environment not affected by major recent melting and melt extraction. Our previous study of xenoliths from Elephant Butte (Rio Grande Rift) indicated that most of the preexisting Proterozoic lithospheric mantle in this region has been convectively removed and recently replaced with asthenospheric mantle (Byerly and Lassiter, 2012). Two populations of xenoliths are present at Elephant Butte. A small number of xenoliths have refractory major element compositions (bulk $Al_2O_3 < 2.3$ wt%, spinel Cr# 0.34 ± 0.12, 1σ), light rare earth element (LREE)–enriched trace element compositions [clinopyroxene $(La/Sm)_N > 2$], and enriched Sr-Nd-Pb isotopic compositions ($^{87}Sr/^{86}Sr$ 0.7032–0.7043, $^{206}Pb/^{204}Pb$ 19.2–19.9, ε_{Nd} 3.7–7.0). Along with xenoliths from the eastern Colorado Plateau, the refractory Elephant Butte xenoliths define a strong Lu/Hf-$^{176}Hf/^{177}Hf$ pseudo-isochron with an apparent age of ca. 1.6 Ga, consistent with estimates for the age of the crust in that region (Nelson and DePaolo, 1985). These refractory xenoliths therefore appear to sample surviving remnants of the original Proterozoic lithosphere beneath the Rio Grande Rift (Byerly and Lassiter, 2012). Another, more abundant, group of xenoliths have fertile major element compositions (bulk Al_2O_3 4.0 ± 0.5, 1σ; spinel Cr# 0.10 ± 0.01, 1σ) and LREE-depleted trace element patterns, each of which coincides with estimates for the average composition of the depleted upper mantle (Salters and Stracke, 2004; Workman and Hart, 2005). The major and trace element patterns are consistent with <4% melt extraction from primitive mantle (McDonough and Sun, 1995). This group of xenoliths derives from asthenospheric mantle that recently accreted to the base of the residual lithosphere at depths of 40–45 km (Byerly and Lassiter, 2012). This interpretation is further supported by the existence of anomalously slow V_p and V_s velocities beneath the central Rio Grande Rift that extend up to ~40 km depth, which are interpreted to be the result of significant lithosphere erosion beneath the central Rio Grande Rift (Gao et al., 2004).

The majority of asthenosphere-derived xenoliths from Elephant Butte have ultradepleted isotopic compositions, yet all maintain fertile major element compositions (Table DR1 in the GSA Data Repository[1]). Most MORB samples (90%) have $^{87}Sr/^{86}Sr$ between 0.7020 and 0.7038, ε_{Nd} between 5 and 12, and ε_{Hf} between 8 and 20. In contrast, the Elephant Butte peridotites have $^{87}Sr/^{86}Sr$ ranging from 0.7018 to 0.7026, ε_{Nd} ranging from 8 to 27, and ε_{Hf} ranging from 12 to 40. The least-depleted samples have Sr, Nd, and Hf isotopic compositions that overlap with estimates for average depleted mantle (Salters and Stracke, 2004; Workman and Hart, 2005). Sr and Nd isotopic compositions, as well as Hf and Nd isotopes, are correlated and extend the mantle array to highly depleted values that are not observed in MORB (Fig. 2). The observed Sr isotopic compositions are consistent with ancient (older than 1 Ga) melt depletion, which would have occurred prior to the recent (likely after 40 Ma, coincident with onset of Rio Grande Rift rifting and/or Farallon slab rollback) convective removal of the Proterozoic lithosphere. The strong correlation between Hf and Nd isotopes in the Elephant Butte xenoliths contrasts with other locales (e.g., Bizimis et al., 2007; Stracke et al., 2011), where decoupling of Hf and Nd isotopes has been interpreted to be the result of recent melt-rock interaction (Bizimis et al., 2004). In addition, the Elephant Butte xenoliths have LREE-depleted compositions, suggesting that their fertile major element compositions are not the result of metasomatism and/or refertilization.

"SLAG" HYPOTHESIS

One hypothesis to explain the isotopic mismatch between average MORB and AP isotopic compositions is that ultradepleted domains are rare in the convecting mantle, but oversampled by AP. If ultradepleted mantle domains are highly refractory, they may be more buoyant than normal mantle (O'Reilly et al., 2009), allowing those domains to float and be oversampled at mid-ocean ridges. If this is the case, MORB and AP may not be directly genetically related. However, the majority of asthenosphere-derived xenoliths from Elephant Butte are relatively fertile, despite having ultradepleted Hf and Nd isotopic compositions similar to values observed in AP. Ultradepleted Hf and Os isotopic compositions have also been observed in ocean island xenoliths from Hawai'i (Salt Lake Crater; Bizimis et al., 2007) and the Ontong Java Plateau (Malaita, Solomon Islands; Ishikawa et al., 2011), as well as in mantle xenoliths from the North China craton that are derived from recently accreted (after 100 Ma) asthenosphere (Chu et al., 2009; Wu et al., 2006; Zhang et al., 2012). The prevalence of ultradepleted domains in myriad tectonic environments is strong evidence that these domains are not rare in the convecting upper mantle. In addition, for the ranges of melt extraction observed in AP (<20%), the density reduction associated with melt depletion at low pressures (<0.5%;

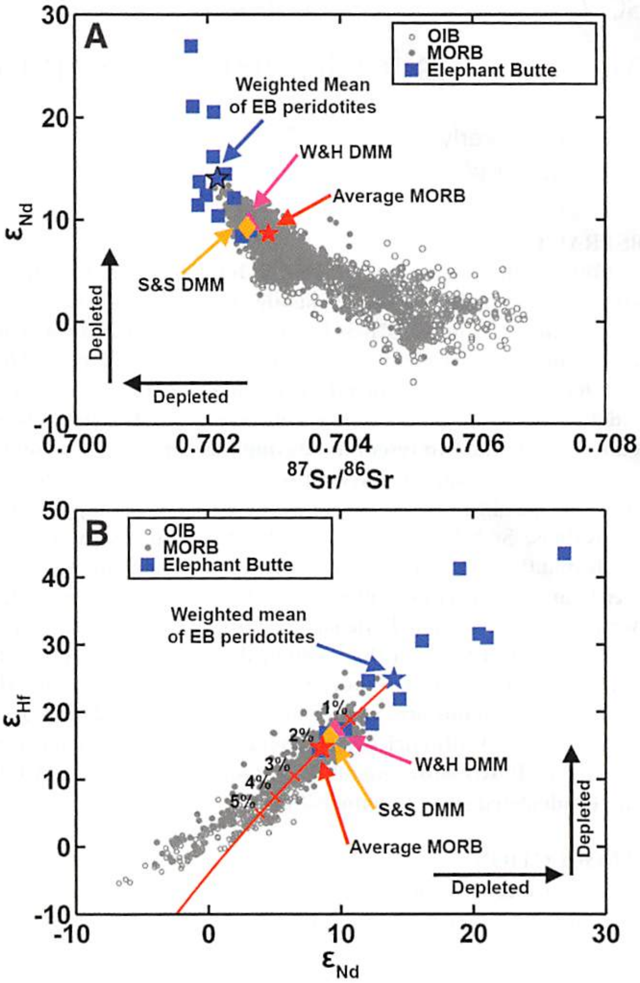

Figure 2. A: Plot of ε_{Nd} versus $^{87}Sr/^{86}Sr$. B: Plot of ε_{Hf} versus ε_{Nd}. Data are from clinopyroxene separates from Elephant Butte (EB; New Mexico, USA) xenoliths. Also shown are mid-oceanic-ridge basalts (MORB) ocean island basalts (OIB), and estimates from Salters and Stracke (2004; S&S) and Workman and Hart (2005; W&H) for average depleted MORB mantle (DMM). MORB and OIB data are from www.earthchem.org/petdb. Majority of EB xenoliths extend to highly depleted Sr, Nd, and Hf isotopic compositions, which are not observed in MORB. Solid red line is our model for mixing recycled 2 Ga MORB with weighted mean EB composition to generate range in modern MORB isotopic compositions. Red tick marks are in 1% intervals to 5% recycled material.

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[1] GSA Data Repository item 2014070, analytical methods; descriptions of pMELTS models, mixing models, and preferential melting models; and isotopic compositions of the Elephant Butte xenoliths, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Schutt and Lesher, 2006) is not sufficient to offset the density increase due to conductive cooling (>1.5%). Therefore, a lid of highly refractory cold material would not be convectively stable. Even if a slag melted, it would not have the same isotopic composition as MORB and could not explain the offset between MORB and AP isotopic compositions.

"GHOST" HYPOTHESIS

A second potential explanation for the mismatch between MORB and AP isotopic compositions is that ultradepleted domains are too refractory to contribute significantly to MORB petrogenesis. Ultradepleted domains from Hawai'i (Bizimis et al., 2007) and the Gakkel Ridge (eastern Arctic Ocean; Liu et al., 2008; Stracke et al., 2011) have more refractory major element compositions (e.g., lower Al_2O_3 and higher spinel Cr#) than estimates for average depleted MORB mantle (Fig. 3). The refractory compositions observed in AP and other ultradepleted domains most likely reflect a mix of recent melt extraction (e.g., at the modern mid-ocean ridge) and ancient melt extraction (evidenced by broad correlations between $^{187}Os/^{188}Os$ and indicators of fertility such as bulk Al_2O_3 or spinel Cr# observed in AP and OIB xenoliths Cr#; Bizimis et al., 2007; Ishikawa et al., 2011; Liu et al., 2008).

To examine the effect of fertility on melt production we used pMELTS software (Ghiorso et al., 2002) to model the adiabatic ascent and melting of mantle with different fertilities beneath a mid-ocean ridge. The models start at 25 kbar and a potential temperature of ~1350 °C. The amount of melt generated is strongly controlled by the starting peridotite fertility. A mantle peridotite with 4.0 wt% Al_2O_3 (average composition of Elephant Butte xenoliths) will generate ~24% melt by 2 kbar (approximate base of oceanic crust), whereas a sample with 1.6 wt% Al_2O_3 (average composition of Salt Lake Crater, Hawai'i, xenoliths) will only generate ~8% melt by 2 kbar. Although it is possible that ultradepleted domains within the convecting mantle with low (<~1 wt%) Al_2O_3 exist as "ghosts," unable to generate appreciable melt beneath mid-ocean ridges, ultradepleted domains with compositions similar to samples from Hawai'i (average $Al_2O_3 = 1.6 \pm 0.7$, 1σ) and the Gakkel Ridge (average $Al_2O_3 = 2.3 \pm 0.4$, 1σ) are sufficiently fertile to generate significant quantities of melt, assuming a typical potential temperature for upper mantle. These domains therefore should be sampled during MORB petrogenesis, leaving unresolved the lack of such isotopic signatures in MORB.

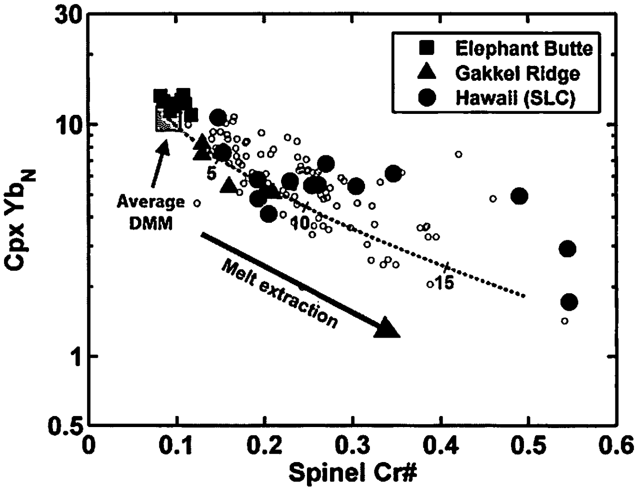

Figure 3. Plot of clinopyroxene (cpx) Yb (normalized to chondrite; McDonough and Sun, 1995) versus spinel Cr# [molar Cr/(Cr + Al)] in ultradepleted domains (modified after Byerly and Lassiter, 2012). Dashed line shows melting model after Hellebrand et al. (2001). Peridotites from Gakkel Ridge (eastern Arctic Ocean) and Salt Lake Crater (SLC, Hawai'i) have refractory compositions that would not contribute significant amount of melt to mid-oceanic-ridge basalt (MORB) petrogenesis. However, Elephant Butte (New Mexico, USA) xenoliths have fertile major element compositions and would generate melts with ultradepleted compositions if brought up beneath mid-ocean ridge. Also shown are global abyssal peridotites (gray circles). DMM—depleted MORB mantle.

"HYBRID" HYPOTHESIS: PREFERENTIAL SAMPLING OF PYROXENITE AND FERTILE PERIDOTITE DURING MORB PETROGENESIS

Because ultradepleted domains in convecting upper mantle are sufficiently fertile to generate melt when advected, there must be widespread generation of isotopically depleted melts beneath mid-ocean ridges. MORBs with such depleted isotopic compositions are not observed. Therefore, an additional isotopically enriched component must also be ubiquitous in the mantle. Melts from this component mix with melts derived from depleted peridotite to yield the isotopic compositions observed in MORB. Pyroxenite or eclogite derived from ancient recycled oceanic crust have frequently been called upon to explain chemical heterogeneities within the upper mantle (Allègre and Turcotte, 1986), and are candidates for the enriched end member that would mix with ultradepleted melts to generate MORB. Pyroxenites and/or eclogites can have a disproportionately large impact on MORB compositions relative to their abundance in the mantle because these lithologies have higher concentrations of incompatible trace elements and experience higher overall degrees of melting than peridotites. In Figure 2B we present a model in which peridotite with the average composition of the Elephant Butte xenoliths is mixed with recycled MORB that was generated at 2 Ga. Mixing between 1% and 5% of the enriched component can account for ~90% of the Hf and Nd isotopic compositions observed in MORB today. The model in Figure 2B represents solid-state mixing. The amounts of each component required are likely similar for mixing of melts as a result of a balance between higher Nd and Hf partition coefficients and higher degrees of partial melting in the enriched component. Observations from MORB melt inclusions (Maclennan, 2008; Shimizu, 1998) and MORB oxygen isotopes (Eiler et al., 2000) support the idea that enriched and/or recycled material is present in the mantle. Mixing of pyroxenite- and peridotite-derived melts has also been proposed as a possible source of the "garnet signature" in MORB (Hirschmann and Stolper, 1996).

The ultradepleted isotopic compositions observed in convecting upper mantle–derived peridotites (Fig. 1) are consistent with the idea that the range of fertilities observed in AP is, to some extent, an inherent heterogeneity that is unrelated to recent melting beneath mid-ocean ridges. The Elephant Butte xenoliths likely represent a fertile end member of upper mantle peridotite. A consequence of a heterogeneous peridotitic upper mantle is that conventional models that use MORB to estimate average upper mantle composition are biased toward more fertile components. We demonstrate this (see the Data Repository) by modeling adiabatic melt generation from heterogeneous peridotitic mantle that underwent variable ancient depletion. Because the more fertile (and less depleted) components generate more melt and have higher incompatible trace element concentrations than the refractory (and more depleted) components, the resulting melts have isotopic compositions that are less depleted than the average source composition. We show a melt model for mantle with bulk Al_2O_3 of 3.2 ± 0.5 (1σ) and a weighted mean ε_{Hf} of ~45 (see the Data Repository), where weighted melts generated from this mantle have ε_{Hf} of ~30. The MORB source is heterogeneous and MORB compositions are biased due to preferential melting of pyroxenitic and fertile peridotitic source components.

CONCLUSIONS

Isotopically ultradepleted components are ubiquitous in the upper mantle, and we demonstrate that these components are not necessarily refractory. As evidenced by the wide range of isotopic compositions observed in convecting upper mantle samples, the convecting peridotitic mantle has undergone variable amounts of melt depletion. Because these ultradepleted components are widespread and capable of generating melt, the mismatch between their isotopic compositions and that of MORB indicates that (1) MORBs oversample fertile (less depleted) peridotitic mantle, and/or (2) an enriched component (pyroxenite and/or eclogite) contributes to MORB petrogenesis.

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