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# Hf isotope systematics of seamounts near the East Pacific Rise (EPR) and geodynamic implications



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# ABSTRACT

We report new Hf isotopic data for basaltic glasses from seamounts flanking the East Pacific Rise (EPR) between 5° and 15°N that have been previously analyzed for Sr–Nd–Pb isotopes as well as major and trace elements. The Hf isotopic data offer new perspectives on the petrogenesis of these samples in a broader context on mantle dynamics. The Hf isotope compositions show significant correlations with Sr–Nd–Pb isotopes and with both abundances and ratios of incompatible elements. The seamount lavas are thus best interpreted as products of melting-induced mixing in a two-component mantle.

The range in composition of EPR seamount lavas cannot be generated by simple mixing of melt and melting of variably heterogeneous mantle in which enriched and depleted materials contribute equally to melting (source mixing). Instead, the trace element and isotope compositions of seamount lavas can be reproduced by melting models in which more enriched, fertile mantle component are preferentially melted during mantle upwelling. At progressively lower degrees of melting, erupted lavas are thus more enriched in incompatible trace elements, have higher <sup>87</sup>Sr/<sup>86</sup>Sr, <sup>208</sup>Pb/<sup>204</sup>Pb ratios and lower <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>176</sup>Hf/<sup>177</sup>Hf ratios. The "EM1" and "pyroxenite" endmember might be the suitable enriched component.

The Hf–Nd isotopic variations on global scale might result from the variations in amounts of residual continental lithospheric mantle that detached into upper mantle during continental rifting. The significant correlations of Rb/Sr vs <sup>87</sup>Sr/<sup>86</sup>Sr, Sm/Nd vs <sup>143</sup>Nd/<sup>144</sup>Nd and Lu/Hf vs <sup>176</sup>Hf/<sup>177</sup>Hf give pseudochron ages of 182  $\pm$  33 Ma, 276  $\pm$  50 Ma and 387  $\pm$  93 Ma, respectively. These different "ages" have no significance, but result from melting-induced mixing with the pseudochron slopes controlled by the compositions of enriched component and depleted end-member.

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## 1. Introduction

Isotopic studies of oceanic basalts provide constraints on models of Earth's chemical differentiation and convection processes. One of the major advances in the solid Earth science over the past 50 years is the recognition of mantle compositional heterogeneity and the identification of several isotopically distinct mantle end-members through these isotopic studies (e.g., Gast et al., 1964; White, 1985; Zindler and Hart, 1986). Numerous geochemical studies of MORB (e.g. Allègre and Turcotte, 1986; Arevalo and McDonough, 2010; Brandl et al., 2012; Donnelly et al., 2004; Haase et al., 2011; Hirschmann and Stolper, 1996; Niu et al., 1999; Phipps Morgan and Morgan, 1999; Schilling et al., 1983; Zindler and Hart, 1986) have shown that even in the absence of nearby hotspots, the upper mantle is chemically and isotopically heterogeneous. The origin of these heterogeneities is debated, but they likely result from recycled material (Donnelly et al., 2004; Niu and O'Hara, 2003; Pilet et al., 2005; White and Hofmann, 1982). The Nd and Hf isotope ratios (i.e., <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>176</sup>Hf/<sup>177</sup>Hf) are shown to be well correlated in ocean island basalts (OIB) due to the similar behavior of the parent–daughter (P/D) pairs (i.e.,  $D_{Sm} > D_{Nd}$  and  $D_{Lu} > D_{Hf}$ ) during mantle melting (Blichert-Toft, 2001; Patchett and Tatsumoto, 1980; Salters and Hart, 1991; Vervoort et al., 1996). In contrast to OIB, mid-







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ocean ridge basalts (MORBs) on a global scale have large variations in Hf isotopic composition at a given Nd isotopic composition (e.g., Blichert-Toft et al., 2005; Debaille et al., 2006; Johnson and Beard, 1993; Patchett, 1983; Patchett and Tatsumoto, 1980; Salters and Hart, 1991; Salters and White, 1998; Salters and Zindler, 1995). A more recent study, however, shows that Hf and Nd isotopes in MORB are in fact well correlated on some ridge segment scales (Salters et al., 2011). This is an important observation that points to large regional scale differences in mantle sources and source histories.

To help address issues on MORB genesis and the variable MORB Hf– Nd isotopic correlations at different ridges (Salters et al., 2011), we study Hf isotope compositions of near-ridge seamounts flanking the East Pacific Rise (EPR) (see Figs. 1 and A1). We choose these seamount lavas because (1) they have already been well-characterized for major elements, trace elements, and Sr–Nd–Pb isotope compositions (Niu and Batiza, 1997; Niu et al., 2002); (2) they represent an integral part of EPR ridge magmatism as they were derived from the same upper mantle source of EPR axial MORB; (3) they have avoided melt homogenization during melt aggregation in the mantle and in the long-lived axial magma chambers, and thus more faithfully record the nature of the MORB mantle source beneath the EPR than axial lavas; and importantly, (4) they display a large compositional spectrum that encompasses much of the global MORB compositional variability from ridges unaffected by mantle plumes/hotspots, and can thus help answer first-order questions on MORB mantle sources and processes, especially beneath the fast-spreading EPR.

# 2. Samples and analytical methods

The samples were dredged during the 1988 Raitt 02 expedition aboard R/V Thomas Washington (Batiza and Niu, 1992; Batiza et al.,



Fig. 1. (a) Tectonic framework of the northern (5°-15°N) EPR and vicinity; (b) simplified map of the study area showing the locations of near-ridge seamounts. The sizes of the circles (sample locations) are not to scale (Niu and Batiza, 1997; Niu et al., 2002).

1990). All the samples studied are basalt glasses. They were collected from near-ridge seamounts within the 1 Ma isochron (< ~ 60 km) of the EPR axis between 5° and 15°N on both the Pacific and Cocos Plates (Fig. 1). These 36 samples have been studied for major and trace elements (Batiza and Niu, 1992; Batiza et al., 1990; Niu and Batiza, 1997) and Sr–Nd–Pb isotopes (all samples were analyzed for Sr isotope, 28 of them were analyzed for Nd isotope and 34 of them were analyzed for Pb isotope, see Niu et al., 2002).

All the samples were carefully hand-picked under a binocular microscope before they were leached at room temperature in 10% H<sub>2</sub>O<sub>2</sub> for a few minutes to remove Mn oxides in possible micro-fractures and other potential labile contaminants. The samples were then repeatedly washed ultrasonically in 18 M $\Omega$  Milli-Q water before digestion. The method of rock digestion and Hf separation follows those of Yang et al. (2010). Hf isotopic analysis was done using a Neptune MC-ICP-MS in the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The analytical details for Hf isotopic measurements are given by Li et al. (2005). Hf isotopic compositions were normalized to  ${}^{179}\text{Hf}/{}^{177}\text{Hf} = 0.7325$ . In our analysis, we measured  ${}^{176}\text{Hf}/{}^{177}\text{Hf}$ values for USGS reference rock standards W-2 ( $0.282711 \pm 0.000013$ vs. reference value:  $0.282715 \pm 0.000030$ , Le Fèvre and Pin, 2001), BHVO-2 ( $^{176}$ Hf/ $^{177}$ Hf = 0.283082 ± 0.000010 vs. reference value: 0.283096  $\pm$  0.000020, Weis et al., 2005) and BCR-2 (  $^{176}\mathrm{Hf}/^{177}\mathrm{Hf} =$  $0.282858 \pm 0.000009$  vs. reference value:  $0.282870 \pm 0.000008$ , Weis et al., 2007). We also measured the in-house standard Alfa Aesar hafnium solution produced by Johnson Matthey Company (i.e. Alfa Hf, 10,000 µg/ml, stock No. 14374, plasma standard solution) (Wu et al., 2006, 2007; Yang et al., 2007). The measured value for Alfa Hf gave an average  ${}^{176}$ Hf/ ${}^{177}$ Hf of 0.282181  $\pm$  0.000010 (2 $\sigma$ , n = 7) (reference

 Table 1

 Hf isotopic data of glass samples from near-ridge seamounts between 5 and 15°N EPR.

Sample	Туре	Latitude/°N	Longitude/°W	Depth/m	<sup>176</sup> Hf/ <sup>177</sup> Hf	2SE	$\epsilon_{Hf}$
R74-5	Ν	10.62	103.84	2320.00	0.283174	0.000012	14.22
R7-13	Ν	8.14	103.19	2020.00	0.283189	0.000015	14.76
R3-4	E	5.78	102.21	1773.00	0.283212	0.000013	15.56
R3-1	N	5.78	102.21	1773.00	0.283194	0.000014	14.93
R3-3	N	5.78	102.21	1773.00	0.283201	0.000017	15.18
R1-14	N	5.77	102.18	1834.00	0.283187	0.000012	14.66
R66-1	Ν	10.14	103.34	2600.00	0.283189	0.000013	14.75
R28-8	N	8.81	103.90	1984.00	0.283156	0.000010	13.57
R103-13	Ν	13.84	103.80	2870.00	0.283201	0.000010	15.16
R22-1	Ν	8.90	104.10	2749.00	0.283161	0.000011	13.77
R25-1	Ν	8.88	103.79	1980.00	0.283158	0.000013	13.64
R65-1	Ν	10.13	103.41	2074.00	0.283189	0.000013	14.63
R8-8	Ν	8.34	103.06	3180.00	0.283153	0.000013	13.49
R19-4	Ν	8.94	104.41	2267.00	0.283158	0.000013	13.65
R60-1	Ν	10.00	104.91	2640.00	0.283213	0.000014	15.61
R71-2	Ν	10.26	103.74	3380.00	0.283173	0.000006	14.18
R21-6	E	8.89	104.14	2657.00	0.283152	0.000011	13.46
R16-2	Ν	8.84	104.57	2985.00	0.283155	0.000013	13.56
R62-4	E	10.03	104.19	2320.00	0.283167	0.000015	13.95
R24-3	N	8.97	103.87	3054.00	0.283142	0.000008	13.10
R102-1	E	13.22	102.68	2350.00	0.283178	0.000013	14.37
R96-24	E	13.07	103.45	2577.00	0.283209	0.000011	15.46
R72-2	E	10.38	103.93	2748.00	0.283120	0.000010	12.29
R4-2	E	5.60	103.02	2263.00	0.283110	0.000009	11.94
R73-1	E	10.38	103.92	2547.00	0.283124	0.000010	12.43
R32-1	E	9.09	104.92	3025.00	0.283084	0.000012	11.03
R110-4	E	14.14	104.36	2760.00	0.283136	0.000009	12.86
R18-3	E	8.93	104.46	2720.00	0.283061	0.000011	10.21
R80-6	E	11.80	103.25	1619.00	0.283144	0.000008	13.14
R17-1&2	E	8.91	104.57	2715.00	0.283027	0.000007	9.01
R109-5	E	14.15	104.30	2610.00	0.283110	0.000011	11.96
R83-2	E	11.24	103.59	2900.00	0.283084	0.000008	11.04
R79-2	E	11.79	103.25	1620.00	0.283047	0.000011	9.72
R78-5	E	11.22	103.58	2450.00	0.283043	0.000009	9.58
R13-1	Alkali	8.40	104.07	2140.00	0.282974	0.000007	7.15
R15-1	Alkali	8.76	104.54	1682.00	0.282966	0.000008	6.86

value: 0.282189  $\pm$  0.000019, Wu et al., 2006). All of these are indistinguishable from their reference values within analytical errors.

# 3. Results

The Hf isotope data are given in Table 1 and presented in Fig. 2. The  $\varepsilon_{Hf}$ are calculated using  $([^{176}Hf/^{177}Hf]_{sample} / [^{176}Hf/^{177}Hf]_{CHUR} - 1) \times 10,000$ (the subscript sample and CHUR denote the value of samples and chondrite), in which,  $[^{176}\text{Hf}/^{177}\text{Hf}]_{CHUR} = 0.282772$  (Blichert-Toft and Albarède, 1997). The  $\varepsilon_{Nd}$  values are calculated in the same manner, and the  $[^{143}\text{Nd}/^{144}\text{Nd}]_{CHUR}=0.512638$  (Dickin, 1997). The  $\epsilon_{Hf}$  values for seamount lavas vary from 15.61 to 6.86. The  $\varepsilon_{Hf}$  and  $\varepsilon_{Nd}$  correlate well (see Fig. 2), giving a linear expression of  $\varepsilon_{Hf} = 1.72\varepsilon_{Nd} - 2.83$ with  $R^2 = 0.91$ . This slope is significantly similar to, although slightly shallower than the mantle array defined by MORB and OIB (i.e.,  $\varepsilon_{Hf} =$  $1.59\varepsilon_{Nd}$  + 1.28, Chauvel et al., 2008). The Hf and Nd isotope analyzed in this study cover the range defined by previous analyses of northern EPR MORB (Salters et al., 2011 and reference therein), and more enriched than MORB from southern EPR (Fig. 2). The large range of isotopic variability of the near-EPR seamount lavas suggests that the scale of mantle source heterogeneities may be as small as a few kilometers or even smaller, as recognized previously (e.g., Batiza and Vanko, 1984; Niu and Batiza, 1997). Large variety in compositions for lavas from seamount located at 12°45′N of EPR also implied that the upper mantle is extremely heterogeneous on the scale of a single seamount (Brandl et al., 2012). It is worthy to note that the HIMU-like samples (R78-5-1 and R83-2, shown in green circles in Fig. 2), are offset from the other samples. It is most likely that some mantle source heterogeneities exist on a small scale and the enriched component may have



**Fig. 2.** Hf and Nd isotopic variations of seamount lavas on the flanks of the EPR between 5° and 15°N. Nd isotope data are from Niu et al. (2002). The oceanic basalt field, defined by MORBs, OIBs and island arc volcanic rocks (IAVs), is from Chauvel et al. (2008) and Vervoort et al. (1999). The mantle array is according to Chauvel et al. (2008). The field of abyssal peridotite and marine sediments are from Stracke et al. (2011), Vervoort et al. (2011), respectively. The Pacific, Atlantic and Indian MORB data are from Salters et al. (2011), Sims et al. (2002), Blichert-Toft et al. (2005), and Janney et al. (2005). The blue and green circles are alkali basalts and HIMU-like samples, respectively. All the samples give a linear expression of  $\epsilon_{Hf} = 1.72\epsilon_{Nd} - 2.83$ . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

different origins and, thus, possess different isotopic signatures (Niu et al., 1999, 2002).

# 4. Discussion

# 4.1. The effects of fractional crystallization

The major element compositions had been published previously (Niu et al., 2002). The low Mg# values (70 to 52) indicate that none are likely to represent primary melts in equilibrium with mantle olivine (Fo = 89), and all have probably undergone some degree of crystal fractionation. However, the large variations in major and trace element are difficult to explain by fractional crystallization. Additionally, the correlations between isotope compositions and incompatible trace element ratios, and major and trace element concentrations (Figs. 3 and 4) are also inconsistent with closed system crystal fractionation. Other processes other than fractional crystallization must be responsible for variation in composition of most seamount lavas. Considering the composition of seamount lavas is similar to, and more primitive than axial lavas, the crustal contamination is also negligible.

# 4.2. Melting of two component mantle

#### 4.2.1. Evidence for melting of a component source

Our new Hf isotopic data correlate with Sr, Nd, and Pb isotopes, with ratios of incompatible elements (Fig. 4) and with the abundances of major-trace elements (Fig. 3). Previous studies also showed that the Sr–Nd–Pb isotopic data of these samples correlate with each other, with ratios of incompatible elements and with the abundances and ratios of major elements (Niu and Batiza, 1997; Niu et al., 1999, 2002). The large variation in major-trace element and isotope and the correlations are result from source heterogeneity and easily explained by mixing between enriched melt (lower MgO, <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>176</sup>Hf/<sup>177</sup>Hf,

higher incompatible element concentrations and <sup>87</sup>Sr/<sup>86</sup>Sr ratios) and relatively depleted melt. Simple mixing of melts derived from lithologically distinct enriched and depleted mantle in variable proportions will result in linear arrays in element-element diagrams, and in all ratio-ratio diagrams in which the denominator element is the same (i.e., A/X vs. B/X diagram) (Langmuir et al., 1978). For the same reason, melting of a source composed of two different lithologies, which are mixed in variable proportions (mixing of sources) but melt to the same extent, also give a straight mixing line. However, the seamount data in this study define curved arrays (Fig. 5), which is inconsistent with the above mentioned mixing. Similar curved arrays have been reported for lavas from the fossil Galapagos Rise (Haase et al., 2011) and seamounts east of the EPR at 12°45′N (Brandl et al., 2012). Variable degrees melting of a two-component mantle in which different lithologies have different trace element and isotope compositions but also different melting behavior may account for the chemical and isotopic variation (Brandl et al., 2012; Haase et al., 2011; Niu and Batiza, 1997; Niu et al., 1999, 2002; Paulick et al., 2010). This concept emphasizes the physical state of a mantle with enriched component as easily melted domains in a more depleted matrix. Increasing evidence suggested that the upper mantle source of oceanic basalts consists of relatively fertile and more refractory lithologies. They have different solidus temperatures and thus begin melting at different depths during adiabatic upwelling. The most important assumption is that the enriched mantle lithologies have lower solidus temperature than the more depleted matrix, thus are preferentially tapped at low degree of melting (Ito and Mahoney, 2005; Prinzhofer et al., 1989; Sleep, 1984). It is evidenced by the clinopyroxenes in residual abyssal peridotites tend to have more radiogenic Nd isotope than lavas from the same section of ridge, indicating a preferential melting of eclogite or pyroxenite with lower Sm/Nd and <sup>143</sup>Nd/<sup>144</sup>Nd ratios during decompression melting (Salters and Dick, 2002). Melting of the fertile lithologies would extract heat from the more refractory matrix, and inhibit the melting of the latter; once

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Fig. 3. Diagram of correlations between Hf isotopic data in this study and the abundances of major and trace elements. Major and trace elements are from Niu and Batiza (1997).

the more refractory lithologies begin to melt, the remaining fertile materials may stop melting (Phipps Morgan, 2001), and the melting paths may be curved.

There have been several attempts to quantify the range in melt compositions produced by melting of two-component mantle (Ito and Mahoney, 2005; Phipps Morgan, 2001; Phipps Morgan and Morgan, 1999; Stracke and Bourdon, 2009). The contribution of fertile lithologies decreased with the increasing degrees of melting, and lavas produced at lower degree of melting are expected to have higher incompatible element concentrations, higher <sup>87</sup>Sr/<sup>86</sup>Sr, and lower <sup>143</sup>Nd/<sup>144</sup>Nd ratios (e.g., Stracke and Bourdon, 2009).

In the following section, the melting model of Stracke and Bourdon (2009) was used to quantitatively model the melt compositions derived from melting of a two-component mantle, in order to investigating the effects of varying solidus temperature, initial proportion of each component, and compositions of both endmembers, and constraining the mantle heterogeneity beneath the EPR.

# 4.2.2. Quantitative modeling of the melting process

The trace-elemental and isotopic compositions, melting behavior, and initial proportion ratio of each component all play an important role in determining melt compositions. Here we assume the simplest case of a two-component mantle, consisting of a volumetrically minor enriched component dispersed in the depleted peridotite matrix. The initial proportion of enriched component is assumed to be no more than 10%. These two components have different solidus temperatures and thus begin melting at different depths during upwelling. Peridotite melting is assumed to start at ~2.5 GPa, and the beginning depth of the enriched component melting is significantly deeper than to similar to that of peridotite melting (Stracke and Bourdon, 2009). Mineral modes and partition coefficients are given in Appendix 1.

The origin of enriched component is unclear, but likely results from subduction and recycling of oceanic crust, sediments, metasomatized oceanic lithosphere or mantle wedge material (e.g., Donnelly et al., 2004; Hofmann and White, 1982; Niu and O'Hara, 2003).

Recycled ancient oceanic crust might be the enriched component (i.e., ROC model) (e.g., Hofmann and White, 1982), although Niu and O'Hara (2003) suggested that oceanic crust is isotopically too depleted. As a variant of the ROC model, Donnelly et al. (2004) suggested that low-degree melts of subducted oceanic crust could metasomatize the overlying mantle wedge, and the metamomatized mantle wedge could recycle by mantle convection to the ridge supplying enriched MORB (E-MORB) source. One difficulty with the model is that the cold oceanic crust that has undergone dehydration may be too refractory to melt at subduction zone. Another problem is that mantle convection model (Hofmann, 1997; Tolstikhin et al., 2006) may not support this scenario, and the mantle wedge "corner flow" (Niu, 2005) is blocked by the subducting slab, thus, it is difficult for the metasomatized mantle wedge to reach the ocean ridge. Terrigenous sediments may provide enriched composition to depleted mantle (DM) source because few OIB source may have a component of subducted terrigenous sediments (Jackson et al., 2007; Mahoney et al., 1995). However, continental crust



Fig. 4. Correlations of Hf isotopes with Sr–Nd–Pb isotopes and with ratios of incompatible elements for near-EPR seamount lavas. The correlations are best interpreted as resulting from melting-induced mixing of a two-component mantle with the enriched component dispersed as physically distinct domains in the more depleted matrix. The correlations also indicate that both the enriched component and the depleted matrix are ancient and have developed their isotopic signatures independently. The Sr–Nd–Pb isotope data are from Niu et al. (2002) and the trace-elements are from Niu and Batiza (1997). Data for ridge axis MORB from EPR 5–15°N are from Sims et al. (2002), Salters et al. (2011), and Gale et al. (2013).

(CC) and global subducting sediments (GLOSS) are characterized by depletions in Nb, Ta, P and Ti and enrichment in Pb (Plank and Langmuir, 1998; Rudnick and Gao, 2003). Such a "CC-like signature" is so strong that it should be inherited in the incompatible element characteristics of OIB and E-MORB if terrigenous sediments were indeed the enriched component of DM (Niu et al., 2012). However, it is not observed in global oceanic basalts except for two OIB suites (Jackson et al., 2007; Mahoney et al., 1995). Furthermore, there is no convincing evidence that the terrigenous sediments are the geochemically enriched components of DM on global scale. Recycled metasomatized oceanic lithospheric mantle (ROLM) had also been proposed as a possible enriched component (Niu, 2008, 2009; Niu and O'Hara, 2003, 2009; Niu et al., 2011, 2012). The deep portion of oceanic lithospheric mantle can be enriched in terms of incompatible elements throughout its long histories through mantle metasomatism by low-degree melt. The melt collects atop the seismic low velocity zone (LVZ), and then percolates through and metasomatizes the growing lithosphere via basal accretion. The percolating/metasomatizing Low-degree melt can precipitate mineral phases (e.g., amphiboles; "macroscopic metasomatism") before finally absorbed ("cryptic metasomatism") in the lithosphere, generating metasomatically veined mantle (e.g., Niu, 2008).

No matter what the enriched component is (recycled crust or lithospheric mantle), the complex process (i.e., melting, metasomatism, and dehydration during subduction) that they had undergone would increase difficulties in determining their initial trace-element and isotopic compositions. Nevertheless, previous research suggested that the enriched endmember of MORBs array in Hf–Nd isotopic diagram tends to plot either within or in the extension of the OIB array, and none of them towards the HIMU component (Salters et al., 2011). Thus, the previous published trace element and isotopic compositions of pyroxenite (recycled MORB), EM1 and EM2 were used to represent that of the enriched component in the modeling. The isotopic compositions of pyroxenite, EM1 and EM2 are from Ito and Mahoney (2005). And the trace element compositions of pyroxenite, EM1 and EM2 are

from Stracke and Bourdon (2009), Willbold and Stracke (2006), and Workman et al. (2004), respectively.

The compositions of depleted endmember are generally estimated from the compositions of oceanic basalts and abyssal peridotites. Actually, the estimated compositions of depleted MORB mantle (DMM) based on that of abyssal peridotites might more faithfully reflect the characteristics of depleted upper mantle due to that the enriched component had been exhausted. And the MORBs, including the most depleted Garrett Transform lavas, are enriched than depleted endmember (discussed below). It is supported by the abyssal peridotites that components of the upper mantle beneath spreading ridges, which have more radiogenic Nd and Hf isotope compositions than those of lavas from the ridge (Salters and Dick, 2002; Stracke et al., 2011). Thus, the estimated composition of DMM mantle based on numerous abyssal peridotites following Workman and Hart (2005) were used here as the depleted endmember in the modeling. The assumption may or may not be realistic, however, it is reasonable. Further researches are needed to better constrain the compositions of depleted/enriched endmembers.

The results of fractional melting model following Stracke and Bourdon (2009) are shown in Figs. 5-7. The enriched components are assumed to preferentially melting than the more depleted matrix. The parameters used in the modeling are summarized in Appendix 1. The compositions, mineralogy, melting behavior, and proportion of both components must be more various than that used in the modeling, however, the melting curves still provide important clues on melting of a heterogeneous mantle that composed of at least two component (i.e., enriched and depleted component). Then, the effects of different variables on melt compositions would be discussed below.

The melting modeling can broadly reproduce the range in compositions of the seamount lavas in this study (Figs. 5, 6, 7). In the La/Nd versus Yb/Nd and La/Yb versus Sm/Yb diagram (Fig. 5), variable degrees of melting of a heterogeneous mantle fit the curved array defined by EPR seamount lavas that mentioned above, which is contrast with the



Fig. 5. Variation of (a) Yb/Nd with La/Nd and (b) La/Yb with Sm/Yb for lavas from seamounts flanking the East Pacific Rise (EPR) between 5° and 15°N. Curves show range in pooled melt compositions produced by variable degrees of fractional melting of a two-component mantle source consisting of 10% enriched component and 90% depleted matrix, calculated using the method of Stracke and Bourdon (2009). The mass fractions of enriched endmembers are labeled. The enriched component is assumed to have a lower solidus temperature and therefore contributes more to melting at low melt fractions, compared to the more refractory matrix, which begins melting at a slightly lower pressure. Thus, unlike two-component mixing of melts or sources that result in linear arrays on these diagrams, the resulting melt evolution paths are curved because with increasing degree of melting, the contribution to the pooled melt from the more fertile component progressively decreases, which reproduce the data array defined by lavas from seamounts in this study. Detailed parameters used in modeling are given in Appendix 1. Data for northern EPR axial MORBs are from Salters et al. (2011), Donnelly (2002), Chauvel and Blichert-Toft (2001) and references therein. "Pyroxenite" endmember

linear arrays of simple mixing. The melting curves have similar trend, however, the "pyroxenite" endmember fits best to the seamount data in this study and also the previous published axial MORB from EPR 5–15°N. The deviation of "EMI" trajectory from the seamount data, especially in Fig. 5b, most likely results from the extremely higher incompatible element concentration and the higher degree of fractionation between LREEs and HREEs in "EMI" source. Meanwhile, the degree of enrichment in incompatible element increased with the increasing incompatibility. Consequently, the "EMI" endmember is too enriched to fit the seamount lava in Fig. 5b, although the increasing degrees of melting. Previous researches suggested that the curvature of melt curves increased with the increasing proportion of enriched endmember relative to depleted endmember (see Fig. 8c in Brandl et al., 2012). And increase in enriched component/depleted component

ratio may lead the EMI endmember to better fit the seamount data in Fig. 5a, however, it is invalid in Fig. 5b.

The effects of difference in solidus temperatures between the two endmembers on melt compositions were shown in Fig. 6. Peridotite melting is assumed to start at ~2.5 GPa (Stracke and Bourdon, 2009). And the melt evolutionary paths that the beginning depth of the enriched component melting is assumed to be similar to and significantly deeper than that of peridotite melting were exhibited in solid lines and dashed lines, respectively. The largest melt heterogeneity in the ratios of trace element is observed for small differences in solidus temperature is too large, the enriched component would be completely exhausted before peridotite melting, and the clear correlations between trace element and isotope ratios of the seamount lavas in this study would not be observed in the pooled melts (Fig. 6). The seamount data



**Fig. 6.** Variation of (a) La/Sm vs. <sup>143</sup>Nd/<sup>144</sup>Nd and (b) Nb/Zr vs. <sup>87</sup>Sr/<sup>86</sup>Sr for lavas from seamounts flanking the East Pacific Rise (EPR) between 5° and 15°N. The symbols are the same as in Fig. 5. The different trends reflect mixtures of melts from peridotite matrix and enriched component with different solidus temperatures. Peridotite melting is assumed to start at about 2.5 GPa in the spinel stability field. The dashed lines and solid lines represent the onset of enriched component melting from depths significantly deeper (i.e., great difference in solidus temperature between the two components) and depths similar to the onset of peridotite melting (i.e., small difference in solidus temperature), respectively. The composition of depleted mantle is from Workman and Hart (2005). The pyroxenite represents a 2 Ga old recycled MORB that has undergone chemical modification during subduction and is isotopically similar to FOZO (Stracke and Bourdon, 2009). The isotopic composition of EM1 and EM2 is from Ito and Mahoney (2005). The large variation in La/Sm and Nb/Zr ratios and their good correlations with isotopes indicating a small difference in solidus temperature between the two components. "EM1" endmember seems to better reproduce the array.

lies between the melt curves at different solidus temperatures, and "EM1 /EM2" endmember, especially in condition that the solidus temperatures of the two endmembers are similar, could better reproduce the seamount data. The "pyroxenite" endmember is significantly depleted in Sr isotope than the enriched seamount lavas (Fig. 6b), indicating that "pyroxenite" endmember is not a reasonable enriched component or other enriched components must also involve in the source. The melting modeling in correlations between Sr–Nd–Pb isotopes further supported that the enriched component might be complex, and it is most likely composed of EM1 and/or pyroxenite (Fig. 7). Melt compositions in assumption that the initial proportion of EM1 and pyroxenite is 0.06 and 0.04, respectively, can match well with the isotopic compositions of seamount lavas (Fig. 7b, c).

In summary, the large variation in trace element ratios (e.g., La/Sm and Nb/Zr) and isotope of seamount lavas in this study and the correlations between them are the result of melting of a heterogeneous mantle.

And "EM1" and/or "pyroxenite" as the enriched component could better fits the seamount data and axial MORB from EPR at 5–15°N both in trace element and isotope compositions in the modeling. Thus, we infer that the metasomatized lithospheric mantle and/or oceanic crust might be the reasonable enriched component in mantle source beneath northern EPR. The parameters used in the modeling should be further constrained.

Furthermore, the most depleted seamount lavas in this study and previous published axial MORB from northern EPR approximate to the depleted endmember, however, it is enriched than the mantle source. Previous researches also suggested that the average incompatible trace element and isotope composition of mantle source is significantly more depleted than mantle-derived magmas (e.g., Brandl et al., 2012; Stracke and Bourdon, 2009). Oceanic basalts were often used to infer the composition of the upper mantle. However, if melting of twocomponent mantle is common and an important process, then the



**Fig. 7.** Isotope ratios of lavas from seamounts flanking the East Pacific Rise (EPR) between 5° and 15°N. The initial depleted:enriched component ratio is assumed to be 90:10. Large open circles show assumed isotope ratios of each component. The dashed curves in figure (b) and (c) using a mixture of 0.06:0.04 EM1:pyroxenite as the enriched component. Px = pyroxenite,  $\phi_m = initial$  proportion of EM1/EM2, and initial proportion of pyroxenite =  $0.1 - \phi_m$ . Data for ridge axis MORB from EPR 5–15°N are from Sims et al. (2002), Salters et al. (2011), and Gale et al. (2013). The EM1 and/or pyroxenite as the enriched component can reproduce the seamount arrays.

studies of oceanic basalts that assume that the isotope compositions of basalts are identical to those of their mantle source might be wrong.

#### 4.3. Implications for Hf-Nd isotopic variations on a global scale

Previous studies show that there is a good correlation between Hf and Nd isotope for global MORBs (e.g., Chauvel et al., 2008; Vervoort et al., 2011). However, a later comprehensive study of MORBs (Salters et al., 2011) shows that the  $\varepsilon_{Hf}$  values of global MORBs vary widely at given  $\varepsilon_{Nd}$  value. Here we use  $\Delta \varepsilon_{Hf}$  values to describe the derivation of the measured  $\varepsilon_{Hf}$  value from that of the mantle array defined by Chauvel et al. (2008), i.e.,  $\varepsilon_{Hf} = 1.59\varepsilon_{Nd} + 1.28$ . It is obvious that the  $\Delta \epsilon_{Hf}$  values of Pacific MORBs, Atlantic MORBs and Indian MORBs are different (Fig. 8b). In general, MORBs and seamount lavas of Pacific spreading centers have the lowest and relatively constant  $\Delta \varepsilon_{Hf}$  values (Fig. 8). However, Atlantic and Indian MORBs range widely in  $\Delta \varepsilon_{Hf}$ values, and the Atlantic MORBs, especially the North Atlantic MORBs, have the highest  $\Delta \varepsilon_{Hf}$  values (Fig. 8). The fundamental reason must be the global scale heterogeneity of DMM, i.e., the large variations in  $\Delta \epsilon_{Hf}$  values are most likely dominated by local variations of source compositions. The above discussed fractional melting modeling of a heterogeneous mantle also supported that the isotopic composition of melt is mainly controlled by source compositions, melting behavior and initial proportion of each component. Addition of a component with high  $\Delta \varepsilon_{Hf}$  values to the mantle source might lead the melt towards high  $\Delta \varepsilon_{\text{Hf}}$  values on different extent. The mantle component with high  $\epsilon_{Hf}$  value is most likely to be the residues of ancient melting events with garnet present as a residual phase. The partition coefficients of Lu between garnet and basaltic liquids is much higher than that of Hf (i.e.,  $D_{Lu}/D_{Hf} \gg 1$ ), and the residues produced by melt extraction at great depth where garnet is stable and as a residual phase of the source would impart an elevated Lu/Hf ratios and evolve to high <sup>176</sup>Hf/<sup>177</sup>Hf in the residues if the partial melting event is ancient (e.g., Schmidberger et al., 2002). Salters et al. (2011) proposed that various amounts of residual oceanic lithosphere (ReLish) can account for the variation in  $\epsilon_{\rm Hf}$  value at constant Nd isotope. And the amount of ReLish that contributes to the Pacific MORB was suggested to be relatively constant and that various widely as to Atlantic and Indian MORBs (Salters et al., 2011). The more uniform  $\Delta \epsilon_{\rm Hf}$  value of Pacific MORB may also simply reflect the fact that melt mixing in magma chambers at fast-spreading ridges is more efficient (Rubin and Sinton, 2007).

Alternatively, the sub-continental lithospheric mantle (SCLM) was also proposed to be a suitable component to produce the high Hf isotope of lavas from Lucky Strike Ridge that along the northern Mid-Atlantic Ridge (Hamelin et al., 2013). The Pacific spreading center is always suggested to be ancient and not associated with the continental rifting, thus, the continental lithospheric mantle is absent or exhausted. In contrast, the opening time of Atlantic and Indian spreading center is no longer than 200 Ma, and the continental lithospheric mantle that detached into the upper mantle can feed the MORB source. It had been approved that the continental materials could introduce into the Atlantic-Indian upper mantle during continental rifting (e.g., Torsvik et al., 2013). Furthermore, ancient depleted continental lithospheric mantle with extremely radiogenic Hf isotopes had been observed (Bedini et al., 2004; Chu et al., 2009; Schmidberger et al., 2002; Simon et al., 2007). Although the Hf and Nd isotopic compositions of SCLM range widely from negative to positive values, most of them have extremely high  $\varepsilon_{\text{Hf}}$  value (even to +200) (Fig. 8) that can interpret the lowest and relatively constant  $\Delta \epsilon_{Hf}$  values for Pacific MORBs and largely various and higher  $\Delta \varepsilon_{\rm Hf}$  values for Atlantic and Indian MORBs.



**Fig. 8.** (a)  $\varepsilon_{Hf}$  versus  $\varepsilon_{Nd}$  and (b)  $\Delta\varepsilon_{Hf}$  versus  $\varepsilon_{Nd}$  diagram of global MORBs. In general, Atlantic MORBs and Pacific MORBs have the highest and the lowest  $\varepsilon_{Hf}$  values at given Nd isotopes, respectively, and Indian MORBs lie between them. In order to show more clearly, the average values are also plotted. The mantle array is  $\varepsilon_{Hf} = 1.59\varepsilon_{Nd} + 1.28$  (Chauvel et al., 2008). The published data is from Agranier et al. (2005), Blichert-Toft et al. (2005), Chauvel and Blichert-Toft (2001) and references therein, Debaille et al. (2006), Dosso et al. (1993), Douglass and Schilling (1999), Fontignie and Schilling (1996), Graham et al. (2006), Hamelin et al. (2011), Hanan et al. (2004), Janney et al. (2005), Kempton et al. (2000, 2002), Klein et al. (1988), Mahoney et al. (2002), Meyzen et al. (2007), Nowell et al. (1998), Patchett (1983), Patchett and Tatsumoto (1980), Pyle et al. (1992), Salters (1996), Salters and White (1998), Salters et al. (2001), and references in  $\Delta\varepsilon_{Hf}$  values between Pacific, Atlantic and Indian MORBs likely results from various contribution of residual continental lithospheric mantle with high  $\Delta\varepsilon_{Hf}$  values. Data for SCLM are from Bianchini et al. (2007), Carlson et al. (2004), Chu et al. (2007), Lapen et al. (2005), Schmidberger et al. (2002), Simon et al. (2007), and Wittig et al. (2007).

## 4.4. Pseudochron ages

Fig. 9 shows that our samples give Rb–Sr, Sm–Nd and Lu–Hf pseudochron ages of  $182 \pm 33$  Ma,  $276 \pm 50$  Ma and  $387 \pm 93$  Ma, respectively. The ages have been reported at other locations of ocean ridge and nearby seamounts (Donnelly et al., 2004; Niu et al., 1996; Zindler et al., 1984). Zindler et al. (1984) suggested that the Sm–Nd pseudochrons of near-EPR seamounts have age significance and interpreted that to be controlled by (1) the position of depleted and enriched end-member in <sup>143</sup>Nd/<sup>144</sup>Nd vs. Sm/Nd space and (2) independent magma source of two end-members. The Rb–Sr and Sm–Nd pseudochron ages of near-EPR seamounts (187 Ma and 238 Ma,

respectively) are similar to our results, which were interpreted to provide constraints on the origin and timing of E-MORB source enrichment (Donnelly et al., 2004). However, Niu et al. (1996) suggested that these pseudochrons are statistically significant mixing trends without chronological significance.

These ages shown by different radioactive decay systems are nonconformable, suggesting that the "ages" are of no chronological significance, but are best explained as results of melting-induced mixing with the pseudochron slopes controlled by the compositions of the enriched component and the depleted end-member. The fractional melting modeling can reproduce the arrays to a first order (Fig. 9) with the "EM1" endmember fitting the seamount data better. It is



**Fig. 9.** The correlations between parent–daughter and isotopes ratios for Rb–Sr, Sm–Nd and Lu–Hf give pseudochron ages of  $182 \pm 33$  Ma,  $276 \pm 50$  Ma and  $387 \pm 93$  Ma, respectively. These different "ages" have no age significance, but are best explained as resulting from melting-induced mixing with the pseudochron slopes controlled by the compositions of the enriched component and the depleted end-member. The two end-members have independently developed their distinct chemical and isotopic signatures. The symbols are the same as in Fig. 4. The fractional melting modeling can reproduce the arrays. The trace-element and Sr–Nd isotope compositions are from Niu and Batiza (1997) and Niu et al. (2002). Data for ridge axis MORB from EPR 5–15°N are from Sims et al. (2002), Salters et al. (2011), and Gale et al. (2013).

consistent with the above conclusion that "EM1" is a possible origin of enriched component. The source mantle contains a volumetrically minor enriched component, and with increasing degree of melting, the contribution to the pooled melt from the more fertile component with higher Rb/Sr, <sup>87</sup>Sr/<sup>86</sup>Sr, and lower Sm/Nd, Lu/Hf, <sup>143</sup>Nd/<sup>144</sup>Nd, <sup>176</sup>Hf/<sup>177</sup>Hf ratios progressively decreases.

# 5. Conclusions

- New Hf isotopic data of basaltic glasses from seamounts flanking the EPR between 5° and 15°N demonstrate that Hf and Nd isotopes of these lavas are correlated and form a well-defined trend that parallels to the mantle array.
- 2. The correlated Hf–Nd isotopic variations, together with their correlations with Sr–Pb isotope as well as with abundances and ratios of incompatible elements, suggest that the geochemistry of EPR and near-EPR seamount lavas is most consistent with melting-induced mixing of a two-component mantle (i.e., an easily-melted enriched component dispersed in the more depleted refractory matrix).
- 3. Fractional melting modeling of a heterogeneous mantle can reproduce the variations in trace-element and isotope compositions of seamount lavas. "Pyroxenite" and/or EM1 endmember better fits the data, indicating that the enriched component is most likely to be recycled oceanic crust or metasomatized oceanic lithospheric mantle.
- 4. The contribution of residual continental lithospheric mantle may interpret the difference in  $\Delta\epsilon_{Hf}$  values between Pacific, Atlantic and Indian MORBs.
- The Rb–Sr, Sm–Nd and Lu–Hf pseudochrons have no age significance, but are mixing lines constrained by the composition of the enriched component and the depleted end-member.

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