Earth and Planetary Science Letters 426 (2015) 293–304

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Depleted components in the source of hotspot magmas: Evidence from the Ninetyeast Ridge (Kerguelen)

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ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form 6 April 2015
Accepted 1 June 2015
Available online 9 July 2015
Editor: T. Elliott

Keywords:
Kerguelen hotspot
Ninetyeast Ridge
source of hotspot magmas
trace element geochemistry
radiogenic isotopic compositions
depleted basalt

ABSTRACT

Although most ocean island basalts (OIB) are enriched in incompatible elements relative to mid-ocean ridge basalts, OIB depleted in these elements also occur on some islands. The Ninetyeast Ridge (NER) in the eastern Indian Ocean is a 5000 km long hotspot track defined by submarine basaltic volcanoes that were islands when they formed from 43 to 77 Ma. A subset of NER basalts, described as depleted, has high abundances of Sc, Y and Lu, which are relatively compatible in clinopyroxene and especially in garnet. It is unusual for magmas to have the trace element characteristics of a mineral. A likely explanation is that the depleted NER basalts were derived from a source that was created as a garnet- and clinopyroxene-bearing residue during partial melting. When this residue formed, the extent of melting must have been low as not all of the garnet and clinopyroxene was melted. To provide sufficient time for the relatively high Lu/Hf of the residue to develop the high $^{176}Hf/^{177}Hf$ that is characteristic of depleted NER basalts, this melting event must have been ancient. In the second much younger melting event that formed the NER, the extent of melting was sufficiently high to eliminate garnet and clinopyroxene from the ancient residue. Basalts erupted on a segment of the Mid-Atlantic Ridge near the Azores were also derived from an ancient garnet-bearing residue. Residues from ancient partial melting events involving low extents of melting are the dominant source of mid-ocean ridge basalts and depleted magmas associated with the Kerguelen and Azores hotspots. In contrast, a very different process has been inferred for creating the source of depleted Icelandic basalts. Their source was gabbro containing cumulate plagioclase and clinopyroxene. Such gabbros are common in the lower oceanic crust, and if recycled into the Icelandic hotspot they are a source of depleted Icelandic basalts.

1. Introduction

Relative to basalts erupted at mid-ocean ridges (MORB), most basaltic lavas erupted at hotspots, such as Hawaii, Samoa, Galapagos, Kerguelen and Iceland, have high $^{87}Sr/^{86}Sr$ coupled with low $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, and higher ratios of (highly incompatible elements)/(moderately incompatible elements) (e.g., Hofmann, 1988, 2004; White, 2010). Consequently these hotspot basalts are described as enriched. Relative to primitive mantle (PM), most MORB have lower $^{87}Sr/^{86}Sr$ coupled with higher $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$, and lower abundance ratios of (highly incompatible elements)/(moderately incompatible elements), and are described as depleted. There is a consensus that MORB are derived from sources that formed as residues created in ancient melting events (e.g., Hofmann, 1988, 2004).

Some hotspot-related lavas have depleted geochemical characteristics; the origin of a depleted component in hotspot-derived magmas is debated. A possible source for depleted magmas erupting at hotspots is MORB, or the source of MORB, that was entrained in an ascending mantle plume and sampled during decompression melting. The depleted MORB-like lavas in some Galapagos volcanoes have been interpreted as a result of thermal and dynamic interaction of the Galapagos mantle plume with overlying MORB-related oceanic lithosphere and shallow asthenosphere (Blichert-Toft and White, 2001; White et al., 1993). A role for

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http://dx.doi.org/10.1016/j.epsl.2015.06.005
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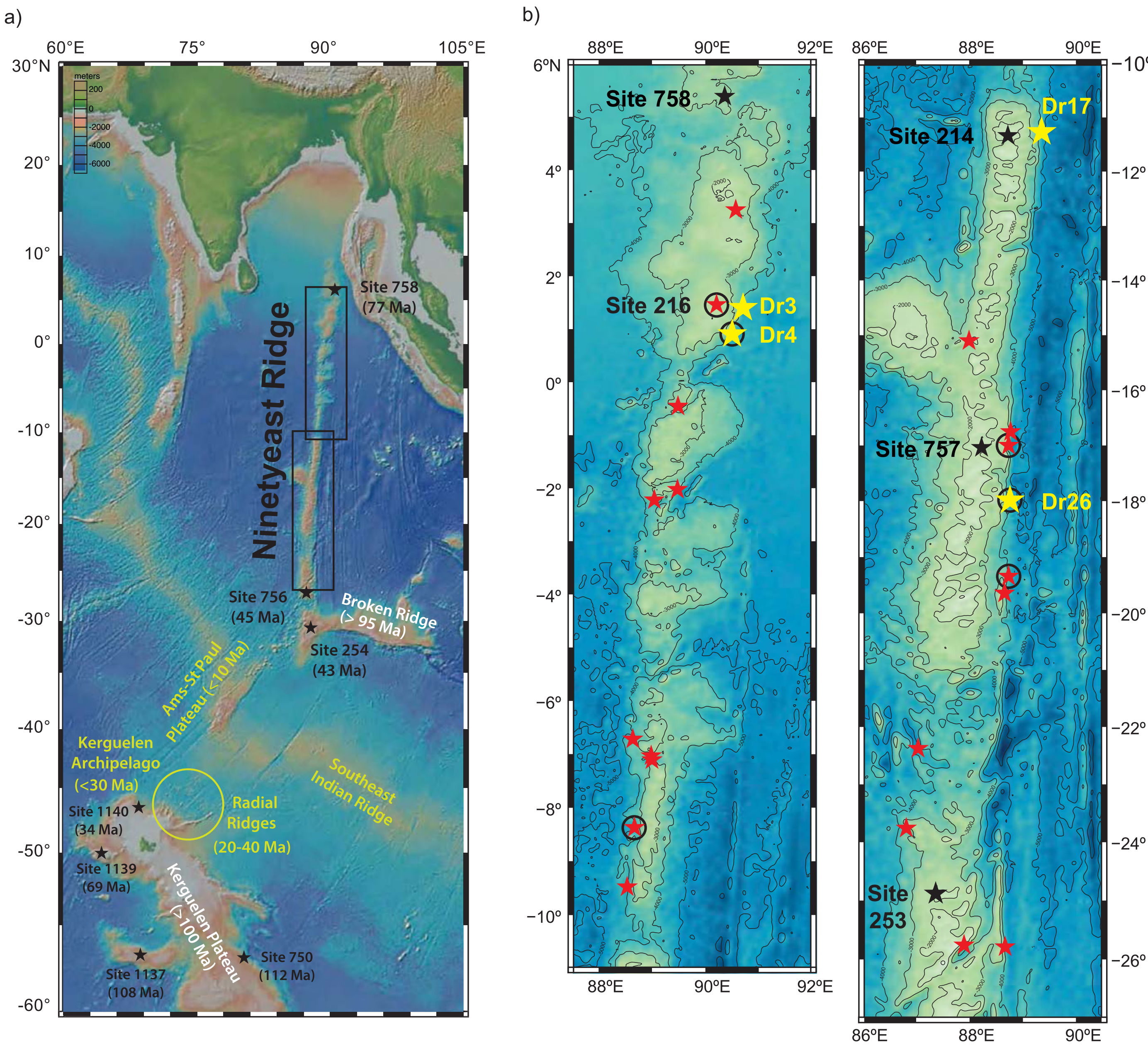

Fig. 1. Bathymetry of the Eastern Indian Ocean and Ninetyeast Ridge (created using GeoMapApp: http://www.geomapapp.org; interval contours are 1000 m). **(a)** Major bathymetric features of the Eastern Indian Ocean with ages in parentheses for Drill Sites 254, 756 and 758 on the Ninetyeast Ridge (NER), Drill Sites 1139 and 1140 on the northern Kerguelen Plateau, Drill Site 1137 on Elan Bank, and Drill Site 750 on the Central Kerguelen Plateau (all indicated by black stars). Age data are from Coffin et al. (2002) and Pringle et al. (2011). The two rectangles indicate regions of the NER shown in panels (b) and (c). **(b)** and **(c)** Bathymetry of the northern and southern NER, respectively. NER dredge locations that recovered basalt are indicated by yellow stars (dredges 3, 4, 17 and 26) and red stars (18 other dredges); red stars with black rims indicate locations with volcanic glasses (Frey et al., 2011) and black stars indicate drill sites that recovered basalt core. (For interpretation of color see Fig. 1 in web version.)

MORB in hotspot related magmas is especially plausible when the hotspot is located near a spreading ridge, e.g., Iceland and the Reykjanes Ridge (Schilling, 1973), the oldest volcanoes in the Hawaiian–Emperor hotspot track (Keller et al., 2000), and the oldest (28–29 Ma) lavas erupted in the Kerguelen Archipelago (Doucet et al., 2002; Gautier et al., 1990; Yang et al., 1998).

Rather than being related to MORB an alternative hypothesis is that depleted components are intrinsic to the hotspot (e.g., Kerr, 1995). Specifically, a depleted component intrinsic to the Icelandic hotspot and compositionally different from North Atlantic MORB has been inferred from trace element abundance ratios (Chauvel and Hemond, 2000; Fitton et al., 1997, 2003; Langmuir et al., 1978) and radiogenic isotopic ratios (Kempton et al., 2000; Taylor et al., 1997; Thirlwall, 1995; Thirlwall et al., 2004) of depleted Icelandic basalts. The inference for an intrinsic depleted component in the Icelandic hotspot has been challenged (Hanan et al., 2000; Stracke et al., 2003).

The Ninetyeast Ridge (NER) in the Eastern Indian Ocean is a 5000 km long chain of submarine volcanoes ranging in age from 77 Ma at ODP Drill Site 758, where the NER is covered by Bengal Fan sediments, to 43 Ma at ODP Drill Site 254, near Broken Ridge that was separated from the Kerguelen Plateau by formation of the Southeast Indian Ridge (Fig. 1). The 2007 cruise KNOX06RR of the Roger Revelle collected 2238 kg of basalt by dredging at

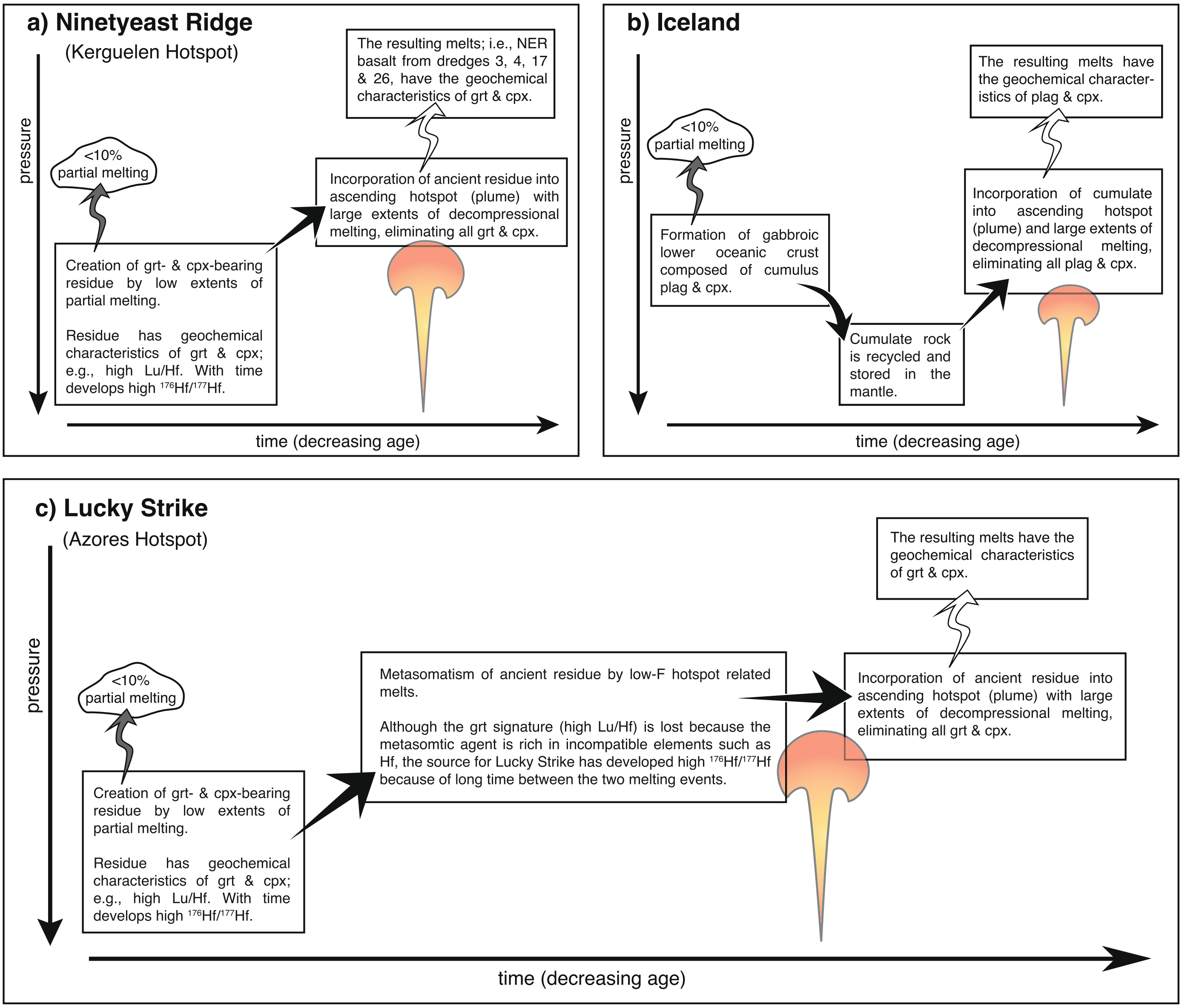

Fig. 2. Sequence of processes showing how the depleted components formed at three hotspots: **(a)** Ninetyeast Ridge where the depleted components formed as garnet- and clinopyroxene-bearing residues during ancient partial melting (this paper); **(b)** Iceland where the depleted components formed as plagioclase and clinopyroxene cumulates in lower oceanic crust that was recycled into mantle and incorporated into the Icelandic hotspot (Chauvel and Hemond, 2000); **(c)** Lucky Strike segment of the Mid Atlantic Ridge near the Azores where the depleted components formed as garnet- and clinopyroxene-bearing residues during ancient partial melting. However, the initial depletion in incompatible elements was eliminated by recent metasomatism, that is mixing with an incompatible element enriched melt derived by low extents of melting of the Azores plume (Gale et al., 2011; Hamelin et al., 2013).

21 locations along the NER (Fig. 1). Our major objective is to obtain and use geochemical and geochronological data for dredged NER basalts to understand the sources and processes that created the NER.

Based on incompatible element ratios of basaltic glasses dredged from the NER and isotopic ratios of Sr, Nd, Hf and Pb for NER basalt from three Ocean Drilling Program drill sites, Frey et al. (2011) and Nobre Silva et al. (2013) concluded that magmas forming the NER contain a depleted component that is geochemically distinct from the source of Southeast Indian Ridge (SEIR) MORB. Frey et al. (2011) inferred that this depleted component originated as a garnet- and clinopyroxene-bearing residue created in an ancient melting event; the extent of melting was insufficient to eliminate garnet and clinopyroxene from this residue. Subsequently, these residues were partially melted to a large extent consuming all of the garnet and clinopyroxene; consequently, these second stage melts have the geochemical signature of the garnet- and clinopyroxene (Fig. 2a).

Basaltic glasses are not abundant on the NER. In this paper we use selected trace element abundance data for 213 whole–rock basalts obtained by dredging the NER, and 74 whole–rock basalts from drill cores recovered at ODP Leg 121 Drill Sites 756, 757 and 758 (Fig. 1). We integrate the trace element and isotopic data sets for dredged basalt and basalt recovered in drill cores from ODP sites 756, 757 and 758 to better characterize this depleted component, to determine its importance in constructing the NER, to understand its origin, and to constrain the time of its formation.

2. Analytical procedures

Except for one dredge all of the NER rocks recovered by drilling and dredging are tholeiitic basalt. Although unaltered glass occurs in pillow basalt from four dredges (Frey et al., 2011), minerals that formed during exposure to seawater are abundant in all samples. Based on observation of hand specimens, rocks with the lowest extent of alteration were selected for study. Avoiding alteration veins and filled vesicles, they were sawed into rectangular slabs. After washing in fresh water, the slabs were broken into 0.5 cm chips using a Rock Labs hydraulic crusher. The chips were washed in distilled water, dried and 100–200 g were ground to a fine powder in a Spex shatterbox using an agate container and puck.

Because our objective is to understand igneous processes that formed the NER, in this paper we focus on trace elements and isotopic ratios that are relatively insensitive to post-magmatic alteration (e.g., Pearce, 1996). Specifically we use abundance data for the trace elements: Sc, Y, Zr, Hf, Nb, Th and the rare earth elements (La, Sm, Nd, Tb, Yb and Lu), and isotopic ratios of Nd and Hf. Trace element concentrations were measured on unleached powders, whereas isotopic ratios were measured on acid-leached powders (Nobre Silva et al., 2009, 2010). Abundance of Nb, Zr and Y were determined by X-ray fluorescence in the laboratory of J.M. Rhodes at the University of Massachusetts, using the procedure of Rhodes and Vollinger (2004). Abundance of Sc, La, Nd, Sm, Tb, Yb, and Hf were determined by inductively-coupled plasma mass spectrometry at Harvard University following the procedures of Huang and Frey (2003) and Rhodes et al. (2012). Isotopic analyses of Nd and Hf were performed at the Pacific Center for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia, on a single dissolution of acid-leached whole rock powders (Nobre Silva et al., 2010). Nd and Hf isotopic ratios were determined by MC-ICP-MS on a Nu Plasma system (Nu Instruments Ltd, UK), under dry plasma conditions, using a membrane desolvator (Nu DSN100) for sample introduction, following analytical procedures detailed by Weis et al. (2006, 2007).

Trace element abundances and isotopic ratios are reported in Table A1. This table also includes the mean values of USGS reference material, BHVO-2, analyzed during the course of this study and results for the Rennes Nd and the JMC 475 Hf standard solutions; results for these isotopic standards are in good agreement with the data reported by Weis et al. (2006, 2007). Table A2 includes the same types of data for 74 drill core samples from ODP Leg 121 Drill Sites 756, 757 and 758 on the NER (Fig. 1). Papers presenting and interpreting the entire geochemical data set, i.e., major and trace element concentrations of 213 whole–rock basalt selected from the 21 dredges and Sr, Nd, Hf and Pb isotopic ratios for the subset of 59 chosen for isotopic studies are in preparation.

3. Results

Relative to SEIR MORB, NER basalts are enriched in highly incompatible trace elements, such as Nb; for example, NER basalts have higher Nb/Y at a given Zr/Y, (Fig. 3a). Also the relatively high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and low $^{176}Hf/^{177}Hf$ of NER basalts require a long-term source with higher Rb/Sr and lower Sm/Nd and lower Lu/Hf than the MORB source (Fig. 9 of Nobre Silva et al., 2013). Based on location, calculated plate motions, and the geochemical similarities of NER basalts with basalts forming the Kerguelen Archipelago, a role for the Kerguelen hotspot has been inferred for construction of the NER (e.g., Frey and Weis, 1995; Nobre Silva et al., 2013; Saunders et al., 1991; Weis and Frey, 1991; Weis and Scoates, 2009).

In addition to an enriched source component derived from the Kerguelen hotspot, a MORB-related component in the source of Kerguelen Archipelago lavas was proposed by Gautier et al. (1990) and Yang et al. (1998). Doucet et al. (2002) concluded that the oldest (∼29 Ma) tholeiitic basalts exposed in the Kerguelen Archipelago show geochemical evidence for significant involvement of a SEIR MORB or a MORB source component. In contrast, the 24–25 Ma mildly-alkalic basalts from the eastern and southeastern parts of the archipelago show little or no contribution of a MORB-related component. Consistent with a MORB-like component in the source of NER magmas, basaltic samples from 6 of 7 drill cores and 17 of the 21 dredges on the NER have incompatible element abundance ratios that are intermediate between the flood basalt of the Kerguelen Archipelago and SEIR MORB (Fig. 3a, b; Frey et al., 1991, 2011; Frey and Weis, 1995; Meleney et al., 2011; Saunders et al., 1991). However, based on isotopic ratios of Sr, Nd, Hf and Pb for basaltic samples from ODP Drill Sites 756, 757 and 758 on the NER (Fig. 1), Nobre Silva et al. (2013) concluded that a depleted but not MORB-like component was in the source of NER basalt.

The depleted but not MORB-related component in the source of NER basalts is the primary focus of this paper. Like SEIR MORB, most samples from dredges 3, 4, 17 and 26 have Nb/Y and Zr/Y lower than Primitive Mantle (PM); however these depleted NER samples are offset from the SEIR MORB field to higher Nb/Y at a given Zr/Y (Fig. 3a), and to higher Y/Nb at a given Zr/Nb (Fig. 3b). Frey et al. (2011, their Fig. 5b) concluded that the relatively high Y of basaltic glasses from dredges 4 and 26 reflects high Y abundance in garnet-bearing residues of partial melting that were subsequently partially melted to form NER basalt (Fig. 2a). These glasses were analyzed by laser ablation inductively coupled mass spectrometry (Frey et al., 2011) and the whole rocks analyzed in this study were analyzed by both X-ray fluorescence and solution inductively coupled solution mass spectrometry (Table A1). Each of the three data sets shows relatively high Y/Nb in samples from dredges 3, 4, 17 and 26. Clearly the offset of NER basalt to high Y/Nb is not dependent on the analytical technique. It is significant that enrichment of Y is accompanied by enrichment in Sc and Lu (Fig. 4a, b, c). These three elements are compatible in garnet relative to a basaltic melt (Table B1).

4. Discussion

4.1. *Mineralogy of the depleted component in the source of NER basalts*

4.1.1. *The role of garnet in the ancient melting event: constraints from the relative enrichment of Y, Sc and Lu in NER lavas from dredges 3, 4, 17 and 26*

During partial melting of garnet lherzolite the abundances of Y, Sc and Lu in the melt are dominantly controlled by coexisting clinopyroxene and garnet. Comparison of measured and calculated ratios of Zr/Nb, Y/Nb, Sc/Nb and Lu/Nb in residues formed by dynamic melting of spinel peridotite and garnet peridotite show that the relatively high Y/Nb, Sc/Nb and Lu/Nb at a given Zr/Nb of dredge 3, 4, 17 and 26 samples can be created by partial melting of either spinel peridotite or garnet peridotite (Fig. 4a, b, c).

Comparison of the partition coefficient ratio D_{Lu}/D_{Tb} for garnet and clinopyroxene shows that garnet is much more effective in fractionating Lu/Tb than clinopyroxene (see Appendix B for mineral/melt partition coefficients). Consequently, supporting evidence for garnet in the residue created during the ancient melting event is the relatively high $(Lu/Tb)_{PM}$ (>1) of basalts from dredges 3, 4, 17 and 26 (Fig. 4d).

4.1.2. *The role of clinopyroxene in the ancient melting event: constraints from Zr/Sm and Hf/Zr in NER lavas from dredges 3, 4, 17 and 26*

In addition to garnet, there is evidence for clinopyroxene in the source of basalts from dredges 3, 4, 17 and 26. NER basalts from these dredges have the lowest Zr/Sm and highest Hf/Zr ratios (Fig. 4e, f). These extremes can be explained by clinopyroxene because the ${D_{Zr/Sm}}^{CPX/melt} < 1$; in contrast ${D_{Zr/Sm}}^{GRT/melt} > 1$. Also clinopyroxene can fractionate Hf/Zr, because ${D_{Hf/Zr}}^{CPX/melt} \sim 2$, whereas ${D_{Hf/Zr}}^{GRT/melt} \sim 1$ (see Appendix B).

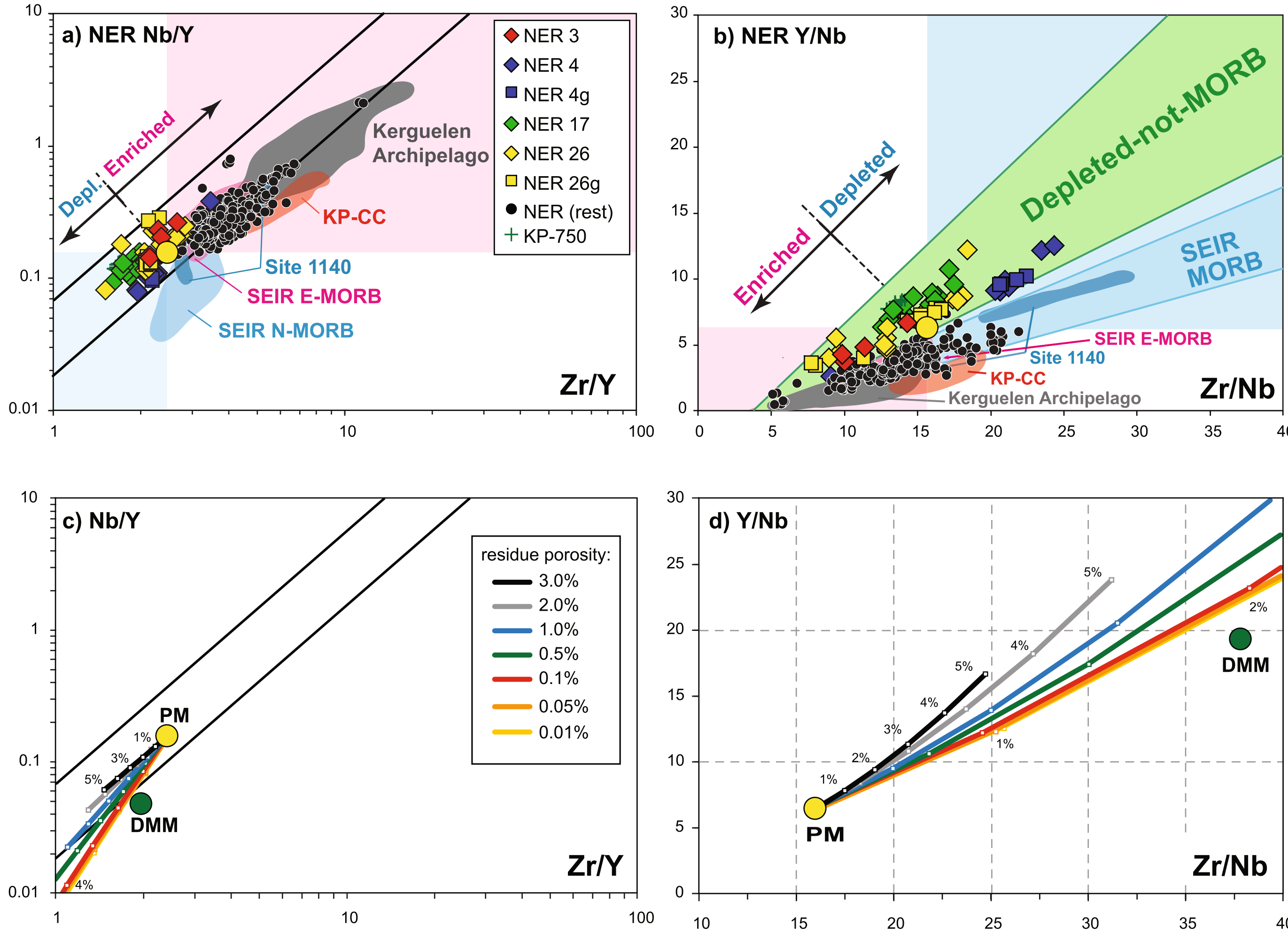

Fig. 3. Nb–Y–Zr discrimination plots. **(a)** Log–log plot of Nb/Y vs. Zr/Y for Ninetyeast Ridge whole-rock basalts from dredges 3, 4, 17 and 26 and glasses (indicated by g in legend) in dredges 4 and 26 (Frey et al., 2011); NER (rest) indicates whole-rock data for all other dredges. Samples from dredges 3, 4, 17 and 26 are offset from the SEIR N-MORB field to high Nb/Y at a given Zr/Y. SEIR basalts are not contemporaneous with NER construction, but there are few data for 43 to 77 Ma Indian Ocean MORB; therefore we use geochemical data for recently erupted SEIR MORB and assume that they are compositionally similar to older Indian Ocean MORB. The KP-CC field shows data for ODP Drill Sites 738 and 1137; their location in this figure is consistent with contamination by continental crust, a process that lowers Nb/Y, as proposed by Frey et al. (2002b) and Weis et al. (2001). A plot with these axes was used by Fitton et al. (1997) to distinguish depleted Icelandic basalt from MORB. **(b)** Linear plot of Y/Nb vs. Zr/Nb for Ninetyeast Ridge basalts and SEIR MORB. Data symbols are as in panel (a). Most NER samples, indicated by filled black circles, plot between the fields for the Kerguelen Archipelago and SEIR MORB. However NER basalts from dredges 3, 4, 17 and 26 are offset to high Y/Nb at a given Zr/Nb (that is within the green "Depleted- not-MORB" field). The linear trend defined by lavas from ODP Drill Site 1140 on the northern Kerguelen Plateau is consistent with mixing between magmas related to the Kerguelen Plume and MORB as proposed by Weis and Frey (2002). In panels (a) and (b) the rose color indicates enriched samples with the ratios Nb/Y and Zr/Y > PM and Y/Nb and Zr/Nb < PM (PM, large yellow circle, is primitive mantle composition from McDonough and Sun, 1995). The blue color indicates depleted samples with Nb/Y and Zr/Y < PM and Y/Nb and Zr/Nb > PM. Data sources for fields in Figs. 3 and 4 are: Douglas-Priebe (1998) and Christie et al. (2004) for SEIR N-MORB, Weis et al. (1998), Doucet et al. (2002), Frey et al. (2002a, 2002b), Yang et al. (1998), Xu et al. (2007) for the Kerguelen Archipelago, Weis and Frey (2002) for Site 1140, and Mahoney et al. (1995) and Ingle et al. (2002) for KP-CC. **(c)** Log–log plot of Nb/Y vs. Zr/Y showing different trajectories for residues created by 1 to 5% (tick marks on trajectory lines) dynamic melting (eqn. (32) of Zou, 1998) of Primitive Mantle (PM) at 3.2 GPa and porosity ranging from 3 to 0.01%. The partition coefficients used are from Salters et al. (2002) and melting parameters are from Salters and Stracke (2004) (see Appendix B). These residues are possible sources for basalts from dredges 3, 4, 17 and 26. The important observation is that for porosity >2% the residues of varying extent of melting are within the field defined by Icelandic basalts as indicated by the two black lines (Fitton et al., 1997), but at lower porosities, such as 0.1%, the residues define steep trajectories that trend out of the field defined by Icelandic basalts (Stracke et al., 2003). **(d)** Plot of Y/Nb vs. Zr/Nb showing that as in panel (c) the trajectories of residues created by varying extents of dynamic melting are sensitive to porosity. (For interpretation of color see Fig. 3 in web version.)

4.2. Ninetyeast Ridge basalts: reconciling contrasting inferences arising from incompatible elemental and isotopic ratios

In trace element ratio plots (Figs. 3, 4), most NER basalts plot between the fields for the Kerguelen Archipelago lavas (assumed to be representative of the Kerguelen plume) and SEIR MORB. However, basalts from four dredges (3, 4, 17 and 26) have incompatible element ratio trends that do not extrapolate to the SEIR MORB field (Figs. 3, 4). Also compared to the Lu/Hf vs. Sm/Nd trend defined by most NER basalts, samples from dredges 3, 4, 17 and 26 are offset to higher Lu/Hf at a given Sm/Nd (Fig. 5a). In contrast, in a plot of $^{176}Hf/^{177}Hf$ vs. $^{143}Nd/^{144}Nd$ the NER basalt samples analyzed for both trace elements and isotopic ratios define a single trend extending from the Kerguelen Archipelago field to a depleted component (i.e., high $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$) that is offset to high $^{176}Hf/^{177}Hf$ from the SEIR MORB field (Fig. 5c).

The greater scatter in trace element ratios compared to isotopic ratios (compare Fig. 5a and c) can be explained by accounting for the effect of partial melting on Lu/Hf and Sm/Nd. The parental magmas for basalts in dredges 3, 4, 17 and 26 formed by relatively high extents of melting that eliminated garnet and clinopyroxene from the residue (Fig. 2a and Frey et al., 2011); consequently these

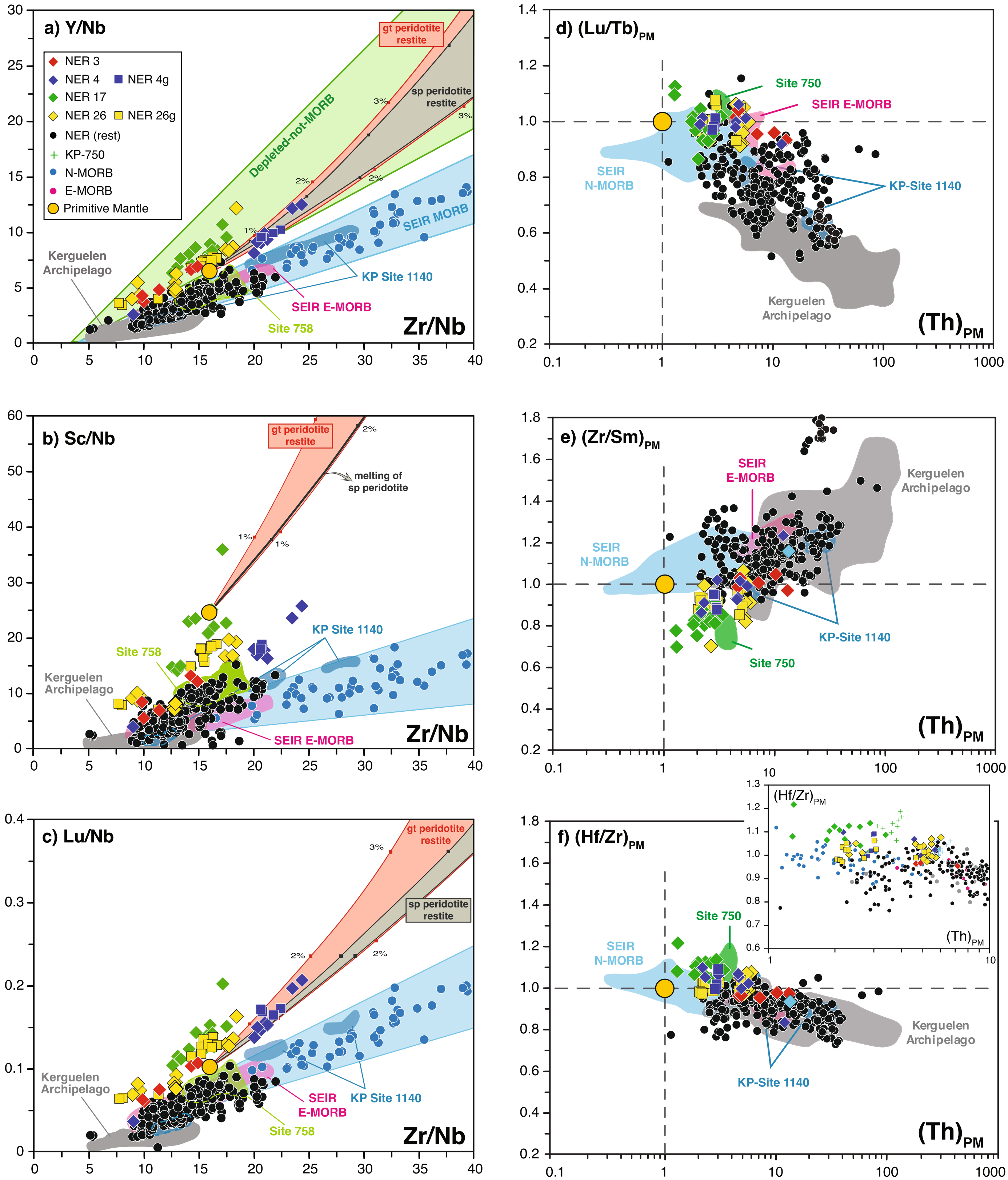

Fig. 4. Ratios sensitive to garnet and clinopyroxene: **(a)**, **(b)**, **(c)** Comparison of Y/Nb, Sc/Nb and Lu/Nb vs. Zr/Nb ratios in basalts from NER dredge and drill sites with data fields for the Kerguelen Archipelago and SEIR MORB. Symbols and data sources are as in Fig. 3. NER whole–rock and glass samples from dredges 3, 4, 17, 26 and ODP Drill Site 750 on the Kerguelen Plateau are offset to high Y/Nb, Sc/Nb and Lu/Nb at a given Zr/Nb. Red and grey fields represent the trajectories for garnet lherzolite and spinel lherzolite residues, respectively, created by 1 to 5% dynamic melting of PM, as indicated by tick marks on red and grey lines. These melting trajectories were calculated assuming 2% porosity and the dynamic melting model of Zou (1998; eqn. (32)). The red and grey fields show the range for different sets of partition coefficients, mineral modes and melting reactions in Table B1; red field is for garnet lherzolite and grey field for spinel lherzolite. **(d)** $(Lu/Tb)_{PM}$ vs. $(Th)_{PM}$ showing that NER basalt from dredges 3, 4, 17 and 26 on the NER and Drill Site 750 on the Kerguelen Plateau are offset to higher Lu/Tb than other NER basalts. **(e)** and **(f)** $(Zr/Sm)_{PM}$ and $(Hf/Zr)_{PM}$ vs. $(Th)_{PM}$ showing that relative to other NER basalts, dredges 3, 4, 17 and 26 and ODP 750 basalts have lower Zr/Sm and higher Hf/Zr at a given Th abundance. (For interpretation of color see Fig. 4 in web version.)

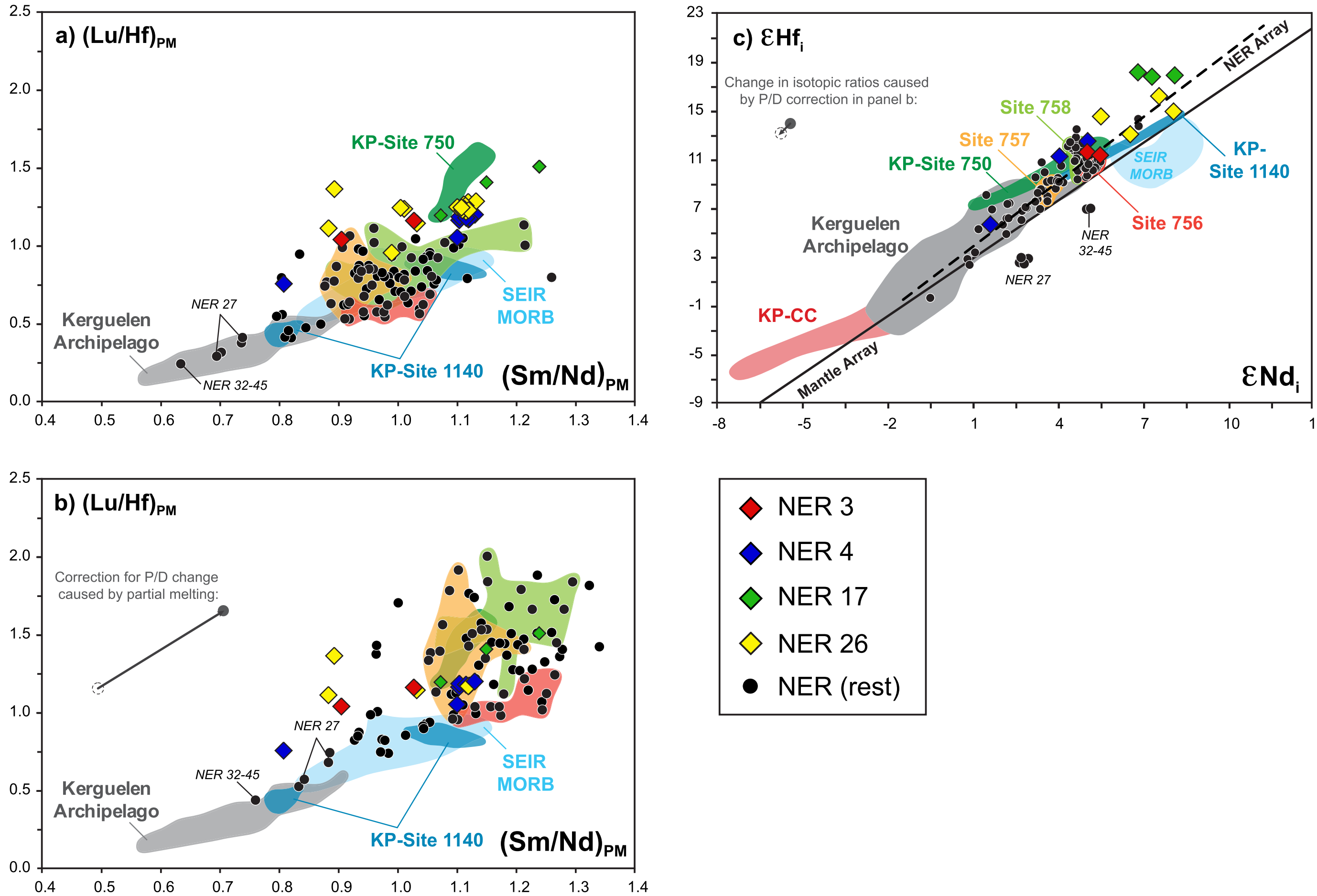

Fig. 5. Hf and Nd isotopic ratios and parent/daughter ratios for Sm–Nd and Lu–Hf systems. **(a)** Measured ratios of $(Lu/Hf)_{PM}$ vs. $(Sm/Nd)_{PM}$ showing that relative to other NER basalts and SEIR MORB, basalts from dredges 3, 4, 17 and 26 and Drill Site ODP 750 have high Lu/Hf at a given Sm/Nd. **(b)** Same as panel (a) but measured values for Lu/Hf and Sm/Nd in NER basalt were adjusted for the decrease in Lu/Hf and Sm/Nd that accompanied the second partial melting process; hence panel (b) attempts to show the ratios in the sources of NER basalts; the typical change from ratio in basalt to that inferred for the source is indicated by the grey arrow connecting the open and filled dots. However the use of a fixed melting extent must introduce scatter (see Appendix D). Samples from dredges 3, 4, 17 and 26 were not adjusted because we infer that their parental magmas formed by high extents of melting (∼30%) so that the measured basalt Lu/Hf and Sm/Nd ratios are the source ratios. **(c)** Initial $^{176}Hf/^{177}Hf$ vs. $^{143}Nd/^{144}Nd$ for NER dredged basalts compared to NER drill core basalts at Drill Sites 756, 757 and 758 (Nobre Silva et al., 2013). The labeled grey arrow connecting the open and filled dots shows the change in isotopic ratios caused by P/D correction in panel b. The changes in $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ resulting from corrections to zero age are negligible. Dredge 17 and 26 samples have higher $^{176}Hf/^{177}Hf$ than SEIR MORB with similar $^{143}Nd/^{144}Nd$. In detail, all NER basalts form a trend (dashed black line) parallel to the mantle array (solid black line, Chauvel et al., 2008), but offset to higher $^{176}Hf/^{177}Hf$. Exceptions are alkali basalts from dredge 27 and sample 32–45, which are the only NER samples that has the geochemical characteristics of basalts erupted at the Amsterdam–St Paul hotspot (Fig. 1a). Kerguelen Archipelago basalts are also offset to higher $^{176}Hf/^{177}Hf$ than the mantle array. Data sources for SEIR MORB (Chauvel and Blichert-Toft, 2001; Mahoney et al., 2002; Nicolaysen et al., 2007), Kerguelen Archipelago (Doucet et al., 2002; Frey et al., 2002a, 2002b; Yang et al., 1998; Xu et al., 2007), basalts from the Kerguelen Plateau KP-CC (Sites 738 and 1137, Ingle et al., 2002, 2003), Site 750 (Frey et al., 2002b) and Site 1140 (Weis and Frey, 2002). (For interpretation of color see Fig. 5 in web version.)

basalts have Lu/Hf and Sm/Nd equal to the ratios in their sources. However, at the low extents of melting appropriate for other NER basalts the partial melts have lower Lu/Hf and Sm/Nd than the ratios in their sources. Correcting for the decrease in Lu/Hf and Sm/Nd caused by partial melting results in overlap of samples from dredges 3, 4, 17 and 26 with other NER samples (Fig. 5b).

4.3. Why do the sources of MORB and the depleted component in NER basalts differ in ratios of incompatible elements?

The sources of N-MORB have long been recognized as residues created during ancient melting events (e.g., Gast, 1968). Residues formed during ancient partial melting events were also the source of the depleted NER lavas. If we assume that both sources were created from primitive mantle, why are these residues so different in abundance ratios of incompatible elements (e.g., Fig. 3c, d)? We suggest differences in porosity as an explanation. Permeability, (k), a measure of how readily fluid flows through a porous media, is related to porosity (θ), the volume fraction of melt, by $k = a^2\theta^\eta$ where a is grain size and η is 2 to 3.

The porosity of partially molten mantle rock, such as peridotite, has been the focus of several experimental studies (e.g., Daines and Richter, 1988; Garapic et al., 2013; Kohlstedt, 1992; Sundberg et al., 2010; Zhu et al., 2011). Emphasis has been on the effects of trapped melt on the physical properties of the asthenosphere, but there are also important geochemical implications. Specifically, the amount of trapped melt strongly controls the incompatible element contents and ratios of (highly incompatible elements)/(moderately incompatible elements) in residues formed by dynamic melting. Experimental results typically yield porosities ranging from 0.02% to 2%, and vary with mineralogy and melt composition. The different ratios of Y/Nb and Zr/Nb in DMM and the source of depleted NER lavas can readily be explained by a dynamic melting model with a porosity of 2%; such a source creates a residue that is a suitable source for most of the depleted NER lavas, whereas a much lower porosity of <0.01% creates a residue

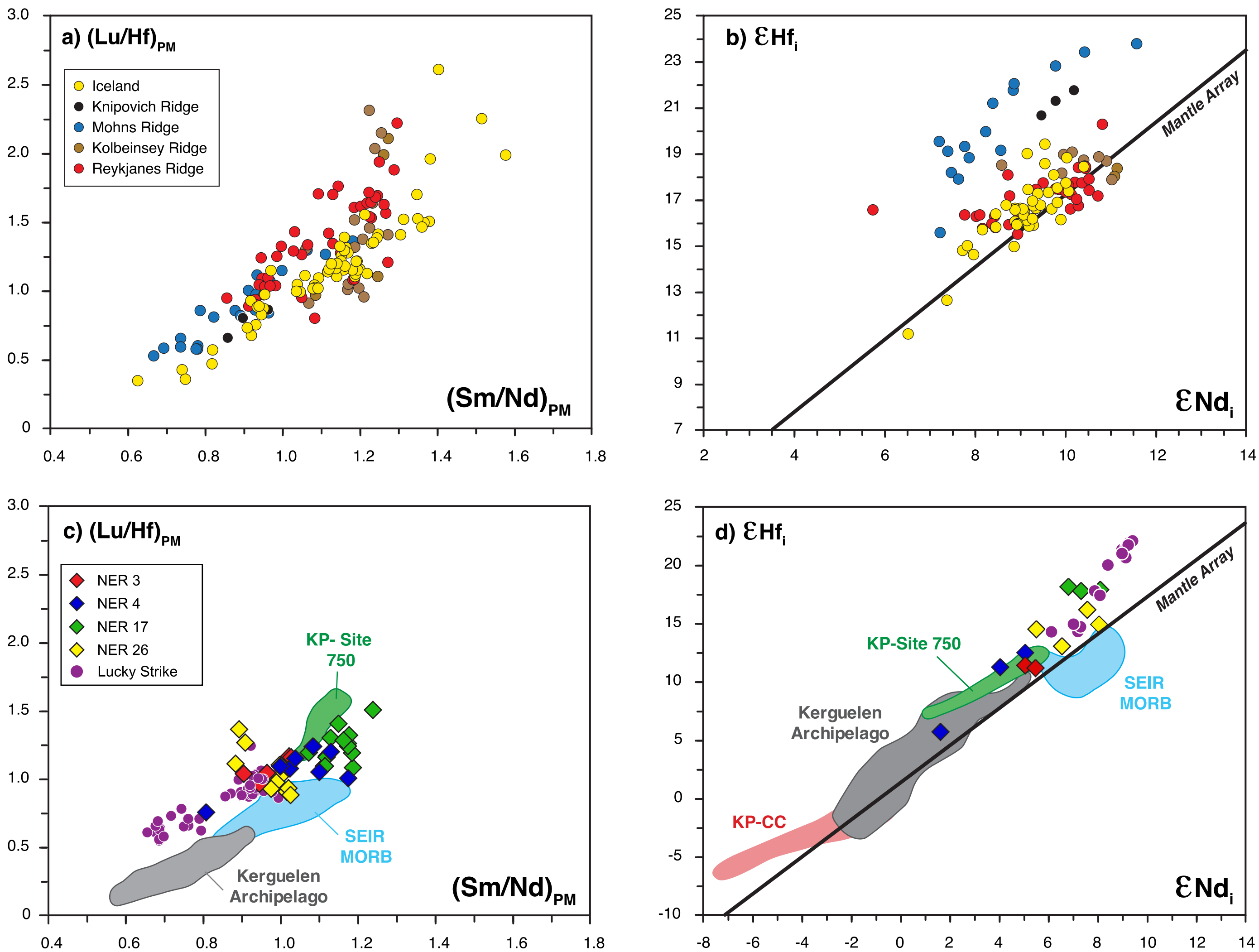

Fig. 6. **(a)** $(Lu/Hf)_{PM}$ vs $(Sm/Nd)_{PM}$ parent/daughter ratios for the Hf and Sm isotopic systems showing data for depleted (i.e., $Nb/Zr < 0.06$) Icelandic basalts compared to basalts from spreading ridges south and north of Iceland. At a given Sm/Nd ratio, most of the spreading ridge basalts have higher Lu/Hf than depleted Icelandic basalts. Icelandic data from Kempton et al. (2000), Koornneef et al. (2012) and Stracke et al. (2003). Spreading ridge data from Kelley et al. (2013). **(b)** ε_{Hf} vs. ε_{Nd} for depleted Icelandic basalts and basalts from spreading ridges north and south of Iceland. **(c)** $(Lu/Hf)_{PM}$ vs. $(Sm/Nd)_{PM}$ Parent/daughter ratios for the Hf and Sm isotopic systems showing data for depleted basalts erupted on the NER and Lucky Strike segment of the MAR. At a given Sm/Nd these near hotspot basalts have higher Lu/Hf than basalts from the SEIR and Kerguelen Archipelago. **(d)** ε_{Hf} vs. ε_{Nd} for basalts from dredges 3, 4 17 and 26 on the NER, and basalts from the Lucky Strike segment of the MAR compared to fields for basalts from Drill Site KP 750 on the Kerguelen Plateau, SEIR MORB, Kerguelen Archipelago and Drill Sites 738 and 1137 on the Kerguelen Plateau (labeled KP-CC). At high ε_{Hf} and ε_{Nd} the trend for the near hotspot depleted basalts is steeper than the trend for SEIR MORB. (For interpretation of color see Fig. 6 in web version.)

that is a suitable source for N-MORB (Fig. 3c, d). These porosity differences may be related to the lengths of the melting column perhaps 150 to 60 km for hotspot volcanism and 60 to 0 km for a spreading ridge. Moreover, it is well established that deformation processes influence permeability and these are likely to differ significantly in hotspot and spreading ridge environments (e.g., Evans et al., 2004).

4.4. Depleted basalts erupted at spreading ridges and hotspot – are they geochemically different?

4.4.1. MORB

The rapidly increasing database for Nd and Hf isotopic ratios establishes that depleted components with high$^{176}Hf/^{177}Hf$ have contributed to MORB and OIB (e.g., Andres et al., 2004; Salters et al., 2011). In order to explain the variable slopes of MORB and OIB in plots of $^{176}Hf/^{177}Hf$ vs. $^{143}Nd/^{144}Nd$, Salters et al. (2011) argued that the sources of MORB and OIB contained variable amounts of garnet-bearing lithosphere that formed as a residue in an ancient melting event, i.e., their "ReLish" component. Because Hf is more compatible than Sr, Nd and Pb, this residue only affects Hf isotopic ratios. North Atlantic MORB is a good example of MORB with widely varying $^{76}Hf/^{177}Hf$; e.g., there are gradients along the spreading ridges both south and north of Iceland; specifically ε_{Hf} varies from 15.5 to 20 south of Iceland along the Reykjanes Ridge and 17 to 19 north of Iceland along the Kolbeinsey Ridge reaching very high values, up to 24, along the Mohns Ridge further north of Iceland (Fig. 6a, b and see Fig. 5 of Blichert-Toft et al., 2005). Andres et al. (2004) concluded that large-scale spatial variations of $^{176}Hf/^{177}Hf$ in North Atlantic MORB reflect variable amounts of a depleted mantle component that formed as a garnet-bearing residue during ancient partial melting events.

The bimodal distribution of $^{176}Hf/^{177}Hf$ in SEIR MORB can also be explained by a source component created as garnet-bearing residue in ancient melting events; their high Lu/Hf evolving with time to high $^{176}Hf/^{177}Hf$ ratios (Graham et al., 2006; Hanan et al., 2013).

4.4.2. Azores

Within the Lucky Strike Segment of Mid-Atlantic Ridge near the Azores, the common basalt type is transitional basalt with $(La/Sm)_{PM} = 1$ to 2 which is intermediate between N- and E-MORB (Gale et al., 2011). Hamelin et al. (2013) found that these transitional basalts have anomalously high ε_{Hf} for a given ε_{Nd} and they extend the trend defined by depleted NER basalts to higher ε_{Hf} and ε_{Nd} (Fig. 6d). Hamelin et al. (2013) explained the isotopic and trace element ratios of Lucky Strike transitional basalts by a three-step process. Step 1 was creation of a ReLish component at 1.2 Ga as a residue of partial melting in the garnet stability field of a MORB source reservoir that had been isolated for 2 Ga. Step 2 was recent mixing of ReLish component (20%), local MORB source (70%) and Azores mantle (10%). Step 3 was adding to this mixture an incompatible element-rich melt created by low extents of melting of the Azores mantle in the garnet stability field. Consequently these Lucky Strike lavas are not depleted in incompatible elements; for example, their $(La/Sm)_{PM}$ is greater than one and their $(Sm/Nd)_{PM}$ and $(Lu/Hf)_{PM}$ ratios are less than one (Fig. 6c). Fig. 2c shows the proposed sequence of processes that created Lucky Strike transitional basalts.

Hamelin et al. (2013) also noted that MORB from 35° to 46°N on the MAR and from Lucky Strike at 37°N define similar trends in ε_{Hf} vs. ε_{Nd}. NER basalts are also on this trend (Fig. 6d). Although it is not possible to define a unique model, formation and aging of a ReLish component is a common process in forming OIB and MORB sources (Salters et al., 2011).

4.4.3. Iceland

The source of most Icelandic lavas contained a component enriched in incompatible elements (e.g., Schilling, 1973). Enriched Icelandic basalts have Nb/Y and Zr/Y greater than PM ratios whereas these ratios are lower than PM ratios in depleted Icelandic lavas (Fig. S1). Fitton et al. (1997, 2003) inferred that the high Nb/Y at a given Zr/Y of depleted Icelandic lavas results from recycling of subducted oceanic crust with a relative enrichment of Nb into the mantle where it became incorporated into the Icelandic hotspot. As an alternative to Nb enrichment, Chauvel and Hemond (2000) proposed that depleted Icelandic basalts are depleted in Zr as shown by low Zr/Y at a given Nb/Y (Fig. S1a). Chauvel and Hemond (2000) emphasized that depleted Icelandic basalts have the distinctive geochemical characteristics of plagioclase, that is, high ratios of Sr/Nd, Eu/Eu* and Ba/Th and low Ce/Pb. Depleted Icelandic basalts also have high Sm/Hf and low Zr/Y; these are characteristics of clinopyroxene. These ratios support the interpretation that an important source component for depleted Icelandic basalt was oceanic lower crust composed of plagioclase- and clinopyroxene-rich cumulate gabbro that was recycled into the mantle where it was incorporated into the Icelandic plume (Fig. 2b and Chauvel and Hemond, 2000; Hemond et al., 1993; Kokfelt et al., 2006). An alternative interpretation is that high Sr/Nd reflects low Nd content rather than Sr enrichment (Stracke et al., 2003); however no process for this depletion has been proposed.

There is debate regarding the depleted component in Icelandic basalt; is it geochemically distinct from the depleted components in the source of MORB erupted in the North Atlantic as advocated by Chauvel and Hemond (2000), Fitton et al. (1997, 2003), Kempton et al. (2000), Taylor et al. (1997), Thirlwall (1995) and Thirlwall et al. (2004)? This inference for an intrinsic depleted component in the Icelandic hotspot has been challenged by Hanan et al. (2000) and Stracke et al. (2003) who concluded "virtually all available isotopic and chemical evidence shows that the depleted Icelandic source component is similar to the ambient MORB source material in the north Atlantic". Fitton et al. (2003) asked, could the offset of Icelandic depleted lavas to high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ be used to determine if depleted Icelandic magmas were derived from a depleted plume component or the depleted source of ambient MORB in the vicinity of Iceland? Consistent with the early isotopic study of Kempton et al. (2000), Fitton et al. (2003) concluded that depleted Icelandic basalt is not derived from the same mantle source as north Atlantic MORB. However, the finding of MORB on Mohns Ridge north of Iceland with higher $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ than depleted Icelandic lavas (Fig. 6b) shows that high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ is not a unique characteristic of the depleted component in Icelandic lavas.

4.4.4. Comparison of NER and Icelandic depleted source components

For depleted NER basalts, the depletion occurred in an ancient melting event that formed a garnet- and clinopyroxene-bearing residue. In contrast, for Icelandic depleted basalts, the depletion process was formation of plagioclase and clinopyroxene cumulate rock (Fig. 2a, b). Because of these differences in mineralogy, depleted NER basalt is enriched in Sc, Y and heavy REE whereas depleted Icelandic basalt is enriched in Sr and depleted in Hf and Zr. Although Lu/Hf is more sensitive to control by garnet than clinopyroxene (see partition coefficients in Appendix B), Chauvel and Hemond (2000) calculated that clinopyroxene is very abundant (49 to 70%) in the cumulate gabbros that served as a source component for depleted Icelandic basalts. Since a cumulate composition is controlled by the bulk-solid partition coefficient that has contributions from each mineral expressed as DX (D is mineral/melt partition coefficient and X is weight percent of that mineral in the cumulate), the abundant clinopyroxene creates high Lu/Hf and with time this source component of depleted Icelandic lavas develops high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$.

4.5. What was the tectonic environment for creating the sources of depleted basalts erupted at hotspots?

For depleted Icelandic basalts, Fitton (2007) inferred relative enrichment of Nb (Fig. S1a), suggesting that the depleted component was created as a residue in a subduction zone prior to recycling into the mantle. Rather than Nb enrichment in depleted Icelandic basalts, Chauvel and Hemond (2000, their Fig. 8) inferred relative depletion of Zr. High ratios of Sr/Nd, Eu/Eu*, Ba/Th and Sm/Hf and low ratios of Zr/Y and Ce/Pb, are characteristics of depleted Icelandic basalts and they are consistent with a source component composed of cumulate gabbro rich in plagioclase and clinopyroxene (Chauvel and Hemond, 2000). There is no compelling evidence for subduction zone processes in depleted basalts from Iceland or the NER. Relative to SEIR MORB, depleted NER basalts have high Y/Nb, Lu/Nb and Sc/Nb ratios. We infer that enrichment in Y, Lu and Sc reflects an ancient depleted source component that formed as a garnet- and clinopyroxene-bearing residue of partial melting. The high $^{176}Hf/^{177}Hf$ require an ancient process but this melting event cannot be associated with a particular tectonic setting. A depleted component also occurs in the Lucky Strike segment of the MAR near the Azores. These regions (Iceland, Azores and Kerguelen) share the characteristics of high magma supply from hotspots located near an active spreading ridge. We suggest that this environment is necessary to generate melts from a relatively refractory mantle source

4.6. Role of garnet-bearing continental crust in hotspot and MORB volcanism

Hamelin et al. (2013, their Fig. 8) considered that garnet-bearing sub-continental lithospheric mantle was an alternative to ancient garnet-bearing residual oceanic lithosphere for the source of transitional basalts erupted on the Lucky Strike segment of the MAR. With respect to the Kerguelen hotspot, there is evidence for garnet granulite from the lower continental crust as a source component for Kerguelen Plateau basalts from ODP Drill Site 750 (Fig. 1a). Site 750 basalt has high Y/Nb, Lu/Nb and Sc/Nb (Fig. 4a, b, c) and also the geochemical characteristics of plagioclase, such as positive anomalies of Sr and Eu and low $^{206}Pb/^{204}Pb$, ~17.5. Frey et al. (2002b) concluded that these features are consistent with a source component derived from garnet granulite that originally formed as a plagioclase-rich cumulate in the lower continental crust. The basalt cores recovered from ODP Drill Site 1137 on Elan Bank and ODP Drill Site 738 on the Southern Kerguelen Plateau (Fig. 1a) provide additional evidence that lower continental crust contributed to basaltic volcanism forming the Kerguelen Plateau (Mahoney et al., 1995; Weis et al., 2001).

Hanan et al. (2004) concluded that anomalously high $^{176}Hf/^{177}Hf$ in Indian Ocean MORB from the Australian Antarctic Discordance could be explained by "melting of lower crustal (garnet) granulite followed by incorporation of the residues into the MORB mantle source." Andres et al. (2004) also suggested that the garnet-bearing lithology in the source of the North Atlantic MORB samples could be garnet granulite. Consistent with lower crustal garnet granulite in their source, ocean floor basalts in these regions have distinctive Pb isotopic signatures, namely relatively low $^{206}Pb/^{204}Pb$ and relatively high $^{208}Pb/^{206}Pb$ and $^{207}Pb/^{206}Pb$. This is not true for depleted NER basalt (Nobre Silva et al., 2013), the Lucky Strike transitional basalt (Gale et al., 2011) or the dominant depleted component in Iceland (component ID1 of Thirlwall et al., 2004). We conclude that lower continental crust garnet granulite was not involved in the mantle source of depleted lavas erupted on the Ninetyeast Ridge, the Lucky Strike spreading center or in Iceland.

There are xenoliths of mafic granulites in alkali basalts erupted in the Kerguelen Archipealgo on the northern Kerguelen Plateau (Fig. 1a). Gregoire et al. (1994) inferred that they formed by underplating of basaltic magma beneath the thick crust of the Kerguelen Plateau. Some of these xenoliths are plagioclase-rich cumulate rocks. They have the mineralogy of the component that was important in the source of depleted Icelandic basalt (Chauvel and Hemond, 2000).

5. Conclusions

The igneous basement of the Ninetyeast Ridge (NER) has been sampled at 7 drill sites and by dredging at 21 locations. The volcanoes forming this 43 to 77 Ma hotspot track are dominantly tholeiitic basalts with incompatible element abundances intermediate between the flood basalts of the Kerguelen Archipelago and SEIR MORB. The Kerguelen hotspot is dominantly composed of enriched peridotite that is the major source of NER basalts. However at four dredge locations the NER basalts are relatively enriched in Y, Lu and Sc compared to MORB and other NER basalts. These NER basalts were derived from a depleted component that is compositionally and isotopically distinct from the source of SEIR MORB. Relative to SEIR MORB these NER basalts are enriched in elements, Sc, Y and Lu, which are readily incorporated into garnet and clinopyroxene. They also have high Lu/Hf at a given Sm/Nd and high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$, defining a trend above the mantle array. These geochemical characteristics of depleted NER basalt can be explained by a two-stage process: (1) formation of garnet-bearing peridotite residues created by low extents of partial melting; in order to explain the high $^{176}Hf/^{177}Hf$ at a given $^{143}Nd/^{144}Nd$ of depleted NER basalt this was an ancient melting event. (2) The depleted NER basalts were created when these aged garnet peridotite residues were partially melted to a high extent, sufficient to eliminate garnet and clinopyroxene from the residue. The same processes can explain the geochemical characteristics of basalts erupted on the Lucky Strike segment of the Mid-Atlantic Ridge near the Azores. In contrast, cumulate gabbro, with abundant plagioclase and clinopyroxene, was a source component for depleted Icelandic basalt.

Acknowledgements

We thank Chief Scientist W. Sager and the officers and crew of the RV Revelle for their shipboard expertise, R. Comer for supervising the dredging operation, and the students who sorted and described the dredged rocks (S. Baumgartner, E. Gauntlett, S. Mallick, E. Mervine, H. Owens, S. Rasmussen and J. Wiltshire). We thank the editor T. Elliott for his perceptive review comments, P. Kelemen and B. Evans for discussions regarding porosity, reviewers G. Fitton and V. Salters for constructive comments and an anonymous reviewer who called our attention to the papers on the Lucky Strike segment of the MAR. NSF Grant OCE-8025147 to F.A. Frey, NSERC Discovery Grant to D. Weis, and NSF Grant EAR 1144727 to S. Huang supported this research project.

Appendix. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.06.005.

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