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Nature of the depleted upper mantle beneath the Atlantic: evidence from Hf isotopes in normal mid-ocean ridge basalts from 79°N to 55°S

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Abstract

Light rare earth depleted Mid-Atlantic Ridge (MAR) basalts unaffected by hotspots (i.e. NMORB) show a very regular decrease in $^{176}Hf/^{177}Hf$ from 79°N to 55°S. The north–south nearly linear gradient ranges from 0.283448 ($\varepsilon_{Hf}=23.9$) to 0.283137 ($\varepsilon_{Hf}=12.9$). This remarkable gradient in NMORB suggests a similar gradient in the depleted upper mantle whose probable origin is explored here. Comparison with previously collected isotope data shows that this regular north to south ε_{Hf} gradient is accompanied by a less pronounced decrease in ε_{Nd} and an increase in $^{207}Pb/^{204}Pb$. In addition to this survey of Atlantic NMORB, $^{176}Hf/^{177}Hf$ are reported for 11 plume-affected enriched MORB from the MAR. Each EMORB is the most LREE enriched basalt from a region of plume–ridge interaction. $^{176}Hf/^{177}Hf$ of these EMORB vary between 0.282891 ($\varepsilon_{Hf}=4.2$) and 0.283198 ($\varepsilon_{Hf}=15.1$). The ε_{Hf} variation of these EMORB is likely due to simple plume–ridge interactions. Isotope–isotope correlations for the NMORB suggest that the regular gradient in ε_{Hf} is probably not caused by mixing with recycled oceanic crust, subcontinental lithosphere or plume-head restite. Rather it is likely caused by mixing with a depleted mantle component that is the residue of ancient mantle melting in the presence of garnet. The correlation between isotope ratios and MAR-to-continent distance suggests that this garnet bearing restite was sequestered in the asthenosphere under the continents until the opening of the Atlantic. An alternative to mixing models is that differences in the evolution of the upper mantle may have given rise to the NMORB isotope gradients. Simple two-stage models would suggest that even small differences in how much melt was extracted from the mantle or when melt extraction began could have caused the observed gradient. In both cases, however, these small differences in evolution must be longstanding, on the order of 1 Ga or more and would have to be gradual on a 15,000-km scale.

Keywords: Mid-Atlantic Ridge; MORB; hafnium isotopes; upper mantle; asthenosphere

1. Introduction

Mid-ocean ridge basalts (MORB) form from the melt, which is produced when the asthenosphere rises

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beneath mid-ocean ridges. This asthenosphere, which is the low-viscosity layer of the mantle, flows in response to subduction of oceanic plates. Trace element and isotope ratios in MORB can be used to study the nature and evolution of the underlying asthenosphere. So-called ''normal'' MORB (NMORB), which have chondrite-normalized La/Sm less than 0.63 [1], generally form when residues of previous melting events are melted again beneath a ridge. Since the initial melting events left a residue highly depleted in incompatible elements, this subsequent melting beneath the ridge produces magma that is also depleted in incompatible elements. Whether or not this depleted trace element character is reflected in an NMORB's radiogenic isotope ratios depends on whether the initial melting events were *recent* (trace element ratios and isotope ratios are decoupled) or *ancient* (trace element ratios and isotope ratios are correlated since there is time for radiogenic ingrowth). ''Enriched'' MORB (EMORB) form either when solidified melt re-melts or when undifferentiated (''primitive'') mantle melts. As with NMORB, how the trace element ratios and isotope ratios in EMORB are related depends on the age of the EMORB source.

A whole spectrum of models has been proposed to explain the occurrence of NMORB and EMORB along mid-ocean ridges. Most models start with the ''standard'' premise that melt and fluid extraction preferentially partitioned incompatible elements into the continents leaving a portion of the mantle depleted. This ''depleted upper mantle'' complement to the continents is the source of isotopically depleted NMORB. Many models have treated the depleted upper mantle as fairly uniform in composition and mean age ($\sim$2 Ga) [2,3].

As part of this ''standard'' asthenosphere model, various mixing scenarios have been suggested to explain the occurrence of EMORB along ridges. The ''mantle blob cluster'' model [4] identifies buoyant blobs of lower mantle material as an enriched source that mixes with the depleted part of the asthenosphere. The ''delamination'', ''veined mantle'', ''plum-pudding'' or ''marble-cake'' models attribute the enriched source to schlieren of delaminated continental lithosphere or stretched and folded recycled oceanic crust [5–9]. In contrast to these stochastic models, the more deterministic ''mantle plume source-ridge sink'' (MPS-MRS) model [10] identifies buoyantly rising plumes rather than passive heterogeneities as an EMORB source.

An alternative to the ''standard'' asthenosphere model is the ''plume fed'' asthenosphere model [11] where plume residues, rather than the direct residue of continent formation, form the MORB source. In this model, plumes contain enriched material embedded in a depleted matrix. Beneath intraplate ocean islands, where the lithosphere is thick, mantle plumes undergo small degrees of melting by preferentially tapping the enriched material (which melt at relatively low temperature) to produce ocean island basalts (OIB). The leftover plume material then feeds the asthenosphere. As the asthenosphere convects, this plume residue may undergo a second stage of relatively large-degree melting beneath spreading centers to produce MORB. The proportions of melt contributed to MORB by (1) enriched material, (2) restite from enriched material recently melted to produce OIB and (3) the depleted matrix determine the MORB's trace element and isotope characteristics.

In order to investigate the nature of the depleted component of the asthenosphere beneath the Atlantic, we measured $^{176}Hf/^{177}Hf$ in MORB collected along the entire Mid-Atlantic Ridge (MAR) from 79°N to 55°S, selecting only those NMORB with the lowest La/Sm from different normal ridge segments unaffected by plumes [10]. We interpret the Hf isotope data together with previously collected Nd isotope data from the same samples in the context of the various asthenosphere models.

As with the Sm–Nd isotope system, Hf (the daughter) is more incompatible than Lu (the parent) such that geochemically enriched material develops low $^{176}Hf/^{177}Hf$ over time. For both systems, deviations of the isotope ratio from bulk silicate earth (BSE) values are denoted by the epsilon notation ($\varepsilon_{Hf} = [^{176}Hf/^{177}Hf]/0.282772 - 1) \times 10{,}000$) where 0.282772 is the bulk earth $^{176}Hf/^{177}Hf$ [12]. Positive ε_{Hf} and ε_{Nd} indicate that a reservoir is depleted in incompatible elements relative to the bulk silicate earth on a time-integrated basis.

Despite the similarities to the Sm–Nd isotope system, the Lu–Hf isotope system is useful in its own right for learning further about the mantle. Since Lu/Hf is fractionated by melting much more than is Sm/Nd, a given degree of ancient melting will result in a more pronounced signal in $^{176}Hf/^{177}Hf$ than in

$^{143}Nd/^{144}Nd$. In addition, because the half-life of ^{176}Lu is shorter than that of ^{147}Sm (e.g., [13]), $^{176}Hf/^{177}Hf$ increases more rapidly than $^{143}Nd/^{144}Nd$. Thus, the dynamic range of $^{176}Hf/^{177}Hf$ is substantially greater than that of $^{143}Nd/^{144}Nd$. In addition, coupled Hf and Nd isotope systematics in basalts can provide information about the mineralogy of the mantle source since Lu is compatible in the presence of garnet [14,15].

2. Mid-Atlantic Ridge

The Atlantic mantle is well suited to the study of large-scale mantle processes since MORB from the entire MAR have been sampled on numerous cruises. The influence of mantle plumes on Atlantic EMORB compositions has been well documented [10] (and references therein) and [16–22]. Corresponding spikes in $(La/Sm)_n$ (Fig. 1 and Table 1) and isotope ratios on MAR basalt profiles support the MPS-MRS model of plume–ridge interaction. According to this model, material from a buoyantly rising plume can either feed the ridge directly if the plume is ridge centered (e.g. Iceland) or material can flow preferentially toward a spreading center if the plume is intraplate and sufficiently close to the ridge (e.g. Discovery). Progressive mixing of enriched plume material with depleted asthenosphere results in regular geochemical gradients varying from EMORB to NMORB along the ridge [10].

In contrast to EMORB, which, according to the MPS-MRS model, arise from *present-day* plume–ridge interactions, occurrence of NMORB with *moderately* enriched isotope ratios has been attributed to the presence of plume-head *restite* beneath the MAR [20–22]. Presumably, these plume-heads melted as the plumes first rose beneath the Gondwanan lithosphere. The plume-heads were stripped of incompatible elements but retained enriched isotope ratios. Subsequent mixing and melting with isotopically depleted asthenosphere material led to eruption of basalts with low $(La/Sm)_n$ but somewhat enriched radiogenic Pb and Sr isotope ratios and depleted Hf and Nd isotope ratios. Mantle pollution by a family of HIMU (high time-integrated U/Pb) plumes (14°, Sierra Leone, Circe, or Ascension and St. Helena) may have caused the so-called "HIMU province" from

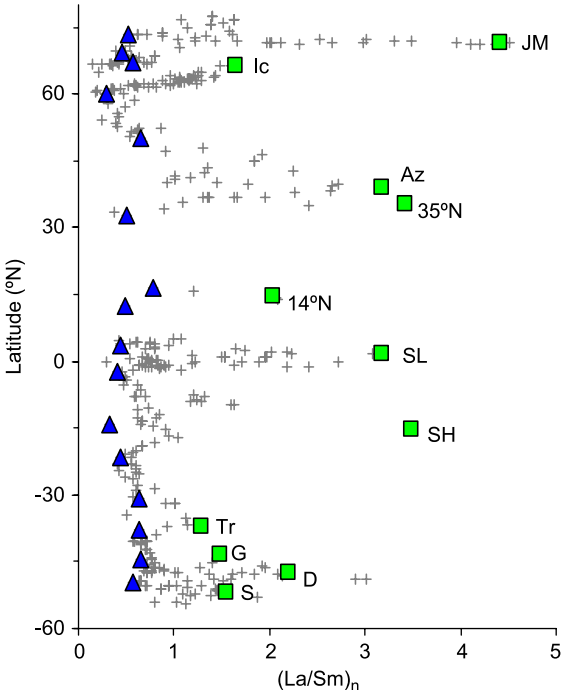

Fig. 1. $(La/Sm)_n$ of Atlantic MORB. Grey crosses are MORB from [10] (and references therein) and [16–22]. NMORB and EMORB included in the present study are identified with blue triangles and green squares, respectively. The EMORB included in the present study are those basalts from each region with the highest $(La/Sm)_n$ (and usually the highest radiogenic Sr) with two exceptions. EW9309 2D-1g is used to represent the Discovery/LOMU plume anomaly and EW9309 21D-1g is used for the Shona plume anomaly (see Table 1). The most LREE-enriched MORB from these two ridge segments would be EW9309 7D-1g or 6g for Discovery/LOMU and AG32-5-1 for Shona. The plumes influencing the MAR are Jan Mayen (JM), Iceland (Ic), Azores (Az), 35°N anomaly (35°N), 14°N anomaly (14°N), Sierra Leone (SL), St. Helena (SH), Tristan (T), Gough (G), Discovery/LOMU (D) and Shona (S). A linear regression through the NMORB included in this study (line not shown) indicates there is no relationship between $(La/Sm)_n$ and latitude ($r^2 = 0.1$).

34°N to 24°S, which is characterized by NMORB with relatively high $^{206}Pb/^{204}Pb$ and relatively low $^{87}Sr/^{86}Sr$ [20].

An alternative origin of the EMORB to NMORB gradients follows from the "plume fed" asthenosphere model [11]. EMORB may result from deep melting beneath a spreading center, which preferentially taps relatively enriched material. The gradient to NMORB then results from progressive melt extraction from the MORB source rather than from mixing of

Table 1
Data for Atlantic MORB

ID	Latitude (°N)	Longitude (°W)	Depth (m)	$(La/Sm)_n$[a]	$^{176}Hf/^{177}Hf$	$^{176}Hf/^{177}Hf \pm 2SE$[b]	$^{143}Nd/^{144}Nd$[c]
NMORB							
EN026 16D-2g	73.41	− 7.39	2623	0.52	0.283448	9	0.513164
TR139 25D-3g	69.15	16.22	1145	0.45	0.283317	8	0.513185
TR139 6D-2g	67.01	18.71	290	0.58	0.283272	6	0.513084
TR41 D22-1	60.02	29.48	978	0.30	0.283276	12	0.513162
TR138 6D-1Bg	50.04	28.93	3370	0.65	0.283429	9	0.513298
TR123 5D-3g	32.62	39.87	2700	0.50	0.283342	8	0.513212
2πD 48-1	16.35	46.66	3500	0.77	0.283328	4	0.513242
2πD 40-2	12.40	44.10	4375	0.49	0.283228	5	0.513224
RC2806 49D-1g	3.70	31.51	3738	0.43	0.283254	7	0.513151
RC2806 1D-1g	− 2.54	12.23	3740	0.41	0.283269	7	0.513234
RC16 7D-1g	− 14.08	14.46	3534	0.33	0.283222	6	0.513199
EN063 02D-5g	− 21.50	11.82	3460	0.44	0.283188	11	0.513152
EN063 24D-5g	− 30.98	13.46	3530	0.64	0.283137	12	0.513092
AII 107-7 13-1g	− 37.83	17.14	2199	0.63	0.283141	10	0.513036
EW9309 40D-4g	− 44.41	15.91	3488	0.69	0.283197	6	0.513042
EW9309 12D-3g	− 49.76	8.03	3874	0.57	0.283152	7	0.513055
EMORB							
EN026 2D-1	71.41	7.49	890	4.41	0.283058	7	0.51291
IC-244-2	66.29	17.11	− 25	1.64	0.283198	8	0.513022
TR154 21D-3g	38.89	30.05	1305	3.17	0.283128	11	0.51289
TR119 7D-1	35.33	34.90	2250	3.42	0.283022	7	0.512835
2πD 45-2	14.50	44.84	3720	2.03	0.283107	5	0.512946
RC2806 40D-3g	1.70	30.64	3515	3.18	0.283089	10	0.512855
ENO61 18d-1g	− 15.46	13.76	2860	3.49	0.283032	6	0.512971
AII 107-7 14-77	− 37.19	17.52	2399	1.29	0.283041	8	0.512851
EW9309 42D-1g	− 43.43	16.17	3449	1.49	0.282985	6	0.512761
EW9309 02D-1g	− 47.55	10.18	2494	2.19	0.282891	6	0.512652
EW9309 21D-1g	− 51.82	5.50	2025	1.56	0.282958	9	0.512818

[a] References for $(La/Sm)_n$ as in Fig. 1. For all analyses, the JMC-475 Hf standard gave $^{176}Hf/^{177}Hf = 0.282160 \pm 0.000010$ and was run alternately with samples.
[b] 2SE refers to 2σ errors.
[c] Hf isotope data from 40-55°S from [39]. Nd isotope data from [16–20,22,40,41] (and URI unpublished data).

plume material with depleted upper mantle. While these so-called melt extraction trajectories (METS) can satisfactorily describe the isotope and trace element systematics of some OIB [23], they remain to be tested in detail for suites of Atlantic MORB.

3. Sample selection and results

In order to study the nature of the depleted components in the Atlantic asthenosphere, we here focus on the most LREE-depleted NMORB from the depleted ends of the $(La/Sm)_n$ gradients caused by interacting mantle plumes. These regions contain little or no enriched plume material. The 16 NMORB selected for this investigation are shown in Fig. 1 (triangles). For comparison, we also measured $^{176}Hf/^{177}Hf$ of the most extreme EMORB from 11 regions of plume–ridge interaction (Fig. 1, squares). In general, these EMORB have the highest $(La/Sm)_n$ and $^{87}Sr/^{86}Sr$ ratios locally (see caption to Fig. 1 for two exceptions).

ε_{Hf} of this very depleted Atlantic NMORB population show a striking linear decrease from north to south along the entire 15,000-km long MAR (Fig. 2a). ε_{Nd} of these same NMORB also decrease from north to south although the gradient is not as pronounced (Fig. 2b). $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ both increase from north to south (Fig. 2c and d). In contrast to these relatively

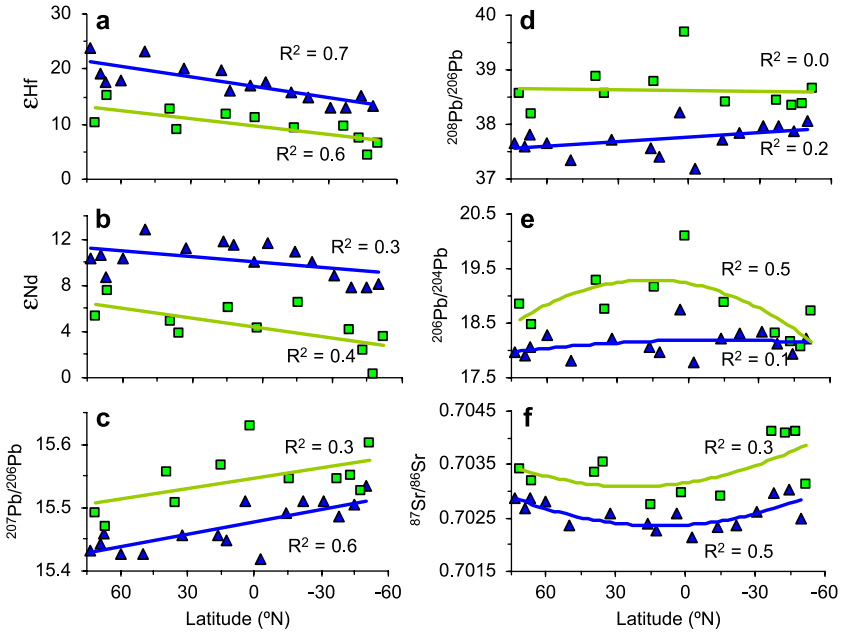

Fig. 2. Isotope profiles for Atlantic MORB. Blue triangles are NMORB and green squares are EMORB. For (a), (b), (c) and (d), the r^2 values are for linear regressions through the NMORB and EMORB data, respectively. The trend lines in (e) and (f) are second order polynomial best fits. Data from the present study and [16–22,39–41] and unpublished data from URI.

linear gradients, $^{87}Sr/^{86}Sr$ shows a broad minimum near the equator (Fig. 2f), whereas $^{206}Pb/^{204}Pb$ shows no regular trend (Fig. 2e). ε_{Hf} does not exhibit a strong correlation with Lu/Hf nor does ε_{Nd} with Sm/Nd (figures not shown) suggesting recent decoupling of the parent/daughter ratios from the isotope ratios.

The identification of large mantle provinces (>10,000 km) with distinctive isotope characteristics such as the DUPAL anomaly [24] or some domains in the Pacific [25] indicates that even though the asthenosphere may be relatively well mixed within a given province, it experiences limited exchange of material between provinces. In contrast to these internally relatively well-mixed provinces, isotope ratios of the isotopically depleted Atlantic NMORB display a remarkably regular 15,000-km long gradient, suggesting that some progressive process is at work.

In principle, the observed isotopic variability in NMORB could be caused by mixing with recycled material which was extracted from the mantle as melt or fluid, processed and subsequently re-mixed with the upper mantle with the requirement that this recycled component was *recently* depleted in incompatible elements. However, the following discussion shows that there is little evidence for mixing with such an ''isotopically enriched'' recycled component. (''Isotopically enriched'' is used here to describe material with high Pb and Sr and low Hf and Nd radiogenic isotope ratios.) Rather, it is likely that variations in the evolution of the upper mantle itself through geological time lead to an ''isotopically depleted'' mantle reservoir that causes the observed isotope gradients by mixing of mantle reservoirs. This suggests the upper mantle is not a uniformly depleted end member mixing with recycled material, but a reservoir which has developed non-uniformly despite asthenosphere convection.

4. Recycling components back into a uniformly depleted upper mantle

Recycled material that is ''isotopically enriched'' may be present in the upper mantle as subducted oceanic crust layers, fragments of the subcontinental lithosphere or plume-head restite. In principle, the presence of recycled material in the Atlantic upper mantle can generate isotopic variability in the NMORB

collected along the MAR due to preferential sampling of recycled material during partial melting. Holness and Richter [26] noted that basalts erupted at fast spreading ridges generally have lower Sr isotope ratios than basalts erupted at slow spreading ridges. They reasoned that beneath fast spreading ridges, the low-degree melts generated at the "wings" of the melting regime are not as effectively channelled to the ridge as similar melts produced at slow spreading ridges. If the asthenosphere is heterogeneous on a small scale with lower melting temperature recycled material in a depleted upper mantle matrix, it is these low-degree melts from the wings that carry the most enriched isotope signature (radiogenic Pb and Sr, unradiogenic Hf and Nd). Thus, fast spreading ridges produce "isotopically depleted" basalts in comparison to basalts from slow spreading ridges.

The spreading rate along the entire MAR is low in comparison to that along the East Pacific Rise. MAR full spreading rate increases steadily from 1.5 cm/year in the Arctic to 3.4 cm/year near 20°S before decreasing slightly down to 3.0 cm/year at the southern end of the MAR (calculated using NUVEL 1, http://www.doherty.ldeo.columbia.edu/users/menke/plates2.html). For the Atlantic NMORB, this increase in spreading rate is accompanied by "isotopic enrichment" (lower ε_{Hf} and higher $^{207}Pb/^{204}Pb$) (Fig. 3), which is the exact opposite of the global correlation suggested by Holness and Richter. Thus, either the MAR gradient in isotope ratios is unrelated to a north–south variation in the efficiency of melt collection or the recycled material has a higher melting temperature than the depleted upper mantle. Much of the literature, however, suggests that the "isotopically enriched" recycled component is a low melting temperature component (e.g. [7,27]). Thus, we conclude that the observed isotope gradient is not related to melt collection modes, but could possibly arise from a gradient in the concentration of recycled materials embedded in the upper mantle feeding the MAR. Possible origins for "isotopically enriched" recycled material mixing with the Atlantic upper mantle are explored below in the context of the MAR isotope gradients.

4.1. Recycled oceanic crust

Several studies have indicated that the NMORB source contains low melting temperature, chemically enriched eclogite or pyroxenite veins or folded layers resulting from the recycling of oceanic crust [7]. Evidence of such a chemically enriched, low melting temperature component, has been found in peridotites recovered from the South West Indian Ridge (SWIR) [27]. The ε_{Nd} composition of these peridotites is higher than that in the spatially associated basalts indicating that a relatively low melting temperature component (with low ε_{Nd} and presumably low ε_{Hf}) in the basalt source was preferentially used up during melting beneath the SWIR.

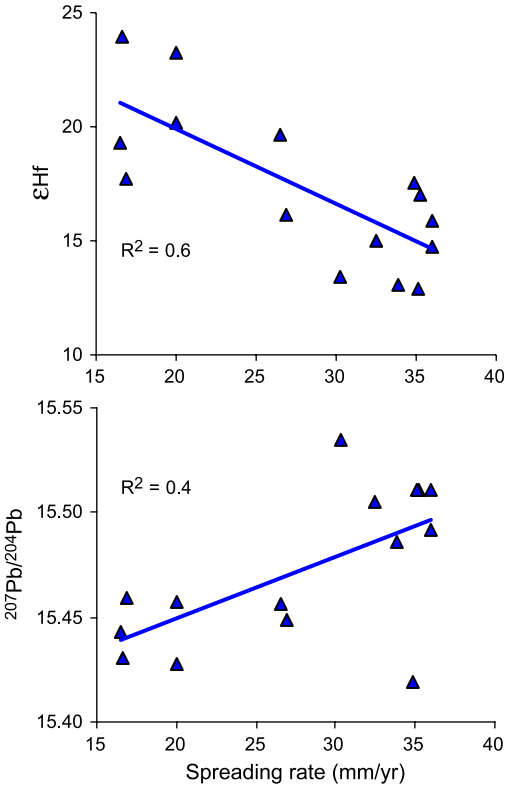

Fig. 3. Isotope ratios in NMORB as a function of Atlantic full spreading rate calculated with NUVEL1, http://doherty.ldeo.columbia.edu/users/menke/plates2.html.

In Pb–Pb and Hf–Pb isotope space (Fig. 4), the Atlantic NMORB fall along an array pointing from a highly depleted component towards EM2 or HIMU, *but clearly, and importantly so, not towards EM1*. This supports the theory that the "isotopically enriched" component in the Atlantic NMORB source is subducted oceanic crust (HIMU) [28] perhaps with some terrigenous sediments involved (EM2) [29]. The

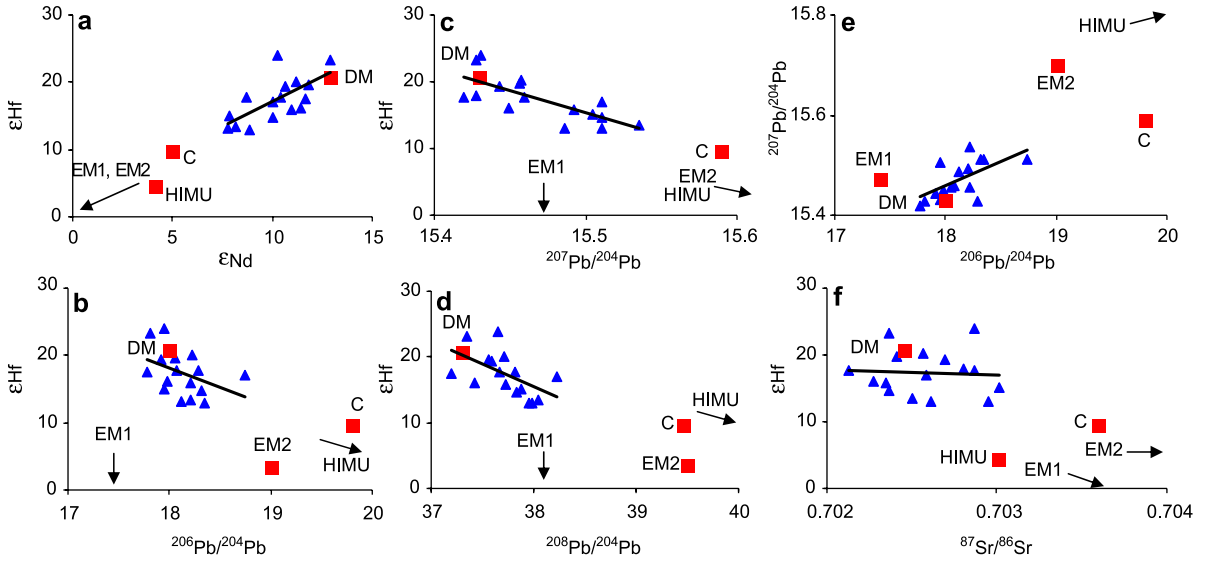

Fig. 4. Isotope–isotope space variations for the Atlantic NMORB (blue triangles). Black lines show linear regressions through the NMORB data. Red squares show mantle end-members for comparison [45–47].

observed "isotopic enrichment" of NMORB towards the south may thus result from an increased concentration of enriched pyroxenite or eclogite veins or layers of recycled oceanic crust in the upper mantle towards the south.

If more recycled oceanic crust contributes to the NMORB to the south, one would expect a corresponding increase in LREE enrichment to the south. However, $(La/Sm)_n$ is independent of latitude and decoupled from the isotope trends (see caption to Fig. 1). Thus, there can only be more recycled oceanic crust towards the south if this component was *recently* depleted in LREE. However, it is neither clear what process could be responsible for this recent depletion nor where the complementary enriched component is hiding. Thus, recycled oceanic crust is unlikely to be the source of the large-scale Atlantic NMORB isotope gradients.

4.2. Subcontinental lithosphere

Pieces of subcontinental lithosphere which were left behind as Laurasia and Gondwanaland broke apart (e.g. [30]) could mix with the depleted upper mantle resulting in the Atlantic isotope gradients. ε_{Hf} and $^{207}Pb/^{204}Pb$ do not correlate with the age of MAR opening, but they do correlate with distance to the bordering continents (Fig. 5). The closer the MAR is to the continents, the more "isotopically depleted" (high ε_{Hf} and low $^{207}Pb/^{204}Pb$) the NMORB, implying a source with high time-integrated Lu/Hf and low time-integrated U/Pb. Presumably, the closer the MAR is to the continents, the higher is the concentration of continental fragments beneath the MAR due to convection and edge effects [31,32]. This would imply that the subcontinental lithosphere fragments are *depleted* in incompatible elements on a time-integrated basis. While the subcontinental lithosphere is depleted in terms of major elements, such as Fe and Al, it is generally enriched relative to the depleted mantle in terms of trace elements and thus has high $^{206}Pb/^{204}Pb$ and Sr and low Nd and Hf isotope ratios (e.g. [33]). Mixing with subcontinental lithosphere is not a likely source of the isotope gradients since it is "isotopically enriched" while we are seeking an "isotopically depleted" source whose concentration increases as MAR-continent distance decreases. An additional and important argument against the role of continental material is based on the extreme heterogeneity of recovered xenoliths both from the lower continental crust and the continental lithosphere (e.g. [34,35]). Since by definition the lithosphere is rigid, presumably once heterogeneities have been established they cannot be efficiently homogenized (even

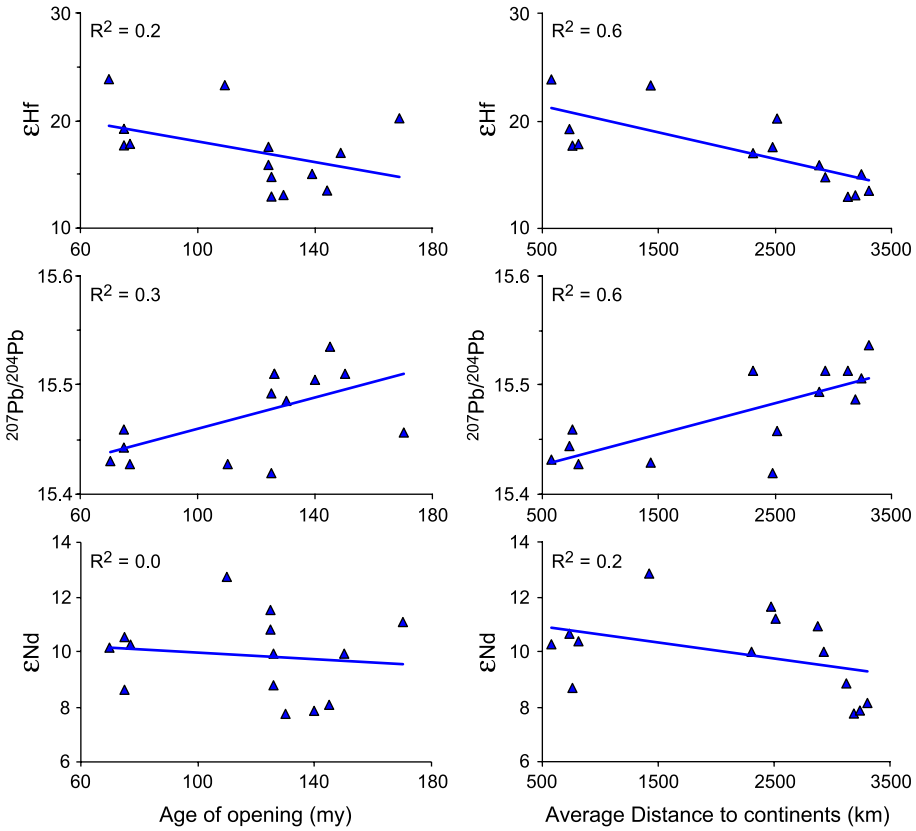

Fig. 5. Isotope ratios as functions of age of opening of the Atlantic and average distance from the MAR to the continents. Age of opening based on the plate reconstructions available at http://museum.gov.ns.ca/fossils/geol/globe.htm.

within the rheological boundary layer at the base of the lithosphere). This is in contrast to the observed regular isotopic trends which suggest that if mixing is involved at all, it likely entails steadily varying proportions of a relatively uniform source. Finally, the MAR NMORB isotope ratios are not correlated with position of the cratons or the thickness of the subcontinental lithosphere [35,36]. Although at some level continental pollution locally may occasionally play an important role in MAR basalt genesis (e.g. [37]), it cannot be invoked to explain the observed overall long-wavelength NMORB isotope gradients.

4.3. Plume-head restite

Fig. 1 shows those EMORB from each section of the MAR with the strongest plume influence (squares). Slopes of linear regressions through the EMORB's ε_{Hf}, ε_{Nd} and $^{207}Pb/^{204}Pb$ profiles largely parallel the NMORB gradients, although there is significant scatter (Fig. 2a–c). The $^{87}Sr/^{86}Sr$ EMORB profile also resembles that of the NMORB (Fig. 2f). This may reflect a genetic link between the local depleted mantle and the locally related mantle plumes.

The entire Atlantic NMORB source may contain plume material which was depleted in incompatible elements during the rising and dispersal of plume-heads in a manner similar to the HIMU province identified by Schilling et al. [20], Hana et al. [21] and Fontignie and Schilling [22]. This would imply that virtually the entire MAR taps upper mantle which has mixed with plume material to some degree, even the most depleted NMORB. However, the $^{206}Pb/^{204}Pb$ profiles of NMORB and EMORB are not similar (Fig. 2e) and the correlation between NMORB and

EMORB for the other isotope ratios is not very strong. Thus, despite the influence of plume-head restite on smaller scales (e.g. the HIMU province), widespread plume-head pollution along the entire MAR is unlikely to be the cause of the observed NMORB Hf and Nd isotope gradients unless these plume-heads had an isotopic signature significantly different from the plume-tails currently feeding the MAR. It is interesting to note that, since ε_{Hf} and ε_{Nd} in HIMU and the depleted mantle are relatively similar, it is not possible to readily discern the HIMU province in Hf or Nd isotope profiles along the MAR. In addition, since HIMU has extremely high $^{206}Pb/^{204}Pb$, the presence of the HIMU province makes it difficult to use lead systematics to investigate the origin of the MAR isotope gradients.

5. Variations in the evolution of the depleted upper mantle

In light of the lack of evidence in favor of mixing the depleted upper mantle with "isotopically enriched" recycled material (whether recently depleted oceanic crust, subcontinental lithosphere or plume-head restite) to generate the Atlantic NMORB, we turn to possible variations *inherent to the upper mantle*. In the following section, we evaluate two different end-member models of upper mantle evolution that do not involve any mixing and finally in Section 6 we evaluate one mixing scenario involving only mantle reservoirs which are "isotopically depleted" (as opposed to the "isotopically enriched" recycled components we considered above).

5.1. Gradient in the cumulative degree of melt extraction experienced by the depleted upper mantle

According to the first model of upper mantle evolution, the Atlantic upper mantle is less incompatible element-depleted (on a time-averaged basis) towards the south due to a progressively lower cumulative degree of melt extraction. Thus, ⟨Lu/Hf⟩ and ⟨Sm/Nd⟩ decrease and ⟨U/Pb⟩ and ⟨Th/Pb⟩ increase southwards and give rise to the observed isotope ratio gradients (Fig. 6a). (Brackets denote time-averaged parent/daughter ratios where the time interval considered is that from the beginning of continent extraction to the present.) This model is consistent with the observation that the $^{176}Hf/^{177}Hf$ gradient is much more pronounced than the $^{143}Nd/^{144}Nd$ gradient, which is to be expected because of the greater fractionation of Lu/Hf by melting relative to Sm/Nd and the shorter half-life of ^{176}Lu relative to that of ^{147}Sm.

This model assumes two stages, each on average with a different mode of upper mantle evolution. During the first stage (from 4.55 Ga to *T*) the upper mantle evolved essentially with BSE parent/daughter ratios. At time, *T*, the upper mantle melted, but the melt extraction varied with location resulting in a gradient in the parent/daughter ratio in the upper mantle. During the second stage (from *T* to the present) the upper mantle evolved with a north–south gradient in the time-integrated parent/daughter

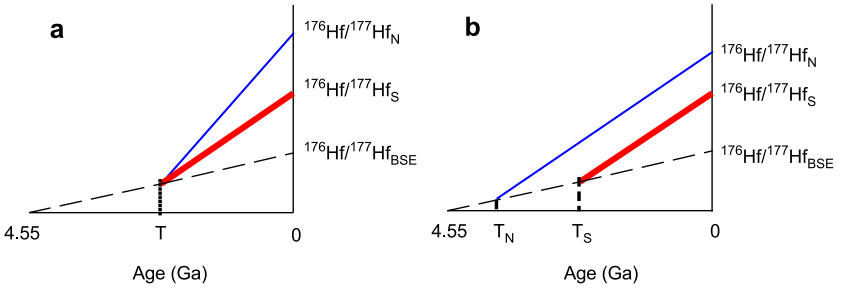

Fig. 6. Schematic of upper mantle evolution models. Dashed lines represent BSE evolution. Blue lines show average evolution of upper mantle beneath the northern MAR and heavy red lines show average evolution beneath the southern MAR. (a) shows isotope evolution for model 1 (gradient in the cumulative degree of melt extraction). (b) shows isotope evolution for model 2 (gradient in the onset age of upper mantle melting and initial continent formation).

ratio, $\Delta\langle Lu/Hf\rangle_{N-S}$. Melting and melt extraction during this second stage can be more complex (more pronounced multiple melting events or continuous melting) but the time-varying parent/daughter ratios at each location can be represented by a constant time-integrated parent/daughter ratio, $\langle Lu/Hf\rangle_N$ and $\langle Lu/Hf\rangle_S$, where the difference between these two is given by:

$$\Delta\langle Lu/Hf\rangle_{N-S} = \Delta(^{176}Hf/^{177}Hf)_{N-S}/(e^{\lambda T} - 1) \quad (1)$$

λ is the decay constant of ^{176}Lu. This equation can be used together with a melting model to calculate the north–south gradient in the cumulative degree of melting, ΔF_{N-S}. For modal fractional melting, this is:

$$\Delta F_{N-S} = (E_S)^x - (E_N)^x \quad (2)$$

E_S and E_N are the enrichment factors for the southern and northern time-integrated parent/daughter ratios relative to bulk silicate earth (e.g. $E_N = Lu/Hf_N/\langle Lu/Hf\rangle_{BSE}$). $x = D_{Hf}D_{Lu}/(D_{Hf} - D_{Lu})$, where the D values are the bulk residual solid/melt partition coefficients. See Table 2.

Fig. 7a shows ΔF_{N-S} as a function of model age calculated from the Atlantic NMORB εHf gradient assuming a *spinel lherzolite* mineralogy during melting. The older the upper mantle model ages are, the smaller must be the difference in degree of cumulative melt depletion between the north and the south. In the limiting case of an upper mantle model age of 4.55 Ga, ΔF_{N-S} is about 0.4%. Even for a model age of 1 Ga, ΔF_{N-S} is only 1%. These numbers are slightly higher than those obtained with analogous calculations using the Sm–Nd system and the Atlantic NMORB εNd gradient (for $T = 4.55$ Ga, ΔF_{N-S} is about 0.2%, for $T = 1$ Ga, ΔF_{N-S} is about 0.5%; Fig. 8a). For comparison, the continental mass represents 0.55% of the mantle mass (4 10^{25} kg) or 2.2.

Using partition coefficients for a *garnet lherzolite* mineralogy reduces ΔF_{N-S} (Fig. 7b). Even in this case, ΔF_{N-S} calculated from the Hf isotope gradient is slightly higher than that calculated from the Nd isotope gradient (Fig. 8b). However, these calculations are all highly sensitive to the values chosen for the partition coefficients (see Table 2). Therefore, despite the discrepancy in ΔF_{N-S} calculated from the Hf and Nd isotope systems, it is quite possible that the observed isotope gradients do in fact result from a slightly lower degree of melt extraction towards the south.

Table 2
Modelling parameters

	OL	OPX	CPX	Sp[a]	Gt
Mineral/melt partition coefficients, K_d					
Hf	0.0001	0.014	0.1595	0.007	0.255
Lu	0.0001	0.1	0.449	0.0045	7.1
Nd	0.0001	0.009	0.178	0.0006	0.052
Sm	0.0001	0.02	0.293	0.0006	0.25
Mineral proportions (modal melting)					
Spinel lherzolite	53%	24%	20%	3%	0%
Garnet lherzolite	55%	22%	15%	0%	8%

Bulk mineral/melt partition coefficients, D	Spinel lherzolite	Garnet lherzolite
D_{Hf}	0.04	0.05
D_{Lu}	0.11	0.66
D_{Nd}	0.04	0.03
D_{Sm}	0.06	0.07

Bulk earth isotope and parent/daughter ratios	
$^{176}Hf/^{177}Hf$	0.279814
Lu/Hf	0.283506
$^{143}Nd/^{144}Nd$	0.512638
Sm/Nd	0.324802

[a] Partition coefficients and mineral proportions are from [42] and references therein. Bulk Earth isotope ratios and parent/daughter ratios are from [12,43–45].

5.2. Gradient in the onset time of continent extraction

The second model of depleted upper mantle evolution ascribes the observed isotope gradients in the isotopically depleted NMORB to a gradient in the onset of upper mantle melting, ΔT_{N-S} (defined as the N–S age difference). In this case, assuming uniform time-averaged parent/daughter ratios (i.e. same cumulative degree of melt extraction), the upper mantle must have started melting progressively earlier towards the north (Fig. 6b).

For a given age of onset of melting in the north, T_N, the observed Hf isotope ratio gradient can be used to calculate both $\langle Lu/Hf\rangle$ and ΔT_{N-S}. As with the previ-

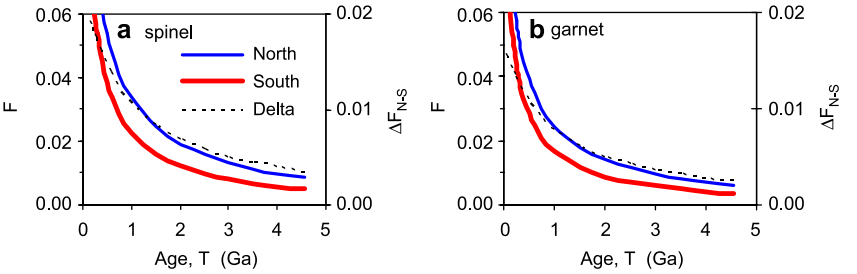

Fig. 7. Model 1. Gradient in the cumulative degree of melt extraction calculated for modal fractional melting of spinel- and garnet-lherzolite. Calculations are based on the Hf isotope gradient. F is the cumulative degree of melt extraction for the mantle beneath northern MAR (blue line) and the southern MAR (heavy red line). Dashed line is the difference between the north and south, ΔF_{N-S}. Calculations are based on a two-stage model where the first stage is BSE parent/daughter ratios and stage two begins at age T. See Table 2 for melting model data.

ous model, the following calculations are based on a two-stage upper mantle evolution model with BSE evolution in the first stage.

$$\langle {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}\rangle = [({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf})_{\mathrm{N},0} - ({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf})_{\mathrm{BSE},0}]/(e^{\lambda \mathrm{TN}} - 1) + \langle {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}\rangle_{\mathrm{BSE}} \quad (3)$$

$$\langle \mathrm{Lu/Hf}\rangle \cong 7.04\langle {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}\rangle \quad (4)$$

Where $({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf})_{\mathrm{N},0}$ is the ratio measured in MORB today in the north and 7.04 is a conversion factor from ${}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}$ atomic ratio to Lu/Hf mass ratio.

$$\Delta T_{\mathrm{N-S}} = \Delta({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf})_{\mathrm{N-S}}/[\lambda(\langle {}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf}\rangle - ({}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf})_{\mathrm{BSE}})] \quad (5)$$

where $\Delta({}^{176}\mathrm{Hf}/{}^{177}\mathrm{Hf})_{\mathrm{N-S}}$ is the observed north–south isotope gradient and $({}^{176}\mathrm{Lu}/{}^{177}\mathrm{Hf})_{\mathrm{BSE}}$ is the bulk silicate earth ratio.

In the limiting case, where melting began 4.55 Ga ago in the north, $\Delta T_{\mathrm{N-S}}$ is 1.9 Ga and ⟨Lu/Hf⟩ of the upper mantle is 0.29 (Fig. 9a). The more recent the initiation of melting in the north, the smaller the $\Delta T_{\mathrm{N-S}}$ and the higher the ⟨Lu/Hf⟩. These calculations agree only moderately well with the same calculations based on the ${}^{143}\mathrm{Nd}/{}^{144}\mathrm{Nd}$ profile (for $T_{\mathrm{N}} = 4.55$ Ga, $\Delta T_{\mathrm{N-S}} = 0.8$ Ga) (Fig. 9b).

Since these calculations do not rely on either partition coefficient data or the type of melting model used, the fact that the Hf- and Nd-isotope-based results are not in mutual agreement suggests that the observed isotope gradients in Atlantic NMORB cannot be due entirely to a gradient in the time of onset of melting. Other processes must be involved as well.

Both models of upper mantle evolution presented above require that the differences, whether in time of melting or degree of depletion, are longstanding on the order of 1 Ga or more. Thus, these differences significantly predate the opening of the Atlantic. None of the evolution models can explain the correlation of isotope ratios with MAR to

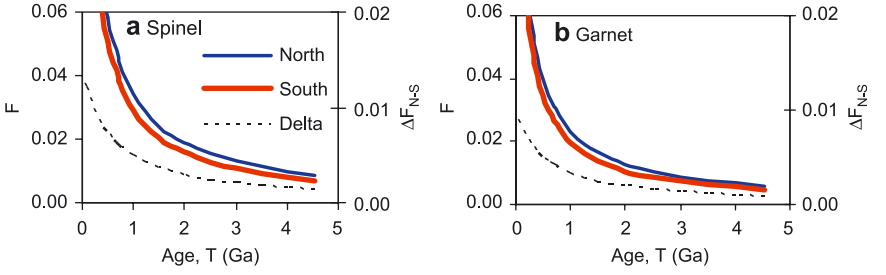

Fig. 8. Model 1. Gradient in the cumulative degree of melt extraction calculated for modal fractional melting of spinel lherzolite (a) and garnet lherzolite (b). Calculations are based on the Nd isotope gradient. See Fig. 7 for definitions of F and $\Delta F_{\mathrm{N-S}}$.

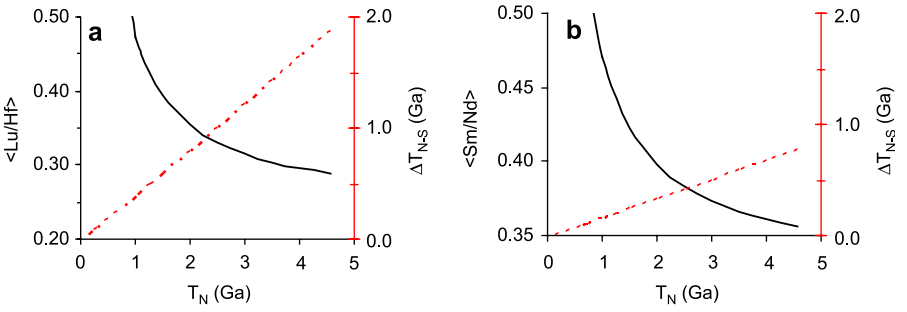

Fig. 9. Model 2. Gradient in onset time of melting, T, calculated from the isotope ratio gradients. (a) is calculated from $^{176}Hf/^{177}Hf$ and (b) is from $^{143}Nd/^{144}Nd$. In each plot, the black line is time-integrated parent/daughter ratio and red dashed line is ΔT_{N-S}, the difference in north–south onset time of melting.

continent distance. This leads us to our preferred interpretation.

6. Preferred model: gradient in the concentration of garnet restite

The mantle beneath the northern MAR may contain more restite from ancient melting in the garnet stability field than the southern mantle. This can be evaluated using the $\Delta\varepsilon_{Hf}$ parameter. $\Delta\varepsilon_{Hf}$ measures the deviation of MORB from the global Hf–Nd isotope correlation (i.e. the "mantle array"). $\Delta\varepsilon_{Hf}$ indicates whether a basalt's isotope composition falls above (positive $\Delta\varepsilon_{Hf}$) or below (negative $\Delta\varepsilon_{Hf}$) the Hf–Nd array. On the basis of $\Delta\varepsilon_{Hf}$, two depleted mantle reservoirs, DMMI and DMMII, have been defined [38]. DMMI has positive $\Delta\varepsilon_{Hf}$ and is the restite of ancient melting in the garnet stability field. DMMII has negative $\Delta\varepsilon_{Hf}$ and results from ancient melting in the spinel stability field. The Atlantic NMORB data fall along a fairly regular trend of decreasing $\Delta\varepsilon_{Hf}$ from north to south (Fig. 10). This is consistent with a model where the Atlantic upper mantle trends from being dominated by ancient garnet restite (deep melting) in the north to ancient spinel restite (shallow melting) in the south. This argument, however, does not constrain the depth of present-day melting beneath the ridge.

This model is the only mixing model evaluated here that can reconcile the sense of the ε_{Hf} and $^{207}Pb/^{204}Pb$ correlations with distance of the MAR to the continents (see Fig. 5). This leaves us with the following scenario. Upper mantle melted anciently and deeply in the garnet stability field, because the Earth presumably was hotter in the past. It is not crucial whether this melting resulted directly in the generation of continents or whether oceanic crust was formed from the melt. What is critical is that restite remained in the garnet stability field during melting. If it had continued to melt beyond the spinel transition, the restite would have given up the excess Lu which was in the garnet and the ancient garnet signature would have been erased. After ancient melting in the garnet stability field, this restite with high Lu/Hf and low $^{235}U/^{204}Pb$ was sequestered under continents, either because that is where it was initially formed or because it was overridden by the continents at some point. Since this "garnet residue mantle" was the deepest part of a column of melted mantle, it was never incorporated as part of the rigid continental

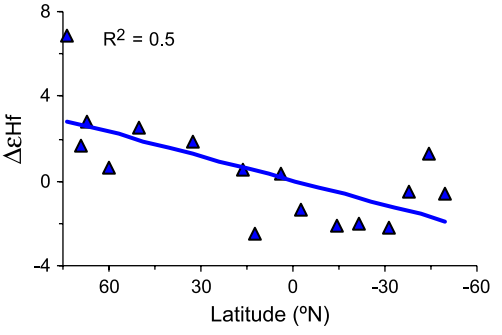

Fig. 10. $\Delta\varepsilon_{Hf}$ versus latitude for Atlantic NMORB. $\Delta\varepsilon_{Hf}$ is the deviation of ε_{Hf} at a given ε_{Nd} from the mantle array [38] where the equation of the mantle array is given by $\varepsilon_{Hf}=1.4\varepsilon_{Nd}+2.8$ (based on literature compilation and unpublished data by JBT for more than 2000 OIB and MORB of global distribution).

lithosphere but remained part of the *asthenosphere*. It could have flowed while it lay under the continents, but it was generally isolated from suboceanic mantle (particularly away from the edges of this reservoir). Then as the MAR began to open, the rifting first tapped this subcontinental mantle. As the rift widened, sub-oceanic mantle (which had not undergone this ancient melt extraction in the garnet stability field) was able to flow into the upwelling region beneath the MAR. Today near the current rift north of Iceland, there is a greater proportion of this garnet residue upwelling mantle beneath the MAR and thus the garnet signature is stronger. In the south Atlantic, the opening is wider and this ''garnet residue mantle'' is more diluted in the NMORB source.

7. Conclusions

The various recycling schemes involving ''isotopically enriched'' components investigated here to determine their possible connection to the observed long-wavelength variation in isotope ratios of Atlantic NMORB each have unsatisfactory consequences. Recycled oceanic crust (HIMU) with or without terrigenous sediment (EM2) can only play a role if there is a mechanism that recently depleted this component. Yet this leaves unanswered the question where the complementary extracted component is. There is no evidence to support the theory that the recycled material is in the form of plume-head restite since isotope ratios in NMORB and the local EMORB are not strongly correlated. Finally, subcontinental lithosphere is difficult to rule out definitively since its composition is not well constrained. However neither oceanic crust, plume-head restite nor subcontinental lithosphere satisfactorily explain the increase in ''isotopic depletion'' (high ε_{Hf}, low $^{207}Pb/^{204}Pb$) with decreasing distance to the continents. In fact, for subcontinental lithosphere this is exactly opposite to the trend that would be expected. Certainly, each of these mixing processes may be influencing the compositions of NMORB locally, but not on the Atlantic-wide scale implied by the Hf isotope data.

Differences in the timing or degree of melt extraction from the upper mantle could reproduce the observed isotope gradient, but again there is no obvious connection between such ancient melting events and correlation between NMORB isotope ratios with the MAR to continent distance. In addition, these evolution models relate to melting events, which took place long before the opening of the Atlantic. Thus, they cannot be independently evaluated using plate reconstruction data or ages of craton formations and their underlying lithosphere thickness [35,36]. Implicit in the evolution models is the assumption that the observed regular Hf isotope gradient has been preserved for a long time, on the order of at least a billion years. Such a regular gradient would be difficult (and likely impossible) to preserve in a convecting mantle.

So we need a mixing endmember (1) whose concentration increases close to the continents, (2) which is the restite of ancient melting in the garnet stability field and (3) whose composition is relatively homogeneous. This component is the mantle restite of ancient melting in the garnet stability field. This was isolated in the mantle under the continents (*below* the incompatible element enriched continental lithosphere) and then upon opening of the Atlantic, was entrained in the convection beneath the MAR. It is most concentrated and effects NMORB compositions most strongly along fresh rifts where the MAR is closest to the continents.

Despite mantle convection, the depleted upper mantle is apparently not a uniform reservoir. The working model presented here could be further tested with NMORB from other mid-ocean ridges. As in this study, care should be taken to include only the most depleted MNORB in order to avoid the influence of any plumes. In addition, the NMORB must cover a large area; regional studies cannot detect such gradual isotope gradients. Such studies would help resolve the question whether mixing of two ''isotopically depleted'' mantle reservoirs is unique to the mantle beneath the MAR or whether such mixing is more widespread.

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