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## Atypically depleted upper mantle component revealed by Hf isotopes at Lucky Strike segment

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### Abstract:

The Earth's upper mantle is commonly depicted as a “marble cake” assemblage of a refractory component mingled with varying amounts of geochemically diverse enriched components. This depleted component controls the major element composition of Mid-Oceanic Ridge Basalts (MORBs). It has long been considered a fairly uniform reservoir, depleted by early melting and well homogenized by subsequent convective stirring. We present new Hf, Nd, Pb and Sr isotopes and trace element data for basalts from the center of the Lucky Strike segment of the Mid-Atlantic Ridge (MAR). Despite the limited size of our sampling area (1.6 km along-axis by 5 km across), these data show a large range of isotopic compositions (similar to that of the whole MAR). It has recently been shown that part of the reason for not observing more segments with correlated Hf–Nd isotope systematics may be the lack of fine-scale sampling. Our data confirm this idea and show strong correlations between all isotope ratios. The systematics of Hf–Nd isotopes in Lucky Strike basalts define an atypical correlation, distinct from the global mantle array, with an anomalously high  $\epsilon_{\text{Hf}}$  for a given  $\epsilon_{\text{Nd}}$ . We illustrate that this atypical trend is the signature of an ancient refractory mantle rather than the product of kinetic processes during the melting event. The existence of this mantle component at Lucky Strike allows us to discuss the structure of the upper mantle around the Azores.

### Highlights

► High spatial resolution sampling of MAR segment shows small scale mantle heterogeneity. ► Samples define an atypical Hf–Nd isotope correlation, distinct from the mantle array. ► Upper mantle near the Azores hotspot contains different refractory components.

**Keywords:** Oceanic basalts ; Mid-Atlantic Ridge ; Lucky Strike ; Mantle heterogeneity ; Hf isotopes

## 26 **1. Introduction**

27 It is now well established that the upper mantle is heterogeneous (Hofmann et al., 2003 ). This  
28 geochemical heterogeneity is evidenced by the composition of basalts which erupted along mid-  
29 oceanic ridges, which reveals the existence of broad mantle isotopic domains (e.g., the DUPAL  
30 anomaly (Dupré and Allègre, 1983)). Each mantle domain is characterized by its intrinsic lithological  
31 and geochemical heterogeneity, suggesting different convective histories (Hamelin et al., 2011;  
32 Hanan et al., 2004; Meyzen et al., 2007; Vlastelic et al., 1999). At a local scale, basalt geochemical  
33 variations are interpreted to result from partial melting of a marble-cake upper mantle (Allègre et  
34 al., 1984; Morgan and Morgan, 1999; Stracke et al., 2005). This geochemical heterogeneity of ridge  
35 basalts has been explained by the addition of various amounts of the FOZO component (Hanan and  
36 Graham, 1996; Hart et al., 1992; Stracke et al., 2005) to a uniformly depleted source (Depleted  
37 MORB Mantle, DMM). This second asthenospheric component is commonly inferred to have been  
38 depleted by previous melting events but subsequently homogenized by convective stirring (Zindler  
39 and Hart, 1986). However, recent studies of abyssal peridotites have revealed that distinct ancient  
40 depletion signals may still be identified in refractory mantle domains (Harvey et al., 2006; Liu et al.,  
41 2008; Salters and Dick, 2002; Seyler et al., 2003; Stracke et al., 2011). This observation adds a new  
42 level of complexity to the interpretation of MORB data and emphasizes the heterogeneous nature of  
43 the depleted mantle.

44 Lu–Hf and Sm–Nd isotope systems have proven to be useful in tracking the signatures of ancient  
45 mantle depletion (e.g., Andres et al., 2004; Graham et al., 2006; Salters et al.; Stracke et al., 2011).  
46 Their parent/daughter ratios are higher in the residue than in the melt, thus developing a radiogenic  
47 signature in time. The similar behavior of these two radiogenic isotope systems during mantle  
48 melting results in strongly correlated  $^{177}\text{Hf}/^{176}\text{Hf} - ^{143}\text{Nd}/^{144}\text{Nd}$  in oceanic basalts, the so-called

49 “mantle array” (Patchett and Tatsumoto, 1980). However, deviations from this basic model have long  
50 been documented, in particular for mid-oceanic ridge samples (Chauvel and Blichert-Toft, 2001;  
51 Debaille et al., 2006; Patchett and Tatsumoto, 1980; Salters and White, 1998). For example, a lack of  
52 correlation between these two systems characterizes MORBs collected between 22°N and 35°N  
53 (Debaille et al., 2006). Anomalously high values of  $^{177}\text{Hf}/^{176}\text{Hf}$  for a given  $^{143}\text{Nd}/^{144}\text{Nd}$  have also  
54 been measured along Mohns ridge (Blichert-Toft et al., 2005). These deviations from the mantle  
55 array model were initially interpreted as the result of isotopic disequilibrium between melts and their  
56 mantle source across the garnet-spinel transition beneath the mid-oceanic ridge (Blichert-Toft et al.,  
57 2005; Debaille et al., 2006). More recently, a systematic study of Hf-Nd isotopes in oceanic basalts  
58 has shown an array of parallel trends on a global scale (Salters et al., 2011). These authors attributed  
59 these sub-parallel arrays to the involvement of varying amounts of highly residual peridotites within  
60 the upper mantle. According to this model, the non-uniformity of the depleted component together  
61 with the lack of fine-scale sampling could explain the lack of correlation between  $\epsilon\text{Hf}$  and  $\epsilon\text{Nd}$  along  
62 the global mid-oceanic ridge system.

63 In the central part of the Lucky Strike ridge segment along the Mid-Atlantic Ridge (MAR), the  
64 exceptional sampling resolution gives an opportunity to examine the different hypotheses for Lu-Hf  
65 and Sm-Nd isotope systematics in the mid-oceanic ridge environment at a local scale. A recently  
66 published petrogenetic model for this area has shown the existence of significant geochemical  
67 variations in the Lucky Strike segment mantle source (Gale et al., 2011). Based on this study, we  
68 have selected a suite of representative samples spanning the whole range of geochemical variation  
69 and located within an  $8\text{km}^2$  in the central portion of the segment. The Lucky Strike segment is also  
70 proximal to, and influenced by the Azores hotspot (Dosso et al., 1999; Langmuir et al., 1997;  
71 Schilling, 1975). Therefore, our new sample collection can also provide new constraints on the origin  
72 of the geochemical anomaly associated with the Azores hot spot-MAR interaction.

## 73 **2. Geological setting and small scale sampling**

74 The area studied is located along the MAR, South-West of the Azores triple junction.  
75 Geochemical evidence together with geomorphological and geophysical characteristics demonstrate a  
76 clear plume-ridge interaction in this region (Asimow et al., 2004; Gale et al., 2011; Gente et al.,  
77 2003; Schilling, 1975). In this area, the MAR is characterized by a succession of segments bound by  
78 left-lateral, non-transform offsets. The Lucky Strike segment (fig. 1) is 60 km-long and bound by  
79 non-transform discontinuities at 37°00'N and 37°35'N. It is a slow ridge segment characterized by a  
80 full spreading rate of 21 mm/yr. This segment, located south west of the Azores hotspot, is  
81 significantly shallower and volcanically more robust than other MAR segments (Cannat et al., 1999;  
82 Escartín et al., 2001). The axial lithospheric structure and composition are typical of slow spreading  
83 ridges, characterized by a well-developed, 11-12km-wide axial valley, and a deepening of 1600m of  
84 the valley floor towards the segment ends (Detrick et al., 1995) where serpentinized peridotites  
85 outcrop (Gràcia et al., 1997). The prominent seamount at the segment center (the Lucky Strike  
86 volcano) is 7km wide and 15km along axis. It is underlain by an axial magma chamber 3.4km below  
87 the seafloor (Singh et al., 2006) and hosts an active hydrothermal field at its summit (Langmuir et al.,  
88 1997). Several volcanic ridges spread north and south from this central volcano suggesting along axis  
89 diking, while magnetic data suggest that magmatic accretion in the center of the Lucky Strike  
90 segment is presently focused in a narrow graben at the top of the central volcano (Miranda et al.,  
91 2005). This area has been well studied since the hydrothermal field discovery in 1992 (Langmuir et  
92 al., 1997), with a uniquely dense sampling among slow-spreading segments; more than 200 basaltic  
93 samples have been collected with dredges, wax cores, submersibles, and other deep-sea vehicles.  
94 Sample distribution along the segment is uneven, with the highest density on the central volcano. We  
95 report here new Sr, Nd, Pb and Hf isotopic data for 18 samples collected there during the

96 Graviduck06 and Bathyluck09 cruises (Table 1), using the Nautilie submersible (IFREMER) and  
97 Remotely Operated Vehicles (Victor; Figure 1).

### 98 **3. Analytical methods**

99 Trace elements were measured using the Bruker 820 ICP-MS quadrupole instrument at the  
100 Laboratoire de Planétologie et de Géodynamique in Nantes. Dissolutions were performed on 50 mg  
101 of sample at a temperatures of 120°C for 12 hours in 1 mL 8N HNO<sub>3</sub> and 0.5 mL ~23N HF. Samples  
102 were evaporated to dryness at 80°C, then re-dissolved in 2mL 8N HNO<sub>3</sub> and re-evaporated. The final  
103 dissolution was made in 4 mL 4N HNO<sub>3</sub> before a 1:5000 dilution in 0.3N HNO<sub>3</sub>. Ge, Rh, In, Tm and  
104 Bi were used for internal standard normalization and the following standards were used for  
105 calibration curves: BHVO-2, W2, DNC-1, BIR-1 and the LDEO (Columbia University) in-house  
106 standard Mid-Atlantic Ridge basalt MAR. The LDEO in-house standard K1919, collected from the  
107 same lava flow as BHVO-1, was also analyzed several times within each analytical run to correct for  
108 instrumental drift. The continental basalt reference material BR, from the CRPG Nancy was analyzed  
109 several times to test our analytical reproducibility. All data are reported in table 1.

110 For isotope measurements, powdered samples (400-700 mg) were dissolved in Savillex vials with  
111 concentrated HF-HBr ultrapure acids (3:1 in volume). Pb, Hf, Sr and Nd were separated from the  
112 same dissolution using four different columns starting with Pb to minimize contamination. The Pb  
113 extraction technique used was from (Manhes et al., 1978), using HBr 0.5M and HCl 6M on AG 1-X8  
114 anion resin. Pb blanks measured using this procedure were < 100 pg, and thus are negligible relative  
115 to the amount of sample analyzed. The effluent containing Hf, Sr and the rare earths were evaporated  
116 and taken up in 6M HCl, evaporated again and taken up in 1 ml of 0.5M HCl/0.15M HF. It was then  
117 ready to pass through an AG 50-X8 cation column (microcolumn Savillex, 30 ml, 6.4mm ID x  
118 9.6mm OD x 25 cm). The first 6 mls containing the Hf-Ti fraction were eluted in 0.5M HCl/0.15M

119 HF. The rest of the elution was completed using 3M HCl to separate Rb from Sr and 4M HNO<sub>3</sub> to  
120 separate Ba from rare earths. Nd was separated from Ce and Sm using 0.2M HCl and 0.35M HCl on  
121 a 0.8x4cm Biorad column loaded with LN Eichrom resin. The Hf-Ti fraction was evaporated and  
122 taken up in 6M HCl with a few µl of H<sub>2</sub>O<sub>2</sub>. It was loaded on a column made of a pipette tip filled  
123 with 100 mg of LN Eichrom resin. Ti was first eluted with 10ml 6M HCl with 50µl of H<sub>2</sub>O<sub>2</sub> and Hf  
124 was collected in 5 ml of 2M HF.

125 Sr isotope ratio measurements were carried out by thermal ionization mass spectrometry using a  
126 Finnigan Mat26x and a Thermo Finnigan Triton. Compositions were normalized for instrumental  
127 mass fractionation relative to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ .  $^{87}\text{Sr}/^{86}\text{Sr}$  of the NBS987 Sr standard during the  
128 course of the analyses yielded  $0.710235 \pm 45$  (n=4, 2σ) for the MAT26x and  $0.710255 \pm 20$  (n=2) for  
129 the Triton. Isotopic compositions of Hf and Pb were measured at Ifremer, Brest, using a MC-ICPMS  
130 Neptune. Repeat measurements of the Hf isotope standard JMC 475 (Denver) during the course of  
131 the analyses yielded  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282145 \pm 13$  (n=8, 2σ). The results were normalized to the value  
132 of 0.282158 using  $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$  for mass fractionation correction. The Pb isotope data are  
133 reported relative to published values for NBS 981 (Catanzaro et al., 1968). The samples were spiked  
134 with thallium to correct for mass fractionation. Based on repeated runs of NBS 981, the estimated  
135 external precision for Pb analyses is ±0.02%, 2σ for  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  and ±0.03%, 2σ for  
136  $^{208}\text{Pb}/^{204}\text{Pb}$ . During the course of the analyses, 10 replicates of the Pb isotope standard NIST981 gave  
137 an average of  $16.930 \pm 0.003$  (2σ) and  $15.482 \pm 0.003$  (2σ) and  $36.668 \pm 0.008$  (2σ) for  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  
138  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  respectively. Isotopic compositions of Nd were measured at Institut  
139 Universitaire Européen de la Mer, Brest, using a Thermo Finnigan, Triton. The measurements were  
140 carried out in static mode. All Nd data are fractionation corrected to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ . During the  
141 course of the study, analyses of the La Jolla standard were performed and gave an average of  
142  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511843 \pm 4$  (n=4 2σ).

143 Using the same analytical method, BCR-2 gave values of  $^{176}\text{Hf}/^{177}\text{Hf} = 0.282861 \pm 9$ ,  $^{206}\text{Pb}/^{204}\text{Pb} =$   
144  $18.7496 \pm 7$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.6175 \pm 7$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 38.7291 \pm 21$ ,  $^{87}\text{Sr}/^{86}\text{Sr} = 0.705008 \pm 8$ ,  
145  $^{143}\text{Nd}/^{144}\text{Nd} = 0.512629 \pm 8$ .

## 146 **4. Results, geochemical variations in Lucky Strike basalts**

147 The Lucky Strike segment contributes to the definition of the general geochemical gradient South  
148 of the Azores (Dosso et al., 1999; Gale et al., 2011; Langmuir et al., 1997; Schilling, 1975). Samples  
149 from this area have long been characterized as enriched in incompatible elements compared to  
150 normal-MORB with  $\text{La}_\text{N}/\text{Sm}_\text{N}$  and  $\text{K}_2\text{O}/\text{TiO}_2$  ratios higher than 1.25 and 0.11 respectively. Our data  
151 are in good agreement with this first order observation. Lucky Strike samples show varying levels of  
152 incompatible element enrichment, with a bi-modal distribution of  $\text{K}_2\text{O}/\text{TiO}_2$  ratios (Fig. 2a). We have  
153 defined two different groups named “transitional-MORB” ( $0.11 < \text{K}_2\text{O}/\text{TiO}_2 < 0.25$ ) and “enriched-  
154 MORB” ( $\text{K}_2\text{O}/\text{TiO}_2 > 0.25$ ), consistent with the definitions in Gale et al. (2011). These two groups  
155 also show different petrographic characteristics: transitional-MORB samples are fresh aphyric  
156 basalts, whereas enriched-MORB samples are slightly altered vesicular basalts with plagioclase (0-  
157 20%) and olivine (0-3%) phenocrysts. Groundmass textures are microcrystalline for E-MORB  
158 samples and vary from microcrystalline to glassy for T-MORB samples.

159 Basalts from the transitional group are found throughout the segment whereas enriched basalts are  
160 found almost exclusively in the center. Our samples were recovered solely in the central part of the  
161 segment within an area of less than  $8 \text{ km}^2$ . They display  $1.25 < \text{La}_\text{N}/\text{Sm}_\text{N} < 2$  typical of transitional  
162 MORB (9 samples) and  $\text{La}_\text{N}/\text{Sm}_\text{N} > 2$  typical of enriched MORB (9 samples) showing therefore the  
163 entire range in incompatible element enrichment previously reported for the whole Lucky Strike  
164 segment (Gale et al., 2011) (Fig. 2a). Figure 2b presents the REE patterns normalized to chondritic  
165 CI values for both groups of samples. Transitional samples are characterized by relatively flat REE

166 patterns with slight enrichments in light REE, whereas enriched samples have marked enrichments in  
167 light REE (60-70x chondrites) and show slight fractionations between middle and heavy REE. It is  
168 worth noting that samples from the Eastern slopes of the central volcano and from the Eastern axial  
169 valley wall (named GRA-Nxx) show the same range of variation as that from samples collected  
170 exclusively on the summit of the Lucky Strike volcano (named B09-ROCxx). This indicates that the  
171 patterns described here do not reflect a temporal variability of basalt compositions at time scales of  
172 about 500 ka (spreading age of the sample furthest from the axis) or less. Sr, Nd and Pb isotopes  
173 show variations that are in good agreement with previous data from this ridge segment (Gale et al.,  
174 2011). The most enriched samples exhibit coherent, more radiogenic Pb, Sr and less radiogenic Nd  
175 than the intermediate group (fig. 4). In binary isotope diagrams, Lucky Strike samples plot along  
176 mixing lines between a depleted mantle component and an enriched component attributed to the  
177 Azores hotspot. In these isotopic dimensions, even the less enriched samples from Lucky Strike are  
178 significantly more enriched than the DMM, which agrees with their major and trace element  
179 compositions. A simple mixing model between the DMM (Salters and Stracke, 2004) and the Azores  
180 mantle (Beier et al., 2007) reproduces the variations in  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $\epsilon\text{Nd}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ .

181 Our new dataset shows a range of values from  $\epsilon\text{Hf} = +14.3$  to  $+22.1$ , comparable to values  
182 previously reported in ridge segments immediately South and North of Lucky Strike (Agranier et al.,  
183 2005; Chauvel and Blichert-Toft, 2001). Despite the limited spatial extent of our sampling area, the  
184 new data show a range of variation that is of the same order of magnitude as that reported for the  
185 entire MAR (Agranier et al., 2005; Andres et al., 2004; Debaille et al., 2006). It is worth noting that  
186 the transitional group extends towards a more radiogenic  $\epsilon\text{Hf}$  end-member in the Hf-Nd isotopic  
187 diagram and therefore plots above the mantle array. In contrast, in the same diagram, the enriched  
188 group extends toward a lower  $\epsilon\text{Hf}$  end-member and plots near the Azores isotopic field, below the  
189 mantle array (fig. 5). The positive correlation between  $\epsilon\text{Hf}$  and  $\epsilon\text{Nd}$  agrees with the expected

190 coherence of Sm-Nd and Lu-Hf isotopic systems during magmatic processes, albeit with an unusual  
191 slope compared to that of the mantle array (Fig. 5). Compared to other isotopic systems, the  
192 systematics of Hf isotopes in this region of the MAR are still poorly known (fig. 3), and the Hf  
193 isotopic ratios reported here are the first for the Lucky Strike segment. Basalts collected along the  
194 MAR between 46° to 35°N reveal a comparable slope, however, (Agranier et al., 2005; Chauvel and  
195 Blichert-Toft, 2001; Dosso et al., 1999; Salters et al., 2011; Yu et al., 1997) which is strikingly  
196 different from the Nd-Hf correlation observed along other regions of the MAR (Fig. 5). The Hf  
197 versus Sr isotope diagram shows a similar abnormal correlation compared to the rest of the MAR.  
198 We additionally observe that the Lucky Strike transitional end-member seems relatively radiogenic in  
199 Pb isotopes ( $^{206}\text{Pb}/^{204}\text{Pb} > 19.35$ ) compared to the classical depleted mantle (Salters and Stracke,  
200 2004) ( $^{206}\text{Pb}/^{204}\text{Pb} \approx 18.20$ ) (Fig. 5a).

201 This unusual isotopic signature is however not unique in MORB, having been detected, for  
202 example, in basalts from Mohns Ridge (fig. 6). The most depleted samples from this northern  
203 Atlantic ridge show values of  $\epsilon\text{Hf}$  for a given  $\epsilon\text{Nd}$  to be very similar to those of Lucky Strike samples  
204 (Blichert-Toft et al., 2005) (Fig. 6). However, important differences exist between the two zones: (i)  
205 Mohns Ridge samples define a hyperbolic  $\epsilon\text{Hf}$ -  $\epsilon\text{Nd}$  array instead of the linear Lucky Strike trend  
206 (Blichert-Toft et al., 2005), (ii) values of Pb isotopic ratios in depleted Mohns Ridge samples are  
207 unradiogenic ( $^{206}\text{Pb}/^{204}\text{Pb} \approx 17.95$ ) and (iii) a geographical trend is present along Mohns Ridge,  
208 whereas the Lucky Strike variability is observed within a small ( $< 8 \text{ km}^2$ ) area on axis, and  
209 reproduced in basalts from other segments in the 45-35°N MAR region near the Azores.

## 210 **5. Discussion**

### 211 **5.1 Significant geochemical variations in basalts at local scale.**

#### 212 5.1.1. Small scale mantle heterogeneities or disequilibrium melting?

213 At this fine sampling scale, it is important to investigate whether the geochemical variations  
214 observed in basalts are the result of mantle heterogeneity or if they are produced by kinetic processes  
215 during melting. Early studies have commonly observed a wide range of  $\epsilon_{\text{Hf}}$  in MORB for a given  
216  $\epsilon_{\text{Nd}}$ , leading to the hypothesis that melts may not be isotopically equilibrated with their peridotitic  
217 sources (Blichert-Toft et al., 2005; Debaille et al., 2006). According to this hypothesis, a highly  
218 variable Hf isotope dataset may result from the disequilibrium melting of a garnet-bearing peridotite  
219 in which the individual mineral phases are not in isotopic equilibrium (Blichert-Toft et al., 2005;  
220 Debaille et al., 2006). Because garnet incorporates Lu preferentially over Hf, it could develop a time-  
221 integrated signature with elevated  $\epsilon_{\text{Hf}}$  values. Preferential melting of garnet would therefore likely  
222 produce highly radiogenic Hf values in basalts.  $\text{Hf}^{4+}$  is expected to possess a lower diffusion  
223 coefficient than  $\text{Pb}^{2+}$  and  $\text{Nd}^{3+}$ , which could explain why this element would be more sensitive to this  
224 kinetic process. If the isotopic composition of a particular mineral phase dominates the isotopic  
225 composition of the generated melt, variable  $\epsilon_{\text{Hf}}$  compositions in MORB may be generated from a  
226 single mantle domain during the current melting event below the present-day ridge. In this  
227 hypothesis, the local depleted mantle identified on  $\epsilon_{\text{Hf}}$  diagrams (fig. 5) may not correspond to a real  
228 end-member, but may instead result from a deviation toward radiogenic  $\epsilon_{\text{Hf}}$  values due to kinetic  
229 processes during mantle melting. This disequilibrium melting hypothesis has been proposed to  
230 explain the high  $\epsilon_{\text{Hf}}$  component found along Mohs and Knipovich ridges (Blichert-Toft et al., 2005)  
231 (fig. 6), and to explain the lack of correlation between  $\epsilon_{\text{Hf}}$  and other isotopes systems along the MAR  
232 between 22 and 35°N (Debaille et al., 2006).

233 Several arguments lead us to rule out this kinetic hypothesis as the cause of observed  $\epsilon_{\text{Hf}}$   
234 variations at Lucky Strike. A primary line of evidence stems from the good correlation between  $\epsilon_{\text{Hf}}$   
235 and other isotopic systems, which is not expected if kinetic processes influenced this isotopic ratio.  
236 An assumption of the disequilibrium melting hypothesis is that partial melting takes place in presence  
237 of garnet, which is irreconcilable with geochemical characteristics of the Lucky Strike transitional  
238 basalts that do not show any fractionation between medium REE and heavy REE as would be  
239 expected if melting occurs in the garnet stability field (Fig. 2b). This conclusion is in good agreement  
240 with a recent petrogenetic model of melt supply to the Lucky Strike segment based on basalt  
241 geochemistry, indicating that melting is controlled by spinel peridotite for the transitional group  
242 (Gale et al., 2011). As recently demonstrated by Salters et al., (2011), a second line of argument  
243 against disequilibrium melting is based on experimental studies of diffusion coefficients in garnet. In  
244 this particular mineral, Dy diffusively equilibrates over 1 mm in 100,000 years at 1400°C (Van  
245 Orman et al., 2002). Even if we consider a diffusion coefficient 10 times slower for  $\text{Hf}^{4+}$ , centimeter-  
246 scale isotopic equilibrium at mantle temperatures is expected to take place over one or two million  
247 years. This equilibration time is orders of magnitude shorter than the time needed to build up a  
248 radiogenic Hf signature. Disequilibrium melting is thus not a plausible hypothesis to explain the  
249 unusually radiogenic Hf characteristic of the most depleted component along Lucky Strike.

250 If melting takes place at isotopic equilibrium, the Hf isotope composition of the melt is controlled  
251 by the whole rock composition of the peridotite. The presence or absence of garnet in the residual  
252 assemblage of the current melting event is therefore irrelevant and the source itself must have an  
253 anomalous isotopic signature.

254 5.1.2. Small scale mantle heterogeneity and efficiency of magma mixing.

255 Our study of a high spatial resolution dataset (<5 km) reveals the existence of incompletely mixed  
256 coexisting primary magmas in the erupted material, despite the melt lens imaged at 3.4 km below the  
257 seafloor (Singh et al., 2006). At first glance, the large variations measured in lithophile element  
258 isotopic systems are in conflict with the lack of variation in He and Ne isotopes measured on samples  
259 from the same cruises (Moreira et al., 2011). Because noble gas analyses require perfectly fresh glass,  
260 He and Ne measurements have been conducted on a slightly different subset of Gravituck06 and  
261 Bathyluck09 sampling, excluding samples from the more enriched group. This sampling bias can  
262 partly explain the observed discrepancy. However, even within the transitional group of Lucky Strike  
263 samples, Sr, Nd, Pb and Hf isotopes illustrate small variations that are not seen in He isotopes. We  
264 propose that this difference is explained by the difference of diffusivity in melt between heavy  
265 radiogenic isotopes and noble gases. The small-scale geochemical variations of trace elements and  
266 Sr, Nd, Pb and Hf isotopes indicate that neither the magma chamber nor the magmatic plumbing  
267 system totally homogenize the melts, therefore preserving, at least partially, the local mantle  
268 heterogeneity signal. These compositionally distinct liquids can be produced simultaneously if the  
269 scales of geochemical heterogeneities in a marble-cake assemblage are smaller than the melting zone.  
270 Beneath the Lucky Strike central volcano, we know that the melting column extends 80 km below the  
271 seafloor. In addition, geophysical evidence has shown that the focusing of melts toward the centers of  
272 segments is common along slow-spreading segments (Detrick et al., 1995), and thus sampling at the  
273 segment center can reflect mantle composition at a larger scale. Depending on the efficiency of  
274 along-axis melt migration, the volume of mantle tapped by the magmatic body could extend up to the  
275 whole ridge segment (70 km at Lucky Strike). This length-scale represents, therefore, an upper limit  
276 for the size of geochemical heterogeneities in the marble-cake assemblage. Within the compositional  
277 heterogeneity of the Lucky Strike dataset, the atypical Hf isotopic signature is only shown by the  
278 transitional group. This observation suggests that this mantle signature is carried by the local, more  
279 refractory, mantle component. This high  $\epsilon_{\text{Hf}}$  signature is absent in Azores' islands basalts, most

280 likely due to the difference of lithospheric thickness between the two geological settings (> 50 km  
281 beneath São Miguel and  $\approx$  10 km beneath the ridge); continuation of melting to shallower levels  
282 beneath a thin lithosphere allows for a higher degree of melting and thus allows for a greater  
283 proportion of melts to derive from the more refractory mantle component. Our study also implies that  
284 interpretation of large- scale sampling of mantle domains using inadequate sample spacing should be  
285 approached with caution. As shown recently by Salters et al. (2011), the long believed lack of  
286 correlation between  $\epsilon\text{Hf}$  and other isotope systems along mid-oceanic ridges is likely the result of a  
287 sampling bias and scarcity of data at a fine scale.

## 288 **5.2 Origin of the mantle component with anomalous high $\epsilon\text{Hf}$ .**

289 According to a recent petrogenetic model based on major and trace element compositions and Sr,  
290 Nd and Pb isotopes, the source of Lucky Strike transitional basalts (called “local DM” in figures 5, 6  
291 and 7) results from a mixing between a DMM-like end member and a metasomatized mantle with an  
292 isotopic composition similar to Azores mantle (Gale et al., 2011). However, since the Azores lavas  
293 have a  $\epsilon\text{Hf}$ - $\epsilon\text{Nd}$  composition below the mantle array, simple mixing cannot account for the high  $\epsilon\text{Hf}$   
294 values (+24) and relatively low  $\epsilon\text{Nd}$  values (+10) measured in the transitional group (fig. 5).

### 295 5.2.1 Ancient, residual mantle component.

296 It has long been suggested that Hf-Nd isotope decoupling in the mantle source can be produced by  
297 an ancient melting event involving garnet fractionation, and subsequent melting of the resulting  
298 mantle residue (Blichert-Toft and Albarede, 1997; Chauvel and BlichertToft, 2001; Salters and Hart,  
299 1989; Salters and Zindler, 1995). Because the ratio of Lu and Hf partition coefficients between garnet  
300 and a basaltic liquid ( $K_{D_{\text{Grt-liq}}^{\text{Lu}}}/K_{D_{\text{Grt-liq}}^{\text{Hf}}}$ ) is very high (> 30), mantle residues produced by melt  
301 extraction at great depth would likely be HREE-enriched relative to Hf. An ancient partial melting  
302 event in the garnet stability field should yield a high  $^{177}\text{Hf}/^{176}\text{Hf}$  signal in the residue, and the

303 amplitude of this signal should increase with the time elapsed since the melting event. In contrast, Sm  
304 and Nd have similar partition coefficients in garnet and spinel peridotite and  $\epsilon_{\text{Nd}}$  is therefore  
305 expected to remain almost unaffected by the two different types of melting events. Given a sufficient  
306 length of time (1-2 Ga), the residual garnet peridotite should therefore develop an isotopic signature  
307 characterized by a steeper slope in  $\epsilon_{\text{Hf}}$  versus  $\epsilon_{\text{Nd}}$  diagram. This interpretation is consistent with the  
308 mixtures of variously-depleted mantle model proposed by Salters et al. (2011) to explain the array of  
309 sub-parallel trends of Hf-Nd isotope ratios in oceanic basalts on a global scale. According to this  
310 model, ancient residual oceanic lithosphere (ReLish, Salters et al., 2011), produced by the extraction  
311 of the crust, is recycled and mingled into the MORB and/or OIB mantle sources. Is the ReLish a  
312 possible component of the Lucky Strike mantle assemblage?

313 As mentioned earlier, the recently published petrogenetic model for Lucky Strike basalts (Gale et  
314 al., 2011) does not fit the unusual  $\epsilon_{\text{Hf}}$ - $\epsilon_{\text{Nd}}$  correlation obtained for our samples. This model can  
315 briefly be summarized by a 2-step geochemical history: i) mixing between the DMM (90%) and the  
316 Azores mantle (10%), and ii) metasomatism by low-degree melts produced in the garnet stability  
317 field in the Azores mantle. The first step defines the regional gradient along the MAR South of the  
318 Azores, whereas the second step generates the local variability shown by transitional and enriched  
319 groups. We attempted to adjust this petrogenetic model and we replaced the DMM component with a  
320 mixture between DMM and ReLish. This latter component is highly depleted and almost completely  
321 exhausted of incompatible elements, and its signatures can easily be overpowered by a small addition  
322 of enriched components. This could explain why the influence of the ReLish component is not  
323 observed on highly incompatible isotopes system (Rb-Sr, U,Th-Pb). We have modeled the trace  
324 elements (REE+Hf) together with the Sr-Nd-Pb-Hf isotope compositions of Lucky Strike basalts. The  
325 details of the melting models are in the supplementary material and results can be seen on figure 5, 6  
326 and 7. In this model, the ReLish component was produced 1.2 Ga ago, by a 6% melting event in the

327 garnet stability field, from a MORB source that has been isolated from the bulk silicate Earth  
328 reservoir for 2 Ga. We are able to reproduce the trace element and isotopic systematics of Lucky  
329 Strike basalts by a two-steps model: i) mixing of 20% of the ReLish component to a mantle  
330 assemblage of DMM (70%) and Azores mantle (10%), and ii) a metasomatism of this local Lucky  
331 Strike mantle by low-F melts produced in presence of garnet from the Azores mantle. This solution is  
332 not unique and it is possible to fit the data with a different set of parameters. For example, the mass  
333 fraction of the ReLish component is inversely proportional to its formation age: a more recent ReLish  
334 would simply imply a greater proportion in the mantle assemblage. Our goal is therefore not to  
335 quantify these melting events accurately, but rather to show that the presence of a ReLish component  
336 in the source of Lucky Strike basalts is able to produce the atypical high  $\epsilon_{\text{Hf}}$  end-member (Fig. 6).  
337 The presence of such refractory component could also explain the relatively low degree of melting  
338 (7%) calculated by Gale et al. (2011) for the present day melting beneath the ridge. Although residual  
339 oceanic lithosphere material is probably a ubiquitous mantle component, due to its refractory  
340 properties, it is expected to contribute little to the observed global MORB variations.

#### 341 5.2.2 Sub-continental lithospheric mantle.

342 A second potential candidate for the atypical source signature in Lucky Strike transitional basalts  
343 is the Sub-Continental Lithospheric Mantle (SCLM). Compositions of the SCLM are primarily based  
344 on xenolith and xenocryst samples. These samples show a large range of Hf isotopic compositions up  
345 to very radiogenic values (Simon et al., 2007). This variability in Hf isotopes is associated with less  
346 variable and less radiogenic Nd isotopic compositions. The SCLM consists mainly of  
347 ultramafic rocks, ranging from lherzolites to dunites. Despite the observed petrological diversity of  
348 this reservoir, a recent tomographic study has suggested that most Archean sub-continental  
349 lithospheric mantle originally consisted of depleted dunites and harzburgites (Griffin et al., 2009). In  
350 intraplate volcanic areas, these refractory peridotites are subsequently metasomatized and refertilized.

351 In xenolith datasets, the decoupling between Hf and Nd isotopes in this subcontinental reservoir has  
352 been interpreted as a result of depletion events followed by carbonatite-type metasomatism (Simon et  
353 al., 2007). This process is expected to link very radiogenic  $\epsilon\text{Hf}$  values with relatively less radiogenic  
354 Nd and enrichment in highly incompatible trace elements, consistent with the geochemical  
355 characteristics of the transitional Lucky Strike basalts (Fig. 5).

356 Several studies have argued for contamination of the MORB source by either the crustal or the  
357 mantle part of the continental lithosphere (e.g. Hanan et al., 2004; Janney et al., 2005). Because the  
358 Rb/Sr ratio is very high in the continental crust, addition of this material to the depleted mantle would  
359 dramatically increase  $^{87}\text{Sr}/^{86}\text{Sr}$  values. In contrast, the mantle portion of the continental lithosphere is  
360 not expected to have an exceptionally high Rb/Sr ratio and is therefore a more likely component. The  
361 presence of relics of SCLM preserved in the upper mantle in the North-central Atlantic area has been  
362 a matter of debate for the last 15 years. For example, SCLM is suspected to explain the distinctive  
363 metasomatic parageneses and garnet signature in spinel-peridotite xenoliths from Cape Verde  
364 Archipelago (Bonadiman et al., 2005). Similarly, the enriched component in the lavas from São  
365 Miguel has been inferred to contain a contribution from localized pieces of SCLM material  
366 (Madureira et al., 2011; Moreira et al., 1999; Widom et al., 1997). According to these studies, this  
367 sub-continental lithospheric mantle originally resided beneath North-western Africa or Iberia and was  
368 delaminated during rifting upon the opening of the Atlantic Ocean basin. However, based on the low  
369  $\epsilon\text{Hf}$  measured in lavas from Azorean islands, other studies have argued against this hypothesis (Beier  
370 et al., 2007; Elliott et al., 2007). In contrast to these studies, we propose that SCLM material is a  
371 potential candidate for the origin of the transitional group basalts, and should be seen as a possible  
372 refractory component of the mantle rather than the source of the enriched basalts. As previously  
373 discussed in §5.1.2, this is in good agreement with the fact that this signature is exclusively observed

374 at the ridge axis, where the shallower melting compared to Azores islands allows more refractory  
375 material to melt.

376 It is important to note that the geochemical composition of the SCLM remains poorly constrained.  
377 It is therefore difficult to produce an incontrovertible mixing model involving this reservoir. SCLM  
378 samples show highly heterogeneous isotopic signatures, which seems to be inconsistent with the  
379 tightly defined nature of the more depleted Lucky Strike end-member. However, based on our  
380 present day knowledge of the Hf-Nd isotope characteristics of SCLM xenoliths, the addition of this  
381 type of material to the Lucky Strike upper mantle could account for the abnormal isotopic signature  
382 of the local depleted end-member.

383 Distinguishing whether the abnormal Hf-Nd isotopic signature is the result of the presence of  
384 residual oceanic lithosphere previously melted in the garnet stability field (*i.e.* ReLish) (§5.2.1) or the  
385 contribution of sub-continental lithospheric mantle (§5.2.2), is not straightforward. Very ancient  
386 depleted signatures in Os isotopes have long been suggested as a characteristic of subcontinental  
387 lithospheric mantle. But recent studies of abyssal peridotites have shown a wide range of  $^{187}\text{Os}/^{188}\text{Os}$   
388 ratios at slow mid-oceanic ridge settings extending to very unradiogenic values (Liu et al., 2008). If  
389 highly depleted Os isotope signatures are not unique to the SCLM, there are no isotopic or chemical  
390 signatures that unambiguously distinguish the two proposed hypotheses.

### 391 **5.3. Geodynamical implications.**

392 We have shown that the unusual Hf isotope signature in basalts from Lucky Strike is best  
393 explained by the melting of a refractory component in the mantle near the Azores rather than by a  
394 kinetic effect during the current melting event. Even if we cannot specify whether this refractory  
395 component is a ReLish or a SCLM, we have shown that this component is mixed with the depleted  
396 mantle and the Azores mantle prior to the addition of the metasomatic agent (low-F melts derived

397 from the Azores; Gale et al., 2011). The existence of this component and its mixing relationship raise  
398 the question of the structure of the upper mantle around the Azores.

399 Since only limited data are available for Hf isotopes compared to other isotope systems, it is not  
400 possible to map precisely the extent of the particular Hf signature recognized in our local scale study.  
401 However, the Nd vs. Hf isotopes of segments North and South of the Lucky Strike segment show a  
402 similar correlation (fig. 5). The latitudinal extension of this atypical correlation is therefore at least  
403 between 46°N to 35°N, and centered at the latitude of the Azores hotspot. This along-axis extension  
404 is significantly shorter than the regional gradients defined by Sr isotopes or La/Sm ratios (Dosso et  
405 al., 1999; Gale et al., 2011; Langmuir et al., 1997; Schilling, 1975). By analogy to observations along  
406 the MAR near Ascension Island (Paulick et al., 2010), the hypothesis involving mixing between one  
407 enriched component and two different depleted components (DMM and ReLish/SCLM) is expected  
408 to produce a cloud or two different trends in Nd-Hf isotope diagrams. Since only one trend is seen  
409 from 46°N to 35°N (Agranier et al., 2005; Chauvel and Blichert-Toft, 2001; Dosso et al., 1999; Yu et  
410 al., 1997) (fig. 4), we can infer that the depleted components in the system are well homogenized.

411 A first possible model for the upper mantle structure in the Lucky Strike and Azores domain is  
412 that the refractory mantle component is a primary constituent of the Azores hotspot, mixing with the  
413 regional mantle (fig. 8A). In this hypothesis, this refractory component has been recycled in the  
414 asthenosphere and brought back to the surface by the hotspot. The initial depletion event could either  
415 be the result of deep ancient melting in an oceanic domain (ReLish) or of some mantle material from  
416 the base of the continental lithosphere (SCLM) which was recycled deep in the mantle.

417 An alternative model is an upper mantle constituted of different coexisting refractory materials  
418 prior to the arrival of the Azores plume (fig. 8B). In this hypothesis, the atypical depleted component  
419 could be a ubiquitous residual mantle component (*i.e.* ReLish) or relics of the SCLM left behind by

420 the North-East drifting of the African continent (fig. 8B). The presence of the particular isotopic  
421 signature in the transitional Lucky Strike samples could be the result of a change of the melting  
422 regime near the Azores (Asimow et al., 2004; Schilling, 1975). Between 46°N and 35°N, the thin  
423 lithosphere and the local increase of mantle potential temperature (Asimow et al., 2004; Schilling,  
424 1975) (+ 35°C) associated with the thermal influence of the Azores enhances mantle melting. These  
425 pressure and temperature conditions would allow melting of the more refractory mantle identified  
426 around the Azores region. Future Hf-Nd studies along segments near Lucky Strike will provide  
427 constraints on the geographical extension of this refractory component and allow study of the along-  
428 axis evolution of its mixing proportions with the ambient mantle.

## 429 **6. Conclusion**

430 We report a strong correlation between Hf and Nd isotopic systems from MORBs within the  
431 Lucky Strike segment along the MAR, which is contrary to the commonly accepted decoupling of  
432 these systems. In good agreement with recent results by Salters et al. (2011), our results suggest that  
433 the lack of correlation between  $\epsilon_{\text{Hf}}$  and other isotope systems along the global mid-oceanic ridge  
434 system is the result of sampling bias. Part of the reason for not observing more segments with  
435 correlated Hf-Nd isotope systematics may be the lack of fine-scale, dense sampling. In order to  
436 discuss the origin and significance of large-scale mantle composition, alternative solutions are (i)  
437 high spatial resolution sampling of the ridge or (ii) statistical techniques such as spectral analyses  
438 (Agranier et al., 2005), where the dataset interpretation is weighted by the sampling density.

439 The Hf-Nd isotope correlation seen in Lucky Strike samples is significantly different from the  
440 global mantle array defined by MORB and OIB, and is characterized by an unusually high  $\epsilon_{\text{Hf}}$  values  
441 for a given  $\epsilon_{\text{Nd}}$ . In every binary isotopic plot, Lucky Strike basalts define a trend from this atypical  
442 radiogenic Hf mantle component toward the Azores enriched mantle. We have shown that kinetic

443 effects cannot account for the observed Hf-Nd systematics in Lucky Strike basalts and that this trend  
444 is best explained by mixing enriched and depleted components in the local mantle. If the origin of the  
445 enriched component is clearly related to the Azores hotspot, the origin of the depleted mantle source  
446 is more controversial. We propose that this unusual end-member could either indicate the presence of  
447 some residual oceanic lithosphere or some sub-continental lithospheric mantle left behind by the  
448 drifting of the African continent. At Lucky Strike, enhanced melting conditions associated with the  
449 Azores plume allow us to detect this refractory component within basalts erupted on-axis. This  
450 observation points towards the existence in the mantle of domains of refractory material that do not  
451 melt in normal mid-oceanic ridge conditions, thus contributing little to the global MORB  
452 compositions. This study emphasizes the heterogeneous nature of the depleted mantle long  
453 considered the archetype of a homogeneous mantle domain.

454

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462

463 **Figure captions**

464  
465 **Figure 1:** Bathymetric maps of (A) the Mid-Atlantic Ridge, (B) Lucky Strike segment and (C) Arctic  
466 ridges. Locations of our new samples (square symbols) are shown together with published samples:  
467 of the entire MAR (gray circles), the Azores geochemical anomaly (yellow circles) and Mohns ridge  
468 (green triangles). Symbols are the same in all the figures, published data are from (Agranier et al.,  
469 2005), (Andres et al., 2004; Andres et al., 2002), (Blichert-Toft et al., 2005), (Castillo and Batiza,  
470 1989), (Chauvel and BlichertToft, 2001), (Debaille et al., 2006), (Dosso et al., 1993; Dosso et al.,  
471 1999; Dosso et al., 1991), (Douglass et al., 1999), (Frey et al., 1993), (Fontignie and Schilling, 1996),  
472 (Hamelin et al., 1984), (Hanan et al., 1986), (Ito et al., 1987), (Machado et al., 1982), (Nowell et al.,  
473 1998), (Paulick et al., 2010), (Salters, 1996), (Schiano et al., 1997), (Schilling et al., 1994), (Shirey et  
474 al., 1987), (Yu et al., 1997).

475 **Figure 2:** A) histogram showing the bimodal distribution of Lucky Strike samples. Two distinct  
476 peaks define the two petrological groups described in this study: “Transitional” if  $K_2O/TiO_2 < 0.25$   
477 and “enriched” if  $K_2O/TiO_2 > 0.25$ . Data are from this study together with unpublished data (Bezou  
478 personal communication), Gale et al. (2011) and Ferreira (2006). B) Diagram showing normalized  
479 REE concentration of the two groups.

480 **Figure 3:** Geochemical gradient south of the Azores. The center of Lucky Strike segment shows a  
481 large range of geochemical variation.

482 **Figure 4:** Binary isotopic plots showing Lucky Strike data compared to previously published MAR  
483 and Azores data. Mixing models between a depleted (DMM, (Salters and Stracke, 2004)) and an  
484 enriched (Azores, Gale et al., 2011) ) components are shown. The chosen Azores mantle composition  
485 assumed is that of the least enriched end-member (Sete Cidades samples, Beier et al. (2007)).

486 **Figure 5:** Hf isotopes versus other isotopic systems. The model modified from (Gale et al., 2011) is  
487 shown as black lines. Small dark squares along these lines represent percentage of low-F melts  
488 additions (1% step) to the local Depleted Mantle (Local DM, see text for further explanations).  
489 Compare to the mantle array, new data from Lucky Strike segment define a trend with very  
490 radiogenic Hf composition for a given  $\epsilon\text{Nd}$ . The same atypical correlation can be observed along the  
491 MAR in samples collected between 46 and 35°N (yellow circles).

492 **Figure 6:** Comparison between Lucky Strike data and Mohns ridge sample, previously described as  
493 geochemically abnormal with  $\epsilon\text{Hf}$  for a given  $\epsilon\text{Nd}$ . The same model shown in figure 5 is reported  
494 here, fractions of low-F melts added to the regional mantle are shown in percent.

495 **Figure 7:** Hf isotopes versus La/Hf, and Nd isotopes versus La/Nd. Metasomatism of the regional  
496 mantle by low-F melts allow to reproduce the geochemical heterogeneity measured at Lucky Strike.

497 **Figure 8:** Two different models for the structure of the upper mantle near the Azores. In the left  
498 column, the atypical depleted component is a primary constituent of the Azores hotspot. In the right  
499 column, this component resides in the upper mantle prior to the plume arrival.

500 **Supplementary figure:** Lu/Hf vs Sm/Nd diagram. Green and orange lines represent melting models  
501 (batch and fractional) with residual spinel and residual garnet, respectively. The black line represents  
502 low-F melts metasomatism model (see text for further explanations). The Lucky Strike abnormally  
503 high Lu/Hf ratio for a given Sm/Nd ratio is well explained by the influence of this recent  
504 metasomatism event.

505

506 **Table 1:** Major element, trace element and isotopes data for samples collected at Lucky Strike  
507 segment center. AIII127-D15G has previously been published in Dosso et al. (1999), except new Pb

508 and Hf isotope measurements done on a MC-ICPMS at SDSU in collaboration with Barry Hanan. <sup>b</sup>

509 Sr isotope measured using a Thermo Finnigan Triton. <sup>c</sup> Sr isotope measured using a Finnigan

510 MAT26x.

511

512 **Table 1**  
513

Sample	AII127- D15G	B09-ROC01	B09-ROC07	B09-ROC08	B09-ROC11	B09-ROC13
Long. (°)	-32.283	-32.282	-32.282	-32.282	-32.277	-32.276
Lat. (°)	37.291	37.284	37.291	37.291	37.297	37.299
Type	T-MORB	E-MORB	T-MORB	T-MORB	E-MORB	E-MORB
SiO <sub>2</sub>	51.4	49.3	51.4	51.5	48.8	50.1
TiO <sub>2</sub>	1.07	1.08	1.05	1.05	1.28	1.20
Al <sub>2</sub> O <sub>3</sub>	14.7	17.0	14.8	15.1	16.4	16.7
FeO	9.8	6.4	9.9	9.5	7.5	6.8
MnO	0.18	0.12	0.18	0.19	0.15	0.13
MgO	8.1	9.4	8.0	8.2	8.2	8.5
CaO	12.1	13.9	12.2	12.4	14.1	14.3
Na <sub>2</sub> O	2.2	2.3	2.3	2.2	2.4	2.3
K <sub>2</sub> O	0.20	0.46	0.16	0.18	0.60	0.70
P <sub>2</sub> O <sub>5</sub>	0.14	0.19	0.12	0.13	0.27	0.23
L.O.I.		0.25	-0.63	-0.51	0.97	0.07
Sum	99.9	101.0	100.7	101.0	101.5	102.0
La	12.45	12.45	5.74	5.74	16.59	15.58
Ce	24.49	24.49	12.32	12.32	31.36	29.74
Pr	2.94	2.94	1.71	1.71	3.65	3.49
Nd	12.35	12.35	8.04	8.04	14.99	14.15
Sm	2.75	2.75	2.39	2.39	3.19	3.11
Eu	0.98	0.98	0.89	0.89	1.11	1.07
Gd	3.19	3.19	3.27	3.27	3.70	3.55
Tb	0.50	0.50	0.58	0.58	0.58	0.55
Dy	3.07	3.07	3.88	3.88	3.56	3.41
Ho	0.63	0.63	0.85	0.85	0.75	0.72
Er	1.74	1.74	2.39	2.39	2.08	2.00
Yb	1.62	1.62	2.34	2.34	1.97	1.91
Lu	0.25	0.25	0.36	0.36	0.30	0.29
Hf	1.9	1.87	1.62	1.62	2.05	1.84
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.702945	0.703118 <sup>b</sup>	0.702957 <sup>b</sup>	0.702933 <sup>c</sup>	0.703109 <sup>b</sup>	0.703049 <sup>c</sup>
εNd	8.97	7.04	9.15	9.12	7.18	7.28
<sup>206</sup> Pb/ <sup>204</sup> Pb	18.822	19.337	18.886	18.94	19.159	19.219
<sup>207</sup> Pb/ <sup>204</sup> Pb	15.538	15.592	15.544	15.546	15.579	15.582
<sup>208</sup> Pb/ <sup>204</sup> Pb	38.421	38.898	38.511	38.547	38.773	38.801
εHf	21.38	-	21.65	20.69	14.36	14.76

514

515

516 Table 1

Sample	B09-ROC14	B09-ROC15	B09-ROC20	B09-ROC21	B09-ROC22	B09-ROC23
Long. (°)	-32.276	-32.275	-32.280	-32.280	-32.280	-32.278
Lat. (°)	37.300	37.301	37.291	37.291	37.291	37.290
Type	E-MORB	E-MORB	T-MORB	T-MORB	T-MORB	T-MORB
SiO <sub>2</sub>	-	48.7	51.6	51.8	51.7	51.6
TiO <sub>2</sub>	-	1.01	1.06	1.06	1.05	1.05
Al <sub>2</sub> O <sub>3</sub>	-	17.9	14.3	15.0	15.0	15.1
FeO	-	6.7	10.3	10.0	9.9	9.5
MnO	-	0.14	0.19	0.19	0.18	0.18
MgO	-	8.7	8.2	8.1	8.1	8.2
CaO	-	14.5	12.3	12.3	12.2	12.5
Na <sub>2</sub> O	-	2.2	2.3	2.3	2.3	2.2
K <sub>2</sub> O	-	0.41	0.16	0.16	0.16	0.18
P <sub>2</sub> O <sub>5</sub>	-	0.18	0.13	0.13	0.12	0.13
L.O.I.	-	0.50	-0.78	-0.77	-0.77	-0.68
Sum	-	101.5	100.8	101.3	101.1	101.0
La	14.03	14.03	4.98	4.98	5.01	5.54
Ce	26.41	26.41	11.25	11.26	11.26	12.15
Pr	3.17	3.17	1.59	1.58	1.59	1.68
Nd	12.85	12.85	7.55	7.57	7.65	7.92
Sm	2.85	2.85	2.34	2.34	2.34	2.37
Eu	1.00	1.00	0.88	0.88	0.88	0.89
Gd	3.29	3.29	3.25	3.26	3.27	3.25
Tb	0.53	0.53	0.59	0.59	0.59	0.58
Dy	3.26	3.26	3.96	3.95	3.93	3.84
Ho	0.68	0.68	0.87	0.87	0.87	0.84
Er	1.90	1.90	2.46	2.47	2.45	2.37
Yb	1.83	1.83	2.45	2.46	2.45	2.34
Lu	0.28	0.28	0.38	0.38	0.38	0.36
Hf	1.69	1.69	1.59	1.59	1.58	1.61
<sup>87</sup> Sr/ <sup>86</sup> Sr	-	0.70304 <sup>c</sup>	0.702915 <sup>c</sup>	0.702926 <sup>c</sup>	0.702921 <sup>c</sup>	0.702962 <sup>c</sup>
εNd	6.10	7.00	9.25	9.40	9.21	9.15
<sup>206</sup> Pb/ <sup>204</sup> Pb	19.355	-	18.888	18.884	18.89	18.932
<sup>207</sup> Pb/ <sup>204</sup> Pb	15.591	-	15.543	15.545	15.544	15.547
<sup>208</sup> Pb/ <sup>204</sup> Pb	38.93	-	38.507	38.513	38.511	38.542
εHf	14.32	14.98	21.97	22.12	21.76	-

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519 Table 1

Sample	B09-ROC24	GRA N05-1	GRA N06-1	GRA N10-2	GRA N10-3	GRA N12-1
Long. (°)	-32.278	-32.220	-32.275	-32.237	-32.257	-32.235
Lat. (°)	37.290	37.285	37.291	37.280	37.285	37.280
Type	T-MORB	E-MORB	E-MORB	T-MORB	E-MORB	E-MORB
SiO <sub>2</sub>	52.1	50.4	48.1	51.7	51.0	50.3
TiO <sub>2</sub>	1.06	1.1	1.12	1.09	0.97	1.01
Al <sub>2</sub> O <sub>3</sub>	15.2	18.7	17.5	15.0	16.6	16.2
FeO	9.6	5.9	6.8	9.4	7.5	7.8
MnO	0.18	0.1	0.14	0.17	0.14	0.16
MgO	8.2	6.8	8.2	8.0	8.3	8.8
CaO	12.6	14.4	15.1	12.4	13.4	13.3
Na <sub>2</sub> O	2.3	2.4	2.0	2.2	2.1	2.1
K <sub>2</sub> O	0.18	0.3	0.46	0.18	0.41	0.30
P <sub>2</sub> O <sub>5</sub>	0.13	0.2	0.24	0.14	0.18	0.20
L.O.I.	-0.53	1.2	1.01	-0.26	0.21	0.53
Sum	102.1	102.1	101.5	101.2	101.6	101.5
La	5.60	8.51	14.01	6.08	11.65	8.68
Ce	12.36	16.93	27.49	13.41	22.36	17.54
Pr	1.70	2.19	3.36	1.83	2.68	2.22
Nd	8.03	9.69	13.90	8.39	11.08	9.63
Sm	2.40	2.50	3.15	2.45	2.58	2.38
Eu	0.90	1.02	1.12	0.92	0.92	0.91
Gd	3.27	3.16	3.57	3.29	3.13	2.96
Tb	0.59	0.53	0.57	0.58	0.51	0.50
Dy	3.87	3.38	3.50	3.78	3.23	3.15
Ho	0.85	0.72	0.73	0.82	0.69	0.67
Er	2.38	1.98	2.02	2.32	1.93	1.88
Yb	2.36	1.91	1.92	2.27	1.86	1.85
Lu	0.37	0.30	0.29	0.35	0.29	0.29
Hf	1.62	2.01	2.09	1.66	1.66	1.71
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.702981 <sup>b</sup>	-	-	-	-	0.702978 <sup>b</sup>
εNd	8.97	7.85	-	-	8.07	8.39
<sup>206</sup> Pb/ <sup>204</sup> Pb	18.944	-	19.229	19.013	19.238	19.003
<sup>207</sup> Pb/ <sup>204</sup> Pb	15.548	-	15.59	15.56	15.583	15.56
<sup>208</sup> Pb/ <sup>204</sup> Pb	38.557	-	38.833	38.624	38.807	38.62
εHf	21.04	17.84	14.33	19.89	17.46	20.05

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720

Figure 1

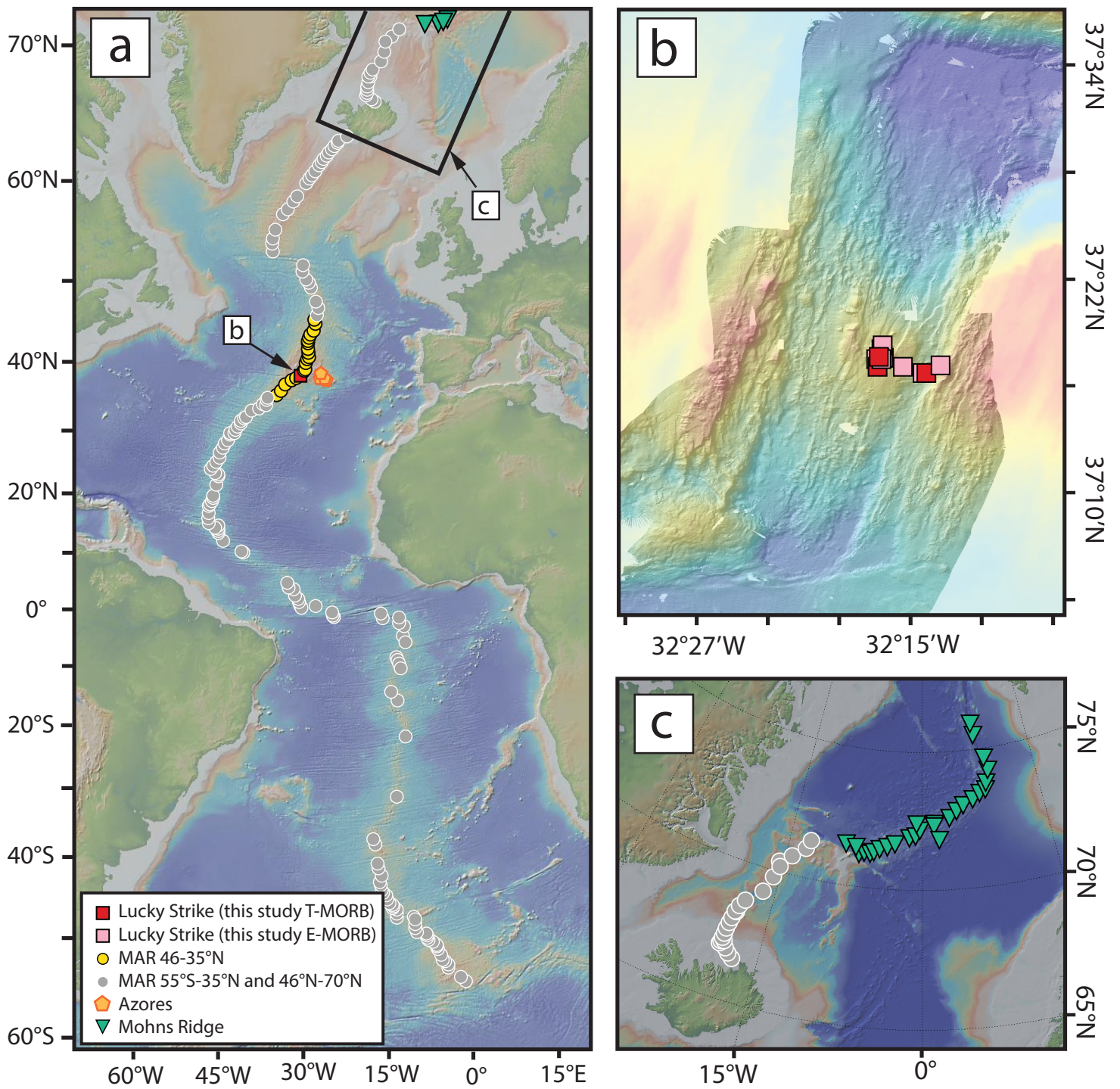


Figure 2

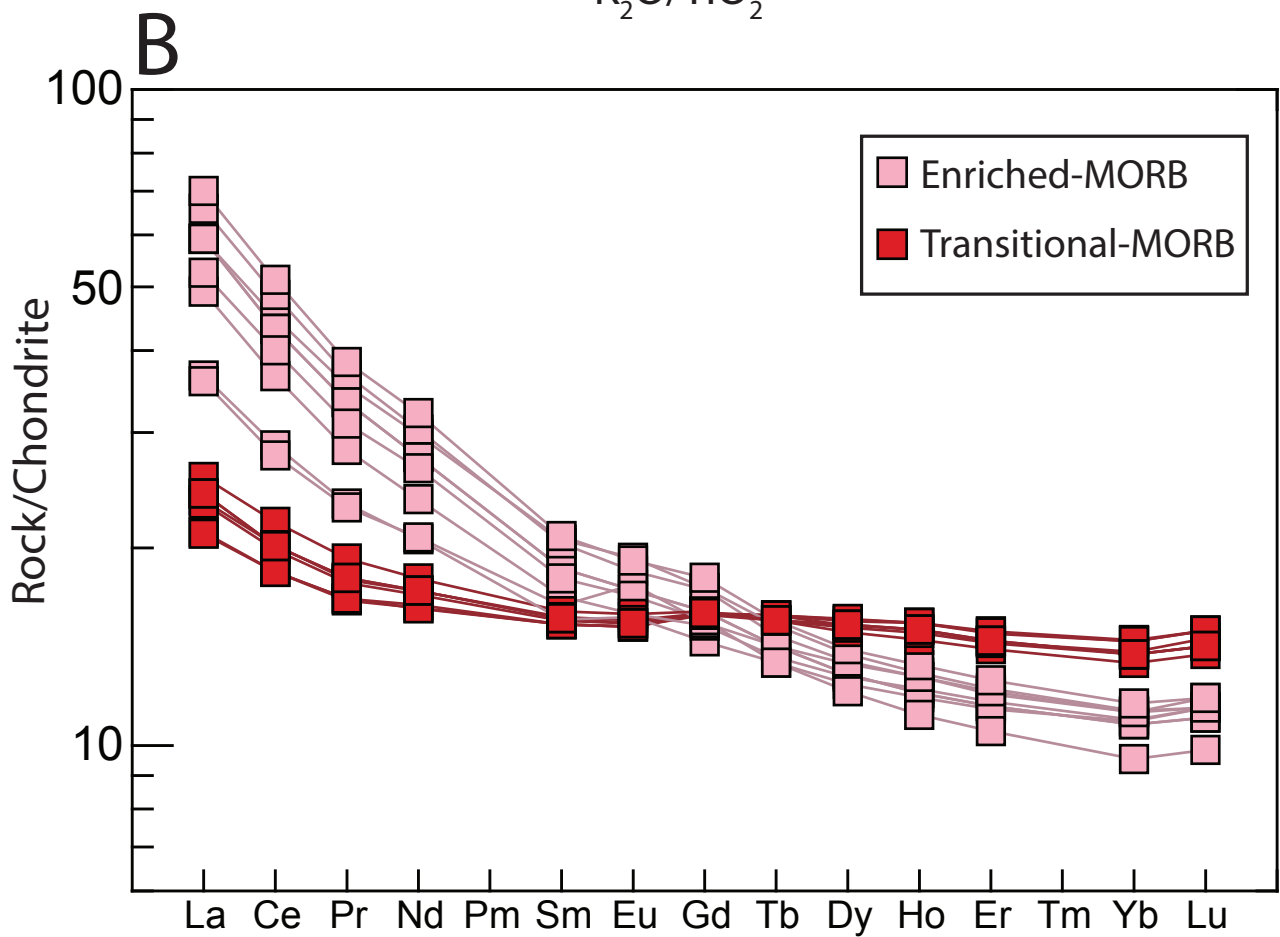
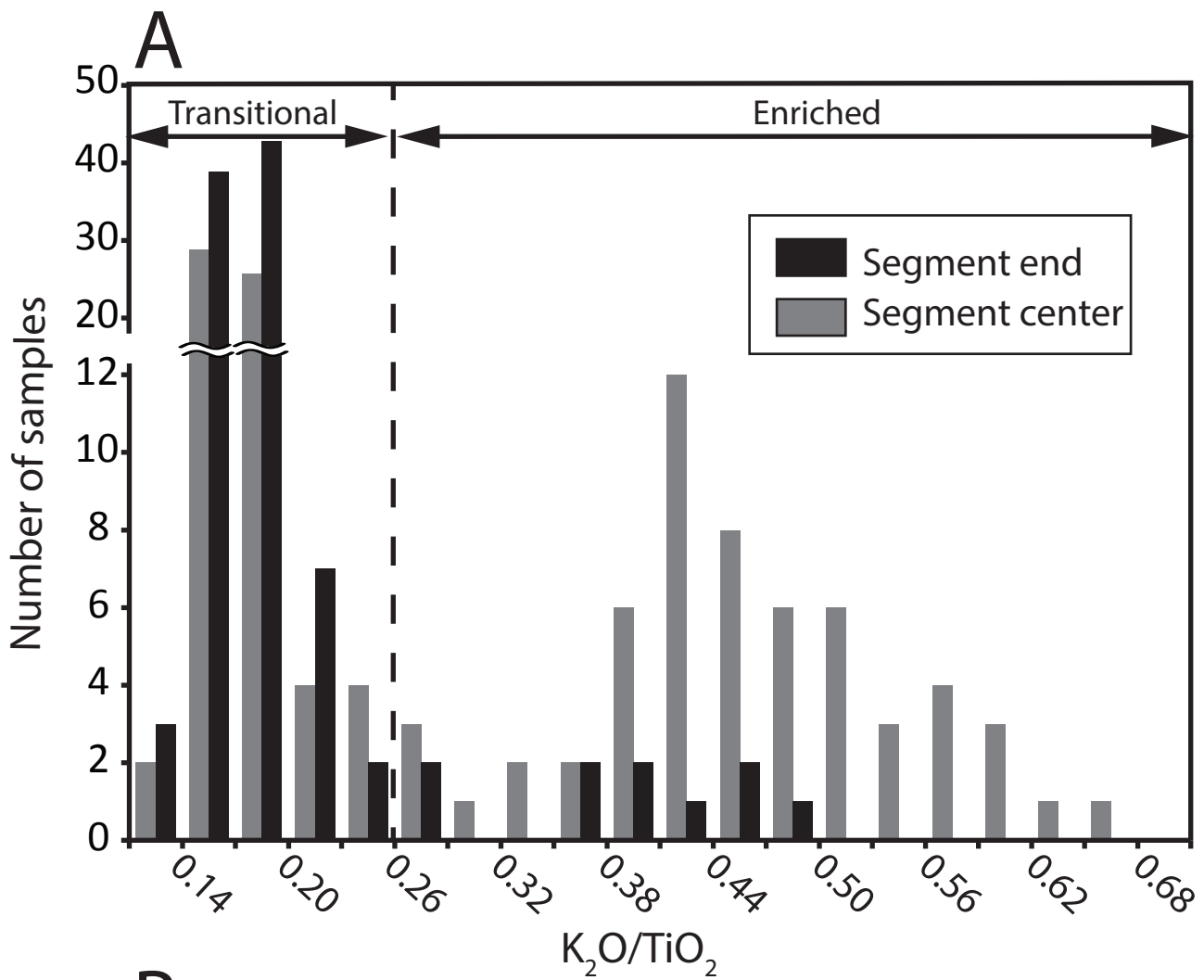


Figure 3

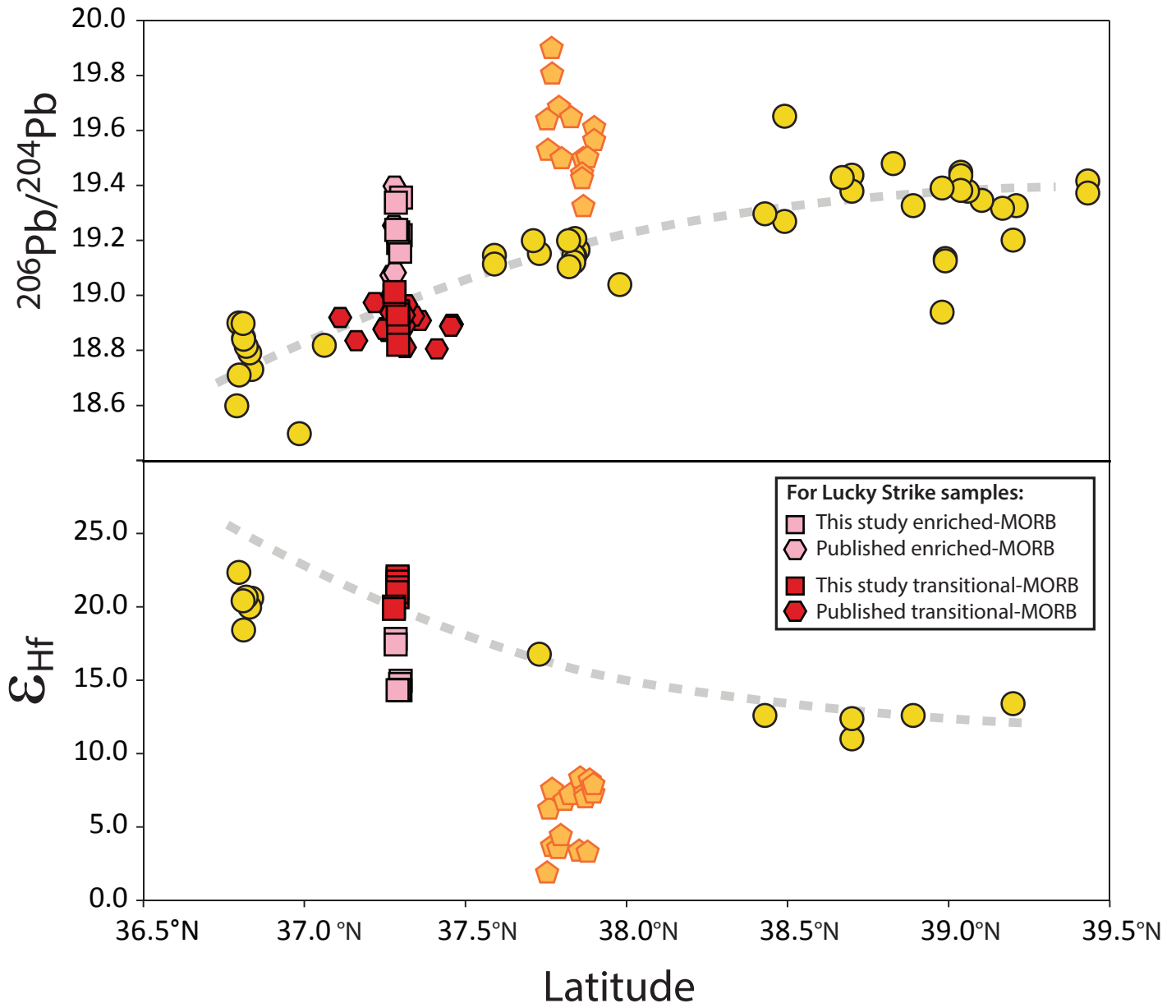


Figure 4

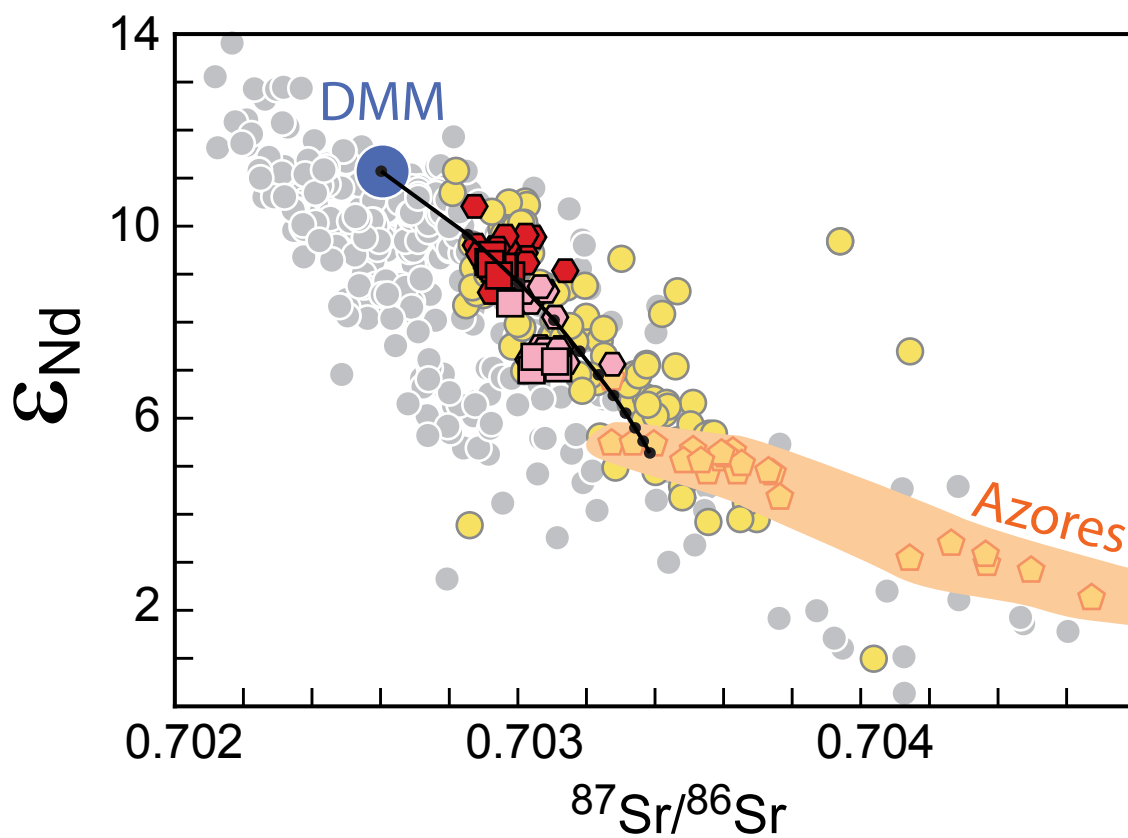
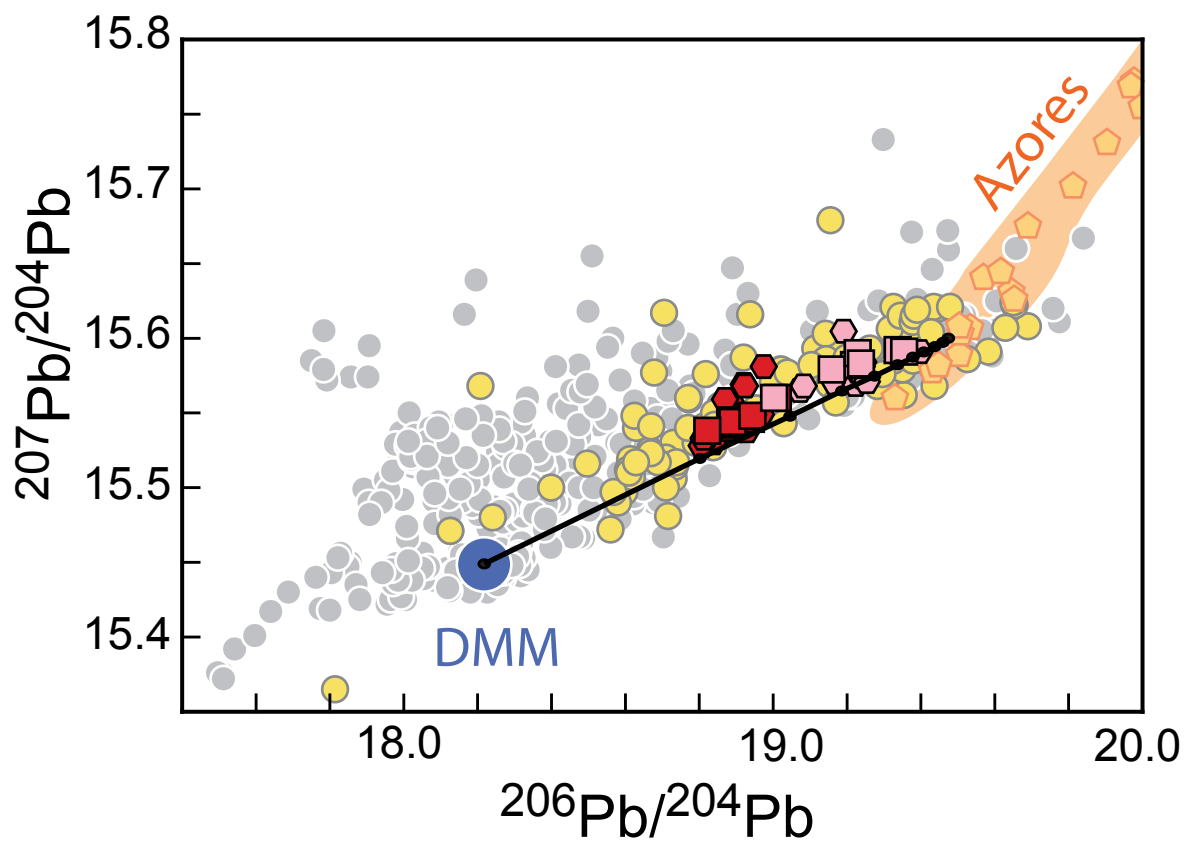


Figure 5

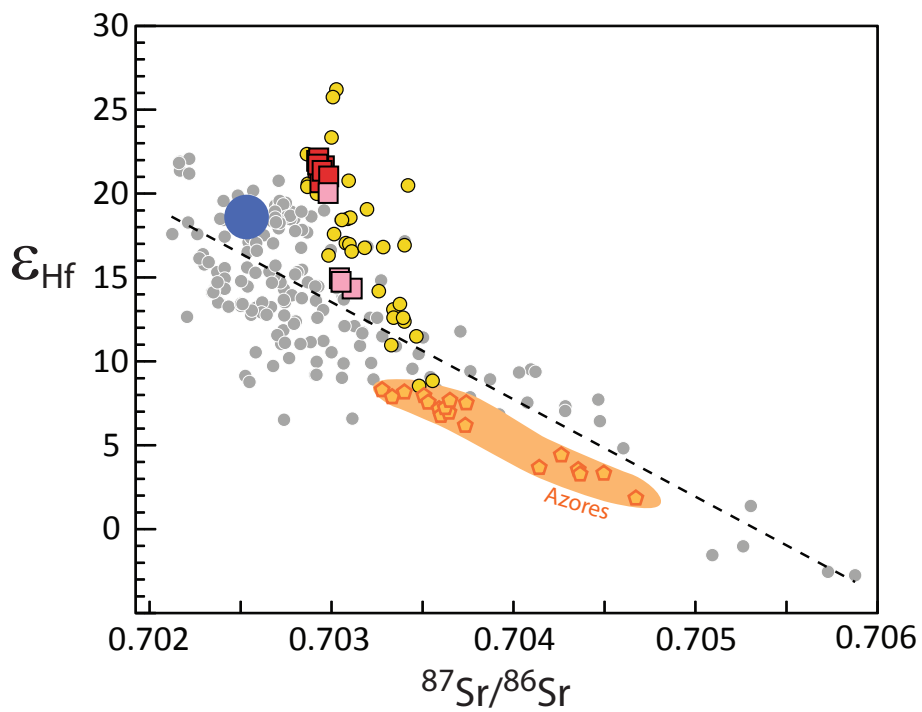
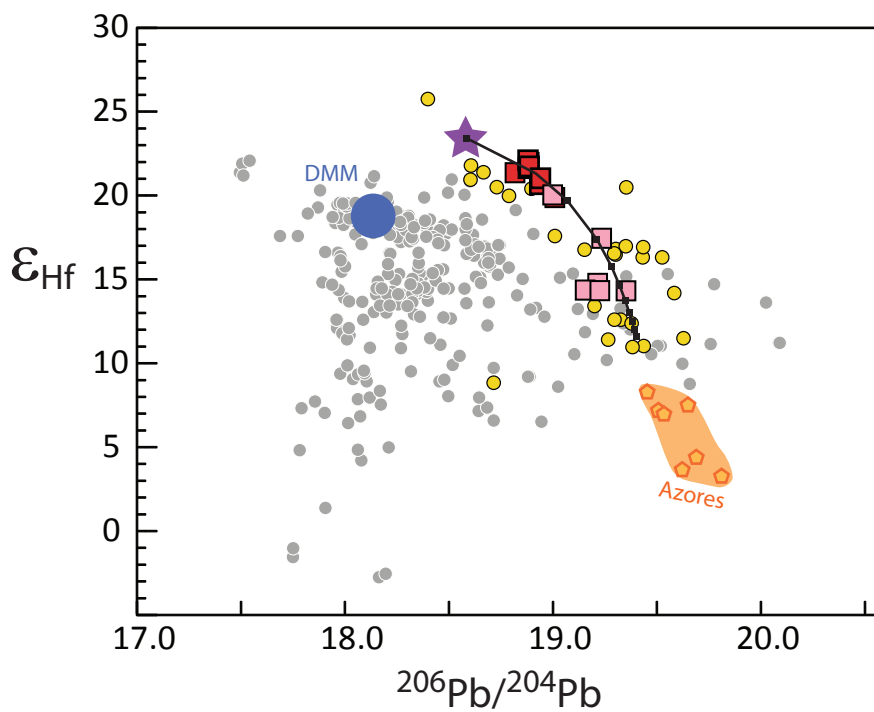
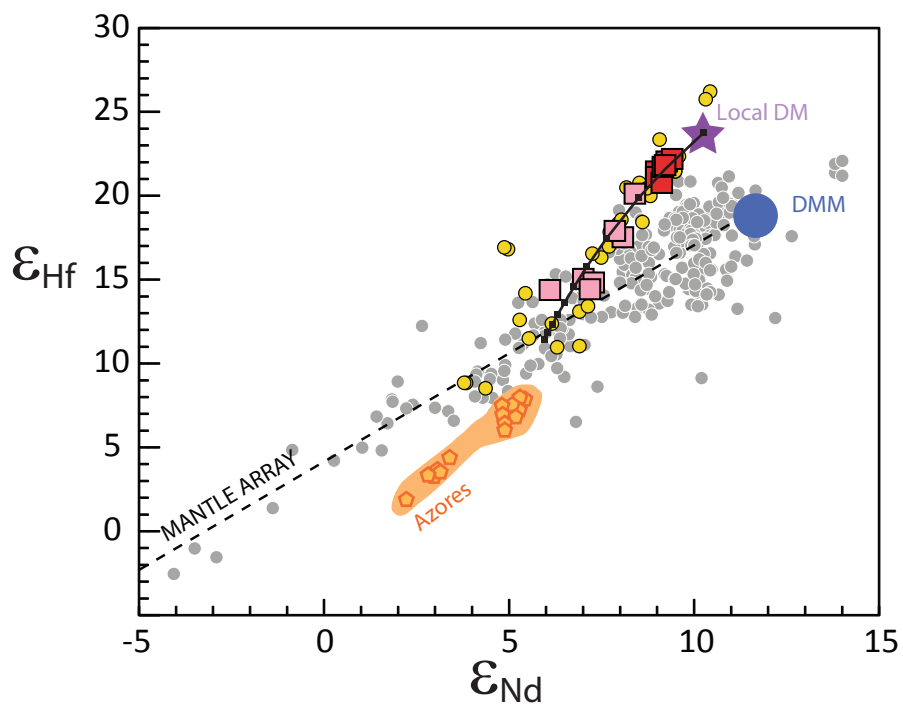


Figure 6

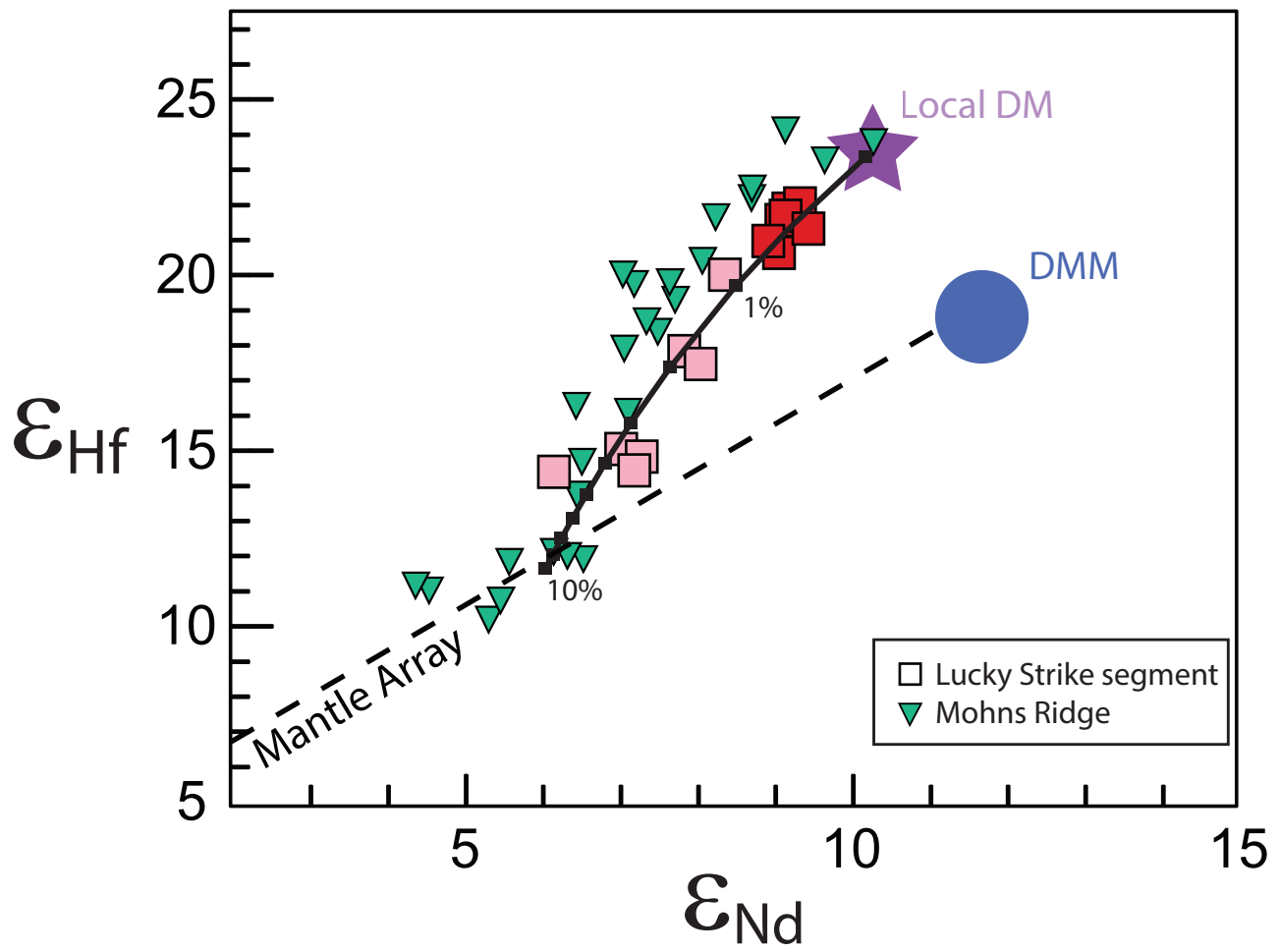


Figure 7

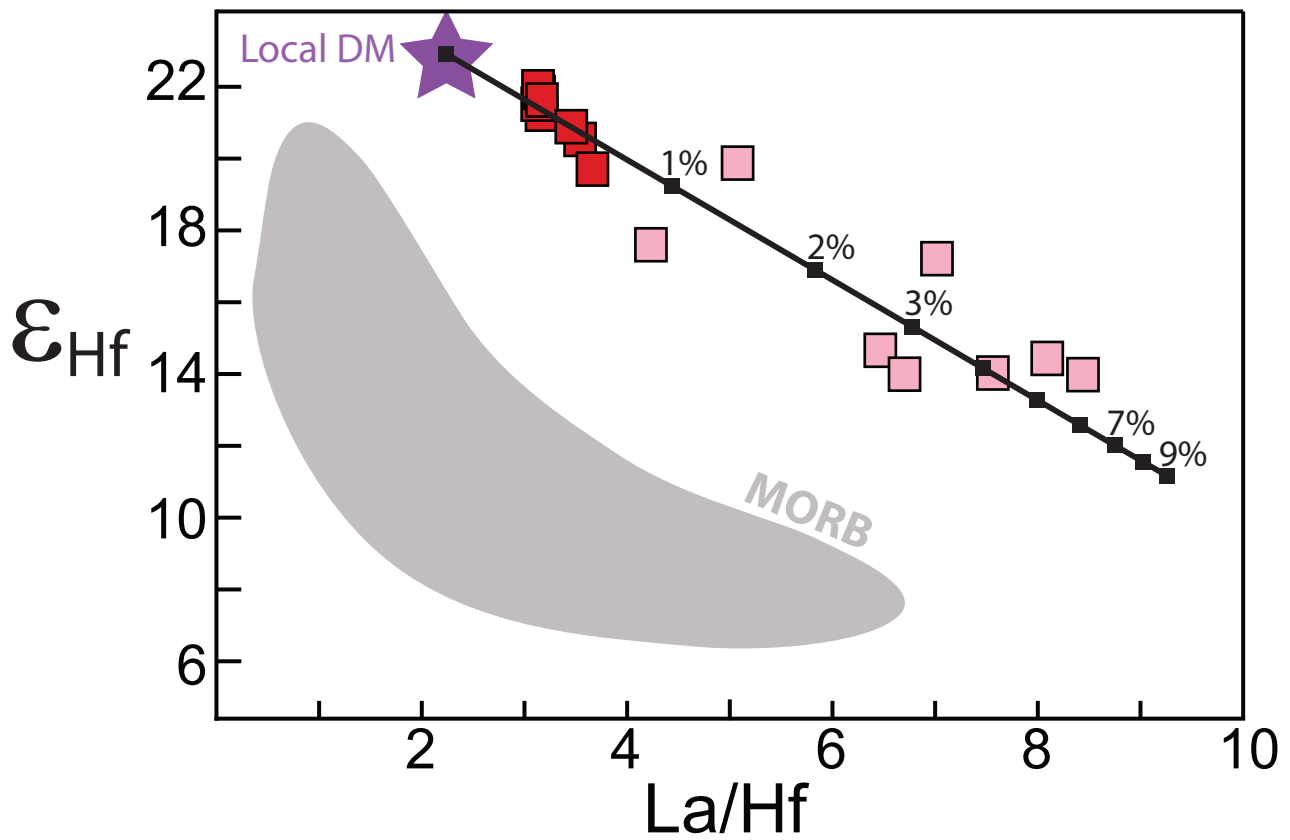
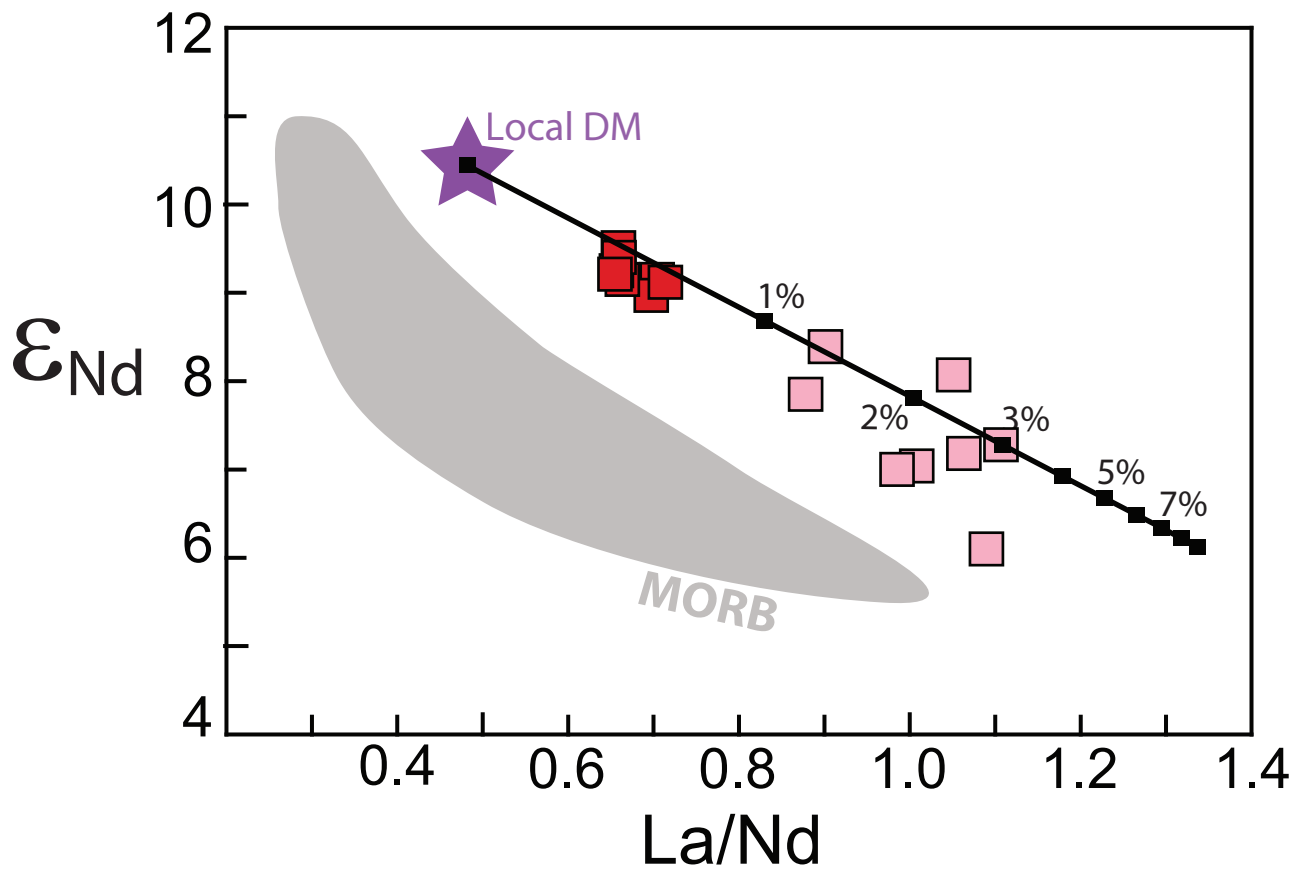
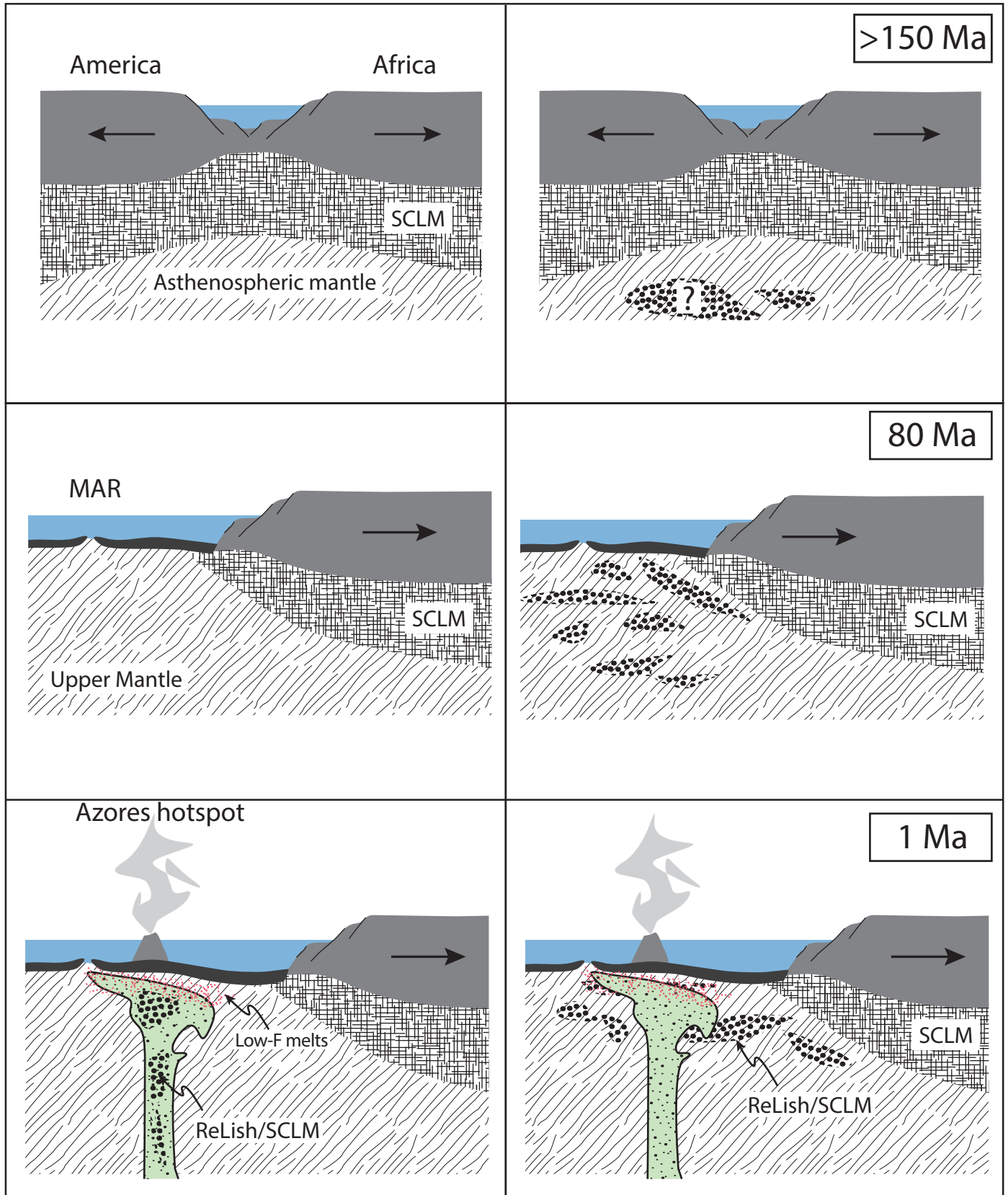


Figure 8



A) Atypical depleted component as a primary constituent of Azores Hotspot

B) Atypical depleted component as a part of the upper mantle