Influence of the Amsterdam/St. Paul hot spot along the Southeast Indian Ridge between 77° and 88°E: Correlations of Sr, Nd, Pb, and He isotopic variations with ridge segmentation

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[1] The submarine Amsterdam-St. Paul (ASP) Plateau, bisected by the Southeast Indian Ridge (SEIR), is a bathymetric high rising ~2 km above the surrounding seafloor that includes the islands of Amsterdam and St. Paul; this excess volcanism is attributed to a mantle hot spot. We obtained new Sr, Nd, and Pb (n = 37) and He isotopic (n = 10) ratios for basalt glasses from 11 SEIR segments on and adjacent to the plateau and from three seamounts on the plateau. The results show systematic spatial variations in these isotopic ratios that correlate with physical segmentation of the ridge. Specifically, lavas from the four ridge segments on the ASP Plateau have higher 208Pb/204Pb at a given 206Pb/204Pb than SEIR basalts distant from ASP Plateau. Surprisingly, lavas from the ridge segment 100 km north of the ASP Plateau are distinguished by the most radiogenic 206Pb/204Pb (up to 19.4) and highest 3He/4He ratios (up to 14.1 R_A). These are characteristics of lavas erupted at Amsterdam and St Paul Islands. The isotopic data for SEIR basalts erupted on or adjacent to the ASP Plateau provide equivocal evidence for a mantle component derived from the distant Kerguelen hot spot. Overall, the Pb-Nd-Sr-He isotope variations within this data set are explained well by three mantle end-members: (1) depleted mantle having relatively low 206Pb/204Pb and 87Sr/86Sr and high 143Nd/144Nd, which has been variably mixed with relatively high 206Pb/204Pb and 87Sr/86Sr and low 143Nd/144Nd, a signature commonly ascribed to detached or eroded metasomatized continental lithosphere, and (3) hot spot–related mantle having elevated 3He/4He and 206Pb/204Pb but intermediate 87Sr/86Sr and 143Nd/144Nd, similar to the common or C material observed in hot spots globally. These results suggest either that the ASP hot spot is isotopically heterogeneous or that the shallow mantle or lithosphere beneath the ASP Plateau contains more continentally derived material than the SEIR mantle ≥500 km away. Perhaps, like the 39°–41°E section of the Southwest Indian Ridge, beneath the ASP Plateau there are rafts of continental material stranded within a local “tectonic corridor,” possibly present since the opening of the Indian Ocean basin.
1. Introduction

Numerous studies have investigated the interaction between mid-ocean ridges and nearby hot spots using geochemical data [e.g., Schilling, 1985; Schilling et al., 1985; Dosso et al., 1999; Douglass et al., 1999; Maia et al., 2001; Detrick et al., 2002; Kingsley et al., 2007]. Recent work has emphasized the importance of understanding how mantle heterogeneity, mantle flow direction, and magma flux modulate the geochemical signals observed along ridge axes during hot spot–ridge interaction [e.g., Ito et al., 2003; Blichert-Toft et al., 2005]. Isotopic ratios of Pb, Sr, Nd, and He are particularly useful for studying the evolutionary history of hot spot–ridge interactions because these ratios in mid-ocean ridge basalt (MORB) distant from hot spots differ significantly from the same ratios in hot spot–related, ocean island basalt (OIB) [e.g., Hofmann, 2004].

The Southeast Indian Ridge (SEIR) is the longest spreading axis in the Indian Ocean, stretching from the Indian Ocean Triple Junction (25.6°S, 70°E) through the Australian–Antarctic Discordance (50°S, 120°E) to the Macquarie Triple Junction in the southwest Pacific Ocean at ~62°S, 160°E (Figure 1). This ridge has interacted during the last 40 million years with two hot spots, Kerguelen and Amsterdam/St. Paul [e.g., Doucet et al., 2004]. Parts of the SEIR migrated over the Kerguelen hot spot, currently represented by the Kerguelen Archipelago and Heard and McDonald Islands, at about 40 Ma when Broken Ridge was separated from the Kerguelen Plateau (Figure 1) [Mutter and Cande, 1983; Tikkur and Cande, 2000]. Presently the SEIR bisects the Amsterdam-St. Paul (ASP) Plateau (Figures 1 and 2). On the basis of isotopic data for the two islands on the ASP Plateau, Amsterdam and St. Paul, the isotopic characteristics of the ASP hot spot vary with location [Doucet et al., 2004]; therefore basalt from specific SEIR segments on or adjacent to the ASP Plateau may be isotopically distinct.

The Boomerang 06 cruise of the R/V Melville mapped ~1630 km of the SEIR and sampled (by dredging and wax coring) 11 ridge segments, with nearly one sampling site per 10 km of ridge on the plateau and one per 14 km from ridge segments adjacent to the plateau [Graham et al., 1999]. This study presents Sr, Nd, and Pb isotopic ratios for 37 basalt glasses recovered from the Southeast Indian Ridge between 32°S, 77°E and 43°S, 88°E and from the ASP Plateau (Figure 2). Also, we present new He isotopic data for 10 samples to complement the existing database (n = 41 [Graham et al., 1999; Burnard et al., 2002]). A major result is that each ridge segment, or in some cases contiguous segments, has distinctive isotopic characteristics. Comparisons of our isotopic data with previous results for Amsterdam and St. Paul Islands [Doucet et al., 2004] reveal that the ASP hot spot exerts considerable influence on the sub-ridge mantle for a lateral distance of ~300 km. Specifically, isotopic characteristics associated with mantle plumes, such as high ⁳He/⁴He, occur on the ASP Plateau and along the axial ridge segment immediately north of the plateau, whereas a low ²⁰⁶Pb/²⁰⁴Pb and relatively high ²⁰⁸Pb/²⁰⁶Pb isotopic signature is restricted to the plateau.

2. Geologic Setting

Spreading along the central and eastern SEIR initiated approximately 83 million years ago following ~13 million years of crustal extension between East Antarctica and southern Australia [Cande and Mutter, 1982; Veevers, 1986; Powell et al., 1988]. The earliest identified magnetic
anomaly is C34 (\(\sim 83\) Ma) [Cande and Kent, 1995], and the initial spreading rate was slow, \(\sim 5\) mm/yr [Cande and Mutter, 1982; Mutter et al., 1985]. Approximately 40 million years ago the spreading rate increased to \(\sim 22\) mm/yr and the SEIR intersected and split Broken Ridge from the Kerguelen Plateau [e.g., McKenzie and Sclater, 1971; Tikku and Cande, 2000]. Presently the SEIR is \(\sim 1150\) km northeast of the Kerguelen Plateau (Figure 1). The full spreading rate is \(63\) to \(65.5\) mm/yr near the ASP Plateau [Conder et al., 2000] and \(70\)–\(75\) mm/yr southeast of \(88^\circ\)E [Sempéré and Cochran, 1997]. Because the Antarctic plate moves relatively slowly in the hot spot reference frame, the ridge is migrating northeastward at a rate of \(\sim 32\) mm/yr [Conder et al., 2000]. The 11 ridge segments between \(77^\circ\) and \(88^\circ\)E (Figure 2) that are the focus of this study are designated F through L using the nomenclature of Royer and Schlich [1988] and Scheirer et al. [2000].

[6] From \(\sim 77^\circ\) to \(79^\circ\)E, the SEIR has a prominent U-shaped bend convex to the southwest (Figures 1 and 2), and this geometry has persisted since a ridge jump toward the Kerguelen hot spot shortly after the ridge propagated through the Kerguelen Plateau at \(\sim 40\) Ma [Müller et al., 1998]. The ASP Plateau on the western limb of the U-shaped offset is an \(\sim 30,000\) km\(^2\) area of shallow bathymetry, \(<2300\) m water depth, rising \(\sim 2\) km above the surrounding seafloor (Figure 3a). Between segments H and I1, the Amsterdam transform fault defines the northern margin of the plateau (Figure 2), whereas the southernmost ridge segments on the plateau (J1 and J2) are overlapping strands that show a gradual change to greater water depths on the southern margin (Figure 3a) [Scheirer et al., 2000].

[7] The plateau includes the volcanic islands of St. Paul and Amsterdam [Doucet et al., 2004] and several seamounts, including St. Pierre and Boomerang Seamount (Figure 2). Hot spot volcanism of the ASP Plateau initiated less than 5 million years ago on the basis of the age of seafloor surrounding the plateau [Scheirer et al., 2000]. Subaerial lavas from Amsterdam are less than \(0.7\) Ma [Gunn et al., 1971] although the most recent paleomagnetic and argon geochronology suggests ages of \(26 \pm 15\) and \(18 \pm 9\) kyr [Carvallo et al., 2003]. The breached caldera of St. Paul is morphologically young and is most likely less than \(0.5\) Ma [Watkins et al., 1974]. The islands are \(\sim 100\) and \(60\) km, respectively, from the nearest ridge segments and St. Pierre seamount is just east of St.
Paul Island. Boomerang Seamount, a currently active volcano [Johnson et al., 2000], is ~10 km northwest of segment I2 and 18 km northeast of Amsterdam Island (Figure 2). In the region of the islands, there is a prominent negative mantle Bouguer gravity anomaly centered to the west of the ridge, interpreted as increased crustal thickness beneath the plateau [Scheirer et al., 2000, Figure 9].

The four ridge segments (I1, I2, J1, J2) located on the plateau show en echelon segmentation (Figure 2), oblique spreading and a propagating rift (segment J2) to the south [Conder et al., 2000; Scheirer et al., 2000]. Ridge segments I1 and I2 jumped southwestward toward the ASP hot spot approximately 0.70 and 0.58 million years ago, respectively [Conder et al., 2000]. Scheirer et al. [2000] suggested that the intersection of the SEIR and the ASP Plateau initially occurred between 5 and 3.5 million years ago. Using an inferred crustal thickness of 13 km based on gravity analysis [Scheirer et al., 2000] and the 30,000 km² area of the plateau, the magmatic flux of the ASP hot spot has been estimated to be between 0.05 and 0.1 km³/yr during the last 3.5 million years; the lower flux does not include production of normal oceanic crust at the ridge axis. For comparison, the magmatic flux during the 24 to 30 Ma eruptions of the flood basalt forming the Kerguelen Archipelago is estimated to have been between 0.009 and 0.42 km³/yr [Nicolaysen et al., 2000].

3. Previous Studies

Early geochemical studies focused on dredged basalts from the SEIR between the Indian Ocean Triple Junction and the ASP Plateau. Hamelin et al. [1985/1986], Michard et al. [1986], and Dosso et al. [1988] documented anomalous isotopic compo-
sitions, which they inferred to be Kerguelen-like, in SEIR basalts dredged in the vicinity of segments J1 and J2 (Figure 2). In 1996, the Boomerang 06 expedition of the R/V Melville surveyed and sampled SEIR segments on and adjacent to the ASP Plateau with the goal of assessing the influence of the Amsterdam-St. Paul and Kerguelen hot spots on SEIR MORB. Conder et al. [2000] and Scheirer et al. [2000] published the geophysical results from this cruise. Graham et al. [1999] showed that SEIR basalts atop the plateau and from segment H north of the plateau have high $^{3}\text{He}/^{4}\text{He}$ ratios, up to 14 $R_A$ (where $R_A$ is the atmospheric ratio), and inferred that hot spot–derived mantle was flowing toward the north. Johnson et al. [2000] described the morphology and chemistry of Boomerang Seamount (Figure 2). A hydrothermal plume discovered in the water column at this locality, $^{210}\text{Po}-^{210}\text{Pb}$ data for the seamount basalts, and the presence of fresh hydrothermal sediment provide evidence that Boomerang Seamount represents a currently active expression of the ASP hot spot.

[10] On the basis of major element data for more than 300 glasses from 89 dredge and wax core sites, Douglas-Priebe [1998] defined a large num-

Figure 3. Along-axis profiles of (a) seafloor depth, (b) $K_2O/TiO_2$, and (c) $^{3}\text{He}/^{4}\text{He}$ ($R/R_A$). Distance along-axis is represented as north (to the left) and southeast (to the right) of St. Paul Island calculated through the pole of plate rotation. Dashed lines indicate the boundaries between ridge segments. The shallow bathymetry of the ASP Plateau (segments I1, I2, J1, and J2) is indicated by pale orange shading and coincides with relatively high $K_2O/TiO_2$ and $^{3}\text{He}/^{4}\text{He}$, but the highest ratios in these parameters occur along segment H north of the plateau [Douglas-Priebe, 1998; Graham et al., 1999]. Data sources include analyses of SEIR basalts and ASP seamounts by Dosso et al. [1988], Graham et al. [1999], Johnson et al. [2000], and this study; analyses of Amsterdam and St. Paul Island lavas are from Doucet et al. [2004].
ner of distinct compositional groups. In general, MORBs that are relatively enriched in K and incompatible trace elements (Table 1) occur atop the ASP Plateau and along the ridge segment north of the plateau (segment H; Figure 3b). Additionally, basalts from ridge segments on the plateau extend to lower Mg# (100 Mg/(Mg + Fe)) than basalts from “normal” ridge segments to the north and south of the plateau (on plateau: 46.5–60.6 Mg#; off-plateau: 55.9–66 Mg#), indicating greater amounts of low-pressure crystal fractionation (Table 1). Although the thickened oceanic crust of the ASP Plateau has led to a greater extent of crystal fractionation, this process cannot explain the K/Ti variation that is accompanied by variable He isotopic ratios [Graham et al., 1999, Figures 3b, 3c, and 2]. Using major and trace element abundance variations and helium isotopic ratios (Figure 3), Douglas-Priebe [1998], Graham et al. [1999], and Johnson et al. [2000] identified two distinct mantle sources for the SEIR basalts between 77° and 88°E.

[11] Burnard et al. [2002] demonstrated, however, that the degree of crystal fractionation and the associated extent of pre-eruptive degassing both control noble gas concentrations in the study region, thereby exerting an influence on the 3He/4He signal for mixtures of MORB and hot spot magma. Pre- and syn-eruptive degassing has clearly affected the noble gas concentrations in these basalts (as well as nearly all MORB). The He concentrations cannot be taken as unmodified magmatic values, and the extent of gas loss may affect the sense of the curvature in inferred mixing relationships on diagrams where 3He/4He variations are compared to those of the lithophile isotope tracers. However, only the very degassed samples, i.e., those having He concentrations below 10⁻⁸ ccSTP/g and low 3He/4He (1–2 RA), appear to have been affected by shallow level (assimilation) processes [Graham et al., 1999]. These low 3He/4He lavas are typically sampled in areas where the magma budget is less robust, such as near propagating rift tips or transform faults. The 3He/4He variations discussed in this study exclude the highly degassed lavas and are therefore taken to reflect variations in the underlying mantle source region of the basalts.

4. Sampling and Analytical Techniques

[12] On the basis of major element compositions [Douglas-Priebe, 1998] and helium isotopic data [Graham et al., 1999], we selected a subset of basalt glass samples for Pb, Nd and Sr isotopic analysis. These samples are from 35 axial sites on the 11 ridge segments. Additional samples include a basalt from a short extensional relay zone within the Zeewolf transform north of segment H (D75-4), a basalt from a small (150 m high) off-axis volcanic cone on the plateau (D58-1), and three basalts from seamounts on the ASP Plateau (WC44 and WC45 from Boomerang Seamount, and WC34 from a small lava field near the base of St. Pierre Seamount). A single glassy sill sampled on St. Paul Island (SP-1a) was also analyzed. For each sample approximately 50 mg of fresh glass fragments were picked under a binocular microscope. These fragments were cleaned ultrasonically with methanol, 4 N HCl, and ultra-pure distilled water, dried and then weighed prior to analysis at the University of Hawaii. Sample dissolution in HF-HNO₃ was followed by separation of Pb, Sr, and Nd by anion and cation exchange chromatography, and isotopic analyses following procedures described by Mahoney et al. [1994]. Helium isotopic analyses followed procedures outlined by Graham et al. [1999].

5. Results

[13] Sample locations, water depths, Mg#, K₂O/TiO₂ and Pb, Nd and Sr isotopic data are in Table 1; new He isotopic data (n = 10) are in Table 2. The isotopic data are examined in this study by separating the samples into three spatial groups: ridge segments (I1, I2, J1, J2) and seamounts located on the ASP Plateau; ridge segments J3, J4, K and L southeast of the plateau; and ridge segments H, G and F north of the plateau (Figures 3 and 4).

[14] Basalts from the seamounts and segments on the ASP Plateau range widely in ³He/⁴He, from 8.6 to 13.4 RA (Figure 3c). These lavas also have a wide range of Pb, Nd and Sr isotopic ratios, and this variability is clearly related to ridge segmentation (Figure 4). For example, samples from segment J1 range to the highest ⁸⁷Sr/⁸⁶Sr, lowest ¹⁴³Nd/¹⁴⁴Nd, lowest ²⁰⁸Pb/²⁰⁶Pb and the highest ²⁰⁸Pb/²⁰⁶Pb (as defined in the Figure 4 caption); in contrast, samples from segment I2 have the highest ²⁰⁶Pb/²⁰⁴Pb atop the plateau.

[15] Surprisingly, the isotopic compositions of lavas from axial segments on the ASP Plateau range to higher ⁸⁷Sr/⁸⁶Sr, lower ¹⁴³Nd/¹⁴⁴Nd and higher ²⁰⁸Pb/²⁰⁶Pb than basalts from Amsterdam or St. Paul Islands (Figure 4). The two seamounts that were sampled atop the plateau also have different isotopic signatures. A presumably young flow at the terminus of a volcanic cone field northeast of the base of St. Pierre Seamount was
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<th>Longitude, °E</th>
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<th>Longitude, °E</th>
<th>Distance From St. Paul Island</th>
<th>Ridge Segment</th>
<th>Depth, m</th>
<th>Mg#</th>
<th>K₂O/TiO₂</th>
<th>⁸⁷Sr/⁸⁶Sr</th>
<th>²⁰⁶Pb/²⁰⁴Pb</th>
<th>²⁰⁷Pb/²⁰⁴Pb</th>
<th>²⁰⁸Pb/²⁰⁴Pb</th>
<th>Pb, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 73-6</td>
<td>36 03.98</td>
<td>78 49.48</td>
<td>−129</td>
<td>H</td>
<td>2659</td>
<td>65.4</td>
<td>0.2647</td>
<td>0.703345</td>
<td>0.512939</td>
<td>10 5.9</td>
<td>0.2</td>
<td>18.552</td>
</tr>
<tr>
<td>WC 47</td>
<td>35 56.31</td>
<td>78 42.54</td>
<td>−147</td>
<td>H</td>
<td>2840</td>
<td>62.3</td>
<td>0.4480</td>
<td>0.703676</td>
<td>0.512843</td>
<td>6 4.0</td>
<td>0.1</td>
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</tr>
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<td>WC 48</td>
<td>35 47.82</td>
<td>78 35.67</td>
<td>−165</td>
<td>H</td>
<td>2900</td>
<td>62.1</td>
<td>0.1429</td>
<td>0.703280</td>
<td>0.512978</td>
<td>6 6.6</td>
<td>0.1</td>
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</tr>
<tr>
<td>D 75-4</td>
<td>35 16.95</td>
<td>78 35.70</td>
<td>−205</td>
<td>H/G</td>
<td>3269</td>
<td>61.9</td>
<td>0.05042</td>
<td>0.702986</td>
<td>0.513063</td>
<td>6 8.3</td>
<td>0.1</td>
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</tr>
<tr>
<td>D 79-1</td>
<td>34 34.15</td>
<td>78 14.19</td>
<td>−284</td>
<td>G</td>
<td>3163</td>
<td>62.3</td>
<td>0.09524</td>
<td>0.702921</td>
<td>0.513024</td>
<td>6 7.5</td>
<td>0.1</td>
<td>18.270</td>
</tr>
<tr>
<td>D 77-3</td>
<td>32 56.72</td>
<td>77 48.93</td>
<td>−437</td>
<td>F</td>
<td>2835</td>
<td>59.8</td>
<td>0.08609</td>
<td>0.702930</td>
<td>0.513045</td>
<td>8 7.9</td>
<td>0.2</td>
<td>17.877</td>
</tr>
<tr>
<td>D 76-5</td>
<td>32 45.77</td>
<td>77 53.19</td>
<td>−447</td>
<td>F</td>
<td>2178</td>
<td>61.5</td>
<td>0.1463</td>
<td>0.702970</td>
<td>0.513012</td>
<td>8 7.3</td>
<td>0.2</td>
<td>17.998</td>
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<tr>
<td>SP-1</td>
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<td>St. Paul Island</td>
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<td>0.3009</td>
<td>0.703500</td>
<td>0.512886</td>
<td>6 4.8</td>
<td>0.1</td>
<td>18.651</td>
<td>5</td>
<td>15.558</td>
</tr>
</tbody>
</table>

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*a* All samples were analyzed at the University of Hawaii unless otherwise indicated. NBS 987 (⁸⁶Sr/⁸⁶Sr = 0.71024 ± 0.00002) was used for the strontium standard, and isotopic fractionation was corrected using ⁸⁶Sr/⁸⁶Sr = 0.1194. For the Nd isotopic analyses, the fractionation correction is ¹⁴⁳Nd/¹⁴⁴Nd = 0.241572, and the measured La Jolla standard value is ¹⁴⁵Nd/¹⁴⁴Nd = 0.511850 ± 0.000011. The fractionation corrections of the Pb isotopic analyses are based on the NBS 981 standard [Todt et al., 1995]. The precisions given by the standard analyses are ±0.01, ±0.01, and ±0.032 for ⁸⁶Pb/⁸⁴Pb, ⁸⁷Pb/⁸⁴Pb, and ⁸⁸Pb/⁸⁴Pb, respectively. The lead concentration data were obtained by isotope dilution of hand-picked glasses and may not accurately reflect the whole-rock Pb abundances. The total procedural blanks were ≤12 pg.

*b* Sample prefixes: WC, waxcore; D, dredge haul.

*c* Distance from St. Paul Island through the pole of plate rotation; positive values are south, and negative values are north.

*d* Ridge segments are named after the convention of Royer and Schlich [1988] and Conder et al. [2000].

*e* Depth in meters below sea surface.
targeted for sampling because of its high reflectivity in side-scan sonar. Sample WC34 from this area, ~30 km southeast of St. Paul Island (Figure 2), has the highest \(^{3}\text{He}/^{4}\text{He} (13.4 \text{ RA}) of the samples from the plateau. WC34 also has relatively high \(^{87}\text{Sr}/^{86}\text{Sr} (0.70478), low \(^{143}\text{Nd}/^{144}\text{Nd} (0.51266) and elevated \(^{208}\text{Pb}*/^{206}\text{Pb}^* (1.03), similar to the extreme values observed on nearby segment J1. Basaltic glasses WC44 and WC45, two wax cores from the floor and rim, respectively, of the summit caldera of Boomerang Seamount (Figure 2), have markedly different isotopic compositions (\(^{87}\text{Sr}/^{86}\text{Sr} = 0.70456 and 0.70381; \(^{206}\text{Pb}/^{204}\text{Pb} = 18.55 and 19.14, respectively).}

Southeast of the ASP Plateau, ridge segments J3, J4, K and L have \(^{87}\text{Sr}/^{86}\text{Sr} ratios that range from 0.70297 to 0.70367 and \(^{143}\text{Nd}/^{144}\text{Nd} values from 0.51289 to 0.51307 (\( \varepsilon_{\text{Nd}} = 4.9 to 8.4), but no systematic increase in \(^{87}\text{Sr}/^{86}\text{Sr} or decrease in \(^{143}\text{Nd}/^{144}\text{Nd} is observed approaching the ASP Plateau. Rather, samples from segment J3 closest to the ASP Plateau have the lowest \(^{87}\text{Sr}/^{86}\text{Sr} and highest \(^{143}\text{Nd}/^{144}\text{Nd} (Figure 4). In contrast, slightly more radiogenic \(^{206}\text{Pb}/^{204}\text{Pb} ratios are observed along segment J3.}

North of the ASP Plateau, segment H lavas are isotopically diverse, having \(^{87}\text{Sr}/^{86}\text{Sr} = 0.70306 to 0.70368, \(^{143}\text{Nd}/^{144}\text{Nd} = 0.51284 to 0.51304, and \(^{206}\text{Pb}/^{204}\text{Pb} = 18.11 to 19.41 (n = 6; Table 1). The highest \(^{3}\text{He}/^{4}\text{He} (14.1 \text{ RA}) and most radiogenic \(^{206}\text{Pb}/^{204}\text{Pb} (19.41) are found in sample WC47, near the center of segment H (Figures 3 and 4). However, \(^{87}\text{Sr}/^{86}\text{Sr} and \(^{143}\text{Nd}/^{144}\text{Nd} ratios along segment H do not reach the extreme values observed along axial segments on the ASP plateau.

Also, there is no simple relation along segment H between isotopic compositions and distance from the plateau, partly because one dredge site (D73) on segment H recovered lavas with highly variable isotopic compositions (Table 1).

Basalt D75-4, recovered along a small extensional relay zone within the Zeewolf transform (between segments G and H), has lower \(^{87}\text{Sr}/^{86}\text{Sr}, \(^{206}\text{Pb}/^{204}\text{Pb} and \(^{3}\text{He}/^{4}\text{He}, and higher \(^{143}\text{Nd}/^{144}\text{Nd}, than any of the segment H lavas (Figures 3 and 4). Relative to basalt from segment F to the northwest, segment G basalts have similar Nd and Sr isotopic ratios but higher \(^{206}\text{Pb}/^{204}\text{Pb} ratios (Figure 4).

6. Discussion

6.1. Islands, Seamounts, and Ridge Segments (I1, I2, J1, J2) on the ASP Plateau

Lavas from Amsterdam and St. Paul Islands on the ASP Plateau define \(^{87}\text{Sr}/^{86}\text{Sr} versus \(^{143}\text{Nd}/^{144}\text{Nd fields that are intermediate between MORB glasses from the SEIR and lavas from the Kerguelen Archipelago (Figure 5). Lavas from Amsterdam and St. Paul Islands have more radiogenic Pb isotopic ratios than SEIR MORB (Figure 6), and these ratios in Amsterdam Island lavas (e.g., \(^{206}\text{Pb}/^{204}\text{Pb} \sim 19.1 [Doucet et al., 2004]) exceed those for lavas from the Kerguelen Archipelago (Figure 6). Notably, lavas from Amsterdam and St. Paul Islands define restricted and distinct fields in radiogenic isotopic ratios, especially in Pb isotopic ratios (Figures 5 and 6). Samples from Boomerang and St. Pierre Seamounts provide additional evidence for ASP hot spot isotopic variability. Specifically, data for a sample from the caldera floor of Boomerang Seamount (WC44) falls within the Pb-Nd-Sr isotopic range of nearby Amsterdam Island lavas, but a sample from the caldera rim (WC45) has higher \(^{87}\text{Sr}/^{86}\text{Sr}, lower \(^{143}\text{Nd}/^{144}\text{Nd}, lower \(^{206}\text{Pb}/^{204}\text{Pb} and higher \(^{208}\text{Pb}/^{204}\text{Pb} than the range of lavas from Amsterdam Island (Figure 4). Also, a sample (WC34) from near St. Pierre Seamount, just south of St. Paul Island, has higher \(^{87}\text{Sr}/^{86}\text{Sr}, lower \(^{143}\text{Nd}/^{144}\text{Nd}, lower \(^{206}\text{Pb}/^{204}\text{Pb} and higher \(^{208}\text{Pb}/^{204}\text{Pb} than the range of lavas from St. Paul Island (Figure 4). Clearly, the ASP hot spot erupts lavas having a wide range of isotopic compositions, and this range is expressed in the youngest seamount volcanism on the plateau as well as by the <1 Ma island lavas [Graham et al., 1999; Johnson et al., 2000; Doucet et al., 2004].

Table 2. New Helium Isotope Data for SEIR Basalt Glasses

| Sample | Ridge Segment | \(^{3}\text{He}/^{4}\text{He} (R/\text{RA}) \pm [\text{He}, \mu\text{ccSTP/g}})
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D51-1</td>
<td>J2</td>
<td>8.93 0.06 0.394</td>
</tr>
<tr>
<td>D59-1</td>
<td>J1</td>
<td>11.89 0.08 0.614</td>
</tr>
<tr>
<td>WC35</td>
<td>I2</td>
<td>10.27 0.06 0.888</td>
</tr>
<tr>
<td>WC37</td>
<td>I2</td>
<td>12.21 0.08 0.113</td>
</tr>
<tr>
<td>WC38</td>
<td>I2</td>
<td>11.34 0.07 0.57</td>
</tr>
<tr>
<td>D66-1</td>
<td>I2</td>
<td>9.67 0.06 0.375</td>
</tr>
<tr>
<td>D67-1</td>
<td>I2</td>
<td>9.86 0.13 0.086</td>
</tr>
<tr>
<td>D73-4</td>
<td>H</td>
<td>10.35 0.06 2.12</td>
</tr>
<tr>
<td>D76-5</td>
<td>F</td>
<td>8.5 0.04 6.8</td>
</tr>
<tr>
<td>D77-3</td>
<td>F</td>
<td>8.57 0.05 2.8</td>
</tr>
</tbody>
</table>

\(^{\text{aGas extractions were performed by in vacuo crushing of hand-picked basalt glass. Reported uncertainties represent the 2 standard error quadrature sum of uncertainties associated with sample, blank, and air standard analyses.}}

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Axial segments I1, I2, J1 and J2 are on the bathymetric high forming the ASP Plateau (Figures 2 and 3a); their negative mantle Bouguer gravity anomalies indicate that the plateau has thickened [Scheirer et al., 2000]. Do the isotopic ratios of lavas from these ridge segments reflect a strong influence from the ASP hot spot? The sample from the base of St. Pierre Seamount has the highest $^{3}$He/$^{4}$He (13.4 R$_{A}$); together with SEIR samples from the nearby ridge segments I2 and J1, a local

![Figure 4](image_url)

Figure 4. Along-axis variations in (a) $^{87}$Sr/$^{86}$Sr, (b) $^{143}$Nd/$^{144}$Nd, (c) $^{206}$Pb/$^{204}$Pb, and (d) $^{208}$Pb*/$^{206}$Pb*. The influence of the Amsterdam-St. Paul hot spot upon SEIR basalts is evident by the deviations in isotopic ratios relative to normal mid-ocean ridge basalts north (segments F and G) and southeast (segments K and L) of the plateau. Note that the highest Pb isotopic compositions, like the $^{3}$He/$^{4}$He shown in Figure 3, occur off the plateau at segment H. In contrast, Sr and Nd isotopes show maxima and minima, respectively, on the plateau. We use the parameter $^{208}$Pb*/$^{206}$Pb* for ASP and SEIR lavas because it can be related to the history of Th/U fractionation. $^{208}$Pb*/$^{206}$Pb* is a measure of the cumulative radiogenic Pb in a sample corrected for the presence of terrestrial primordial Pb ($^{208}$Pb*/$^{206}$Pb* = [$^{208}$Pb/$^{204}$Pb$_{sample}$ – 29.475]/[$^{206}$Pb/$^{204}$Pb$_{sample}$ – 9.307]) [Allègre et al., 1986; Galer and O’Nions, 1985]. Data sources are as in Figure 3, with additional data from Hamelin et al. [1985/1986], Michard et al. [1986], Price et al. [1986], and Dupré and Allègre [1983].

Axial segments I1, I2, J1 and J2 are on the bathymetric high forming the ASP Plateau (Figures 2 and 3a); their negative mantle Bouguer gravity anomalies indicate that the plateau has thickened crust [Scheirer et al., 2000]. Do the isotopic ratios of lavas from these ridge segments reflect a strong influence from the ASP hot spot? The sample from the base of St. Pierre Seamount has the highest $^{3}$He/$^{4}$He (13.4 R$_{A}$); together with SEIR samples from the nearby ridge segments I2 and J1, a local
high in $^{3}$He/$^{4}$He is defined (Figure 3c). These ratios are higher than observed in SEIR basalt distant from the plateau [Graham et al., 2001]. Surprisingly, lavas from segment J1 range to higher $^{87}$Sr/$^{86}$Sr and lower $^{143}$Nd/$^{144}$Nd than lavas from Amsterdam and St Paul Islands (Figures 4 and 5). Earlier studies of samples dredged from segment J1 [Hamelin et al., 1985/1986; Michard et al., 1986; Dosso et al., 1988] found similar results, and these authors speculated that material derived from the distant Kerguelen hot spot was actively involved in construction of the ASP Plateau. However, new isotopic data show that two of the three samples from Boomerang and St. Pierre Seamounts, which are clearly linked to the excess magmatism of the ASP hot spot, also have relatively high $^{87}$Sr/$^{86}$Sr and low $^{143}$Nd/$^{144}$Nd (Figure 5). This isotopic signature, previously inferred to implicate involvement of the distant Kerguelen hot spot, occurs in the youngest volcanism atop the plateau [Johnson et al., 2000] and therefore seems intrinsically associated with the ASP hot spot.

[21] Confirmation of the ASP hot spot influence on axial ridge lavas erupted on the plateau is clearly seen in the Pb isotopic data. In the $^{206}$Pb/$^{204}$Pb versus $^{208}$Pb/$^{204}$Pb plot (Figure 6a), basalt from ASP segments J1, J2, I1 and I2, along with lavas from Amsterdum Island, Boomerang Seamount and St. Pierre Seamount, define a trend with relatively high $^{208}$Pb/$^{204}$Pb for a given $^{206}$Pb/$^{204}$Pb. These lavas have high $^{208}$Pb*/$^{206}$Pb* (Figure 4d), a characteristic of the DUPAL anomaly, a wide, nearly global swath of isotopically distinct ocean island basalts centered at $\sim$$30^\circ$S. Hart [1984] defined this isotopic anomaly on the basis of deviation from a “northern hemisphere reference line” in Pb-Pb isotopic ratio diagrams and relatively high Sr isotopic ratios ($>$0.705). Among SEIR basalts on the plateau, the J1 segment lavas range to more extreme $^{208}$Pb*/$^{206}$Pb* ratios ($>$1.05) than lavas from Amsterdam and St. Paul Island, and two of the three seamount samples also have higher $^{208}$Pb*/$^{206}$Pb* than island lavas (Figure 4d).

[22] In summary, lavas associated with the ASP hot spot show significant isotopic variability. Although isotopic heterogeneity was previously established by inter-island differences between St Paul and Amsterdam lavas [Doucet et al., 2004], even more isotopic diversity is shown by nearby seamounts and the SEIR segments on the ASP Plateau.

6.2. Ridge Segments (H, G, F) North of the ASP Plateau

[23] Segment H lavas define near-linear trends in isotopic ratio plots such as $^{87}$Sr/$^{86}$Sr versus $^{143}$Nd/$^{144}$Nd, $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb, $^{143}$Nd/$^{144}$Nd versus $^{206}$Pb/$^{204}$Pb and $^{87}$Sr/$^{86}$Sr versus $^{206}$Pb/$^{204}$Pb (Figures 5–7); these trends are consistent with mixing of two isotopically distinct end-members. The $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram (Figure 6a) provides the best illustration of mixing because the relative errors are small and mixing trends show little scatter. Segment H samples also show a linear relationship in $^{4}$He/$^{3}$He versus $^{87}$Sr/$^{86}$Sr (Figure 8). If mixing between two end-members is the dominant process responsible for the isotopic variation of segment H lavas, the linearity of the isotopic trends requires that Sr/Nd, Sr/Pb and Sr/He abundance ratios are similar in both end-members.

[24] Along segment H there is no observed systematic relationship between isotopic ratios and distance to the islands (Figure 4). The large variation in geochemical characteristics occurs over distances much less than the $\sim$90 km length of segment H. This variation probably occurs at the scale of lava flows, because a single dredge haul (D73) exhibits between 65 and 85% of the total variability in He-Pb-Nd-Sr isotopic ratios along segment H (Table 1). Therefore mixing proportions between the two end-members appear to be variable at a scale of kilometers or less along segment H. Moreover, the isotopic extremes along segment H are defined by samples collected only 18 km from
each other: sample D73-4 with $^{87}\text{Sr}/^{86}\text{Sr} = 0.70306$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51304$, $^{206}\text{Pb}/^{204}\text{Pb} = 18.11$ and $^3\text{He}/^4\text{He} = 10.4$ RA, and sample WC47, with $^{87}\text{Sr}/^{86}\text{Sr} = 0.70368$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51284$, $^{206}\text{Pb}/^{204}\text{Pb} = 19.41$ and $^3\text{He}/^4\text{He} = 14.1$ RA (Table 1). Sample D73-4 has isotopic ratios trending toward those of the “background” or depleted mantle (DM) more distant from the ASP Plateau, whereas sample WC47 has isotopic ratios similar to the “common” mantle component $C$ described by Hanan and Graham [1996] (Figures 5, 6, and 7).

[25] In summary, the most important observations for segment H are as follows:

[26] 1. Segment H lavas are mixtures derived from the hot spot–related $C$ component and the depleted mantle (DM).

[27] 2. The geochemical characteristics of the C-type magma source are most clearly expressed at segment H north of the ASP Plateau, but they are also obvious at local scales on the ASP Plateau, i.e., at segment I2, Boomerang Seamount and Amsterdam Island (Figure 6).
3. Lavas from segments J1 and J2 on the ASP Plateau range to the highest $^{87}\text{Sr}/^{86}\text{Sr}$, lowest $^{143}\text{Nd}/^{144}\text{Nd}$ and highest $^{208}\text{Pb}*/^{206}\text{Pb}*$ (Figures 4 and 5) and reflect the presence of a third, DUPAL-like component, either in the hot spot source or in the ambient upper mantle beneath the ASP Plateau. This DUPAL component is much less abundant, and perhaps absent, in the mantle source of segment H lavas (Figure 4d).

Possible explanations for this surprising spatial distribution of the C and DUPAL-type components include the following:

1. Hot spot mantle is present beneath segment H, but it is spatially zoned with respect to the high $^{208}\text{Pb}*/^{206}\text{Pb}*$ (DUPAL) component. This component is much less abundant, or absent, in hot spot material beneath segment H.

2. The high $^{208}\text{Pb}*/^{206}\text{Pb}*$ component is well mixed within the hot spot source, and it resides in a mineral assemblage that has a relatively low solidus. Consequently, partial melting concentrates the high $^{208}\text{Pb}*/^{206}\text{Pb}*$ isotopic component in lavas erupted on the ASP Plateau, from segments I1, I2, J1, and J2 plus St. Pierre and Boomerang seamounts. Residual hot spot-related asthenosphere depleted in this component flows northward beneath the damming effect of the Amsterdam Transform Fault (Figure 2), and subsequent upwelling at segment H creates melts that lack the high $^{208}\text{Pb}*/^{206}\text{Pb}*$.

Figure 7. (a) $^{87}\text{Sr}/^{86}\text{Sr}$ and (b) $^{143}\text{Nd}/^{144}\text{Nd}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the Southeast Indian Ridge, Amsterdam and St. Paul Islands, Kerguelen Plateau (ODP Sites 747 and 750), Kerguelen Archipelago, and Heard Island. The SEIR lavas define two trends similar to those observed for the Pb isotopes alone (Figure 6). One trend is between mantle component C and depleted mantle DM (most evident in segment H lavas and some lavas from segments F and G north of the plateau), while a second trend is between C and DUPAL mantle (most evident in some basalts atop the ASP Plateau, from segments I1, I2, J1, and J2 plus St. Pierre and Boomerang seamounts). Data sources as in Figure 6.
3. The ASP hot spot represents an upwelling C-rich mantle plume that interacts extensively with shallower non-plume material beneath the ASP Plateau and the nearby SEIR for lateral distances of ~300 km. The composition of this “background” mantle beneath the SEIR varies laterally. Beneath segment H this background mantle is predominantly DM, but beneath the ASP Plateau it contains high $^{208}\text{Pb}*/^{206}\text{Pb}*{\text{ component, commonly inferred to be continental material stranded during opening of the Indian Ocean [Mahoney et al., 1991, 1992; Janney et al., 2005; Meyzen et al., 2005]. If this high $^{208}\text{Pb}*/^{206}\text{Pb}*{\text{ source resides in the upper asthenosphere, it is remarkable that the plateau-bounding transform faults within the lithosphere mark the boundary of its expression in SEIR lavas. Alternatively, the source of the high $^{208}\text{Pb}*/^{206}\text{Pb}*{\text{ component is continental material within the lithosphere of the ASP Plateau, perhaps analogous to Elan Bank, a part of the Kerguelen Plateau interpreted to be a micro-continental formed during the breakup of Gondwana [Borisson et al., 2003].}

Lavas from north of segment H show no significant influence of the ASP hot spot. Sample D75-4 is from a small relay zone, within the Zeewolf Transform which separates segments G and H (Figure 2). This sample is one of the most “depleted” basalts in its isotopic composition, having $^{206}\text{Pb}/^{204}\text{Pb} = 17.91$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.51306$ ($\varepsilon_{\text{Nd}} = 8.3$), $^{87}\text{Sr}/^{86}\text{Sr} = 0.70244$ and $^{3}\text{He}/^{4}\text{He} = 9.0$ $R_A$ (Table 1). Furthermore, lavas from segments F and G have isotopic compositions anticipated for normal SEIR basalt away from the ASP hot spot (Figures 3–6). The absence of ASP hot spot influence beyond the Zeewolf Fracture Zone suggests that the thermal and geochemical anomaly associated with the hot spot is shallow enough at this distance that this fracture zone defines the northern boundary of hot spot–derived material.

6.3. Influence of the Kerguelen Hot Spot on the ASP Plateau and SEIR Southeast of the Plateau

Yale and Phipps Morgan [1998] used a numerical model to explore the interaction of the off-axis Kerguelen hot spot with the SEIR and concluded that the entire ASP Plateau was affected...
by Kerguelen hot spot mantle flowing northward to the SEIR. Furthermore these authors suggested that there was shallow along-axis flow of the Kerguelen hot spot–related material away from the plateau. Our geochemical data do not support this model. For example, Pb isotopic ratios in some SEIR segments, such as I2 on the ASP Plateau, exceed those in Kerguelen Archipelago lavas. Such radiogenic Pb ratios are a characteristic of Amsterdam Island lavas (Figure 6). We conclude that the diversity of Pb isotopic ratios in ASP-related lavas is inconsistent with mixing of only SEIR and Kerguelen hot spot components (Figure 6). Nevertheless, we ask: can some of the isotopic complexity of SEIR lavas in the area be explained by a Kerguelen-like component?

[35] Because both the ASP and Kerguelen hot spots have relatively high 87Sr/86Sr and low 143Nd/144Nd compared to most SEIR basalts (Figure 5), Sr and Nd isotopes alone are not diagnostic in assessing the relative roles of the different hot spots. Trends of 87Sr/86Sr and 143Nd/144Nd versus 206Pb/204Pb are more useful for such an assessment (Figure 7). As previously noted, lavas from segment H north of the ASP Plateau define a trend, extending from C to depleted mantle as sampled by SEIR basalt distant from hot spots. Lavas from segments F and G are also on the same trend as segment H (Figure 7). Compared to this trend, data for lavas from axial segments I2, J1 and J2 on the ASP Plateau are offset at a given 206Pb/204Pb to higher 87Sr/86Sr, lower 143Nd/144Nd and higher 208Pb/204Pb (Figures 6 and 7). Data for basalt from the Kerguelen Archipelago are similarly offset from the trend between depleted mantle and C, and one of the Boomerang Seamount lavas also lies in the Kerguelen field (Figures 6 and 7). This isotopic similarity could be interpreted as reflecting an influence of the distant Kerguelen hot spot. However, young seamounts on the ASP Plateau are clearly related to ASP hot spot volcanism, and we conclude that the isotopic offset of lavas from SEIR segments on the ASP Plateau is related to a Kerguelen-like component that is either within the ASP plume itself, or within the upper mantle or lithosphere beneath the plateau.

[36] On the basis of linear gravity anomalies extending northeast from the Kerguelen Archipelago to the SEIR south of the ASP Plateau, Small et al. [1995] proposed asthenospheric flow of Kerguelen hot spot material toward the SEIR in the vicinity of segments J4 and K (Figure 2). In a Pb-Nd-Sr-He isotopic study of SEIR basalts from 86° to 118°E, Mahoney et al. [2002] noted that the one place in the entire region where isotopic variations appear broadly consistent with the presence of a moderate amount of hot spot–derived mantle is at the western edge of the study area, at ~86°–90°E, i.e., segment L located southeast of the ASP Plateau (Figure 2). Collectively, our isotopic data and those of Mahoney et al. [2002] provide only weak evidence supporting the involvement of Kerguelen-derived material anywhere along the SEIR. For example, compared to lavas from segments F and G (>250 km north of the ASP Plateau), segments K and L (>400 km south of St. Paul Island) have higher 87Sr/86Sr and lower 143Nd/144Nd (Figure 4). This difference might reflect a weak interaction of the Kerguelen hot spot with the SEIR in this region, but it may also be due to intrinsic heterogeneity in the upper mantle MORB source. More detailed sampling along axial segments K and L, plus off-axis sampling along the gravity highs associated with the aseismic ridges that extend east-northeast from the Kerguelen Plateau toward the SEIR is needed to fully evaluate the effect, if any, of the Kerguelen hot spot on these ridge segments, which are currently >1400 km from the Kerguelen Archipelago.

6.4. Geochemical End-Members Required by the SEIR and ASP Plateau Basalts

[37] Figure 6 shows the necessity for at least three distinct components to explain the isotopic variation of lavas from ridge segments on and adjacent to the ASP Plateau. Lavas from SEIR segments adjacent to the plateau, i.e., segments F, G, H, J3, J4, K and L, define a trend between the C end-member and depleted mantle (DM). In contrast, ASP Plateau segments, especially I2, J1 and J2, define a different trend between the C end-member and a mantle source with higher 208Pb/204Pb, 87Sr/86Sr and lower 143Nd/144Nd at a given 206Pb/204Pb than DM (Figures 6a and 7). In order to distinguish this component, we refer to this end-member as the DUPAL-type component. Its end-member composition has 206Pb/204Pb <16.6 and εNd ~ ~8 [Mahoney et al., 1996], significantly lower than values suggested for the EM I component that is widely observed in OIBs and continental volcanic rocks (e.g., 206Pb/204Pb = 17.4 [e.g., Hofmann, 2004]).

6.4.1. DUPAL Component and the Southeast Indian Ridge

[38] The isotopic characteristics of axial segments J1 and J2 (i.e., relatively high 87Sr/86Sr and 208Pb*/204Pb*
and low $^{143}\text{Nd}/^{144}\text{Nd}$) are similar to but not as extreme as those of the $39^\circ-41^\circ$E axial segment of the Southwest Indian Ridge, where Mahoney et al. [1992] and Janney et al. [2005] suggested that upper mantle between two transform faults contains stranded continental lithosphere that had been thermally eroded from Indo-Madagascar in the mid-Cretaceous. Meyzen et al. [2005] inferred that stranded lower continental crust is embedded in the SWIR upper mantle. Similar conclusions have been reached for a section of the southernmost Mid-Atlantic Ridge [Kamenetsky et al., 2001] and sections of the Australian-Antarctic Discordance [Hanan et al., 2004].

[39] Our results for ASP segments J1 and J2 are consistent with these inferences and suggest that isolated fragments of former continental lithosphere are also beneath the ASP Plateau. Continental components have also contributed to Cretaceous basalt that forms part of Kerguelen Plateau [Mahoney et al., 1995; Weis et al., 2001; Frey et al., 2002a]. Several studies have postulated dispersion of continental lithospheric fragments throughout the Indian Ocean Basin, e.g., beneath the Seychelles [Müller et al., 2001] and the Kerguelen Plateau [Mahoney et al., 1995; Nicolaysen et al., 2001; Ingle et al., 2002]. Smaller amounts of widely dispersed material derived from continental lithosphere also appear to be a plausible explanation for the pervasive DUPAL isotopic signature that characterizes Indian MORB east of $26^\circ$E [e.g., Mahoney et al., 1992; Escrig et al., 2004; Janney et al., 2005; Meyzen et al., 2005]. Several authors have proposed that delamination of lower crustal eclogite could deliver and disperse continental lithosphere into the upper convecting mantle [e.g., Elkins-Tanton, 2005; Jull and Kelemen, 2001], a process that may have been aided by the Mesozoic breakup of Gondwana.

### 6.4.2. Origin of the DUPAL Component in Southeast Indian Ridge MORB

[40] $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$, versus $^{208}\text{Pb}*/^{206}\text{Pb}*$ show that there is a coupled time-integrated relationship between Rb/Sr (also Sm/Nd) and Th/U in the mantle sources of the SEIR lavas from $77^\circ$ to $88^\circ$E (Figure 8). This covariation is observed in both MORB and OIB [e.g., Hofmann, 2004], and the trend of oceanic basalts to high $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{208}\text{Pb}*/^{206}\text{Pb}*$ tracks the inferred DUPAL-type component (Figure 8). This component has been attributed to diverse origins, including ancient recycled sediments [Rehkamper and Hofmann, 1997], delaminated lower continental crust [Escrig et al., 2004; Hanan et al., 2004; Meyzen et al., 2005], and continental mantle lithosphere [Mahoney et al., 1991, 1992; Janney et al., 2005].

[41] The nearly linear trend defined by J1 and J2 lavas (Figure 8) requires a nearly homogeneous DUPAL-type component. Although DUPAL-type material appears to be isotopically variable from place to place, the quasi-linear trends with different slopes for different suites of oceanic island lavas within the region of the DUPAL anomaly (e.g., Pitcairn/Gambier, Walvis Ridge, Heard Island, and the Kerguelen Archipelago in Figure 8) suggests that the DUPAL-type component is relatively homogeneous for a given lava suite. A commonality is that the isotopic trends require that Rb/Sr and Th/U have been correlated on a long-term basis. Modern abyssal sediments [e.g., Ben Othman et al., 1989] and samples of granulitic lower continental crust [e.g., Huang et al., 1995] do not define correlations of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{208}\text{Pb}*/^{206}\text{Pb}*$ (Figure 8). If recycled sediments or lower continental crust are responsible for the DUPAL-type component, then these materials must be modified to form a component with both high Rb/Sr and Th/U. It is possible that modern-day examples, such as sediments that have not been processed through a subduction zone, or lower continental crustal xenoliths, are not representative of DUPAL sources. A more plausible explanation is that DUPAL-type components result from the incompatible element enrichment associated with partial melt [e.g., Rogers et al., 1992]. Low-degree partial melts have relatively high Rb/Sr, and high Th/U if the residual assemblage contained garnet. We suggest that the linearity of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{208}\text{Pb}*/^{206}\text{Pb}*$ (Figure 8) and the inferred long-term correlation of Rb/Sr and Th/U are most readily explained by an ancient partial melting process; that is, we propose that the DUPAL-type component expressed on the ASP Plateau was created prior to or during the breakup of Gondwana, when continental mantle lithosphere was fertilized by the addition of small degree partial melts formed by melting of garnet peridotite.

### 6.4.3. Mantle Component C and the Southeast Indian Ridge

[42] The lavas with the highest $^{3}\text{He}/^{4}\text{He}$ ratios, from along segment H, have intermediate ratios of $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 9). This has been a common observation since the discovery of very high $^{3}\text{He}/^{4}\text{He}$ ($>30$ RA) in oceanic basalts [e.g., Kurz et al., 1982]. That is, the highest $^{3}\text{He}/^{4}\text{He}$ values
are associated neither with a primitive mantle source nor with Sr-Nd-Pb isotopic end-members such as HIMU, EM I or EM II. Ellam and Stuart [2004] used Tertiary lavas associated with the Iceland mantle plume to show that very high $^{3}$He/$^{4}$He compositions (up to 50 RA) are associated with low $^{87}$Sr/$^{86}$Sr, i.e., there is a negative trend for He/$^{4}$He versus $^{87}$Sr/$^{86}$Sr (the "proto-Iceland plume trend"). Ellam and Stuart [2004] explained positive trends, like those shown by segment H (Figure 9) and OIB suites such as the Galapagos and Loihi, as mixing trends involving DM and the OIB high $^{3}$He/$^{4}$He component.

[43] Is there a systematic spatial arrangement of these components within the Indian Ocean mantle? A common, but increasingly questioned inference is that high $^{3}$He/$^{4}$He represents a deep mantle source, such as lower mantle that has been isolated for at least the past 1–2 Ga [Class and Goldstein, 2005]. Saal et al. [2005] proposed an alternative view. They found that Pb isotopic ratios of melt inclusions in phenocrysts of Pacific island basalts are very diverse, but these ratios define arrays that can be explained as two-component mixing lines involving a C-like component, with high $^{206}$Pb/$^{204}$Pb (and by inference high $^{3}$He/$^{4}$He), and more extreme (in terms of Sr, Nd and Pb isotopic ratios) OIB-type end-members. The ubiquity of C as an isotopic end-member led Saal et al. [2005] to conclude that the C component is located within the oceanic lithosphere. We note, however, that C is prevalent in MORB, both globally [Hanan and Graham, 1996] and especially along the SEIR near the ASP Plateau. In near-axis locations, the oceanic lithosphere is newly formed from the convecting mantle; consequently we favor a sub-lithospheric origin for the C component. Our isotopic results for the SEIR and ASP Plateau lavas are most readily accounted for if the mantle component C resides in a deep-sourced mantle plume. An alternative explanation is that C is distributed throughout the mantle [Ito and Mahoney, 2005].

6.4.4. Refining Mantle Source Contributions to SEIR Lavas Using Principal Components Analysis (PCA)

[44] Binary isotopic plots (Figures 5–7) are useful in defining the isotopic heterogeneity of sources for SEIR basalts, but concurrent evaluation of Sr, Nd, He and three Pb isotopic ratios requires an approach to investigate six dimensions. Principal Components Analysis (PCA) is a standard tool in the evaluation of OIB and MORB multidimensional isotopic variability [e.g., Blichert-Toft et al., 2003; Agranier et al., 2005; Debaille et al., 2006]. The
The objective in using PCA is to evaluate the data set by describing the minimum number of components that are necessary to explain the total population variance, and this can reduce the dimensionality by combining variables. The presumption is that this dimensionality is equivalent to the number of geochemical end-members present. PCA may reveal this dimensionality more clearly in cases where mixing relations on isotope-isotope diagrams are ambiguous [Debaille et al., 2006]. Each principal component (PC) is derived from linear combination of an eigenvector of the correlation matrix with an original isotopic variable [e.g., Davis, 1986; Albare`de, 1995]. The first principal component captures the greatest possible variance, while each successive component captures a portion of the remaining variance, with the requirement that it is uncorrelated with any previously defined component (i.e., the components are mutually orthogonal). Thus the analysis has the same total variation and structure as the original data. Our analysis uses standardized eigenvectors so that the squares of these elements sum to 1 for each principal component.

[45] Our initial PCA uses Sr, Nd and Pb isotopic ratios for SEIR segments on and adjacent to the ASP Plateau (Figure 10). The results show that only two principal components are needed to account for 99.4% of the variance; PC1 (>69%) and PC2 (>30%) together account for >99.3% of the variance, indicating that 2 principal components (3 geochemical end-members) are sufficient to account for the Sr-Nd-Pb isotopic variability in our SEIR sample suite, consistent with deductions based on the isotope-isotope diagrams in Figures 5–7. Estimated locations for global mantle end-members DM, EM I, EM II, HIMU, and C are shown for comparison. Mixtures of the three geochemical end-members (DM, C, and EM I) create the volume represented by the grey shaded region in this projection when the end-members have equivalent Sr/Nd/Pb abundance ratios (i.e., linear mixing results).

Figure 10. Graphical representation of a principal components analysis for $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ variations measured in the SEIR study suite. The PCA results are given in Table 3. Data for Amsterdam and St. Paul Islands [Doucet et al., 2004] were not used in the PCA but are included for comparison. PC1 (>69%) and PC2 (>30%) together account for >99.3% of the variance, indicating that 2 principal components (3 geochemical end-members) are sufficient to account for the Sr-Nd-Pb isotopic variability in our SEIR sample suite, consistent with deductions based on the isotope-isotope diagrams in Figures 5–7. Estimated locations for global mantle end-members DM, EM I, EM II, HIMU, and C are shown for comparison. Mixtures of the three geochemical end-members (DM, C, and EM I) create the volume represented by the grey shaded region in this projection when the end-members have equivalent Sr/Nd/Pb abundance ratios (i.e., linear mixing results).
To test whether our inferences remain consistent, we extended our consideration of Sr, Nd, and Pb isotopes to He isotopes, we performed a second (He-Sr-Nd-Pb) principal components analysis. In this case we find that 66% of the variance is explained by the first principal component (similar to the value of 69% from the first PCA that excluded He) and 27.4% is accounted for by PC2 (Table 3). The sample topology of the PC1-PC2 projection (Figure 11) is broadly similar to the case without He isotopes (Figure 10). Although two principal components account for >93% of the variance in this case, about 6% of the variance initially appears to require a third principal component that is not observed using Sr-Nd-Pb isotopes alone. The implications of this observation are discussed below.

Debaille et al. [2006] proposed that the apparent need for a third principal component may be an artifact of mixing between geochemical end-members if they have very different elemental abundance ratios (e.g., He/x, where x = Sr, Nd, Pb). We further evaluated this possibility by calculating binary mixing curves between C and EM I (DUPAL-type component), assuming equal Sr/Nd/Pb elemental abundance ratios in the end-members, but different \(^{3}\text{He}/^{204}\text{Pb}\) ratios. Binary mixing curves are shown by the dashed lines in Figure 11. Our PCA results are consistent with the presence of only three geochemical end-members (i.e., 2 principal components) if the concentration ratio for \(^{3}\text{He}/^{204}\text{Pb}\) in the C end-member (assumed to have high \(^{3}\text{He}/^{4}\text{He}\) of 15 RA) is significantly greater than \(^{3}\text{He}/^{204}\text{Pb}\) in the EM I (DUPAL) end-member (assumed to have low \(^{3}\text{He}/^{4}\text{He}\) of 6 RA). The plot of PC3 versus PC2 (Figure 11c) is notable in this regard, because some lavas lie outside the plane of linear mixing shown by the grey field. The upward scatter in PC3-PC2 space (Figure 11c) includes St. Paul Island, St. Pierre Seamount and several J1/J2 segment lavas from the southern sector of the plateau, while the downward scatter includes the lava (WC44) from the active floor of Boomerang Seamount [Johnson et al., 2000], plus a few lavas from segment I2 along the northern sector of the plateau. If only DM, C and EM I (DUPAL) mantle components are truly involved, then this scatter indicates that the C and the DUPAL component may have very different concentration ratios involving helium. Another possibility is that shallow level degassing has modified magmatic He contents to different extents, prior to the mixing of magmas derived from these different mantle sources. The scatter of lavas above the plane in PC3-PC2 space (in Figure 11c, toward the example mixing curve for a \(^{3}\text{He}/^{204}\text{Pb}\) ratio that is a factor of 100 larger in C than in EM I) is broadly consistent with the physical interpretation of these geochemical end-members, wherein C represents plume-derived material having an elevated helium concentration compared to EM I which represents recycled continental lithosphere.

In summary, PCA suggests that only three geochemical end-members are required to explain the full variability of Pb, Nd, Sr and He isotopic data in the ASP region. Although our results are

### Table 3. Principal Components Analysis

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
</tr>
</thead>
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<tr>
<td><strong>Sr-Nd-Pb</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Eigenvalue</td>
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<td>0.0192</td>
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<td>Percent variance</td>
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<td>30.12</td>
<td>0.64</td>
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<tr>
<td>Cumulative percent variance</td>
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<td>99.36</td>
<td>100</td>
<td></td>
</tr>
<tr>
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<tr>
<td>(^{87}\text{Sr}/^{86}\text{Sr})</td>
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<td>-0.290</td>
<td>0.690</td>
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<td>(^{143}\text{Nd}/^{144}\text{Nd})</td>
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<td>0.136</td>
<td>0.716</td>
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<tr>
<td>(^{206}\text{Pb}/^{204}\text{Pb})</td>
<td>0.301</td>
<td>0.947</td>
<td>0.108</td>
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<tr>
<td><strong>He-Sr-Nd-Pb</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>1.090</td>
<td>0.247</td>
<td>0.0197</td>
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<tr>
<td>Percent variance</td>
<td>66.09</td>
<td>27.25</td>
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<td>0.49</td>
</tr>
<tr>
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<td>99.51</td>
<td>100</td>
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<td></td>
</tr>
<tr>
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Figure 11. Graphical representation of a principal components analysis for $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$, and $^3\text{He}/^4\text{He}$ variations measured in the SEIR study suite. Data for Amsterdam and St. Paul Islands [Doucet et al., 2004] were not used in the PCA but are included for comparison. A value of 15 RA was assumed for $^3\text{He}/^4\text{He}$ in each island sample, similar to the highest value measured at the islands (M. Moreira, personal communication, 2005). Estimated locations for global mantle end-members DM, EM I, EM II, HIMU, and C are shown for comparison. Mixtures of three geochemical end-members (DM, C having high $^3\text{He}/^4\text{He}$, and EM I having low $^3\text{He}/^4\text{He}$) create the volume represented by the gray shaded regions under the stringent condition that the He/Sr/Nd/Pb concentration ratios are the same in all of these end-members. This mixing field forms a triangle in Figures 11a and 11b, but it forms a band in Figure 11c because in this projection the DM, EM I, and C end-members are co-linear. For C and EM I, two additional cases are shown for each end-member, depicted with blue arrows: a high $^3\text{He}/^4\text{He}$ variant (15 RA) at the arrowheads and a low $^3\text{He}/^4\text{He}$ variant (6 RA) at the opposite end. This range was chosen because it is possible that these mantle end-members are isotopically heterogeneous in $^3\text{He}/^4\text{He}$, and because the complexity of mixing within the Earth has made it difficult to precisely characterize a single $^3\text{He}/^4\text{He}$ for these end-members. The PCA results are given in Table 3. PC1 (>66%) and PC2 (27%) together account for >93% of the variance. The addition of He isotopes to the PCA appears to indicate the need for a small additional principal component (PC3, 6%). This may suggest the presence of a fourth geochemical end-member (having intermediate Sr, Nd, and Pb isotope composition) that is most effectively detected by its elevated $^3\text{He}/^4\text{He}$. There are, however, complexities related to mixing of the geochemical end-members if they have different elemental abundance ratios (e.g., He/Sr and He/Pb). One example is depicted in each of these diagrams by the binary mixing curves (dashed lines) between mantle component C ($^3\text{He}/^4\text{He} = 15$ RA) and EM I ($^3\text{He}/^4\text{He} = 6$ RA). The dashed curves depict the mixing of these two geochemical end-members assuming they have identical Sr/Nd/Pb elemental abundance ratios but widely different He/Pb abundance ratios (i.e., $r = ^3\text{He}/^{204}\text{Pb}_C/(^3\text{He}/^{204}\text{Pb})_{\text{EMI}}$), as indicated by the $r$ values on the diagrams ($r = 100$ and 0.01, respectively). See the text for further discussion.
somewhat inconclusive for precisely characterizing the high $^3$He/$^4$He end-member, they do suggest that it is reasonably well represented by the Pb-Nd-Sr isotope composition of the mantle component C (Figure 11).

7. Conclusions

[59] The bathymetric high forming the ASP Plateau includes two islands, associated seamounts and four SEIR segments whose lavas range widely in Sr, Nd, Pb and He isotopic ratios; MORB from SEIR segments adjacent to the plateau are also isotopically heterogeneous. Several of these ridge segments, however, erupt MORB with distinctive isotopic signatures. Individual ridge segments atop the plateau and adjacent segments to the north and south show distinguishable isotopic and spatial correlations. The isotopic characteristics of SEIR basalt erupted on and adjacent to the ASP Plateau can be explained by the same three components required for MORB from the SWIR [Meyzen et al., 2005] and the SEIR distant from hot spots [Mahoney et al., 2002], i.e., end-members with the isotopic characteristics of C, high $^{208}$Pb*/$^{206}$Pb* DUPAL-type mantle, and Indian Ocean depleted mantle. Specifically, the variable isotopic ratios of lavas erupted on the ASP Plateau are consistent with mixing between the C end-member of Hanan and Graham [1996] and DUPAL-type material having relatively low $^{143}$Nd/$^{144}$Nd and $^{208}$Pb/$^{204}$Pb, and high $^{87}$Sr/$^{86}$Sr and $^{208}$Pb*/$^{206}$Pb*, that characterizes Indian Ocean basalt [e.g., Hart, 1984]. Surprisingly, the highest $^3$He/$^4$He ratios (up to 14.1 RA) and most radiogenic Pb isotope compositions ($^{206}$Pb/$^{204}$Pb = 19.4) occur in lavas from segment H, immediately north of the ASP Plateau and separated from it by the prominent Amsterdam Fracture Zone. Isotopic data for the six segment H lavas define mixing trends involving only two geochemical end-members, the mantle component C and the depleted mantle end-member sampled by SEIR MORB far from hot spots.

[51] Why are the highest $^3$He/$^4$He and $^{206}$Pb/$^{204}$Pb lavas, presumed to be hot spot–related, erupted at the periphery of the ASP plateau, while the strongest DUPAL-type signatures are spatially limited to the plateau? Alternatives include (1) a spatially zoned hot spot source; (2) a hot spot source composed of components with different solidus temperatures [Ito and Mahoney, 2005]; or (3) a high proportion of DUPAL-type material, present either as a continental fragment within the plateau or as delaminated continental lithosphere in the shallow convecting mantle beneath the plateau, that has been intersected by a C-rich mantle plume. The positive correlation between $^{87}$Sr/$^{86}$Sr and $^{208}$Pb*/$^{206}$Pb* defined by SEIR lavas on the ASP Plateau, and by DUPAL-type lavas in general, reflects long-term aging of a material with high Rb/Sr and Th/U. Such a correlation is expected for magma formed by low extents of melting; hence we suggest that DUPAL-type materials may have been formed by ancient addition of small degree melts to continental lithospheric mantle.

Acknowledgments

[52] We thank Dan Scheirer and Don Forsyth for their help and leadership with the geophysical data acquired during the Boomerang 06 expedition and Captain Eric Buck and crew of the R/V Melville for their dedication that made it such a successful cruise. We also thank the TAAF (Terres Australes et Antarctiques Francaises) for clearance to work in territorial waters around Amsterdam and St. Paul Islands. D.G. thanks John Lupton for access to the helium isotope lab at PMEL in Newport, Oregon, which is supported by the NOAA Vents Program. K.N. thanks Denys Vonderhaar and Khal Spencer for familiarizing her with lab protocol at the University of Hawaii. Manuel Moreira generously shared his unpublished helium isotopic data for St. Paul and Amsterdam Islands. Dominique Weis, Mark Kurz, two anonymous reviewers, and the editor Vincent Salters provided comments that significantly improved the manuscript. Figures 1 and 2 were produced using GeoMapApp (http://www.marine-geo.org/geomapapp), which is supported by NSF and internal funding from Lamont-Doherty Earth Observatory. This project was supported by NSF OCE94-17353 to K.J. and D.G.

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