JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. B6, PAGES 13,831–13,849, JUNE 10, 1996

Role of the Kerguelen Plume in generating the eastern Indian Ocean seafloor

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Abstract. Mid-ocean ridge basalts (MORB) in the Indian Ocean have Sr-Nd-Pb isotopic characteristics that distinguish them from seafloor basalts in the Atlantic and Pacific Oceans. These differences have important implications for mantle dynamics. We discuss the isotopic variation with eruption age of seafloor basalts recovered by deep sea drilling at 10 sites in the eastern Indian Ocean ranging in age from Eocene to Late Jurassic. Except for alkalic basalts recovered from near Christmas Island in the northeast Indian Ocean, the basement lavas are tholeiitic basalts that are characterized by a wide range in incompatible element abundance ratios, such as La/Yb and Zr/Nb. Most of the tholeiitic basalts from seven sites are geochemically similar to recent Indian Ocean MORB, but the alkalic basalts and tholeiitic lavas from two other sites have isotopic and incompatible element abundance ratios similar to lavas associated with the Kerguelen Plume. Two of these three sites, however, are not close to the track of this plume. The Dupal isotopic signature (relatively high $^{87}Sr/^{86}Sr$ and high $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$) is characteristic of lavas that have been attributed to the Kerguelen Plume, i.e., the Kerguelen Archipelago, Ninetyeast Ridge, and Kerguelen Plateau. Among eastern Indian Ocean seafloor basalts, a Dupal component is apparent in basement lavas from six of the seven drill sites in the eastern Indian Ocean that range in inferred age from ~57 to 125 Ma. The oldest (~155 Ma) seafloor lavas recovered from the Indian Ocean, derived from a spreading center in the Argo Abyssal Plain near northwest Australia, have high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$ similar to the most depleted recent Indian MORB. Because the oldest volcanism on the Kerguelen Plateau (~118 Ma) is the first evidence of the activity of the Kerguelen Plume, this plume is inferred to be the source of Dupal isotopic characteristics in Indian Ocean MORBs. Some recent Indian Ocean MORB are also distinctive because many have relatively low $^{206}Pb/^{204}Pb$ (<17.4). Some of the oldest (110 to 155 Ma) seafloor lavas in the eastern Indian Ocean also have relatively low $^{206}Pb/^{204}Pb$ ratios. This low $^{206}Pb/^{204}Pb$ signature predates volcanism associated with the Kerguelen Plume and may reflect a significant role for continental lithosphere as a long-term source component for Indian Ocean MORB.

Introduction

Basalts erupted from active spreading ridge axes in the Indian Ocean define fields in Sr-Pb, Nd-Pb, and Pb-Pb isotopic space that are distinct from the fields of mid-ocean ridge basalts (MORB) erupted in the Atlantic and Pacific Oceans [e.g., *Subbarao and Hedge*, 1973; *Dupré and Allègre*, 1983; *Hamelin et al.*, 1985/1986; *Michard et al.*, 1986; *Price et al.*, 1986; *Ito et al.*, 1987; *Dosso et al.*, 1988; *Mahoney et al.*, 1992]. These differences require that the basaltic Indian Ocean crust is derived from mantle sources that are unlike the sources of Atlantic and Pacific MORB. *Hart* [1988] proposed that oceanic island basalts (OIB) in the Indian Ocean are an important part of a large distinctive mantle isotopic domain (Dupal anomaly) that is centered at ~30°S and is defined by $^{87}Sr/^{86}Sr$ >0.705 and relatively high $^{208}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$. The distinctive isotopic characteristics of Indian Ocean MORB have been attributed to the influence of Dupal components from the Kerguelen Plume [*Hamelin et al.*, 1985/1986; *Dosso et al.*, 1988; *Storey et al.*, 1989], perhaps with contributions from the Crozet and Marion plumes [*Mahoney et al.*, 1992]. An alternative explanation for the distinctive isotopic characteristics of Indian Ocean MORB, which is not mutually exclusive [*Weis*, 1992], is that ancient Gondwanaland continental lithosphere was dispersed and incorporated into the Indian Ocean MORB source during the breakup of Gondwanaland [*Mahoney et al.*, 1989, 1992].

The geochemical characteristics of Indian Ocean seafloor as a function of eruption age are important in evaluating alternative interpretations for the distinctive geochemical features of recent Indian Ocean MORB. The Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) recovered basalts of variable age, up to 155 Ma, from several sites within the eastern Indian Ocean. We studied these basalts in order to assess the relative roles of components derived from depleted mantle, mantle

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Paper number 96JB00410.
0148-0227/96/96JB-00410$09.00

plumes, and continental lithosphere in the sources of basalt at each DSDP site and to determine how the proportions of these components changed with eruption age. In this paper we focus on 10 sites that are not on the Ninetyeast Ridge; *Frey and Weis* [1995] focus on the Ninetyeast Ridge.

Research Approach

Excluding the Ninetyeast Ridge, the eastern Indian Ocean was sampled at nine DSDP sites and one ODP site (Figure 1). Petrographic and geochemical characteristics of basalts from these DSDP sites were reported in the initial reports for DSDP Legs 22, 26, and 27 [*von der Borch et al.*, 1974; *Davies et al.*, 1974; *Veevers et al.*, 1974], and a summary was given by *Frey et al.* [1977]. However, these previous studies did not include isotopic data for Sr, Nd, and Pb or precise abundance data for the incompatible trace elements, Rb, Ba, Nb, Sr, Zr, Hf, and Y. This paper focuses on the isotopic ratios and abundance ratios of highly incompatible elements of eastern Indian Ocean seafloor basalts because these ratios are sensitive measures of geochemical heterogeneity in the oceanic mantle; e.g., they distinguish MORB from OIB [e.g., *Weaver*, 1991; *Hart et al.*, 1992]. Old ocean floor rocks have been affected by postmagmatic alteration; thus abundance data for Y, Zr, Nb, and rare earth elements (REE) are important because these elements are relatively immobile during postmagmatic alteration on the seafloor [*Bienvenu et al.*, 1990]. In our discussion, we use "depleted" to refer to basalts that have Rb/Sr, Nb/Zr, La/Yb, Ce/Y and Nd/Sm ratios less than the estimated bulk earth ratios [e.g., *Sun and McDonough*, 1989]; that is, these basalts (and their mantle sources) are relatively depleted in the highly incompatible elements, Rb, Nb, La, Ce, and Nd. With time these depleted sources develop $^{143}Nd/^{144}Nd$ greater than the bulk earth estimate and $^{87}Sr/^{86}Sr$ less than the bulk earth estimate. Conversely, relative to bulk earth, enriched basalts have higher Rb/Sr, Nb/Zr, La/Yb, Ce/Y, Nd/Sm, and $^{87}Sr/^{86}Sr$ but lower $^{143}Nd/^{144}Nd$.

Analytical Techniques

A subset of previously analyzed samples was selected to encompass the major element compositional range of these ocean floor lavas [*Frey et al.*, 1977]. Trace element abundances were determined by X ray fluorescence and instrumental neutron activation analysis (Table 1). Analytical procedures, and evaluation of data accuracy and precision are given by *Frey et al.* [1991]. Trace element analyses were done on unleached powders, but for isotopic analysis, the samples were leached in acid to remove secondary alteration phases. We used a leaching

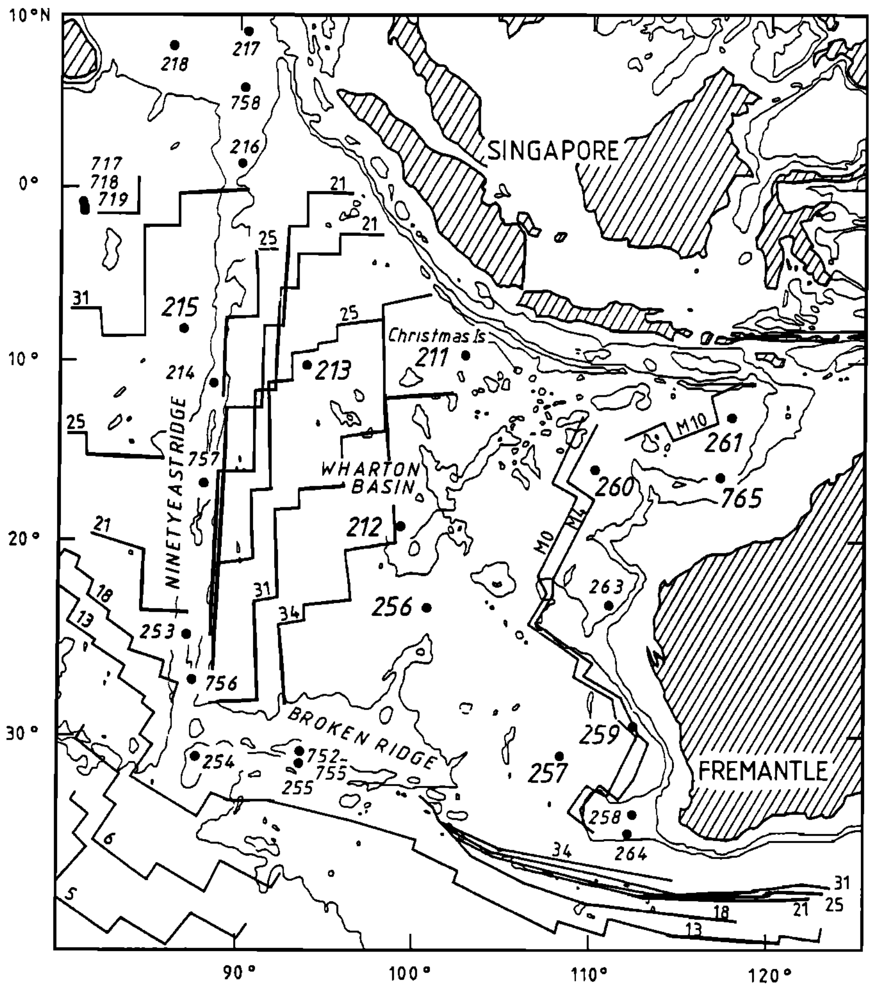

Figure 1. Location map for the eastern Indian Ocean showing selected magnetic anomalies, and major bathymetric features such as the Ninetyeast and Broken Ridges. DSDP and ODP drill sites are indicated as solid circles. The 10 seafloor sites discussed in this paper are shown by larger numbers.

procedure comparable to *Mahoney's* [1987], i.e., "cold" acid leaching (HCl 6 N), with elimination of the fines by removing the acid immediately after 30 min in an ultrasonic bath (the time period of 30 min is critical as it allows for a slight increase in temperature, which is necessary to strengthen the leaching effect). This leaching procedure was repeated until a colorless solution was obtained [*Weis and Frey*, 1991], up to 10 steps for the most altered samples. After acid leaching, the remaining powder was rinsed with quartz-distilled water at least three times. The powder was dried on a hot plate until a constant weight was achieved. The difference between this final weight and the starting weight is the weight percent loss caused by acid leaching; typically, this was between 50 and 60%. The large weight loss reflects dissolution of minerals formed during low-temperature alteration.

The samples were processed following standard chemical separation procedures (i.e., HF-$HClO_4$ dissolution and anion exchange column separation of the different isotopes following the method described by *Weis et al.* [1987]). The blanks for the columns were below 3 ng Sr, and the total blanks for the whole procedure were below 6 ng for Sr and below 2 ng for Nd. These blanks are negligible relative to the concentrations in the samples. For Pb isotopes, the samples were processed in a clean, over pressurized (>3 mm Hg) laboratory, using reagents purified in a subboiling still. Pb was separated on anion exchange columns in a HBr-HCl medium, following a method derived from *Manhès et al.* [1978]. Pb and U concentrations were measured on the same sample solution (aliquots were split before loading on columns and spiked with a ^{235}U-^{206}Pb mixed spike). U was separated in a HNO_3 medium. Total blank values for Pb for the whole chemical procedure were typically below 1 ng.

Sr isotopic compositions were measured on single Ta filaments in the dynamic mode on a VG Sector 54 mass spectrometer. The internal precision for measured $^{87}Sr/^{86}Sr$ is better than 1 x 10^{-5}. The measured values are normalized to $^{86}Sr/^{88}Sr = 0.1194$. For each barrel of 20 filaments, four analyses of NBS 987 Sr standard were made. The average of $^{87}Sr/^{86}Sr$ over the time period the DSDP analyses were made is 0.710232 ± 8 ($2\sigma_m$ for 18). An evaluation of between-run precision is also given by the replicate analyses reported in Table 2. Nd isotopic compositions were measured on triple Ta-Re filaments with the VG Sector 54 multicollector mass spectrometer (analyses of the Merck Nd standard yielded $^{143}Nd/^{144}Nd = 0.51173 \pm 1$ and $^{145}Nd/^{144}Nd = 0.348417 \pm 5$ ($2\sigma_m$ for 12)). Nd was run as a metal, and for each run the 146, 145, 144, and 143 isotopes were measured with all values normalized to $^{146}Nd/^{144}Nd = 0.7219$.

Pb isotopic compositions and Pb and U concentrations by the isotope dilution (ID) technique were measured on single Re filaments with a Finnigan MAT 260 mass spectrometer, using the H_3PO_4-silica gel technique [e.g., *Cameron et al.*, 1969]. All the results were corrected for mass fractionation (0.13% ± 0.04% per amu) on the basis of 72 analyses of the NBS 981 Pb standard [*Catanzaro et al.*, 1968] for a temperature range of 1090° to 1200°C. Between-run precisions are better than ≈0.1% for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and better than ≈0.15% for $^{208}Pb/^{204}Pb$. The Pb and U concentrations have better than 2% precision.

The evolution of isotopic ratios with time must be considered when comparing present-day radiogenic isotopic ratios in lavas of different ages. *Mahoney and Spencer* [1991] discussed this problem in regard to lavas from the Ontong Java plateau. They noted that the Rb/Sr, Sm/Nd, U/Pb, and Th/Pb in tholeiitic basalts are relatively low so that over 100 Myr there is relatively little change in $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$. For example, in 120 Myr a $^{238}U/^{204}Pb = 20$ (a relatively high value for unaltered oceanic basalts [*White*, 1993]) creates a change in $^{206}Pb/^{204}Pb$ of only 0.38. In addition, tholeiitic basalts are commonly interpreted to result from relatively high extents of melting. Assuming parent/daughter abundance ratios are not strongly affected by the partial melting process, the isotopic ratios in the sources and tholeiitic lavas evolve similarly with time. Therefore *Mahoney and Spencer* [1991] concluded that over 100 Myr, age corrections are relatively small, especially when compared to isotopic differences among OIB, MORB, and oceanic plateau basalts.

However, postmagmatic alteration processes increase the complexity of inferring magmatic isotope ratios of old altered seafloor lavas, because postmagmatic alteration may affect isotopic ratios and parent/daughter abundance ratios. Typically, the isotopic ratios of Nd and Pb in oceanic basalts are not significantly changed during postmagmatic alteration, but formation of secondary phases with relatively high $^{87}Sr/^{86}Sr$ is common [e.g., *Mahoney*, 1987; *Weis and Frey*, 1991; *Mahoney and Spencer*, 1991; *Staudigel et al.*, 1995]. As discussed earlier, in an effort to remove such secondary phases, the sample powders were repeatedly acid-leached before determination of $^{87}Sr/^{86}Sr$. Although most of the samples define an inverse $^{143}Nd/^{144}Nd$-$^{87}Sr/^{86}Sr$ trend similar to that of unaltered oceanic basalts (Figure 2), we cannot be certain that these procedures completely remove all effects of postmagmatic alteration.

In contrast to unaltered tholeiitic basalts, corrections for radiogenic growth after eruption may be relatively large in highly altered lavas. This is especially true for Sr and Pb isotopic ratios, because Rb/Sr and U/Pb ratios may be significantly changed during alteration [e.g., *Staudigel et al.*, 1995]. If alteration occurred soon after eruption, then over 100 Myr, the measured Sr and Pb isotopic ratios may differ considerably from those of the unaltered lavas at the time of eruption. In contrast, neither Sm/Nd nor $^{143}Nd/^{144}Nd$ in ocean floor basalts are usually significantly changed by postmagmatic alteration. In addition, the long half-life of ^{147}Sm and low Sm/Nd lead to a relatively small age correction.

For each DSDP site studied, Figure 2a shows fields for the present-day $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values measured on the acid-leached residues. It also shows the age-corrected values calculated with the unleached whole rock Rb/Sr and Sm/Nd and ages inferred from magnetic anomalies or the age of the sediments overlying basaltic basement (Table 2). These corrections are likely to be too large for the Sr isotopic ratios because the Rb/Sr of the whole rock is probably larger than that of the acid-leached residue and the alteration processes did not occur instantaneously upon eruption. Moreover, there is an inherent uncertainty in calculating initial isotopic ratios because the age of the basalts is not precisely known. However, it is significant that except for one sample from Site 212 (high $^{87}Sr/^{86}Sr$), age-corrected data points for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ in acid-leached residues define a general inverse trend that largely overlaps the trend for recent MORB and OIB from the Indian Ocean (Figure 2b).

Figure 3a shows the effects of age correction on $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ based on the inferred minimum age of the basalt and the $^{238}U/^{204}Pb$ measured on the acid-leached residues (Table 2). Accurate ^{232}Th abundance data are not available (below INAA detection limit in MORB); thus no correction was made to $^{208}Pb/^{204}Pb$ ratios. The $^{238}U/^{204}Pb$ ratios of Indian Ocean MORB are typically 5 to 10 [*White*, 1993], but in the acid-

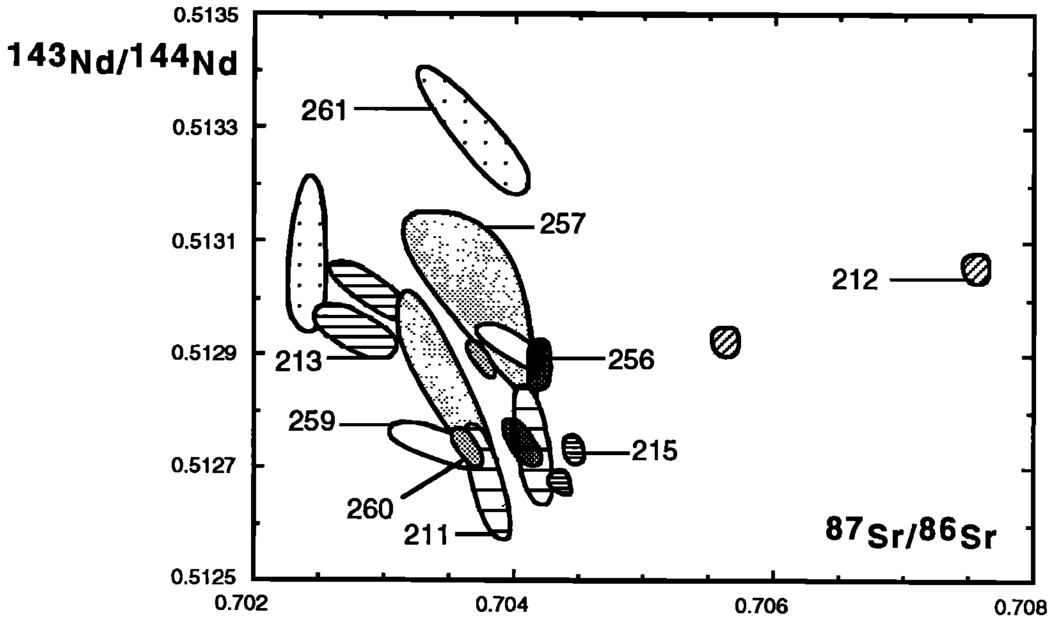

Figure 2a. The ratio of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ plot for basalts from the eastern Indian Ocean seafloor. For each site, the two fields indicate the effects of age corrections on $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ using measured Rb/Sr and Sm/Nd on unleached samples. Fields to the right are for acid-leached residues and fields to the left show age-corrected values. Ages (Table 2) were inferred from the age of the sediments overlying basaltic basement or nearby magnetic anomalies.

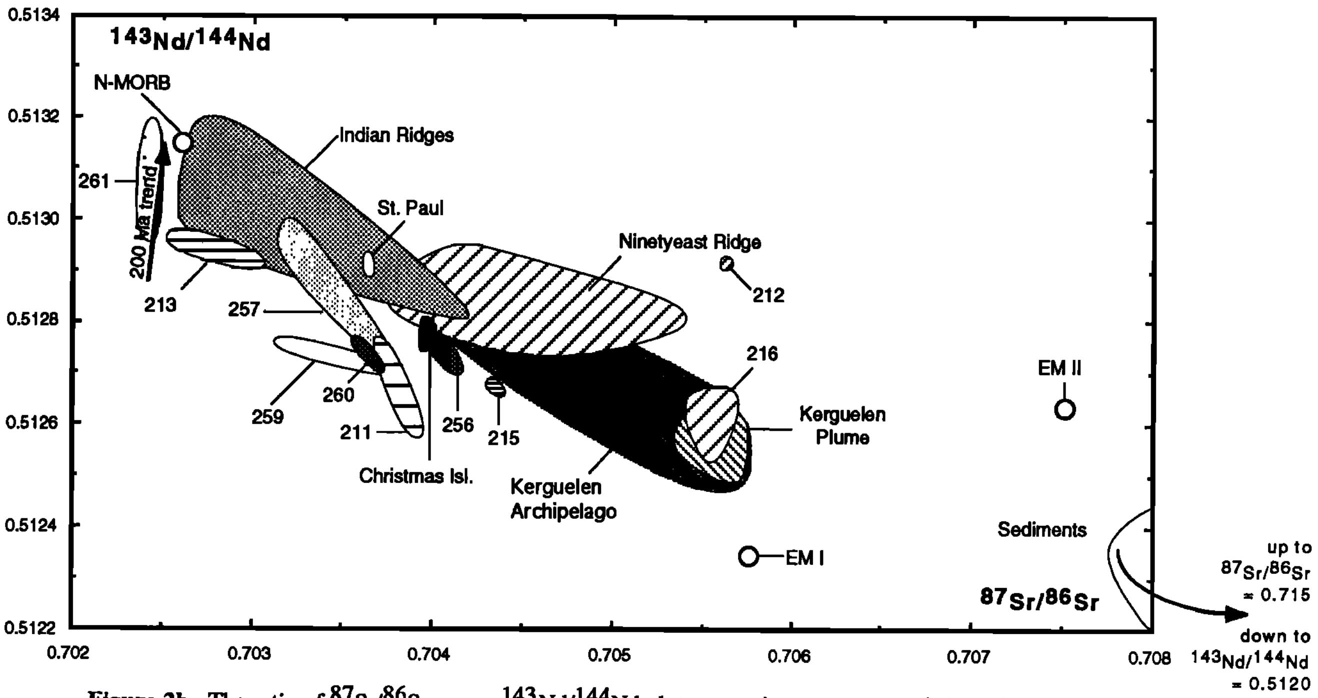

Figure 2b. The ratio of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ plot comparing age-corrected fields for old eastern Indian Ocean crust (this paper) to lavas from Ninetyeast Ridge drill sites with data for Site 216 shown as a distinct field [*Mahoney et al.*, 1983; *Hart*, 1988; *Saunders et al.*, 1991; *Weis and Frey*, 1991; *Frey and Weis*, 1995], fields for recent Indian Ocean MORB (see references in works by *Weis et al.* [1992] and *Le Roex et al.* [1983], *Hamelin et al.* [1985/86], *Michard et al.* [1986], *Price et al.* [1986], *Dosso et al.* [1988], and *Mahoney et al.* [1992]), the mantle components normal MORB (NMORB), enriched mantle 1 (EM1), and EM2 [*Zindler and Hart*, 1986] and fields for the Kerguelen Archipelago [*Gautier et al.*, 1990; *Weis et al.*, 1993a, b], Christmas [*Hart*, 1988; *Falloon et al.*, 1989], and St. Paul Islands [*Dosso et al.*, 1988]. The Kerguelen Plume composition is as defined by *Weis et al.* [1993a]. The Banda Sea sediment field is from *Vroon et al.* [1993]. Compared to the present-day fields for Indian Ridges and Kerguelen Archipelago, the fields of most DSDP sites (e.g., Site 259) are offset to lower $^{143}Nd/^{144}Nd$ at a given $^{87}Sr/^{86}Sr$. This offset reflects aging of the mantle source; e.g., the arrow labeled "200 Ma trend" shows aging of a MORB-like source for 200 Ma (parent/daughter ratios for this source are averages for depleted MORB, Rb/Sr = 0.011 and Sm/Nd = 0.336 [*Hofmann*, 1988]; because of changes caused by melting these are maximum and minimum ratios, respectively.

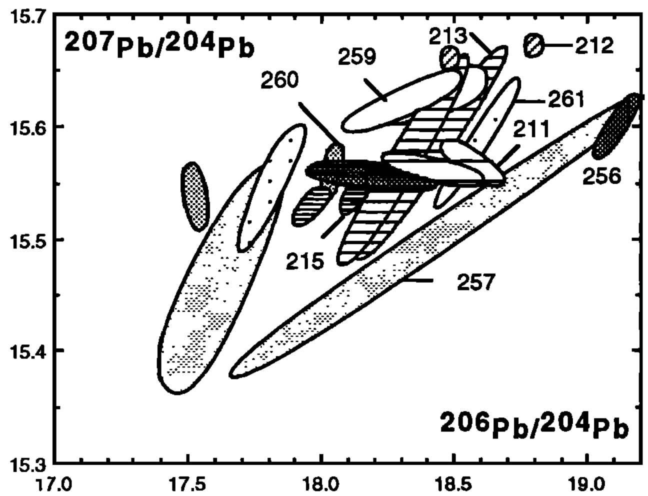

Figure 3a. The ratio $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot for old eastern Indian Ocean basalts showing the effects of age corrections for in situ U decay (measured fields on right and age-corrected fields on left; U/Pb measured on acid-leached residues). The age-corrections are especially large for Site 257 lavas, and the spread in $^{206}Pb/^{204}Pb$ is diminished by the age correction. Ages used for each site are given in Table 2. The true magmatic ratios are intermediate between the measured and age-corrected ratios (see discussion in text).

leached residues of these DSDP samples, $^{238}U/^{204}Pb$ ranges from 4.8 to 163 and only 9 of 18 samples have $^{238}U/^{204}Pb$ below 30. Consequently, in Figure 3a the $^{206}Pb/^{204}Pb$ age corrections for some samples are significant. As with the age-corrected $^{87}Sr/^{86}Sr$, we infer that the true magmatic $^{206}Pb/^{204}Pb$ ratios at the time of formation are intermediate between the measured and age-corrected ratios. An important result is that the age-corrected $^{206}Pb/^{204}Pb$ ratios for these DSDP basalts are within the range defined by young MORB and OIB from the Indian Ocean (Figures 3c and 3d). Because of the low abundance of ^{235}U the age corrections for $^{207}Pb/^{204}Pb$ are less significant (Figure 3a).

Results: General

Although these basalts have been affected by postmagmatic alteration, major element analyses of the least altered lavas, and in some cases fresh glasses, show that the basalts are tholeiitic at eight of the nine DSDP sites studied [*Frey et al.*, 1977]. Alkalic basalts containing titanaugite, amphibole, and small amounts of biotite and high abundances of relatively immobile incompatible elements (Figure 4) were recovered only at Site 211 [*Frey et al.*, 1977]. Abundances of Zr and Ce are positively correlated with Nb abundance and reflect magmatic characteristics (Figure 4). Abundances of Rb and Ba are not as well correlated with Nb abundance which probably reflects the effects of postmagmatic alteration; the scatter shows the difficulty in making a reliable age correction on the basis of measured Rb/Sr. The Sr, Nd, and Pb isotopic ratios in these DSDP basalts range widely, but they generally overlap with the range defined by Indian Ocean MORB, lavas from the Ninetyeast Ridge, and lavas from the Kerguelen Archipelago (Figures 2b, 3c and 3d). In the following section, we discuss each site proceeding from west to east across the eastern Indian Ocean.

Results: Specific

Site 215 (8°7.30'S, 84°47.50'E)

This site was drilled 240 km west of the Ninetyeast Ridge and is off the ridge at >5000 m water depth (Figure 1). Approximately 25 m of tholeiitic basalt, composed of at least 14 pillowed flows, were penetrated beneath ~59-60 Ma sediments [*Hekinian*, 1974]. Unaltered glass is abundant in this core, and the high K_2O (~1%) and P_2O_5 (~0.25%) contents of these glasses indicate that these basalts are enriched in incompatible elements relative to depleted MORB [*Melson et al.*, 1975; *Frey et al.*, 1977]. These glasses (15 samples) are similar in composition, and our study of four additional whole rocks from different core sections confirms the geochemical homogeneity of lavas at this site (Table 1).

Site 215 basalts are more enriched in incompatible elements (i.e., higher Ce/Y and La/Yb and lower Zr/Nb) than basaltic lavas recovered from the Ninetyeast Ridge (Figure 5), a linear volcanic ridge (Figure 1) that is interpreted to be the trace of the Kerguelen Plume on the Indian Plate [e.g., *Weis et al.*, 1992]. Relative to the transitional basalts of the Kerguelen Archipelago [*Gautier et al.*, 1990], the Site 215 basalts have similar Ce/Y but tend to lower La/Yb and Zr/Nb (Figure 5). In addition, Site 215 basalts have $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ similar to these transitional Kerguelen basalts (Figures 2b, 3c and 3d). Although the calculated initial $^{206}Pb/^{204}Pb$ (17.94-17.99) are lower than in lavas from the Kerguelen Archipelago, the relatively low measured $^{206}Pb/^{204}Pb$ (18.10-18.15) overlap with those of the upper Miocene alkaline lavas of the southeast Kerguelen Archipelago, which have been interpreted by *Weis et al.* [1993a] to be representative of the Kerguelen Plume (Figures 3c and 3d). Therefore basalts from Site 215 have the high Δ7/4 (8-9) and Δ8/4 (81-85) that define the Dupal isotopic anomaly and characterize the Kerguelen Plume [e.g., *Gautier et al.*, 1990; *Weis et al.*, 1989a, b], where $\Delta 7/4 = [(^{207}Pb/^{204}Pb)_{sample} - (^{207}Pb/^{204}Pb)_{NHRL}] \times 100$, with the NHRL equation being $^{207}Pb/^{204}Pb = 0.1084\,(^{206}Pb/^{204}Pb) + 13.491$) and $\Delta 8/4 = [(^{208}Pb/^{204}Pb)_{sample} - (^{208}Pb/^{204}Pb)_{NHRL}] \times 100$, with the

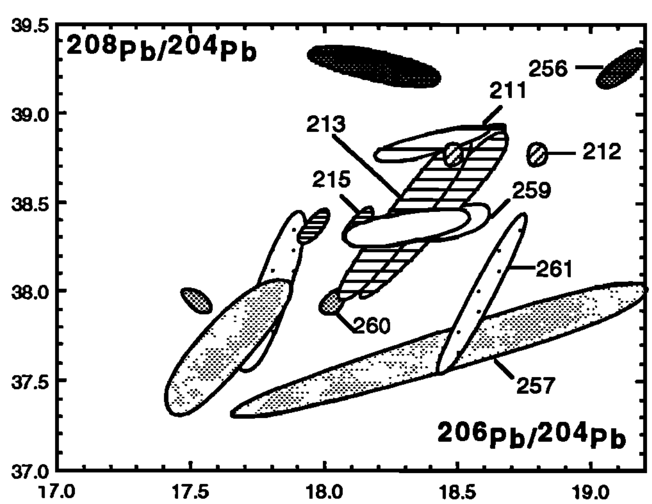

Figure 3b. The ratio $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot showing effects of age corrections on $^{206}Pb/^{204}Pb$. (See Figure 3a caption.). No corrections are indicated for $^{208}Pb/^{204}Pb$ as no accurate ^{232}Th abundance data are available.

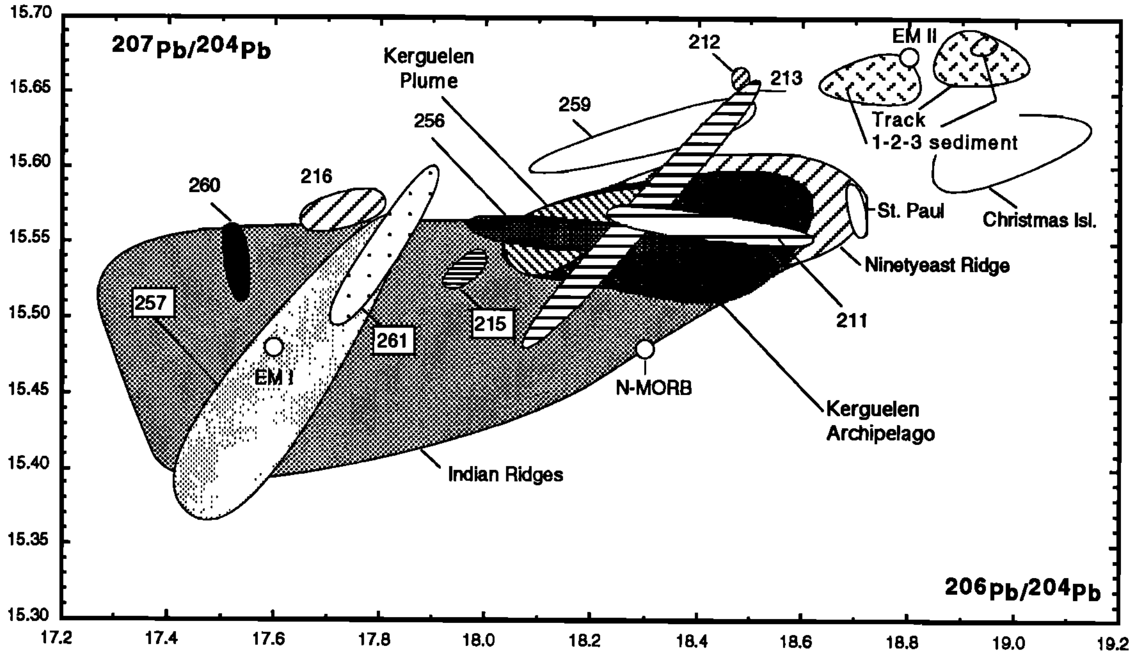

Figure 3c. The ratio $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot comparing age-corrected fields for old Indian Ocean crust basalts (Figure 3a) to fields for the Ninetyeast Ridge (data for Site 216 are shown as a separate field), recent Indian Ocean MORB, mantle components, and the Kerguelen, Christmas and St. Paul Islands. Data sources are as given for Figure 2b. One sample of Site 260 (20-1, 16-18 cm) has a $^{206}Pb/^{204}Pb > 20$ and has not been plotted. Track 1-2-3 sediment fields are data for sediments collected from three transects in the Banda Sea [*Vroon et al.*, 1993].

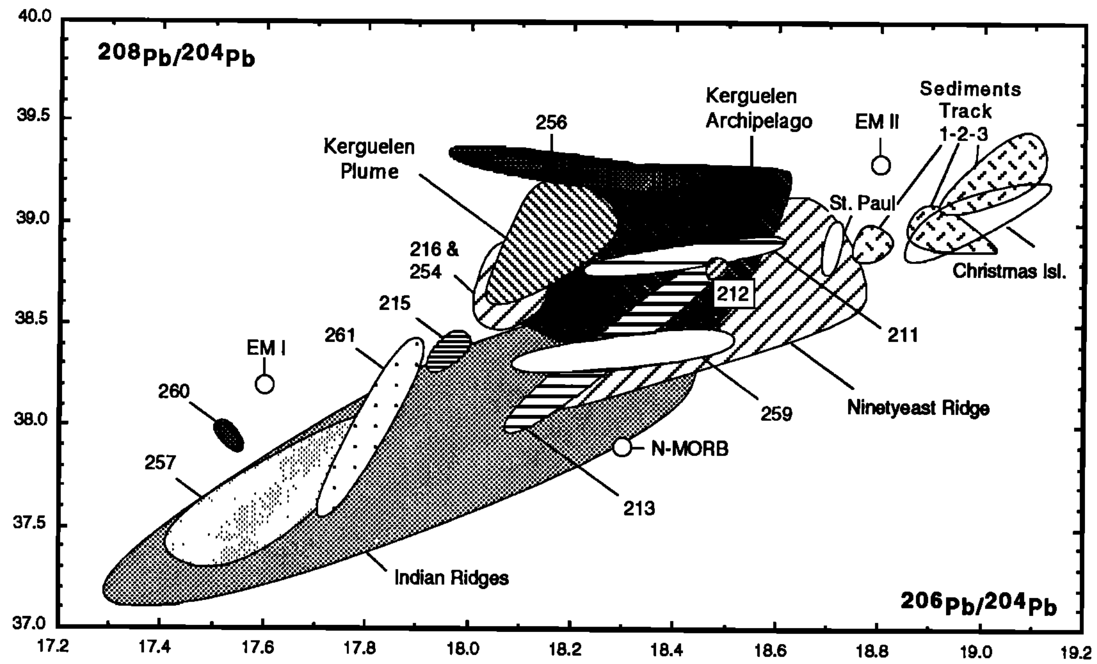

Figure 3d. The ratio $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot (only $^{206}Pb/^{204}Pb$ data have been age corrected, see Figure 3b). Fields are as in Figure 3c, except that data for the two Ninetyeast Ridge sites (216 and 254) with relatively low $^{206}Pb/^{204}Pb$ are indicated.

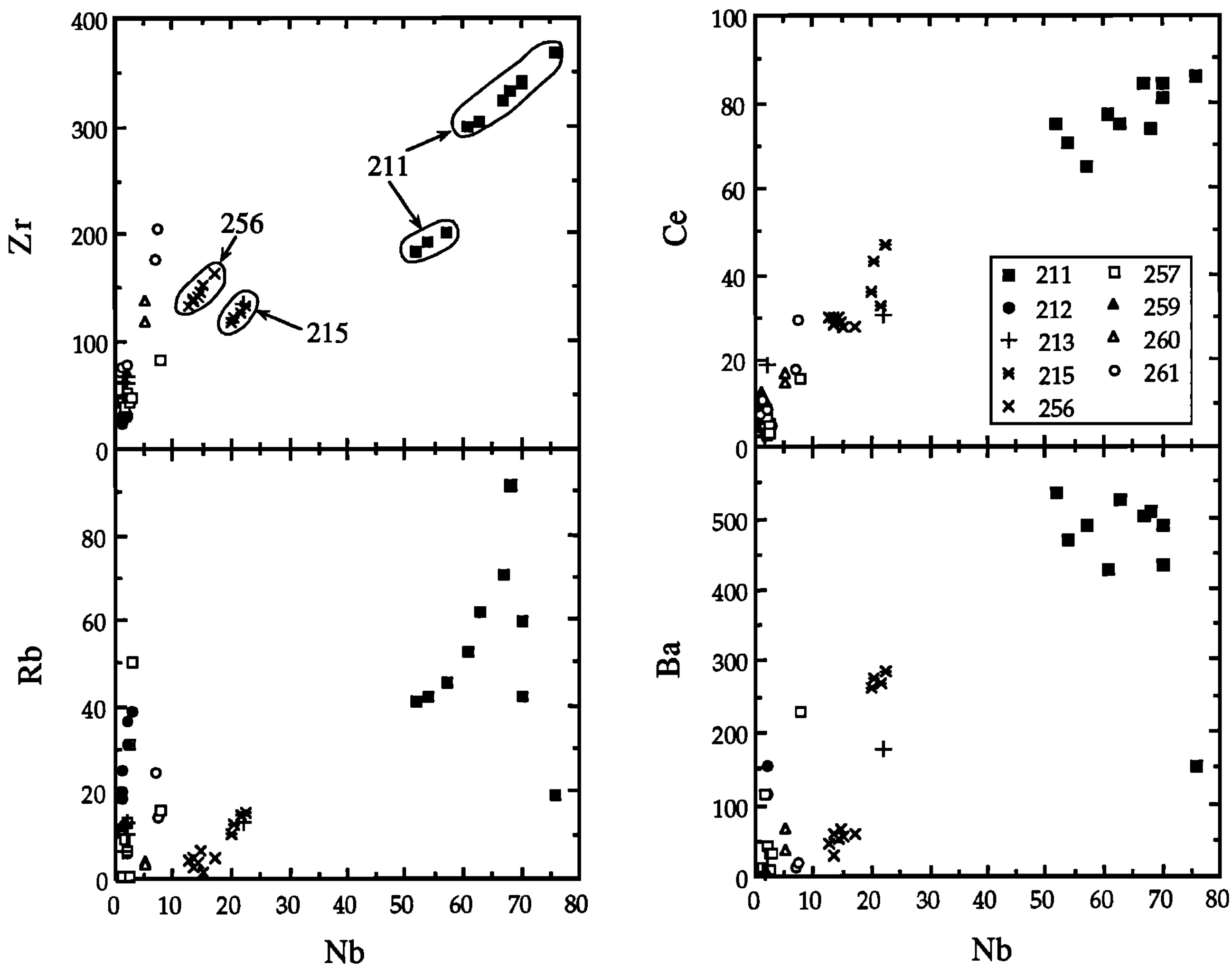

Figure 4. Abundance of various incompatible elements (in ppm) versus Nb content (in ppm) in basalts from the eastern Indian Ocean seafloor. The highest abundances are in the alkalic basalts from Site 211. Except for Rb and Ba, which have been affected by postmagmatic alteration, the abundances of incompatible elements are positively correlated.

NHRL equation being $^{208}Pb/^{204}Pb = 1.209\ (^{206}Pb/^{204}Pb) + 15.627$ [*Hart*, 1984].

Site 213 (10°12.71'S, 93°53.77'E)

This site is in the western Wharton Basin 500 km east of the Ninetyeast Ridge and separated from the Ninetyeast Ridge by the Ninetyeast Fracture Zone. It is near the east-west trending Chron 25; if these basalts formed at a spreading ridge axis, they erupted at the east-west striking spreading center that became extinct in the middle Eocene (Figure 1). Eighteen meters of pillow basalt were recovered beneath 56-58 Ma sediments. In contrast to Site 215, glasses from this site have low K_2O (0.06%) and P_2O_5 (0.09%) contents [*Melson et al.*, 1975]. *Frey et al.* [1977] concluded that Site 213 basalts are depleted MORB. Our study of five samples confirms that most of the basalts in this core are depleted MORB in composition (Figures 4 and 5) and in Sr and Nd isotopic ratios (Figure 2b). However, the lowermost basalt studied from this core is geochemically distinct. It is relatively enriched in the incompatible elements Ba, Nb, Sr, Zr, and light REE (Table 1 and Figure 4) and has higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than the sample with lower incompatible element abundances. However, its Sr and Nd isotopic ratios are within the Indian Ocean MORB field (Table 2 and Figure 2b). Compared to Indian Ocean MORB, this sample has anomalously high Pb isotopic ratios, e.g., $^{207}Pb/^{204}Pb = 15.65$, which is also higher than those of lavas from the Kerguelen Archipelago (Table 2 and Figures 3c and 3d).

Site 212 (19°11.34'S, 99°17.84'E)

This site was drilled in the deepest part of the Wharton Basin (6233 m) at the southern end of a long linear topographic high, the Investigator Ridge, and near the east-west trending Chron 34 (Figure 1). The sediment overlying the basalt lacks fossils, and the age of the basement is poorly constrained to be ~100 Ma [*Sclater et al.*, 1974]; *Powell et al.* [1988] used magnetic anomalies to infer a basement age of 90 Ma. Five meters of pillow basalt were penetrated. These basalts are very altered, typically 5-10% weight loss on ignition [*Hekinian*, 1974]. Analysis of a single glass chip and whole rocks shows that these basalts have very low TiO_2 and Zr abundances [*Melson et al.*, 1975; *Frey et al.*, 1977]. Our data for six basalts show that they have very high Cr abundances (~800 ppm, Table 1) which is consistent with the high MgO (9.0%) and CaO (13.5%) of the glass. The whole rocks also have low abundances of

Table 1. Abundances of Trace Elements in DSDP Basalts From the Eastern Indian Ocean

	Site 215			
	18-2 47-53	18-2 106-110	18-3 110-112	19-2 145-150
Rb	15.5	14.5	10.6	12.7
Sr	284	284	282	294
Ba	285	269	262	274
V	213	187	174	192
Cr	258	237	299	215
Ni	105	101	100	92
Zn	72	64	58	64
Ga	17.2	18.4	17.6	17.7
Y	27.4	26.6	27.0	27.3
Zr	134	127	118	122
Nb	22.5	21.6	20.2	20.6
Hf		2.82	3.1	-
La		14.5	16.2	
Ce	47	32.6	36	43
Nd		16.8	20.1	
Sm		4.17	4.5	
Eu		1.41	1.5	
Tb		0.75	0.8	
Yb		2.56	2.5	
Lu		0.37	0.51	

	Site 213				
	17-2 108-110	17-3 90-99	18-2 115-117	19-2 54-56	19-2 127-130
Rb	12.3	10.5	6.5	13.3	13.3
Sr	127	136	121	122	260
Ba	7	15		14	176
V	230	256	236	248	219
Cr	327	319	330	354	225
Ni	90	104	82	101	71
Zn	106	84	151	132	146
Ga	15.8	17.0	16.2	16.5	18.6
Y	22.5	26.7	23.6	26.7	29.0
Zr	61	62	64	68	135
Nb	1.6	2.0	1.1	2.1	22
Hf					3.2
La			2.2		18.8
Ce	3	19	7.6	6.3	30.8
Nd			6.2		16.4
Sm			2.18		4.23
Eu			0.85		1.65
Tb			0.64		0.74
Yb			2.55		2.75
Lu			0.41		0.39

incompatible elements such as Y, Zr, Nb, and REE; the erratic and high contents of Rb and Ba reflect the high extent of alteration (Table 1 and Figure 4). However, these low abundances are not accompanied by MORB-like Zr/Nb, Ce/Y, and La/Yb, which are more similar to the ratios in lavas from the Ninetyeast Ridge (Figure 5).

One sample from Site 212 was analyzed for its isotopic compositions. It has a $^{143}Nd/^{144}Nd$ typical of depleted MORB, but even the acid-leached residue has still a very high $^{87}Sr/^{86}Sr$ (0.70755) that must reflect the extremely altered nature of these basalts [*Hekinian*, 1974]. Apparently, some of the postmagmatic phases were not removed by the acid leaching. With respect to Pb isotopic ratios, this sample is similar to the lowermost basalt studied at Site 213; that is, it has Pb isotopic ratios higher than Indian Ocean MORB and its $^{207}Pb/^{204}Pb$ (15.66) is higher than lavas from the Kerguelen Archipelago, comparable to those of Indian Ocean sediments [*Vroon et al.*, 1993]. Hence it has a high $\Delta 7/4$ of 14.4, although its $^{208}Pb/^{204}Pb$ falls within the Kerguelen field (Figures 3c and 3d).

Slte 211 (9°46.53'S, 102°41.95'E)

This site was drilled in deep water (5525 m) west of Christmas Island. Christmas Island is composed of alkaline basalts ranging

Table 1. (continued)

	Site 212					
	39-1 134-136	39-1 146-149	39-2 0-14	39-2 39-42	39-2 60-64	39-3 145-147
Rb	39.0	368	24.9	18.7	20.2	31.1
Sr	75	112	72	67	68	93
Ba		153	11		9	116
V	224	189	240	206	221	206
Cr	820	782	881	764	786	872
Ni	144	138	148	144	141	160
Zn	86	78	93	71	84	76
Ga	-	11.9	15.0	13.6	13.9	12.6
Y	16	13.8	11.9	15.2	16.9	15.7
Zr	45	31	30	24	26	32
Nb	3	2.1	1.2	1.3	1.3	2.1
Hf						0.64
La	1.9					2.39
Ce	5	7.6	4.2	9.6	7.3	6.2
Nd	3.4					3.5
Sm	1.08					1.29
Eu	0.47					0.49
Tb	0.32					0.30
Yb	1.17					1.72
Lu	0.18					0.28

	Site 211									
	Diabase Sill				Basement					
	12-1 23-25	12-1 143-145	12-2 100-102	14-2 55-61	15-2 14-16	15-2 95-97	15-3 40-46	15-3 40-45	15-3 67-70	15-4 70-73
Rb	42.0	41.0	45.1	42.0	18.9	70.4	61.7	59.3	91.4	52.4
Sr	447	540	514	447	265	535	595	482	530	411
Ba	469	534	488	489	151	501	526	432	508	426
V	154	147	165	215	163	119	118	102	146	137
Cr	299	274	222	92	94	53	57	58	72	85
Ni	116	136	101	107	103	68	63	79	118	111
Zn	94	82	90	113	111	87	80	107	101	85
Ga	19.9	18.0	18.2	19.9	20.1	20.0	20.5	20.0	21.2	19.0
Hf	4.12									5.82
Zr	193	183	201	342	368	323	304	338	333	300
Nb	54	52	57	70	76	67	63	70	68	61
Hf	4.12									5.82
La	35.3									37.3
Ce	70.7	75	65	84	86	84	75	81	74	77.3
Nd	29.3									32.4
Sm	6.01									7.04
Eu	1.93									2.29
Tb	0.69									0.78
Yb	1.75									2.28
Lu	0.26									0.33

in age from Eocene to Miocene [*Smith and Mountain*, 1925; *Falloon et al.*, 1989]. These basalts have relatively radiogenic Pb isotopic compositions with $^{206}Pb/^{204}Pb > 18.8$ [*Hart*, 1988]. At Site 211 a 10-m-thick diabase sill ($^{40}Ar/^{39}Ar$ age of 71 Ma [*McDougall*, 1974]) occurs 18 m above an amphibole-bearing basaltic basement that is inferred to be >76 Ma. Although the sill has significantly lower abundances of Nb and Zr than the basement lavas (Table 1 and Figure 4), all of the lavas from this site are alkalic basalts that are very enriched in incompatible elements relative to the lavas from the other sites (Figure 4). In terms of La/Yb, Ce/Y and Zr/Nb, Site 211 lavas are similar to the mildly alkaline suite of the Kerguelen Archipelago (Figure 5). These are the only alkalic lavas recovered from the eastern Indian Ocean seafloor.

The Sr and Nd isotopic ratios of a basement lava from Site 211 are close to those of Christmas Island lavas (Figure 2b). Compared to lavas from Christmas Island, this Site 211 basalt has lower $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ (Figures 3c and 3d), but its $^{206}Pb/^{204}Pb$ ratio is nevertheless the highest value measured on samples of the northeastern Indian Ocean seafloor (except for an anomalous sample from Site 260, Table 2). The Pb isotopic ratios of the sill sample overlap with the upper Miocene alkalic

Table 1. (continued)

	Site 256							
	9-3 15-17	9-3 52-54	9-3 138-140	10-1 141-143	10-4 62-64	10-4 114-116	11-1 27-30	11-3 148-150
Rb	5.1	2.8	5.1	6.6	1.8	2.6	4.4	3.6
Sr	191	168	176	172	186	172	166	170
Ba	60		59	64	56	28	46	51
V	545		424	426	486	416	410	426
Cr	116		110	100	120	130	155	102
Ni	73		78	73	76	85	90	77
Zn	134		136	127	139	134	141	127
Ga	21.3	20.5	20.5	21.2	21.9	20.0	19.0	19.9
Y	33.7	34.3	35.2	34.8	33.8	34.7	33.7	35.0
Zr	164		140	146	154	137	133	143
Nb	17.0		13.6	14.8	15.3	13.3	12.5	14.4
La		9.0		10.1		10.4	9.8	
Ce	28	33	29	29	28	30	30	30
Nd		17		18		17	18	
Sm		4.31		4.86		4.73	4.85	
Eu		1.37		1.55		1.59	1.57	
Tb		1.1		0.83		1.1	1.1	
Yb		3.0		3.4		3.4	3.3	
Lu		0.47		0.65		0.54	0.53	
	Site 257							
	11-1 122-124	11-3 25-27	14-5 25-27	16-1 65-67	16-3 31-33	17-1 70-72	17-1 97-99	17-5 67-69
Rb	16.1	9.5	13.0	6.3	0.5	31	50	0.5
Sr	204	76	76	93	80	80	87	83
Ba	229	114	11	41	12	11	33	34
V	217	285	325	288	256	243	274	264
Cr	425	492	183	365	435	179	232	226
Ni	83	117	87	116	100	77	121	88
Zn	75	92	93	81	70	79	82	83
Ga	14.0	13.3	17.0	16.0	15.7	14.9	15.0	15.7
Y	18.5	15.9	24.3	17.6	21.8	17.8	22.0	21.4
Zr	82	39	52	51	43	43	48	47
Nb	7.6	1.6	2.1	2.0	1.3	2.5	2.9	2.6
Hf	1.89	1.09	1.78					
La	6.11	1.60	1.78		1.41			
Ce	16.1	5.4	6.6	2.7	4.9	4.9		3.1
Nd	10.5	4.5	5.6		4.9			
Sm	2.75	1.64	2.06		1.60			
Eu	1.03	0.64	0.81		0.71			
Tb	0.54	0.37	0.49		0.36			
Yb	1.93	1.95	2.84		2.5			
Lu	0.29	0.30	0.43		0.42			

lavas of the Kerguelen Archipelago. Therefore among all lavas recovered by drilling from the eastern Indian Ocean seafloor, these Site 211 alkalic basalts are geochemically the most similar to recent lavas erupted in the Kerguelen Archipelago [*Weis et al.*, 1993a, b]. However, Site 211 is not close to the track of the Kerguelen Plume or any other recognized plume. It is likely that lavas from this site are related to the volcanism that created the northeast trending bathymetric highs that form the Cocos-Keeling Plateau-Christmas Island complex (Figure 1).

Site 256 (23°27.35'S, 100°46.46'E)

This site is in the southern Wharton Basin. Although drilled in deep water (5361 m), the site is near a trend of bathymetric highs extending northeast from Broken Ridge, i.e., Golden Draak knoll, Batavia knoll, and Zeewk knoll (Figure 1) (see Figure 5 of *Powell et al.* [1988] for details). Based on fossils, the minimum basement age is 102 Ma; using magnetic anomalies, *Powell et al.* [1988] inferred a basement age of 125 Ma. Basement penetration of 19 m recovered Fe-Ti rich tholeiitic basalts. Both the major element and incompatible element abundances of Site 256 basalts are similar to basalts recovered from the Ninetyeast Ridge (Figure 5 and *Frey et al.* [1977]. Moreover, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, and $^{207}Pb/^{204}Pb$ in Site 256 lavas overlap with the range of Ninetyeast Ridge basalts (Figures 2b, 3c and 3d).

Site 257 (39°59'S, 108°21'E)

DSDP Sites 257, 259, and 260 are near the western coast of Australia (Figure 1). This basaltic seafloor is inferred to have

Table 1. (continued)

	Site 259		Site 260		Site 261				
	38-1 65-67	41-1 101-104	18-2 140-142	20-1 16-18	33-1 101-105	34-1 75-77	35-2 120-123	36-1 60-63	39-1 11-13
Rb	7.2	12.1	3.6	3.1	20.3	10.9	14.2	24.4	6.1
Sr	91	99	129	112	81	87	98	91	85
Ba	7		64	35			20	12	
V	270	260	479	391	333	323	431	539	321
Cr	148	185	125	106	172	181	38	22	165
Ni	59	45	210	51	85	76	55	53	78
Zn	112	132	178	151	104	92	213	166	94
Ga	16.8	17.0	21.9	19.8	17.1	17.5	21.1	23.2	18.0
Y	29.9	33.1	31.8	37.1	30.6	33.1	61.8	47.3	32.4
Zr	72	74	138	119	72	77	205	176	78
Nb	2.1	1.3	5.3	5.5	0.9	1.1	7.5	7.1	2.0
Hf	1.92	2.04	3.14		1.83		5.75		
La	5.07	4.39	7.60	6.0	1.99	2.34	8.35		2.45
Ce	10.6	12.8	14.9	17	7.7	11	29.6	17.9	9
Nd	8.9	8.9	10.1	9.7	7.1	7.1	23.5		7.8
Sm	3.09	3.20	3.95	3.75	2.76	3.11	7.84		3.16
Eu	1.03	1.17	1.46	1.21	1.04	1.03	2.62		1.17
Tb	0.63	0.83	0.79	-	0.70	0.73	1.63		0.79
Yb	3.04	3.27	3.31	4.1	3.45	3.4	5.96		3.90
Lu	0.43	0.50	0.47	0.65	0.53	0.62	0.85		0.60

In parts per million. Sample designation indicates core and section number followed by an interval in centimeters. Data for REE (Lu through Lu) and Hf are by instrumental neutron activation at MIT; data for other elements are determined by X ray fluorescence at University of Massachusetts, Amherst. When Ce abundances are not accompanied by other REE data, Ce was determined by XRF. For discussion of precision and accuracy, see *Frey et al.* [1991].

formed at the northeast-southwest oriented spreading ridge that separated Greater India from Australia [e.g., *Markl*, 1974; *Veevers et al.*, 1974; *Rundle et al.*, 1974; *Fullerton et al.*, 1989]. At Site 257, Middle Albian ~106-110 Ma sediments occur 13 m above the basaltic basement. Basement penetration was 64.5 m. Although basalts from core 11 have ~100 Ma K/Ar ages roughly consistent with the age of the overlying sediments, much older K/Ar ages (157 to 196 Ma) were obtained from basalts lower in the core [*Rundle et al.*, 1974]. Based on extrapolation of magnetic anomalies, inferred basement ages range from 110 to 130 Ma (*Powell et al.* [1988] and *Luyendyk and Davies* [1974], respectively). Most of the basalts from this core have incompatible element abundance ratios intermediate between SEIR MORB and lavas from the Ninetyeast Ridge (Figure 5). Their isotopic ratios overlap with the Indian Ocean MORB field (Figures 2b, 3c and 3d). In contrast, the uppermost basalts (core 11, section 1, Table 1) have La/Yb, Ce/Y and Zr/Nb similar to basalts from Site 256 and lavas from the Ninetyeast Ridge (see *Fleet et al.* [1976] and Figure 5). The uppermost lava is also similar to Ninetyeast Ridge lavas in Sr and Nd isotopic ratios, although its combination of Sr-Nd is not within Ninetyeast Ridge field (Table 2 and Figure 2b). It also has higher Pb isotopic ratios than the depleted lavas from Site 257 (Table 2). Although the accuracy of the K-Ar ages is unknown, it is intriguing that the K-Ar age (~100 Ma [*Rundle et al.*, 1974]) of the uppermost basalts is also similar to the minimum age inferred for the enriched basalts at Site 256. However, like other Site 257 lavas, the enriched basalt has relatively low $^{206}Pb/^{204}Pb$ (17.57). This is much lower than that found in lavas from the Ninetyeast Ridge and Indian OIB. Thus the youngest Indian ocean crust sampled at Site 257 is geochemically enriched, similar to lavas subsequently erupted on the Ninetyeast Ridge. However, all basalts at Site 257 plot within the Indian Ridges field in Pb-Pb diagrams (Figures 3c and 3d) and have the low $^{206}Pb/^{204}Pb$ that is characteristic of many Indian Ocean MORB and which has not been found in lavas related to the Kerguelen Plume.

Site 259 (29°37'S, 112°42'E)

Based on the age of overlying earliest Aptian sediments, basement at this site is older than ~112 Ma; *Powell et al.* [1988] used magnetic anomalies to infer a basement age of 125 Ma. As at Site 257, the oceanic crust at Site 259 is presumed to have formed at a northeast-southwest oriented ridge. The Site 259 lavas have La/Yb, Ce/Y, and Zr/Nb typical of depleted SEIR MORB (Figure 5). The two analyzed samples are geochemically similar, except for a difference in Zr/Nb which probably reflects analytical error at these low Nb contents (~2 ± 0.6 ppm, Table 1 [*Rhodes et al.*, 1990]). The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ overlap with the high $^{87}Sr/^{86}Sr$ end of the recent Indian Ocean MORB field; the offset of the age-corrected values to lower $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ (Figure 2b) is consistent with aging of a depleted mantle (MORB) source. In Pb isotopes, both lavas have $^{206}Pb/^{204}Pb$ at the high end of the Indian Ocean MORB field. However, like the depleted basalts from Site 212 and the enriched basalt from Site 213, these Site 259 lavas have $^{207}Pb/^{204}Pb$ greater than any lava from the Kerguelen Archipelago (Figures 3c and 3d), with Δ7/4 of 14.0-14.3 and Δ8/4 of 32.7-60.7.

Site 260 (16°9'S, 110°18'E)

Like the basement at Sites 257 and 259, oceanic crust at Site 260 in the northeast Indian Ocean (Figure 1) is inferred to have

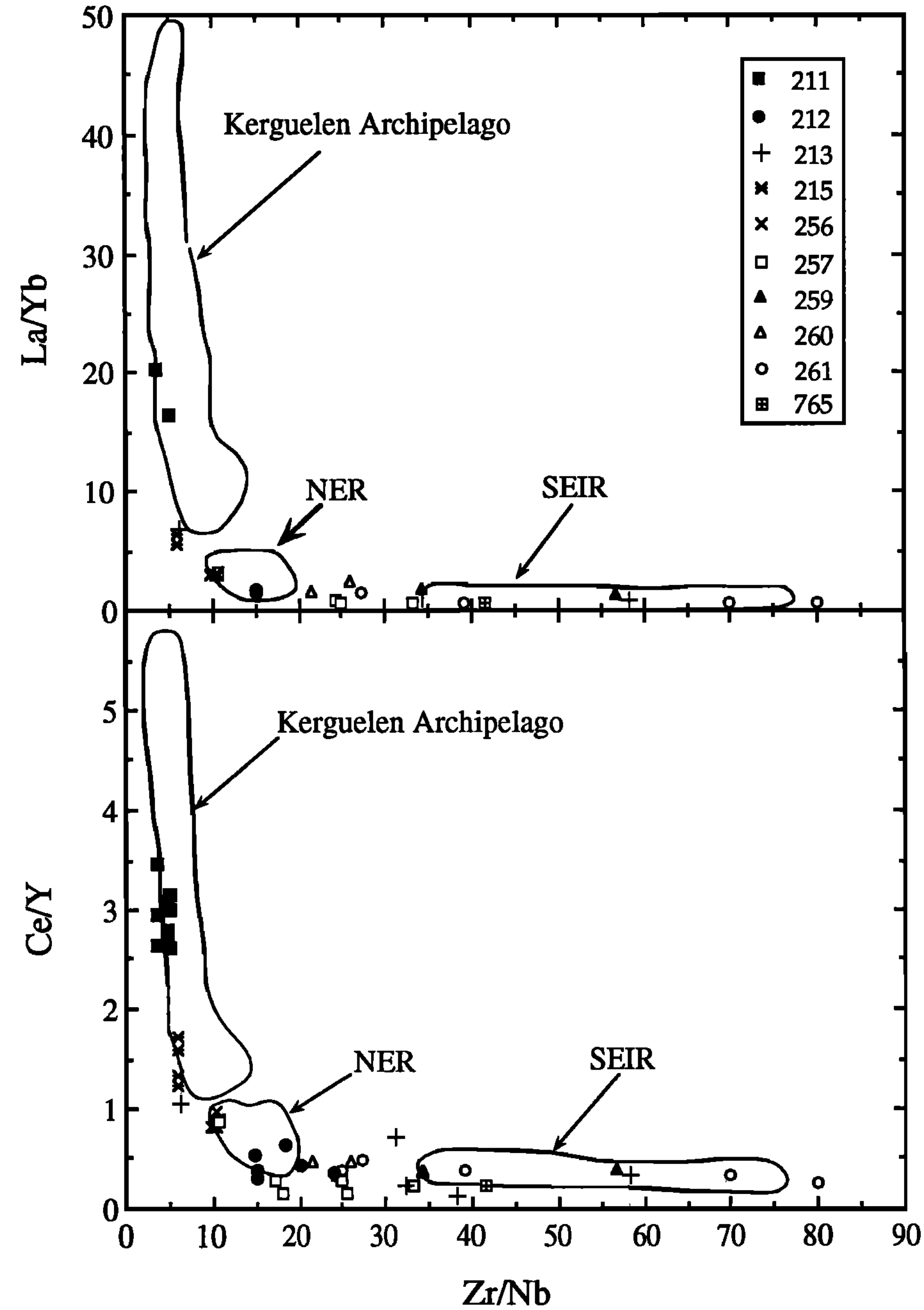

Figure 5. Ce/Y and La/Yb versus Zr/Nb in basalts from the eastern Indian Ocean seafloor (data from Table 1 and average for Site 765 lavas from *Ishiwatari* [1992] compared to fields defined by lavas from the Kerguelen Archipelago [*Storey et al.*, 1988; *Gautier et al.*, 1990; *Weis et al.*, 1993a], Ninetyeast Ridge [*Frey et al.*, 1991], and Southeast Indian Ridge (SEIR MORB) [*Price et al.*, 1986]; the range for Kerguelen Archipelago lavas from low to high La/Yb and Ce/Y reflects the evolution from older, ≈25 Ma, transitional basalts to younger, <10 Ma, highly alkaline lavas. We use these elements because they are relatively unaffected by postmagmatic processes. The selected ratios involve elements of different incompatibility and they illustrate the diversity of these DSDP lavas. These ratios clearly distinguish depleted MORB from OIB and enriched MORB; La/Yb indicates the slope of a chondrite-normalized REE plot (La/Yb is ≈1.48 in chondrites); Ce/Y (≈0.39 in chondrites) is also plotted because there are more data for these elements (Table 1). These incompatible element ratios show that most of the basement sites in the eastern Indian Ocean have recovered basalts which are intermediate between depleted MORB and Ninetyeast Ridge lavas. Only Site 211 and Site 215 basalts are within the field of lavas from the Kerguelen Archipelago.

formed from the northeast-southwest spreading center that separated Greater India from Australia. At Site 260, the recovered basalt is interpreted to be a sill that is overlain by 105 Ma sediments. Although 9 m of basalt was penetrated, only 0.5 m of core was recovered. Similar to basalts from Site 257, Ce/Y, Zr/Nb and La/Yb in the Site 260 lava are intermediate between SEIR MORB and lavas from the Ninetyeast Ridge (Figure 5). Consistent with this result, measured $^{87}Sr/^{86}Sr$ and

Table 2. Sr, Nd, and Pb Isotopic Data and Pb and U Concentrations by Isotope Dilution in DSDP Basalts From the Eastern Indian Ocean

Leg	Site	Sample	Age, Ma	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr^{a}$	$2\sigma_m$	$^{87}Sr/^{86}Sr$ Initial [b]	$^{143}Nd/^{144}Nd^{a}$	$2\sigma_m$	εNd	$^{143}Nd/^{144}Nd$ Initial [b]	εNd Initial [c]
22	213	18-2 115-117	57	0.155	(0.702696)	(10)	0.70257	(0.513043)	(13)	7.9	0.51296	7.8
					0.702809	33						
					0.702611	14						
22	213	19-2 127-130	57	0.148	(0.703082)	(7)	0.70296	(0.512977)	(14)	6.6	0.51292	6.9
					0.703172	8						
				0.148	0.703109	7	0.70299					
					0.703173	6						
22	215	18-2 106-110	60	0.148	(0.704451)	(6)	0.70433	(0.512738)	(9)	2.0	0.51268	2.3
					0.704461	7						
22	215	18-3 110-112	60	0.109	(0.704462)	(6)	0.70437	(0.512723)	(8)	1.7	0.51267	2.1
					0.704420	8						
22	211	12-1 23-25	76	0.272	(0.704194)	(6)	0.70390	(0.512656)	(24)	0.4	0.51259	1.1
					0.704167	22						
22	211	15-4 70-73	76	0.369	(0.704096)	(7)	0.70370	(0.512824)	(18)	3.6	0.51276	4.3
					0.704118	21						
22	212	39-1 134-136	90	1.51	(0.707548)	(42)	0.70562	(0.513055)	(34)	8.1	0.51292	7.8
27	260	20-1 16-18	105	0.080	(0.703702)	(8)	0.70359	(0.512910)	(10)	5.3	0.51276	4.8
					0.703768	7						
27	260	18-2 140-142	105	0.081	(0.703805)	(6)	0.70369	(0.512872)	(17)	4.6	0.51272	4.1
								0.512853	21	4.2		
26	257	16-3 31-33	110	0.0181	(0.703232)	(7)	0.70320	(0.513128)	(30)	9.6	0.51299	9.6
					0.703194	10						
					0.703233	8						
26	257	11-3 25-27	110	0.362	(0.703761)	(3)	0.70320	0.513104[d]	168[d]	9.1	0.51294	8.7
					0.703721	8						
26	257	11-1 122-124	110	0.228	(0.704114)	(5)	0.70376	(0.512835)	(19)	3.8	0.51272	4.4
26	256	10-1 141-143	125	0.111	(0.704188)	(8)	0.70399	(0.512903)	(16)	5.2	0.51277	5.6
					0.704151	9						
					0.704227	9						
26	256	10-4 114-116	125	0.0437	(0.704203)	(8)	0.70412	(0.512855)	(7)	4.2	0.51272	4.7
					0.704259	9		0.512860	25	4.3		
27	259	38-1 65-67	125	0.229	(0.704205)	(11)	0.70380	(0.512885)	(33)	4.8	0.51271	4.6
					0.704198	11						
					0.704257	11						
					0.704240	24		0.512886	35	4.8		
27	259	41-1 101-104	125	0.354	(0.703802)	(5)	0.70317	(0.512938)	(31)	5.9	0.51276	5.5
								0.512965	49	6.4		
27	261	33-1 101-105	152	0.73	(0.703982)	(12)	0.70242	(0.513208)	(22)	11.1	0.51297	10.4
					0.703979	18						
27	261	35-2 120-123	152	0.419	(0.703340)	(10)	0.70243	(0.513380)	(50)	14.5	0.51318	14.4
					0.703341	20						
					0.703328	25						

[a] The different numbers correspond to duplicate analysis on the VG54 mass spectrometer and show the between-run reproducibility. The number in parentheses is the run with the better precision and stability and is the one used in this paper.

[b] "Initial" values, i.e., measured ratios corrected for in situ decay of ^{87}Rb, ^{147}Sm, ^{238}U, and ^{235}U, respectively, for the age given See analytical section in the text for discussion.

[c] ε_{Nd} calculated for the "initial" values and relative to bulk earth values at the age given for each sample (BE(0): $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$).

[d] Very low intensity analysis, poor precision. This $^{143}Nd/^{144}Nd$ value is used in the plots because it is not significantly different from the value from another sample at the same site (Leg 26, Site 257, 16-3 31-33).

$^{143}Nd/^{144}Nd$ overlap with the enriched end of the MORB field (Figure 2b) and like the Site 259 lavas, the offset of age corrected $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ from the field for recent MORB (Figure 2b) is consistent with aging of a depleted mantle source. The Pb isotopic characteristics of these two Site 260 samples are unusual (Figure 3), one sample has relatively low initial $^{206}Pb/^{204}Pb$ (~17.5) and a high $^{207}Pb/^{204}Pb$ (15.5), whereas the other has unusually high initial $^{206}Pb/^{204}Pb$ (20.3) and $^{207}Pb/^{204}Pb$ (15.8) (not plotted on Figure 3).

Site 261 (12°57'S, 117°54'E)

This site in the northern Argo Abyssal Plain penetrated 47 m of basalt below sediments of 152 Ma (Figure 1). Thus these basalts are the oldest recovered by DSDP in the eastern Indian Ocean, and they are similar in age to the 155 Ma basalts recovered at ODP Site 765 in the southern Argo Abyssal Plain [*Ludden and Dionne*, 1992]. The basaltic core can be divided into three units [*Robinson and Whitford*, 1974]. The uppermost unit A is a 10-m

Table 2. (continued)

Pb ppm	U ppm	$^{238}U/^{204}Pb$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$ Initial [b]	$^{207}Pb/^{204}Pb$ Initial [b]	Ce/Pb
0.07	0.01	9.0	18.17	15.491	38.01	18.09	15.49	108.6
0.29	0.08	17.7	18.66	15.66	38.84	18.50	15.65	21.7
0.37	0.1							
0.76	0.21	17.5	18.15	15.548	38.42	17.99	15.54	42.9
1.02	0.28	17.3	18.10	15.533	38.32	17.94	15.53	35.3
0.94	0.29	19.7	18.48	15.582	38.77	18.25	15.57	75.2
1.2	0.09	4.80	18.65	15.557	38.90	18.59	15.55	64.4
0.17	0.06	22.6	18.80	15.673	38.77	18.48	15.66	29.4
0.18	0.44	163	22.85	15.911	38.07	20.29	15.79	94.4
0.28	0.15	33.6	18.05	15.579	37.96	17.52	15.55	53.2
0.3	0.15	31.3	18.03	15.544	37.92	17.54	15.52	
0.06	0.01	14.3	17.72	15.386	37.35	17.47	15.37	81.7
0.12	0.07	36.3	18.06	15.439	37.47	17.44	15.41	45.0
0.76	0.95	80	19.19	15.627	38.01	17.82	15.56	21.2
0.13	0.12	61	19.17	15.621	39.33	17.98	15.56	223.1
0.21	0.11	33.9	19.05	15.58	39.2	18.39	15.55	142.9
0.41	0.05	7.7	18.26	15.61	38.31	18.11	15.60	25.8
0.33	0.03	4.82	18.58	15.648	38.42	18.49	15.64	38.8
0.33	0.03	4.82	18.58	15.635	38.44	18.50	15.63	
0.12	0.06	30.9	18.46	15.537	37.62	17.72	15.50	64.2
0.7	0.38	34.6	18.72	15.634	38.39	17.89	15.59	42.3

coarse-grained sill with a highly depleted MORB composition (Figure 5) whose $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are at the depleted end of the Indian Ocean MORB field (Figure 2b). Although the older, underlying units B and C are less depleted in incompatible element abundances than unit A, the sample from unit B has equally low $^{87}Sr/^{86}Sr$ and even higher $^{143}Nd/^{144}Nd$ (Table 2 and Figure 2b). These Site 261 lavas have Sr and Nd isotopic signatures similar to those of Site 765 basalts [*Ludden and Dionne*, 1992], and they have lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ than basalts from the other eastern Indian Ocean sites studied in this paper (Figure 2b). Site 261 lavas have the low $^{206}Pb/^{204}Pb$ ratios typical of some Indian Ocean MORB, but they have relatively high $^{207}Pb/^{204}Pb$ (15.50 to 15.59), although not as high as in depleted MORB samples from Sites 212 and 259 (Figure 3c).

Discussion

Occurrence of Enriched MORB

At three of the studied DSDP sites, the recovered basalts are highly enriched in incompatible elements relative to MORB. At Sites 215 and 256, the tholeiitic lavas have isotopic and incompatible element ratios similar to lavas associated with the Kerguelen Plume (Figures 2b, 3c, 3d and 5). Because the Ninetyeast Ridge, which is interpreted to be a hotspot track related to the Kerguelen Plume [e.g., *Weis et al.*, 1992], is only 240 km east of Site 215, it is conceivable that the >60 Ma basaltic basement at Site 215 is related to the Ninetyeast Ridge. Site 256 is located on a northeast trending series of bathymetric highs emanating from Broken Ridge (Figure 1), which formed as the northern portion of the Kerguelen Plateau. This very large plateau is also interpreted to be a manifestation of the Kerguelen Plume [e.g., *Davies et al.*, 1989; *Weis et al.*, 1989a; *Salters et al.*, 1991; *Storey et al.*, 1992; *Müller et al.*, 1993]. Ages for lavas from the Kerguelen Plateau range from 85 to 118 Ma [*Leclaire et al.*, 1987; *Whitechurch et al.*, 1992; *Pringle et al.*, 1994], whereas lavas from Broken Ridge have ages ranging from 63 to 89 Ma [*Duncan*, 1991]. Because of their geochemical similarities with lavas related to the Kerguelen Plume and their minimum ~102 Ma and maximum 125 Ma age, Site 256 lavas may represent early volcanism related to the Kerguelen Plume.

In contrast, the enriched alkalic lavas at Site 211 in the northern Wharton Basin cannot be directly related to the Kerguelen Plume. Site 211 is located on a series of northeast trending bathymetric highs whose origin is unknown, and their strike is not consistent with the trace of a known hotspot. The alkalic basalts at this site, however, have compositional similarities to the much younger basalts forming the Kerguelen Archipelago (Figure 5). Although lavas from nearby Christmas Island have higher $^{206}Pb/^{204}Pb$ than Kerguelen lavas, the Pb isotopic fields defined by lavas from Site 211 overlap the Kerguelen field (Figures 3b and 3c). In addition, a basement sample from this site has Sr and Nd isotopic ratios close to the low $^{87}Sr/^{86}Sr$-high $^{143}Nd/^{144}Nd$ end of the range defined by lavas from the Ninetyeast Ridge and Kerguelen Archipelago (Figure 2b). Therefore lavas with geochemical characteristics similar to lavas associated with the Kerguelen Plume have erupted in locations where the volcanism cannot be directly related to the Kerguelen Plume.

Lavas at two sites (257 and 213) range widely in ratios of incompatible elements but have Sr and Nd isotopic ratios close to or within the Indian MORB field. At Site 257, close to the southwest coast of Australia (Figure 1), the uppermost lavas are compositionally very similar to the enriched lavas at site 256. An important difference is that all of the relatively old Site 257 basalts have low initial $^{206}Pb/^{204}Pb$ (<17.8). This feature is a distinctive characteristic of some recent Indian Ocean MORB, which has not been observed in lavas from the Kerguelen Archipelago (Figures 3c and 3d). Site 213 is located in a region where the east-west magnetic lineations are remarkably clear (Figure 1), and the basement is inferred to have been formed from an east-west spreading ridge axis well north of the Kerguelen Plume [e.g., *Royer et al.*, 1991]. Consistent with this interpretation, most of the Site 213 core is depleted MORB. However, the lowermost basalt in this core is enriched in incompatible elements (Table 1 and Figures 4 and 5) and has anomalous Pb isotope ratios that are much higher than Indian Ocean MORB. In fact, $^{207}Pb/^{204}Pb$ even exceeds that measured in lavas from the Kerguelen Archipelago (Figure 3c and Table 2).

Occurrence of Depleted MORB

Most of the basalts from six DSDP sites (Sites 212, 213, 257, 259, 260, and 261) and ODP Site 765, ranging in inferred ages from ~56 to 155 Ma, are geochemically similar to Indian Ocean MORB. They have relatively low La/Yb and Ce/Y, $(^{87}Sr/^{86}Sr)_i$ < 0.7038 (the Site 212 sample is an exception) and $(^{143}Nd/^{144}Nd)_i$ > 0.5127 and $(\varepsilon_{Nd})_i$ > 4.1(Figures 2 and 5). These basalts, however, have diverse Pb isotopic characteristics (Figure 3). Lavas associated with the Kerguelen Plume, i.e., those forming the Kerguelen Archipelago and Ninetyeast Ridge, have initial $^{206}Pb/^{204}Pb$ of 17.67 to 18.71 (Figure 6a). Enriched and depleted lavas from DSDP sites with ages of <125 Ma (Sites 213, 215, 211, 212, 256, and 259) have $^{206}Pb/^{204}Pb$ within this range (Figure 6a). These lavas contrast with some recent Indian Ocean MORB, some lavas recovered from the Kerguelen Plateau, and some of the lavas from the oldest eastern Indian Ocean drill sites, Sites 257 and 765, which range to much lower $^{206}Pb/^{204}Pb$ (to 17.30, Figure 6a). Thus unusually low $^{206}Pb/^{204}Pb$ is characteristic of both recent Indian Ocean MORB and relatively old seafloor in the eastern Indian Ocean, but it is not characteristic of <82 Ma lavas associated with the Kerguelen Plume (Figure 6a). Similarly, relatively high Δ8/4 values are associated with lavas from the Kerguelen Plume and lavas at the seven DSDP sites ranging in age from ~56 to 125 Ma (Sites 213, 215, 211, 212, 260, 256, and 259). In contrast, lavas from DSDP Sites 257 and 261 have much lower Δ8/4 (Figure 6b). Lavas from DSDP Site 261 and ODP Site 765 are the oldest Indian Ocean seafloor studied, and they also have higher $(^{143}Nd/^{144}Nd)$, >0.51285, than lavas associated with the Kerguelen Plume; thus they are similar to recent Indian MORB (Figure 6c).

Source of Anomalously High $^{207}Pb/^{204}Pb$

At three of the DSDP sites studied, some of the basalts have anomalously high $^{207}Pb/^{204}Pb$ (Sites 212, 213, and 259), i.e., higher than Indian Ocean MORB and lavas from the Kerguelen Archipelago (Figure 3c). Conversely, in the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram (Figure 3d), most of these samples plot within the Kerguelen and Ninetyeast Ridge fields. In an oceanic environment, only sediments have such high $^{207}Pb/^{204}Pb$. The Site 212 basalt has also a high age-corrected $^{87}Sr/^{86}Sr$ (0.70741) indicating that some of the postmagmatic phases were not removed by acid leaching.

In Pb-Pb diagrams (Figure 3c), the samples with anomalous $^{207}Pb/^{204}Pb$ plot on trends between the Indian MORB field and the field for Indian Ocean sediments [*Ben Othman et al.*, 1989; *Vroon et al.*, 1993]. In general, abundance ratios of Ce/Pb are unusually high in these eastern Indian Ocean basalts (12 of 18 samples have Ce/Pb >40, Table 2, compared to a typical MORB ratio of ~25 [*Hofmann et al.*, 1986]). Samples with anomalously high $^{207}Pb/^{204}Pb$, however, have lower Ce/Pb, <40 (Table 2). Mixing calculations by *Ben Othman et al.* [1989] in their study of sediment recycling into the mantle indicate that the addition of only 1% sediment to the mantle leads to low Ce/Pb and anomalously high $^{207}Pb/^{204}Pb$. We conclude that these samples may contain small amounts of sediment that were not removed by acid leaching. Therefore we do not use these high $^{207}Pb/^{204}Pb$ values in our discussion of source components.

Origin of the Dupal Anomaly

Following numerous previous studies starting with *Subbarao and Hedge* [1973], *Dupré and Allègre* [1983] showed that many oceanic island basalts in the Indian Ocean have distinctive Sr, Nd, and Pb isotopic ratios, which *Hart* [1984] termed the Dupal anomaly. This large distinctive isotopic domain is centered at ~30°S and is defined by $^{87}Sr/^{86}Sr$ >0.705 and Δ8/4 > +60 [*Hart*, 1988]. *Hart* [1988] noted that only three localities in the northern hemisphere have lavas with a Dupal signature. The distinctive isotopic characteristics of Indian Ocean MORB in comparison to Atlantic and Pacific MORB are interpreted to result from a Dupal component incorporated into the Indian Ocean asthenosphere. This isotopically distinctive asthenosphere has also been inferred to be the source for lavas erupted in the marginal basins of the western Pacific. *Hickey-Vargas et al.* [1995] conclude that Indian Ocean asthenosphere, perhaps flowing in along the northern

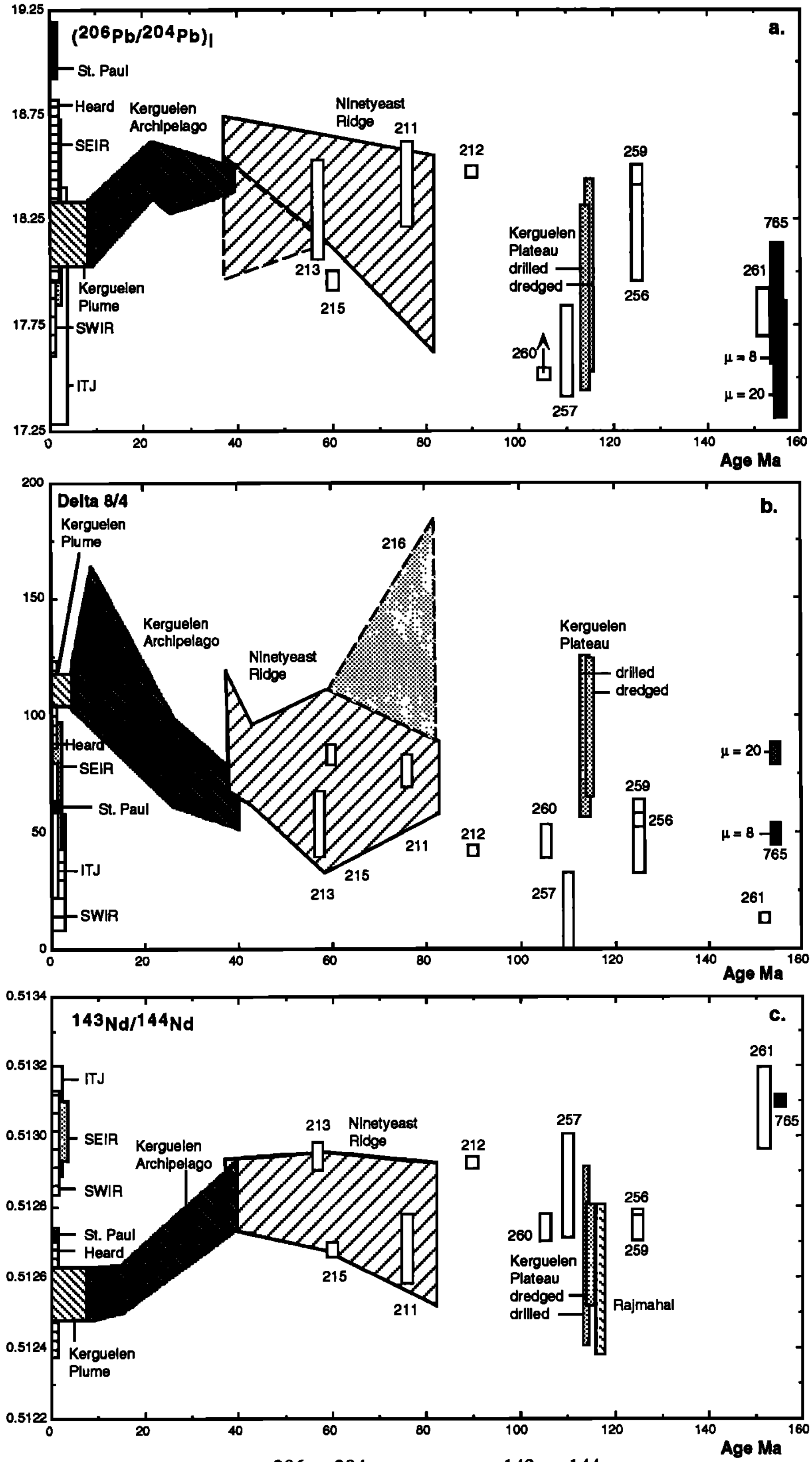

Figure 6. (opposite) Isotopic parameters $(^{206}Pb/^{204}Pb)_i$, Δ8/4 and $(^{143}Nd/^{144}Nd)_i$ versus age for eastern Indian Ocean seafloor. (a) All $^{206}Pb/^{204}Pb$ ratios are age-corrected. The upward arrow for Site 260 indicates that the ratio for a sill in this core is off-scale at 20.3. Because U and Pb data are not available for all lavas from Site 765, corrected ratios are shown for two assumed $^{238}U/^{204}Pb$ ratios (u = 8 and 20). (b) The Δ values for the older basalts are maximum values because $^{206}Pb/^{204}Pb$ ratios have been age corrected, but the $^{208}Pb/^{204}Pb$ ratios have not been corrected because precise Th abundance data are not available. (c) All $^{143}Nd/^{144}Nd$ ratios are age-corrected. ITJ, SWIR, and SEIR indicate Indian Ocean triple junction, Southwest Indian Ridge, and Southeast Indian Ridge, respectively. Dashed lines in Ninetyeast Ridge field (Figures 6a and 6b) are defined by data from DSDP Site 216 [*Frey and Weis*, 1995]. Field labeled Kerguelen Plume is from *Weis et al.* [1993a]. Data for Site 765 are revised from *Ludden and Dionne* [1992; J.N. Ludden, personal communication, 1995]; data from Heard Island are from *Barling et al.* [1994]; all other data sources are as indicated in caption for Figure 2b.

boundary of Australia prior to ~50 Ma, was an important source component for these western Pacific lavas. Of the 10 drill sites that recovered basalts from the eastern Indian Ocean, lavas at seven sites (<125 Ma) have $\Delta8/4$ >33 (range 33 to 85). In contrast, the presence of a Dupal component is not obvious in the oldest lavas from the eastern Indian Ocean seafloor; for example, lavas from Sites 261 and 765 (~152 to 155 Ma) have very high $^{143}Nd/^{144}Nd$ (Figure 6c), and low $^{87}Sr/^{86}Sr$ (Figure 2b and *Ludden and Dionne* [1992]) and lavas from Site 261 have very low $\Delta8/4$ (Figure 6b). Therefore, in the eastern Indian Ocean seafloor, there is evidence for a Dupal component that has persisted since ≈125 Ma. We emphasize that this 125 Ma age is not rigorously constrained because the ages of basement lavas at these DSDP sites have not been reliably determined. The earliest manifestation of Dupal characteristics in dated lavas is in the oldest lavas associated with the Kerguelen Plume; i.e., the 110-118 Ma lavas forming the Kerguelen Plateau. Because ≈118 Ma corresponds to the first unambiguous evidence of activity of the Kerguelen Plume, we infer that the Dupal anomaly is carried by the Kerguelen Plume and that the source of this anomaly is deep within the mantle [e.g., *Castillo*, 1988; *Weis et al.*, 1989a].

The origin of the geochemical characteristics of the Dupal anomaly [*Dupré and Allègre*, 1983; *Hart*, 1984], with its subequatorial concentration, is an unresolved problem [*Hart*, 1988]. Most geochemical models require a long isolation time (1 to 2 Gyr) to develop the isotopic characteristics of OIB. A commonly proposed origin for the Dupal anomaly is recycling of subcontinental lithosphere into the mantle by a delamination process [*Hart et al.*, 1986; *Hawkesworth et al.*, 1986; *Hart*, 1988; *Sun and McDonough*, 1989]. We propose that the concentration of the Dupal anomaly to the subequatorial southern hemisphere may be directly connected to the nearly fixed location of the African continent (and by extension the Gondwana supercontinent). This would allow either for a thermal blanketing [*Anderson*, 1982] or an underplating (thickening) of the lithosphere, which would favor delamination. An important aspect of the Indian Ocean and the eastern Atlantic Ocean is the occurrence of major flood basalt provinces on the surrounding continents [*White and McKenzie*, 1989]. Because continental flood basalt provinces reflect a large magmatic output in a relatively short interval of time, they could generate a thickened lithospheric mantle. This thickened lithospheric mantle could subsequently delaminate cold lithosphere into the asthenospheric mantle through a process of thermal erosion or delamination. The oldest flood basalts in this region are the Karoo and Ferrar, which erupted in the middle to early Jurassic. Delamination resulting from these volcanic events preceded the first manifestations of the Kerguelen Plume by <100 Myr.

Source of Anomalously Low $^{206}Pb/^{204}Pb$

A distinctive feature of some recent Indian Ocean MORB is relatively low $^{206}Pb/^{204}Pb$, e.g., lavas from the Triple Junction and portions of the SWIR (Figure 6a). Lavas from Sites 257 and 765 also range to low $^{206}Pb/^{204}Pb$ (Figure 6a). The origin of the mantle component with low $^{206}Pb/^{204}Pb$ is uncertain. *Mahoney et al.* [1992] discussed two alternative possibilities: 1) Gondwana Precambrian lithosphere or (2) mantle plumes. The $^{206}Pb/^{204}Pb$ values of Indian Ocean basalts as a function of eruption age are important in evaluating these alternatives. Evidence against a plume origin is that recent lavas related to Indian Ocean plumes do not have similarly low $^{206}Pb/^{204}Pb$ [*Mahoney et al.*, 1992]. We favor a continental lithosphere origin for the low $^{206}Pb/^{204}Pb$ because (1) some continental basalts from Madagascar [*Mahoney et al.*, 1992] and western Australia [*Frey et al.*, 1996] have unusually low $^{206}Pb/^{204}Pb$; (2) some of the oldest basalts (110 to 155 Ma) in the eastern Indian Ocean have lower $^{206}Pb/^{204}Pb$ than lavas associated with Indian Ocean plumes (e.g., Figure 6a and *Mahoney et al.* [1995]) and (c) the low $^{206}Pb/^{204}Pb$ component in Indian Ocean MORB has been present since the initial formation of the ocean, and, although minor in volume, it is widely distributed on each of the Indian Ocean ridge systems.

Summary

Eastern Indian Ocean seafloor basalts ranging in age from Eocene to late Jurassic are tholeiitic basalts, except at one site near Christmas Island where alkalic basalts were recovered. Both enriched and depleted MORB have been recovered. The isotopic characteristics of basalts younger than 125 Ma indicate the presence of a Dupal component (lavas from Site 257 are an exception) that is absent in the oldest (155 Ma) seafloor samples. The first evidence of activity of the Kerguelen Plume is at 118 Ma with volcanism on the Kerguelen Plateau. This leads us to conclude that the Kerguelen Plume is the carrier of the Dupal anomaly in the Indian Ocean. In addition, we propose that the concentration of this anomaly in the southern hemisphere is related to the nearly fixed location of the African continent above the mantle. This situation favored recycling of continental lithosphere into the mantle via delamination. Delamination resulted either from thermal blanketing or underplating.

Some of the oldest seafloor lavas which predate volcanism associated with the Kerguelen Plume have the low $^{206}Pb/^{204}Pb$ values that are characteristic of some recent Indian Ocean MORB. Relatively low $^{206}Pb/^{204}Pb$ is typical of continental basalts in Madagascar and western Australia; therefore we infer that widely dispersed continental lithosphere is the source of the low $^{206}Pb/^{204}Pb$ in Indian Ocean MORB.

Relatively old, >45 Ma, eastern Indian Ocean seafloor resulted from the activity of three different spreading systems which have been active at different time periods; in order of decreasing age these are a nearly east-west striking ridge in the Argo Abyssal plain bordering Northwest Australia, a northeast-southwest ridge bordering southwest Australia, and an east-west spreading system in the Wharton Basin (Figure 1). Basalts from the oldest spreading center, sampled at Sites 261 and 765 in the Argo Abyssal Plain, are depleted MORB that are very much like lavas erupted along the active Southeast Indian Ridge. In contrast basalts from the Wharton Basin, sampled at Sites 213, 212, and 256, have isotopic ratios indicating the presence of a Dupal component which was derived from the Kerguelen Plume.

Acknowledgments. We thank J. M. Rhodes for use of the XRF facility at the University of Massachusetts, Amherst; P. Ila for assistance in data acquisition; J.–P. Mennessier for help with the isotope chemistry; J. Scoates for editorial assistance; and H.-J. Yang for graphics. We also thank J. Ryan, the JGR Associate Editor and an anonymous reviewer for constructive reviews, and we have benefited from discussions with M. Coffin and J. Veevers. This research was supported by U.S. NSF grants OCE-8823028 and EAR-9303535 and Belgian FRFC grant 2.9002.90.

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(Received March 1, 1995; revised January 22, 1996;
accepted January 31, 1996.)