# 42. THE GEOCHEMISTRY OF OCEANIC CRUST AT THE ONSET OF RIFTING IN THE INDIAN OCEAN<sup>1</sup>

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### ABSTRACT

Indian Ocean crust formed at Sites 765 and 766 is geochemically comparable to that presently forming in the Red Sea. In both cases, we interpret the crust as reflecting high degrees of mantle melting that are associated with an enhanced thermal gradient below recently rifted continental lithosphere. Asthenospheric melts formed in this environment are rich in CaO and FeO, poor in Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub>, and characterized by depleted rare earth element (REE) profiles ([La/Sm]<sub>n</sub> approximately 0.5–0.6). Both the Red Sea basalts and the basalts at Sites 765 and 766 are distinct from those erupted at the present Mid-Indian Ocean Ridge.

The isotope characteristics of the Site 765 basalts define a geochemical signature similar to that of the present-day Mid-Indian Ocean Ridge basalts (MIORB). The Indian Ocean mantle domain is distinct from that of the Atlantic and Pacific oceans, and this distinction has persisted since Jurassic time, when the Site 765 oceanic crust was formed.

### INTRODUCTION

Largely because of the difficulties when sampling oceanic basement at continental margins, the composition of oceanic crust at the onset of oceanic rifting is poorly constrained. Rifted margins are commonly covered by a thick sequence of sediments related to subsidence on a passive margin that followed the initial formation of oceanic crust, and thus penetration of the entire sediment section by drilling often is impossible. Where true oceanic crust was sampled at the oceanic margins during the Deep Sea Drilling Project (DSDP), drilling was continued until bit destruction, and usually only a few meters of basement were recovered. A notable exception for DSDP was at Sites 416 and 417 in Cretaceous crust in the west-central Atlantic Ocean. One of the prime objectives of Leg 123 was to obtain a sedimentary section and oceanic basement from the oldest (Late Jurassic) Indian Ocean crust in the Argo Abyssal Plain off the northwestern Australian margin. The low sedimentation rates on this margin since its formation in the Latest Jurassic provided a compact 930-m sedimentary section. This enabled Leg 123 scientists at Site 765 to complete high-resolution biostratigraphic and sedimentological studies of the post-rifting history of the northwestern Australian margin, in addition to relatively easy penetration of 270 m of basement. A second hole (Site 766) was drilled into younger oceanic crust (Early Cretaceous) on the continental margin adjacent to the Gascoyne Abyssal Plain. In this case, the basement was characterized as transitional in acoustic characteristics (see Buffler et al., this volume). In contrast to Site 765, where true oceanic basement was sampled, the acoustic basement at Site 766 comprised a suite of intrusions that had been interbedded with clastic sediments. The tholeiitic magmas that formed the intrusions at Site 766 may overlie highly attenuated northwestern Australian margin basement.

The scientific importance of sampling oceanic crust at the onset of rifting relates to the thermal properties of the mantle at this stage in the formation of an oceanic basin. Given the high heat flux that might characterize a thermal anomaly associated with continental break-up (White and McKenzie, 1989; McKenzie and Bickle, 1988; Campbell and Griffiths, 1990), basalts that erupted in this environment should reflect a higher extent of mantle melting than those that erupted at a mid-ocean ridge axis in a mature ocean basin. For a mid-ocean ridge basalt (MORB) mantle of relatively constant composition, the greater extent of melting should be reflected in high CaO contents relative to Na2O and higher total-FeO contents (Dick and Fisher, 1984; Klein and Langmuir, 1987, 1989). Although variations in trace elements in MORB are greater than for major oxides, increases in the amount of melting (or two-stage melting) should result in higher chondrite-normalized REE depletion of (La/Sm)<sub>n</sub> and Zr/Nb. While basalts that erupted at the present-day ridge axes do show a range in compositions, which may reflect variable amounts of mantle melting (i.e., Dick and Fisher and Klein and Langmuir, op. cit.), basalts that erupted at a rifted continental margin should reflect a greater extent of mantle melting as a result of the higher heat flux at the onset of oceanic crust formation (i.e., White and McKenzie, 1989; McKenzie and Bickle, 1988). This conclusion is supported by Keen et al. (1990), who correlated basement compositions for old oceanic crust (including Site 765) with water depths, based on seismic backtracking calculations from passive margin subsidence curves. In all cases, the implied basement thickness, extrapolated from water depths and correlated with the degree of melting (Klein and Langmuir, 1987), is greater than that of the average of today's ridge axes.

In the Indian Ocean, ocean basement has been sampled near the continental margin in two places: (1) the Argo Abyssal Plain at Sites 765 and 766 (Leg 123), which are located on Jurassic ocean crust formed at the onset of rifting of the Indian Ocean, and (2) the Red Sea, where active rifting is forming new Indian Ocean crust that has been sampled by dredging and submersibles (Eissen et al., 1989). In this chapter, the geochemistry of basalts that erupted in these two regions is compared with that of basalts that erupted at the Mid-Indian Ocean Ridge. While the database is limited, the Indian Ocean does provide two sites where fresh basalts may be sampled from oceanic crust near a continental margin zone of extension.

Basalts that erupted along the present-day Indian Ocean ridges are characterized by isotope compositions that are distinct from those that erupted along the Atlantic and Pacific mid-oceanic ridge axes (Ito et al., 1987; Klein et al., 1988). These differences are largely identifiable in terms of lower <sup>206</sup>Pb/<sup>204</sup>Pb ratios at

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equivalent <sup>87</sup>Sr/<sup>86</sup>Sr and <sup>143</sup>Nd/<sup>144</sup>Nd values and reflect a higher "Dupal" component in Indian Ocean MORBs (Dupré and Allègre, 1983; Hart, 1984; Hamelin et al., 1985). The longevity of these geochemical characteristics has been addressed by isotope analyses in fresh glass samples from Site 765; these results have important consequences for Indian Ocean tectonics and mantle dynamics.

# VOLCANISM ON THE NORTHWESTERN AUSTRALIAN MARGIN

## Northwestern Australian Continental Margin

Seaward-dipping reflectors, which are interpreted as lava flows, have been reported for this margin (Mutter et al., 1988) and are cited as evidence that this was a volcanically active margin when it was rifted. A series of plateaus (the Scott Plateau, the Joey Rise on the Exmouth Plateau, the Wallaby Plateau, the Naturaliste Plateau, and the Zenith Seamount, identified in Fig. 1) probably reflect thick accumulations of volcanic rocks (Veevers and Cotterill, 1978; White and McKenzie, 1989). Although an extended history of Triassic-Jurassic rifting and subsidence prior to breakup existed, White and McKenzie (1989) argued that the final episode of break-up occurred in response to a thermal plume that caused the widespread volcanism now represented in these plateaus. This event was coincident with the uplift of the margin and the formation of an erosional unconformity on the Exmouth Plateau (von Rad and Exon, 1983). The thickest assemblage of volcanic rocks on the continental margin that represents this event has been sampled in the Wallaby Plateau (von Stackelberg et al., 1980). Geochemical data from von Stackleberg et al. (1980), recent analyses performed by the authors, and analyses of bentonite horizons on the Exmouth Plateau (Thurow and von Rad, this volume) indicate that these volcanic rocks are alkaline and subalkaline basalts and rhyolites. The oldest samples, alkaline rhyolites that are underlying Jurassic carbonates in the Wombat Plateau, have been dated by K/Ar at 213 to 192 Ma and may reflect volcanism in response to passive rifting of the margin. The major phase of rifting of the margin occurred between approximately 160 Ma (Site 765) and 130 Ma (Site 766). K/Ar dates from the Scott Plateau of 128 to 132 Ma (von Stackleberg et al., 1980) may reflect the peak of the volcanism that is associated with rifting of the margin. However, K/Ar ages as young as 83 to 89 Ma (von Stackleberg et al., 1980) from the Wallaby Plateau must reflect (1) continued volcanism that is associated with rifting and (2) possible migration of this volcanism toward the west in response to the opening of the Gascoyne and Cuvier abyssal plains.

## Site 765

The locations of Sites 765 and 766 are shown in Figure 2. Seismic studies at Site 765 indicate that this site is clearly in oceanic basement and is less than 75 km oceanward of a prominant magnetic anomaly that represents the ocean/continent boundary (Veevers et al., 1985). A reevaluation of the magnetic lineations in the Argo Abyssal Plain (Sager et al., this volume) places Site 765 between marine magnetic anomalies 25 and 26, corresponding to lower Valanginian to Hauterivian (about 160 Ma). These results are inconsistent with the biostratigraphic ages, for which a maximum age of upper Valenginian is represented (McMinn et al., this volume; Kaminski et al., this volume). These discrepancies may reflect erosion of the sediments directly overlying basement, patchy sedimentation, or inconsistencies during calibration of the marine magnetic anomalies. Radiometric dates for the basement indicate ages of approximatively 155 Ma (Ludden, this volume).

At Site 765, Holes 765C and 765D penetrated 28 and 271 m into volcanic basement, respectively. Twenty-two volcanic units



Figure 1. Location of Sites 765 and 766 (Leg 123) and Sites 759 through 764 (Leg 122) in the Argo and Gascoyne abyssal plains.



Figure 2. Volcanicity on the west Australian margin. Modified from White and McKenzie (1989). Shaded areas represent possible volcanic plateaus. Radiometric ages for the volcanic events are given in the text.

were distinguished on the basis of lithological and geochemical variations. The main lithologies recovered were pillow basalt (54%), massive basalt (28%), diabase (4%), autoclastic breccia (6%), and tectonically brecciated pillow basalt (8%) (Ludden, Gradstein, et al., 1990). Despite the section's being one of the oldest representatives of oceanic basement cored by either ODP or DSDP, rock preservation in it is excellent. Fresh glass is present in pillow margins and within hyaloclastite breccia. Low-temperature alteration is not pervasive and is reflected in well-defined zones of oxyhydroxide and smectite precipitation that extend into the basalts from celadonite and calcite-rich veins (Gillis et al., this volume). Generally, the basalt samples taken at 3 to 4 cm from the low-temperature alteration zones are unaltered or only mildly altered.

Although geochemical data indicate that the lavas are typical, although somewhat evolved, MORB tholeiites, the phenocryst assemblage is atypical for MORBs (Ishiwatari, this volume). The lavas are dominantly aphyric or sparsely phyric, with rare samples having up to 10% phenocrysts. Plagioclase is the dominant phenocryst, while clinopyroxene is the only mafic member in many lavas. Olivine, when observed, has been highly altered and is xenocrystic (Ishiwatari, this volume). In the upper 50 m of basalt, frequent xenocryst clots of calcic plagioclase and clinopyroxene occur.

### Site 766

Site 766 is located at the foot of the western escarpment of the Exmouth Plateau, facing the Gascoyne Abyssal Plain in a water depth of 4008 m (Fig. 1). This site is on the geophysical continent/ocean boundary limit of the most eastward seafloor segment of the Gascoyne Abyssal Plain. The Cape Range Fracture Zone that separates the Gascoyne Abyssal Plain from the Cuvier Abys-

sal Plain to the south extends in a southeast-northwest direction slightly south of the site location. Geophysical investigations (Buffler et al., this volume; Ludden, Gradstein, et al., 1990) indicate that the site is located on transitional ocean crust (i.e., seismic velocities between those of continental basement and those of oceanic basement). The igneous units at Site 766 were encountered below 458 m of sediment. Because of the inclined nature of the contact and the baking of the sediments, the first basalt drilled was interpreted as an intrusive sheet (Ishiwatari, this volume). This unit was followed by an 8-m interlayered sequence of 1- to 1.5-m-thick intrusions and dark green to dark gray siltstone. Below this sequence, coring recovered 60 m of diabase, again interpreted as a thick intrusion. Drilling was terminated while still within this intrusion; thus, Leg 123 scientists were unable to confirm the continuity of these intrusions with volcanic basement. The most reasonable interpretation for this site is that it is located at the outermost limit of the continent/ocean boundary and represents contemporaneous intrusion and sedimentation during the final stages of rifting of the northwestern Australian continental margin. While the low K2O contents of these intrusions argue against contamination by continental crust or synrift sediments, one cannot discount the possiblity that Site 766 is underlain by thinned continental basement.

# GEOCHEMISTRY OF VOLCANIC ROCKS AT SITES 765 AND 766

## **Analytical Techniques**

New geochemical data for the REEs, Th, U, Hf, Ta, and Sc, and for isotopes from glass separates (Site 765 only) are given in Tables 1 and 2, respectively. Whole-rock samples were crushed on board the JOIDES Resolution in a WC grinding vessel. The data and analytical uncertainty for the major elements and for the trace elements, Nb, Zr and Y, were presented in Ludden, Gradstein, et al. (1990) and were obtained by X-ray fluorescence (XRF) on board the JOIDES Resolution. The shipboard XRF data were verified by DCP and INAA analyses, and the REE data were cross calibrated between the Lamont-Doherty DCP laboratory and the Université de Montréal geochemical laboratories (see Plank and Ludden, this volume). The REEs, Th, U, Hf, Ta, and Sc, were determined at the Université de Montréal by INAA using rock powders. The samples were irradiated for 2 hr in a Slowpoke II reactor at a constant neutron flux of  $2 \times 10^{12}$  n/cm<sup>2</sup>/s and counted over a 7- to 60-day period after irradiation using two Ge detectors having a resolution of 0.6 and 1.2 KeV at 122 KeV and 1.33 MeV. respectively. The analytical precision for La, Sm, Eu, Yb, and Sc is <5% and that for Ce, Nd, Ho, Tb, Lu, Ta, Hf, Th, and U is between 5% and 10%.

For each of three samples, 100 mg of fresh glass that had been broken into 1-mm-sized fragments in an agate mortar was selected under a binocular microscope to be free of inclusions, vesicles, microphenocrysts, and altered glass. The glass separates for Srisotope analyses were leached in 2.5N HCl and analyzed using an NBS 12-in. mass-spectrometer at the Université de Montréal. Dissolution and separation of Sr were performed using the standard procedure of Hart and Brooks (1977), and 87Sr/86Sr ratios were normalized to the Eimer & Amend standard value of 0.70800. Samples analyzed for Pb-isotopes and Pb/U determination were washed with "two bottle" distilled H2O, followed by "two bottle" distilled methanol and then analyzed following the technique of Mànhes et al. (1978) at the Université du Québec à Montréal. Because of the need to conserve glass separates for future research (ICP-MS in progress) and because of the limited amount of high-purity samples available, the Nd-isotopes, determined at the University of Alberta, were conducted on leached whole-rock

#### Table 1. INAA analyses of Sites 765 and 766 basalt.

Hole	7650	765D	766A	766A	766 A	766A	766A									
Core- section	63R-01	01R-01	07R-02	13R-03	15R-02	16R-01	18R-01	19R-01	19R-02	22R-01	23R-01	48R-07	49R-04	53R-03	55R-02	55R-03
Interval (cm)	122-124	094-096	009-011	019-021	014-017	039-041	112-114	072-078	032-034	118-121	062-064	025-027	106-108	091-093	074-076	105-118
La	2.2	2.1	2.1	1.9	2.1	1.3	2.2	2.7	2.7	2.0	2.4	5.2	1.7	3.2	2.7	2.8
Ce	7	8	7	5	9	6	7	10	9	7	7	18	6	11	9	9
Nd	7	8	8	6	9	6	8	9	9	8	6	15	6	10	9	9
Sm	3.23	2.98	3.07	2.17	3.24	1.90	3.18	3.48	3.84	2.67	2.63	5.22	2.23	4.14	3.20	3.65
Eu	1.10	1.03	1.06	0.84	1.10	0.62	1.12	1.24	1.30	0.96	0.97	1.72	0.89	1.31	1.13	1.25
Тъ	0.9	0.8	0.9	0.6	0.8		0.9	1.1		0.8	0.7			1.1	0.9	
Ho	1.4	1.4	1.3	1.0	1.4	0.8	1.5	1.9	1.7	1.2	1.1	1.8	1.0	1.8		1.8
Tm		0.5	0.5	0.4			0.6			0.5						
Yb	4.1	3.6	3.7	2.9	3.9	2.3	3.9	4.6	4.7	3.5	3.3	5.3	3.0	5.6	4.7	5.0
Lu	0.59	0.60	0.55	0.44	0.66	0.42	0.60	0.66	0.68	0.50	0.56	0.80	0.49	0.90	0.73	0.81
Sc	46.63	47.86	46.56		45.5	35.5	47.23	47.99	48.1	45.22	46.5	61.2	52.56	51.37	49.3	49.4
Hf	2.9	2.5	2.3	2	3.2	2.3	2.8	2.9	3.4	2.1	2.2	5.4	1.8	3.7	2.8	3.2
Та	2.4	1.3	1.8	0.92	1.9	0.28	1	1.8	3.3	0.7	1.1	1.2	2.3	1.5	1.9	1.5
Th	0.3	0.3	0.3	0.5	0.3		0.5	0.5	0.4	0.3	0.6	0.8		0.6	0.2	0.5
U	0.19	0.11	0.15	0.14	0.2	0.16	0.13	0.14	0.7	0.11	0.6	0.3	0.2	0.5	0.16	0.2

Table 2: Sr, Nd and Pb Isotope Data for Basalts from Site 765,

Sample		87Sr/ 86Sr	143Nd/ 144Nd	206РЬ/ 204РЬ	207РЬ/ 204РЪ	208РЬ/ 204РЬ
765C 063R-01 098-102	Glass	0.70299 +/- 3				
765D 005R-01 053-056	Glass	0.70294 +/- 4		18.062	15.548	37.886
65D 024R-03 098-104	Glass	0.70277 +/- 3		18.178	15.651	38.111
765C 063R-01 122-124	WR			18.184	15.418	37.528
765D 001R-01 094-096	WR		0.51309 +/- 2	18.121	15.490	37.680
765D 013R-01 019-021	WR			18.415	15.448	37.397
765D 027R-02 096-098	WR		0.51309 +/- 1	18.119	15.502	37.781

samples because seawater contamination was considered negligible.

#### Geochemistry of Volcanic Rocks from Sites 765 and 766

The general petrological and geochemical characteristics of the lavas are presented by Ishiwatari (this volume). Both sites are characterized by relatively Fe-rich tholeiites having trace-element characteristics typical of normal mid-ocean ridge basalts (N-MORB). In general, samples from Site 766 have higher TiO<sub>2</sub>, total-FeO, and Zr contents than those from Site 765, indicating a more fractionated composition. FeO contents are >10 wt% for all samples, while the most evolved sample from Site 766 (Sample 123-766A-48R-7, 25–27 cm) has a total FeO content of 15.7 wt%; TiO<sub>2</sub> of 2.79 wt%; and Zr of 168 ppm, approaching the compositions of Fe-Ti MORBs from the East Pacific Rise (Perfitt et al., 1983). In both sites, total FeO contents are greater than those of MIORBs (Fig. 3).

Downhole variation in degree of fractional crystallization was observed for Site 765. This is demonstrated in Figure 4, where Zr and TiO<sub>2</sub> contents are plotted relative to stratigraphy. A distinct cyclicity for these elements can be observed, while the TiO<sub>2</sub>/Zr values remain constant. These variations can be explained in terms of low-pressure fractionation of the phases observed within the basalts. The results of a simple least-squares mixing calculation (Bryan et al., 1969) are presented in Table 3. The variation in major elements can be explained by crystal fractionation of plagioclase and clinopyroxene in approximately equal proportions. Note that olivine is not observed as a phenocryst phase in these basalts and that they represent evolved compositions that might reasonably crystallize clinopyroxene. To achieve a realistic solution to the model, one must remove an oxide phase. In most variation diagrams, total FeO does not display the enrichment trend typical of less-evolved tholeiites (Ishiwatari, this volume). In fact, FeO/MgO values in basaltic glasses from this site display a subtle negative correlation with TiO<sub>2</sub> (the opposite of what one might expect to result from gabbroic fractionation). Ishiwatari interprets this variation as reflecting source heterogeneity in FeO/MgO for the Site 765 basalts.

The REE fractionation exhibited by the Leg 123 lavas is shown in Figure 5. Patterns for the samples from Sites 765 and 766 are depleted with  $(La/Sm)_n$ , which ranges from low values of 0.5 to 0.7; the lavas are characterized by well-developed Eu anomalies. The profiles display a parallel evolution, which is coupled with increasing Zr and other incompatible trace elements. These data are consistent with the results of the fractionation calculations (Table 3) that indicate a low-pressure fractionation process involving approximately 30% extraction of plagioclase and clinopyroxene. The samples from Site 766 exhibit similar LREE depletion, but have higher total REE values in the most evolved samples; again, this is consistent with highly fractionated MORB magma.

Given the relatively minor variation in REE fractionation and constant ratios for Zr, REEs, and Nb, source heterogeneity is probably of minor importance for generating the geochemical trends displayed by the Site 765 and 766 lavas. The somewhat ambiguous geochemical trends displayed by the lavas (Ishiwatari, this volume; Ludden, Gradstein, et al., 1990) are more likely the consequence of a fractionating basaltic magma that was "hungup" on its low-pressure cotectic.

## Geochemistry of Leg 123 Lavas Relative to MIOR and Red Sea Rift Lavas

Despite the effects of low-pressure fractionation, the most mafic lavas at Site 765 are easily identifiable, and one can project approximate fractionation trajectories. At Site 765, a value of



Figure 3. Comparisons of the geochemistry of Site 765 and 766 magmas with the range in compositions from the MIOR. Data for MIOR from Frey et al. (1977); Price et al. (1986); Dosso et al. (1988); Humler and Whitechurch (1988). Fields for Red Sea rift are from glass analyses provided in Eissen et al. (1989).

Most primitive to most evolved basalt									
	$\mathrm{SiO}_2$	Al <sub>2</sub> O <sub>3</sub>	FeOt	MgO	CaO	Na <sub>2</sub> O	TiO <sub>2</sub>	K <sub>2</sub> O	Factor
Product	51.07	13.96	11.70	7.28	11.31	2.59	1.66	0.30	76.5
CPX	52.76	3.31	5.10	18.50	19.90	0.02	0.27	0.15	10.0
PLAG	45.00	35.00	0.00	0.00	18.50	1.50	0.00	0.00	12.5
MT	0.00	0.00	99.99	0.00	0.00	0.00	0.00	0.00	1.5
Parent	50.05	15.27	10.95	7.13	13.11	2.01	1.25	0.25	
Result	49.99	15.41	10.95	7.25	13.01	2.12	1.31	0.25	
Difference	-0.06	0.14	0.01	0.08	-0.10	0.12	0.06	0.02	

Table 3. Leg 123 Site 7	65, Fracti	onal crystallisation	model.
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	Parent	Product	Factor
	(ppm)	(ppm)	(ppm)
Zr	70	95	1.35
Y	30	42	1.40
Nb	1.8	2.5	1.39
La	2.0	2.7	1.35
Sm	2.7	3.8	1.40
Yb	3.5	4.7	1.40
Hf	2.3	3.4	1.47
Ni	80	70	0.85
Cr	210	180	0.85

approximately 1.2 wt% TiO<sub>2</sub> is equivalent to 8 wt% MgO. Relative to other MORBs, the Site 765 magmas are rich in CaO (approximately 13.5–14.0 wt%) and FeO (approximately 9.5–10.5 wt%), and poor in Na<sub>2</sub>O (approximately 1.8–2.0 wt%) and Al<sub>2</sub>O<sub>3</sub> (approximately 13 wt%). For trace elements, the Leg 123 lavas are poor in Zr (65–70 ppm) and La (approximately 2.0 ppm). These characteristics are exemplified in Figure 3, where the Leg 123 lavas (in particular those from Site 765) project to CaO-rich and Na<sub>2</sub>O-poor compositions.

Glass analyses for the Red Sea rift (Eissen et al., 1989) are shown as a field in Figure 3. In terms of CaO, Na<sub>2</sub>O, TiO<sub>2</sub>, and  $Al_2O_3$ , the Red Sea lavas overlap with and/or trend toward the compositions defined by the Leg 123 lavas and are also distinct from lavas from the MIOR and the Mid-Atlantic Ridge, as demonstrated by Eissen et al. (1989).

One of the most important characteristics of the Leg 123 lavas is their high degree of LREE depletion (Fig. 5). The degree of depletion is comparable to, or slightly greater than, that of the most primitive samples from the Red Sea rift (Fig. 5). In general, with rare exceptions, primitive samples from modern MIORs are characterized by  $(La/Sm)_n$  values of approximately 0.7 to 0.9 (Dosso et al., 1988; Price et al., 1986). Similarly, Mid-Atlantic Ridge basalts in the 22° to 27° regions have  $(La/Sm)_n$  values greater than 0.7. Notable exceptions are from areas of thick



Figure 4. Downhole variation in TiO2 and Zr abundances for Site 765 lavas.

oceanic crust (shallow water depths) of the Koblenski Ridge (Schilling et al., 1983).

## Isotope Composition of Jurassic MORB From the Indian Ocean

In Figure 6, the <sup>143/144</sup>Nd and <sup>206/204</sup>Pb results from the Site 765 basalts have been compared to samples from the MIOR and oceanic islands. As demonstrated by Ito et al. (1987) and Klein et al. (1988), the MIORB reservoir is distinct from that supplying basalts that erupted at ridge axes in the Atlantic and Pacific oceans. This is best demonstrated in the <sup>143/144</sup>Nd and <sup>206/204</sup>Pb diagram, as the database for the two oceans is most differentiated in terms of these isotopes. The Leg 123 data fall within the modern MIOR field, indicating that the Indian Ocean mantle reservoir was characterized by distinct composition at 150 Ma and that the

"Dupal" anomaly (Hart, 1984) is not a recent feature on Earth. The Red Sea basalts fall within the limit of the Indian Ocean and Atlantic-Pacific domains and are geographically at the limit of the Dupal domain defined by Hart (1984).

# DISCUSSION

# Geochemical Characteristics of Magmas at the Onset of Oceanic Rifting

Both the Red Sea basalts and the Leg 123 basalts were formed near the continental margin at the onset of rifting in the Indian Ocean. The Red Sea represents crust formed by the melting of Indian Ocean mantle since the last 3 Ma (Eissen et al., 1989). Site 765 basaltic crust, on the other hand, formed from Indian Ocean



Figure 5. Chondrite-normalized REE plots for lavas from Sites 765 (upper diagram) and 766 (lower diagram). Red Sea samples field from Eissen et al. (1989).

mantle about 155 Ma ago. In both cases, the tectonic environment is that of a recently formed oceanic basin, with thinned continental crust in close proximity and with a significant mantle thermal anomaly associated with the rifting process. Despite the presence of these thermal plumes (the Afar hot spot for the Red Sea and the hot spot that erupted the mafic plateaus represented in Fig. 1 for the northwestern Australian margin), the basalts that erupted at both sites are LREE-depleted MORBs having geochemical characteristics that are generally distinct from those of MORBs that erupted in mature ocean basins (i.e., the Central Mid-Indian Ocean Ridge, the East Pacific Rise, and the Mid-Atlantic Ridge). In terms of major elements, the magmas are high in CaO and FeO and low in Na<sub>2</sub>O and Al<sub>2</sub>O<sub>3</sub>, relative to MORBs that erupted in the Central Indian Ocean ridges. In addition, these lavas have low (La/Sm)<sub>n</sub> and low incompatible trace elements (such as Zr and Nb), relative to MIORs and other MORBs that erupted in mature ocean basins. All of these characteristics reflect the great extent of mantle melting that might be expected to characterize a hot oceanic mantle at the onset of oceanic rifting (cf. Klein and Langmuir, 1987). Keen et al. (1990) suggested that such geochemical characteristics are typical of old oceanic crust in all oceanic basins. Their data were based on a correlation of geochemistry with depths to oceanic basement defined from seismic backtracking calculations; the depth indicated for Site 765 is approximately 2.5 km. Both the Red Sea and Leg 123 data indicate that the Indian Ocean mantle was hotter at the inception of oceanic rifting, while the ridges that are distant to the continental margins, in general, were formed over a cooler mantle, with the consequent differences in basalt geochemistry and thickness of oceanic crust.

### Isotope Evolution of the Indian Ocean MORB Reservoir

As demonstrated in Figure 6, Jurassic Indian Ocean mantle was similar in isotopic character to the mantle now being sampled at the MIOR. Its distinctive character must pre-date the formation of the present Indian Ocean. Paleomagnetic data indicate that Site 765 was erupted at approximately 30°N (Ogg, this volume). Hart (1984) suggested that the Dupal characteristics of the Indian Ocean have a prolonged history in the Earth (possibly as much as 1700 Ma) and that these anomalies represent material having continental characteristics that was reinjected into the mantle during the mid-Proterozoic. The Leg 123 results indicate that this material was available in the upper Indian Ocean mantle at the onset of rifting; the transfer of the Dupal-type mantle into the MORB reservoir therefore must either have pre-dated rifting of the Indian Ocean or may be a general characteristic of the Indian Ocean MORB reservoir.

### CONCLUSIONS

Basalts at Site 765 and Site 766 were erupted on the northwestern continental margin at the onset of rifting of the Indian Ocean at 155 Ma. They are LREE-depleted MORBs that are characterized by higher CaO and FeO and lower Na<sub>2</sub>O, Al<sub>2</sub>O<sub>3</sub>, (La/Sm)<sub>n</sub> and incompatible trace elements than basalts erupted at the present MIOR. They share many geochemical similarities to tholeiitic basalts of the Red Sea rift. Both Site 765 and the Red Sea basalts were formed at the onset of rifting of the Indian Ocean at 155 Ma and 3 to 5 Ma, respectively. The geochemical characteristics of both regions reflect high-degrees of melting of the oceanic mantle that may be related to the enhanced thermal regime characteristic of the initial stages of continent to oceanic rifting. In the case of the Red Sea, the thermal anomaly is reflected by the presence of the Afar hot spot and for the northwestern Australian margin by extensive plateaus of volcanic rocks that were formed at the time of continental break-up (160-130 Ma). The geochemical characteristics recognized for the Red Sea and Sites 765 and 766 may be applicable generally to oceanic crust formed at the onset of rifting.

Isotopic characteristics of Jurassic MORB were similar to those of MORB currently being erupted in the Indian Ocean. In both cases, the basalts are isotopically distinct from those erupted in the Atlantic and Pacific oceans, indicating that the source of Indian Ocean MORB was of Dupal composition from the onset of spreading.

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Figure 6. <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>206</sup>Pb/<sup>204</sup>Pb variations for lavas from the ridge axes of the Indian Ocean. Leg 123 Jurassic basalts and Red Sea basalts indicated by shaded boxes. Indian Ocean data from following sources: Cohen et al. (1980, 1982); Dosso et al. (1979, 1980, 1988); Eissen et al. (1989); Hamelin and Allègre (1985); Hamelin et al. (1985); Ito et al. (1986); Klein et al. (1988); Michard et al. (1986); Price et al. (1986); Roden et al. (1984); Storey et al. (1988).

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