10. PETROLOGY, GEOCHEMISTRY, AND MINERALOGY OF THE EARLY CRETACEOUS EVOLVED N-MORB FROM SITES 765 AND 766, EASTERN INDIAN OCEAN¹

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ABSTRACT

The Early Cretaceous basaltic rocks obtained from Sites 765 and 766 in the eastern Indian Ocean floor were mostly iron-rich normal mid-ocean ridge basalts (N-MORB), which were derived from a depleted mantle source having strongly light rare earth element (LREE)-depleted rare-earth patterns and a high titanium/zirconium (Ti/Zr) ratio. Basaltic rocks in the upper part of the Site 765 basement section include megacrysts and gabbroic fragments of widely varying mineral chemistry. These megacrysts range from An₉₀ plagioclase, including highly magnesian basaltic glass coexisting with augite of Mg# (= 100 Mg/[Fe+Mg]) at 85, to An₅₀ plagioclase coexisting with hypersthene. This varying mineralogy of megacrysts and gabbroic fragments indicates that a considerable degree of fractional crystallization took place in the magma chamber. The unusual negative correlation between incompatible elements (e.g., TiO₂) and FeO*/MgO observed among Site 765 basement basalts and fresh volcanic glasses suggest source-mantle heterogeneity in terms of FeO*/MgO. Strontium isotope ratios (87 Sr)⁶⁶Sr) of the basaltic rocks from both sites are between 0.7027 and 0.7033 and are comparable to those of mid-Indian Ocean ridge basalts (MIORB).

The basalt pebbles encountered in the sedimentary section may have been transported from the basement highs nearer the Australian continent and include basaltic compositions ranging from primitive N-MORBs to evolved enriched(E)-MORBs. Their mantle source was not as depleted as that of the basement basalts. These rocks may be the products of earlier volcanism that took place during the rifting of the Australian continent.

INTRODUCTION

This chapter describes the petrography, geochemistry, and mineral chemistry of the basaltic rocks that constitute one of the oldest basement regions of the floor of the eastern Indian Ocean off the northwestern margin of Australia. The basalt pebbles encountered in the turbidites of the overlying Cretaceous and Tertiary sediments also were studied in some detail, because they were derived from areas nearer the Australian passive margin and thus could provide information about volcanism associated with early rifting events prior to ocean floor spreading.

Chemical and isotopic heterogeneities having a scale of 100 km in the mantle along ocean ridges were established in the 1970s (Wood et al., 1979, and references therein), and a global anomaly was recognized in the 1980s (Dupré and Allègre, 1983; Hart, 1984). The present Mid-Indian Ocean Ridge (MIOR) lies mostly in this "Dupal anomaly" that dominates the Southern Hemisphere. The isotopic difference between MIORB and the other MORBs in the Pacific and Atlantic oceans has been explained by the contamination of the depleted N-MORB source in a shallow mantle with the deeper, enriched Dupal material. The anomaly of MIORBs is especially distinct in the area around the triple junction (70°E, 26°S) (Price et al., 1986).

The presence of this global isotopic anomaly and the two-street chemical layering model of the mantle (MORB source/Dupal material) has been challenged by Holness and Richter (1989), who postulated smaller-scale, but widespread, heterogeneity in the mantle. These authors documented that the trace-element and isotope chemistries of MORBs correlate well with the spreading rate of the ridge in the Atlantic and Pacific oceans; the lanthanum/samarium (La/Sm) and ⁸⁷Sr/⁸⁶Sr ratios decrease with spreading rate. This correlation may result from a mantle composed of a fine patchwork of the enriched and depleted segments, perhaps on a scale of 1 km or smaller, and selective melting of the enriched segments in a slow-spreading environment.

The evolved N-MORBs of Early Cretaceous age obtained from the basement sections of Sites 765 and 766 constrain these global and local mantle heterogeneities, as discussed above.

DESCRIPTION AND RESULTS

Lithostratigraphy of the Drilled Basement Section

The lithostratigraphy of the basaltic basement drilled at Site 765 is presented in Figure 1. The basement is composed of pillow lava (54%), massive lava flows (28%), basaltic breccia (8%), hyaloclastite (6%), and a diabase sill(?) (4%). The basement sections of Holes 765C and 765D are divided into 24 lithologic units, which were based primarily on visual differences in the core, but in some cases were divided by a geochemical change in a visually homogeneous lithology.

The sediment/basement interface was recovered from Hole 765C at a depth of 935 mbsf, where red calcareous clay of early Berriasian or late Valanginian age conformably overlies the altered green hyaloclastite (Ludden, Gradstein, et al., 1990, p. 184, Fig. 89). The matrix of the hyaloclastite is white calcite crystals with some red clay. The hyaloclastite is only 10 cm thick and is underlain by a thick pile of pillow lavas.

The sediment/basement interface was not recovered in Hole 765D, which is a maximum of 100 m away from Hole 765C. The upper 50 m of the basement section (i.e., from Unit 1 to Unit 3) consists of massive lava flows, with intercalations of breccia and hyaloclastite. The lower 200 m is composed mainly of pillow lavas, with intercalations of at least five massive lava flows and at least five breccia/hyaloclastite sequences. Unit 7 is distinctly coarser-grained than others and may be a diabase sill (or a lava flow) about 10 m thick, although the upper and lower contacts were not recovered.

The basement basalts of Hole 765C and in the upper 50 m of Hole 765D include many megacrysts (as defined by Donaldson and Brown, 1977) of plagioclase and clinopyroxene, as well as

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Figure 1. Lithostratigraphy of Site 765 basement. Symbols (1) diabase sill, (2) sheet flow, (3) alternation of breccia and sheet flow, (4) pillow lava, (5) hyaloclastite, and (6) breccia. "Sv" signifies the occurrence of segregation vesicles at the level. Bulk rock TiO_2 contents are based on shipboard XRF analyses (see *Init. Repts.* volume for data).

fragments of gabbroic rocks up to 1 cm in diameter (see Ludden, Gradstein, et al., 1990; p. 189, Fig. 95 and p. 190, Fig. 97). The megacrysts and gabbroic fragments from Hole 765D are of a relatively evolved composition, as indicated by the occurrence of hypersthene-bearing gabbro fragments, but those from Hole 765C

are primitive and bear highly magnesian basaltic melt inclusions (Plate 1).

The basement rocks are locally fresh despite their Early Cretaceous age. Fresh glass having an obsidian luster in some cases is preserved in the chilled rim of a pillow lava or in the fragments of green hyaloclastite (see Ludden, Gradstein, et al., 1990; p. 184, Fig. 90). In most cases, however, this glass was replaced by green clay, zeolite, and calcite. Alteration halos (2 or 3 cm wide) have developed along joints in pillow lavas or massive lava flows throughout the basement section (see Ludden, Gradstein, et al., 1990; pp. 196–197, Figs. 100–103 and Adamson et al., this volume).

Many pebbles of basaltic rocks were recovered from the conglomerate beds in the sedimentary section. These are associated with a large number of sandstone, mudstone, limestone, and ironstone pebbles. The age of the conglomerate beds that contain these basaltic pebbles ranges from Late Cretaceous to Quaternary. However, the majority occur in a Miocene turbidite sequence occupying more than one-half the thickness of the sedimentary section. Some pebbles are *in-situ* with molded contacts, but others occur as "drill breccia." These dropped from the wall of the drill hole and then were accidentally recovered later on top of a subsequent core. Including these "drill breccia," more than 100 basalt pebbles were found from 44 levels. Most pebbles are 2 to 5 cm in diameter and subangular to well-rounded. The largest pebble was 14 cm long and more than 6 cm wide.

The lithostratigraphy of Site 766 "basement" is presented in Figure 2. The lowermost part of the sedimentary section is composed of massive black siltstone of Valanginian age, with pyrite nodules and wood fragments. The basaltic rocks forming the acoustic basement are intrusions cutting the siltstone. Units 1, 2, and 3 are gently inclined sills having a thickness of 2.5, 0.4, and 2.0 m, respectively. These sills have fine-grained chilled margins, and the adjacent siltstone was thermally hardened for 10 cm from the contact. The interface between Unit 2 and the sediments is



Figure 2. Lithostratigraphy of Site 766 "basement." Basalt (Units 1 through 3) and diabase (Units 4 and 5) were intruded into black siltstone of Valanginian age (dots). Units 1 through 4 may be gently inclined sills, while Unit 5 may represent steeply dipping dikes. Unit 4 is vesicular. Solid line in Unit 5 indicates a chilled margin, and thick broken lines represent gabbroic layers. "qz" represents the occurrence of euhedral igneous quartz in the mesostasis; "sv" signifies that of segregation vesicles.

sinuous. Unit 4 is distinguished from the other units by its highly vesicular nature. This unit may also be a sill, although its lower contact was not recovered. The lowest unit of Hole 766A is a medium- to coarse-grained diabase body (Unit 5) at least 47 m thick. All internal features of Unit 5 (such as cooling boundaries, coarse-grained gabbroic layers as thick as 10 cm, and parallel platy joints at 2- or 3-cm intervals) are consistently inclined at 50° to 60° (see Ludden, Gradstein, et al., 1990; p. 318, Fig. 47; p. 322, Fig. 50; and p. 333, Fig. 72), suggesting that the diabase body is a steeply inclined dike. Units 1, 2, and the upper part of 4 have been strongly altered, while the other parts are relatively fresh. However, no glass was preserved at this site.

Petrographic Characteristics of the Basaltic Rocks

The basaltic rocks forming the basement of Site 765 are mostly aphyric. Grain size of the groundmass, defined by the average length of the 10 largest plagioclase laths in a thin section, ranges from 0.1 mm in the pillow margins to 0.4 mm in the pillow cores, and is 0.6 to 0.8 mm in a thick massive flow, and as large as 1.2 mm in the diabase sill. Plagioclase, clinopyroxene, and olivine occur as phenocrysts. The abundance of clinopyroxene, the scarcity of olivine, and the absence of spinel as phenocryst are unusual for MORBs and suggest evolved magmas. The evolved nature of the magma is also suggested by the occurrence of segregation vesicles (Anderson et al., 1984; Sato, 1978). The segregated magma is of Fe-Ti basalt composition, and is now composed of quench crystals of ilmenite, Fe-Ti augite, and plagioclase (Plate 1, Fig. 1).

As mentioned in the lithostratigraphy section, a number of megacrysts and gabbroic fragments were found in the upper 50-m section of the basement at Site 765. Of their constituent minerals, plagioclase is abundant, clinopyroxene common, and orthopyroxene rare. The plagioclase megacrysts exhibit remarkable concentric zoning and dense accumulations of tiny glass inclusions of about 10 mm in diameter occur in some zones (Plate 1, Fig. 2). The lavas of the upper part of Hole 765D tend to bear megacrysts and gabbroic fragments made of low-An plagioclase, low-Mg clinopyroxene, and rare orthopyroxene; these lavas may have sampled higher parts of a solidifying magma chamber than those in Hole 765C, which contain megacrysts and gabbroic fragments with plagioclase as calcic as An_{90} and clinopyroxene having a Mg# as high as 85.

The petrographic characteristics of Site 766 basement are diverse (Fig. 2). Unit 1 is moderately phyric, with plagioclase, clinopyroxene, and olivine phenocrysts, and is clearly distinguished from the other aphyric units. Unit 4 is highly vesicular. These vesicles are filled with green clay minerals or calcite. The coarse-grained diabase or gabbro of Unit 5 bears euhedral or subhedral quartz as the latest crystallization product in its mesostasis. This indicates that the magma was silica-saturated and evolved.

Bulk Rock Chemistry of the Basaltic Rocks

Five pebbles and 39 basement rocks of Site 765, as well as one pebble and 13 "basement" rocks of Site 766, were analyzed for major and trace elements in the shipboard XRF laboratory (see Ludden, Gradstein, et al., 1990 for these data). In addition, the fresh volcanic glass samples were analyzed by an energy-dispersive X-ray analyzer EDAX-9100 on the Akashi a-30A SEM of the Faculty of Science, Kanazawa University. Natural minerals and quenched glass beads of molten Geological Survey of Japan (GSJ) standard rocks were used as standards.

The average chemical composition of Site 765 basement closely resembles that of typical MORBs in respect to low P_2O_5 and moderate TiO₂ (1.5 wt%), while being slightly poorer in MgO and richer in FeO^{*} (Table 1). The latter features indicate that the

Table 1. Representative bulk-rock chemistry of the basaltic rocks from Sites 765 and 766.

	Site	765	Site 766				
Unit	Basement	Pebble	Unit 1	Unit 3	Units 4,		
No. ^a	38(9)	1(1)	1(1)	1(1)	11(3)		
Major elements (in oxide wt%)					
SiO ₂	50.53	49.40	47.41	50.05	50.60		
TiO ₂	1.50	1.15	2.97	1.10	1.79		
Al ₂ O ₃	14.79	19.37	16.88	15.15	13.34		
bFeO"	11.08	9.17	15.88	9.38	13.77		
MnO	0.21	0.14	0.15	0.16	0.23		
MgO	6.82	6.96	5.46	7.82	6.86		
CaO	12.03	10.77	7.22	13.45	10.66		
Na ₂ O	2.35	2.85	4.01	2.77	2.59		
K ₂ O	0.59	0.15	0.09	0.06	0.05		
P ₂ O ₅	0.10	0.04	0.23	0.06	0.11		
Total	100.00	100.00	100.00	100.00	100.00		
^c LOI	1.12	3.64	2.26	1.10	0.78		
FeO [*] /MgO	1.62	1.32	2.91	1.20	2.01		
Minor elements ((in ppm)						
Rb	10	1	<1	<1	<1		
Ba	11	12	10	<1	6		
Nb	2	2	5	2	3		
Ce	11	5	24	6	12		
Sr	89	233	129	107	77		
Zr	83	64	167	56	94		
v	378	250	617	303	427		
Y	36	23	46	26	42		
Cr	194	607	160	315	118		
Ni	75	360	61	70	61		
Cu	71	81	92	116	95		
Zn	104	85	155	84	114		
Co	53	55	55	47	55		
Sc	47	40	51	49	50		
Hf	2.4	1.7	3.7	2.0	2.5		
Rare earth eleme	nts (in chondr	ite-normali	zed values	.)			
La	^d 5.6	4.8	11.6	<4	6.2		
Ce	8.1	<7	15 3	<7	9.3		
Sm	13.9	8.7	19.1	87	15.2		
En	13.7	9.8	17.0	8.8	13.9		
Yb	15.2	8.8	17.3	9.1	19.3		
1	12.0	0.5	16.0	0.0	10.0		

Note: The major-element oxide values are normalized to total 100%. Co, Sc, Hf, and REEs were analyzed using INAA method, and the other elements using shipboard XRF analysis.

^a Number of XRF and INAA (in parentheses) analyses averaged.

b Total Fe as FeO.

^c LOI = loss on ignition.

^d 3.2 to 4.5 in the upper part and 6.0 to 7.0 in the lower part of the basement section.

magma was evolved. The average K_2O and rubidium contents are distinctly higher than N-MORB, but these contents are positively correlated with the loss on ignition, and thus may have been introduced during alteration. The chemical composition of the basaltic rocks is relatively homogeneous throughout the whole basement section of Site 765 (dots in Figs. 1 and 3A), which consists of several repetitions of slightly evolved and primitive lavas superimposing each other. Systematic downhole differentiation is absent.

The basaltic pebbles in the sedimentary section of Site 765 have a highly diverse chemistry. These pebbles include depleted N-MORBs that are richer in chromium and nickel than the most primitive basalt of the basement, T- or E-MORBs with LREE/ HREE ratios larger than chondrite and with clinopyroxenes having an alkalic differentiation trend (see next section), and the oceanic andesite having 54 wt% SiO₂. Note that even the most



Figure 3. TiO_2 -Zr diagram for basaltic rocks at Sites 765 (dots) and 766 (circles) rocks (A) in comparison with representative basaltic rocks of the Indian Ocean floor (B). Unit 1 of Site 766, for example, is designated as "766-1," and pebbles are represented by "P." The basaltic rocks from Sites 259, 260, and 261 from the eastern Indian Ocean floor (Robinson and Whitford, 1974) also are plotted in **B**. MIOR 70°E and SWIOR represent Mid-Indian Ocean Ridge 70°E and Southwest Ridge, respectively (both after Price et al., 1986). FeTiB 90ER stands for Fe, Ti-basalt of Ninetyeast Ridge (Thompson et al., 1986), EPR 19S for East Pacific Rise 19°S (Erzinger, 1986), and MAR 34-36N for Mid-Atlantic Ridge 34°–36°N (Wood et al., 1979). The numbers in italic are Ti/Zr ratios.

primitive N-MORB pebbles contain more Na_2O than the differentiated basement basalt. This does not result from the more intense alteration of the pebbles, because fresh glass in another N-MORB pebble is also more sodic than the glass that formed pillow margins of the Site 765 basement (Table 2). These features suggest that the pebble basalts were derived from a more enriched source than the basement basalts of Site 765. The glass samples from Site 765 basement resemble their crystalline counterparts (Tables 1 and 2). Among the five pillowmargin glass samples listed in Table 2, however, an unusual trend was observed. TiO₂ (possibly also Na₂O and K₂O) decreases with increasing FeO*/MgO. This trend cannot be reconciled with general fractionation processes in ordinary terrestrial basaltic magmas. Nevertheless, the trend itself is due neither to analytical error

		Site	Site 765 glass inclusions in plagioclase						
	Pebble			Basement	Basement				
Sample: Interval (cm):	B31X-1 151-153	D24R-3 91-96	D5R-1 48-50	C63R-1 55-57	C63R-2 13-15	C63R-1 122-124	C63R-3 76-81	C63R-3 76-81	C63R-2 61-63
SiO ₂	50.46	50.17	51,42	51.55	51.98	51.05	50.92	51.38	51.51
TiO ₂	1.38	1.62	1.54	1.49	1.49	1.45	0.96	0.98	0.69
Al ₂ O ₂	15.71	14.52	14.04	13.81	13.49	13.82	5.89	8.62	8.57
Cr2O3		0.21					0.41	0.16	0.00
FeO*	9.29	11.23	11.04	11.85	11.94	12.96	13.32	12.05	12.72
MnO	0.16	0.25	0.21	0.20	0.21	0.18	0.34	0.33	0.17
MgO	7.98	7.75	7.10	6.85	6.74	6.82	15.23	12.93	11.93
CaO	11.79	11.75	12.45	11.82	12.16	11.72	12.27	11.49	12.69
Na ₂ O	3.11	2.27	2.03	2.41	1.99	1.72	0.43	1.46	1.54
K ₂ O	0.12	0.23	0.00	0.02	0.00	0.03	0.24	0.60	0.19
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
FeO [*] /MgO	1.16	1.45	1.55	1.73	1.77	1.90	0.87	0.93	1.07

Table 2. Major-element chemistry of volcanic glass in pillow margins and of glass inclusions in plagioclase megacrysts.

Note: The oxide values are normalized to total 100%.

nor to faulty sampling, because the identical trend can be observed among 39 crystalline basalt samples of Site 765 that were analyzed in the shipboard XRF laboratory (Fig. 4). The origin of this unusual trend will be discussed later.

The most primitive magma at Site 766 crystallized as Unit 3. This is an N-MORB having 8 wt% MgO, 300 ppm Cr_2O_3 , and only 60 ppm zirconium (Fig. 3A). The most evolved magma is that of Unit 1, an Fe-Ti basalt having 16 wt% FeO* and 3 wt% TiO₂. Units 4 and 5 are evolved N-MORBs having FeO* and TiO₂ values averaging 14 and 1.8 wt%, respectively (Table 1). Thus, each unit of Site 766 has unique petrographic and chemical characteristics, although all units exhibit systematic increase of TiO₂ with increasing FeO*/MgO (Fig. 4). This contrasts with the trend observed at Site 765. The Ti/Zr ratio is uniform (= 120) throughout all units (Fig. 3A), suggesting that they are comagmatic. However, the REE geochemistry shown below indicates that Units 3 through 5 are derived from a more depleted source than that of Units 1 and 2.

Rare Earth Elements in Basaltic Rocks

Two pebble samples, eight samples from Site 765 basement, and six samples from Site 766 were analyzed for REEs and Co, Sc, and Hf by neutron activation methods using the Kyoto University reactor and a gamma-ray spectrometer having a Ge(Li) detector at the Radio-Isotope Center, Kanazawa University. The results are presented in Figure 5 and summarized in Table 1. The Leedey chondrite was used to normalize the REE values.

A pebble sample (123-765D-IR-1, 6-8 cm) shows a LREE-enriched pattern with a $(La/Sm)_N$ ratio (lanthanum/samarium ratio in chondrite-normalized values) of 1.63, which is comparable to that of T- or even E-type MORBs. Another pebble sample (123-765B-13R-1, 96–98 cm) shows an LREE-depleted pattern with a



Figure 4. TiO_2 -FeO*/MgO relationship among Site 765 volcanic glasses (open circles) and crystalline basalts (solid circles). The two suites exhibit an identical, but unusual trend, i.e., TiO_2 decreases with increasing FeO*/MgO. Site 765 glass inclusions in plagioclase megacrysts (open triangles) and Site 766 basalts and diabase (open squares) also are shown for comparison (see text for discussion).



Figure 5. Chondrite-normalized REE patterns of basaltic rocks at Sites 765 and 766. Leedey chondrite was used for normalization.

 $(La/Sm)_N$ ratio at 0.55, but it is not as LREE-depleted as the basement rocks of Site 765 (<0.48).

The basement rocks of Site 765 invariably show the LREE-depleted patterns that are typical of N-MORBs. The REE distribution shows uniform concentration of HREE averaging 14 times chondrite and strong depletion in LREEs (Table 1), i.e., a typical pattern of N-MORBs. The N-MORBs of Site 765 are homogeneous in respect to the heavy and intermediate REEs, whose concentration ranges from 11 to 16 times that of chondrite. The light REEs, however, show significant stratigraphic change. The upper part of Site 765 basement is poor in La (<1.9 ppm), while the lower part is relatively rich in La (>2.2 ppm). The (La/Sm)_N ratio is 0.2 to 0.35 in the upper, megacryst-bearing lavas originated from a more depleted source than the lower lavas.

The Site 766 "basement" also may be divided into two parts in terms of REE chemistry, i.e., the upper part showing a relatively flat pattern and the lower part with an LREE-depleted pattern. The porphyritic Fe-Ti basalt of Unit 1 shows a flat but slightly LREEdepleted pattern with a (La/Sm)_N ratio of 0.69. The HREE concentrations are 17 times those of chondrite. The aphyric basalt forming a small irregular sill or flow (Unit 2) is characterized by a fairly flat REE pattern, with a (La/Sm)_N ratio of 1.03. In contrast, the lower, thick diabase intrusions of Units 4 and 5 show a strongly LREE-depleted pattern, with (La/Sm)_N ratios between 0.30 and 0.38. These rocks are fractionated, and their HREE contents approach 20 times those of chondrites. Unit 3 is the poorest in REE concentrations (9 times that of chondrite for HREE) in agreement with its primitive chemistry, such as low FeO*, high Cr, and so forth. LREE content of Unit 3 was below the detection limit, suggesting an LREE-depleted pattern.

Strontium Isotope Chemistry

Strontium isotope ratios of four basalt samples were measured at the Institute for Study of the Earth's Interior, Okayama University, under the instructions of H. Kagami and with the assistance of T. Nakajima of Kanazawa University. Prior to this measurement, the powdered rock samples were leached with 6N-HCl to eliminate the effect of alteration minerals. The results are listed in Table 3.

The samples from Units 15 and 16 from the lower part of Hole 765D have ⁸⁷Sr/⁸⁶Sr ratios of 0.7028 and 0.7027, respectively. The crystalline basalt of Unit 3 and the diabase of Unit 5 of Site 766 have ratios of 0.7030 and 0.7033, respectively. As these basaltic rocks are poor in rubidium (10 ppm or less) and relatively rich in strontium (80–100 ppm), the initial ⁸⁷Sr/⁸⁶Sr ratio (SrI) at the time of their formation (Early Cretaceous) may have been lower than the present ratio by only 0.0001 or less. The present MIORB shows SrI values of between 0.7030 and 0.7033 in the vicinity of the triple point and 0.7027 in the other ridge segments. The measured SrI ratios of Site 765 and 766 basalts are within this range.

Mineral Chemistry

Clinopyroxene

Fe-Mg-Ca plots of pyroxenes in basalts from Sites 765 and 766 are presented in Figure 6, and representative pyroxene analyses are listed in Table 4. The clinopyroxene megacrysts from the Hole 765C basalts have a Mg# as high as 87. The clinopyroxene megacrysts from the upper basalt flows of Hole 765D are richer in Fe and have a Mg# of between 71 and 81, the range that roughly corresponds to that of the phenocrysts and groundmass clinopyroxenes from the Site 765 basalts. The brown dendritic clinopyroxene in the segregation vesicles is as Fe-rich as Mg# 50. The clinopyroxene in diabase exhibits strong chemical zoning. For example, the most primitive basalt forming Unit 3 of Site 766 bears clinopyroxene having a Mg# of 85 in the core and 25 in the rim (Table 4). These clinopyroxenes follow a typical tholeiitic trend in the Ca-Mg-Fe diagram with relatively low Ca concentrations. In contrast, the clinopyroxenes in the basalt pebbles from the sedimentary section of Site 765 follow an alkali-basaltic trend, keeping high Ca concentrations through fractionation (Fig. 6).

The megacryst, phenocryst, and groundmass clinopyroxeness from basement at Sites 765 and 766 contain 2 to 4 wt% Al_2O_3 and less than 1 wt% TiO₂, the range that corresponds to that of tholeiitic clinopyroxenes (Fig. 7). The differentiated clinopyroxenes in the segregation vesicles contain 5 to 6 wt% Al_2O_3 and 2 wt% Ti₂O. However, the clinopyroxenes from a few basalt pebbles contain more than 6 wt% Al_2O_3 not withstanding their magnesian compositions. This again indicates an alkalic basalt affinity of the magma from which these pebbles were derived. Similar alkali-tholeiite transitional basalt with a Ca-rich clinopyroxene trend was reported from the Asal Rift in the Afar area (Bizouard and Richard, 1980).

Orthopyroxene

A single crystal of orthopyroxene occurs in a gabbroic fragment from the upper 50-m section of the basement at Hole 765D. This is a pleochroic hypersthene with a Mg# of 68. The associated coarse-grained clinopyroxene (Mg# = 71) is as rich in Fe as the groundmass clinopyroxene (Mg# = 72), and the associated coarsegrained plagioclase (An₅₂) is more sodic than the groundmass plagioclase (An₆₆).

Plagioclase

The plagioclase megacrysts from Hole 765C are as calcic as An_{86-91} , while those from Hole 765D are as sodic as An_{52} . The groundmass plagioclase of the basalt and diabase from Site 765 ranges from An_{60} to An_{70} . The plagioclase segregation vesicles is about An_{86} . The plagioclase phenocryst from Unit 1 of Site 766 is the most calcic at that site (An_{86}). The groundmass plagioclase in the most primitive basalt of Unit 3 is An_{73} , and that of the diabase in Units 4 and 5 is An_{61} to An_{61} . Although the coexisting clinopyroxene shows strong chemical zoning, the plagioclase in the diabase is almost homogeneous. The groundmass plagioclase from the basalt pebbles ranges from An_{54} to An_{67} , and the phenocryst is as calcic as An_{75} .

The An₆₅₋₇₅ plagioclase in some pebble samples (123-765D1R-1, 6-8 cm, and 123-766A-9R-5, 74-76 cm) includes a 1.4 mol% Or component and is distinctly more potassic than any plagioclase from the basement (<0.4 mol% Or). This clearly indicates the K-enriched nature of the magma, which formed basalt pebbles.

The relationship between the An content of the plagioclase and the Mg# of the coexisting clinopyroxene is shown in Figure 8. The plagioclase-clinopyroxene pairs from Sites 765 and 766 plot mostly at the evolved end of the MORB field, while the megacryst pairs plot at the primitive end. The quenched pairs in the segregation vesicles are on the tholeiitic differentiation trend of the Bushveld Complex. The plagioclase-clinopyroxene pairs in the basalt pebbles have a more diverse composition, and some of them do not follow the general differentiation trend of the basement rocks.

Glass Inclusions in Plagioclase Megacrysts

These inclusions have a primitive chemistry (Table 2), with low FeO*/MgO (0.8–1.0), low TiO₂ (0.7–1.0 wt%), and high CaO (11–13 wt%). These inclusions can coexist with Fo₈₈ olivine, and they may be parental to the evolved N-MORBs at Sites 765 and 766 (Fig. 4). These inclusions are richer in MgO and FeO* and poorer in Al₂O₃ than those reported from the Atlantic and Pacific oceans, but the FeO*/MgO ratios are roughly the same (Fig. 9). The difference may result from post-entrapment chemical changes. The crystallization of plagioclase at the wall of the liquid inclusion causes depletion of the plagioclase component (Al, Ca) and enrichment of the plagioclase-incompatible elements (Fe, Mg) in the residual liquid (Fig. 9). The high Mg# of these glass inclusions suggests that the primary magma of the basement basalt at Site 765 was as primitive as that of Atlantic and Pacific N-MORBs.

Spinel

Spinel was found only in the primitive basalt pebbles at Site 765 as microphenocrysts or inclusions in olivine phenocrysts. These are ferric-poor chromian spinels with a Cr/(Al + Cr) value of about 0.4, which is typical of MORBs (Table 3).

Magnetite

Magnetite occurs as an interstitial mineral in diabase and includes as much as 23 wt% TiO_2 (Table 3).

DISCUSSION

Origin of Negative Correlation between TiO₂ and FeO*/MgO

The negative correlation of TiO_2 with FeO^{*}/MgO in the Site 765 basement (as shown in Fig. 4) was observed among both the

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	Site 765									Site 766								
				Megacrysts		Basalt		Diabase		Basalt	"Basement"							
Occurrence:	В	asalt pebble	es	ir	h basalt flow	1	flo	w	sill	(?)	pebble	Unit 1	Uni	it 3	Unit 4		Unit 5	
Core: Interval (cm):	C13R-2 39-43	C20R-1 6-7	D1R-1 6-8	C63R-4 68-73	D5 51	R-3 -57	D23 62-	R-2 66	D24 104-	R-1 111	A9R-5 74-76	A49R-1 9-13	A49 106-	R-4 108	A50R-2 26-28		A55R-2 74-76	
Mineral:	spinel	gm-cpx	gm-cpx	cpx	cpx	opx	gm-cpx	sv-cpx	cpx core	rim	ph-cpx	ph-cpx	cpx core	rim	gm-cpx	cpx core	rim	Ti-mt
SiO ₂		50.06	45.86	52.61	51.85	53.16	50.89	47.13	51.78	49.92	51.43	50.67	50.81	48.35	51.25	51.73	48.98	
TiO ₂	0.88	1.26	3.18	0.27	0.51	0.40	0.87	2.15	0.85	0.96	0.66	1.11	0.60	0.56	0.73	0.53	0.53	22.88
Al ₂ O ₃	30.57	5.58	6.61	3.30	2.10	1.47	4.15	4.45	3.13	1.90	3.26	3.56	4.57	1.58	3.38	2.84	1.49	1.69
Cr ₂ O ₃	32.36	0.28	0.31	0.40	0.18	0.04	0.33	0.05	0.60	0.15	1.00	0.57	1.00	0.00	0.72	0.59	0.07	0.15
Fe ₂ O ₃	7.03																	23.01
FeO	13.27	7.70	11.19	5.09	10.92	19.04	9.08	19.05	7.03	20.27	5.94	9.26	5.71	28.43	8.24	8.05	27.48	51.31
MnO		0.13	0.18	0.01	0.10	0.43	0.19	0.29	0.13	0.60	0.02	0.28	0.31	0.62	0.27	0.29	0.78	0.39
MgO	15.89	14.01	11.03	18.45	14.81	23.23	16.31	10.62	16.44	9.40	16.68	16.58	16.66	5.49	16.78	16.09	9.09	0.57
CaO		20.98	21.18	19.84	19.53	2.23	18.18	16.26	19.77	16.61	20.87	17.66	19.92	14.97	18.29	19.67	11.46	
Na ₂ O			0.46	0.02				0.28	0.19	0.14	0.31	0.42	0.00	0.34	0.34	0.21	0.12	
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Cation numbers	s on 0 = 6 (p	yroxenes) a	nd 0 = 4 (sp	inels) basis														
Si		1.853	1.746	1.914	1.937	1.959	1.881	1.823	1.907	1.942	1.890	1.877	1.871	1.945	1.893	1.914	1,946	
Ti	0.019	0.035	0.091	0.007	0.014	0.011	0.024	0.062	0.024	0.028	0.018	0.031	0.017	0.017	0.020	0.015	0.016	0.640
AI	1.056	0.243	0.296	0.141	0.092	0.064	0.181	0.203	0.136	0.087	0.141	0.155	0.198	0.075	0.147	0.124	0.070	0.074
Cr	0.750	0.008	0.009	0.011	0.005	0.001	0.010	0.002	0.017	0.005	0.029	0.017	0.029	0.000	0.021	0.017	0.002	0.005
Fe ³⁺	0.155																	0.643
Fe ²⁺	0.325	0.238	0.356	0.155	0.341	0.586	0.281	0.616	0.216	0.659	0.182	0.287	0.176	0.956	0.254	0.249	0.913	1.595
Mn		0.004	0.006	0.000	0.003	0.013	0.006	0.009	0.004	0.020	0.001	0.009	0.010	0.021	0.008	0.009	0.026	0.012
Mg	0.694	0.773	0.626	1.000	0.824	1.275	0.898	0.612	0.902	0.545	0.913	0.915	0.914	0.329	0.923	0.887	0.538	0.031
Ca		0.832	0.864	0.773	0.781	0.088	0.720	0.674	0.780	0.692	0.821	0.701	0.785	0.645	0.723	0.779	0.488	
Na			0.034	0.001				0.021	0.014	0.011	0.022	0.030	0.000	0.026	0.024	0.015	0.009	
Total	2.999	3.986	4.028	4.002	3.997	3.997	4.001	4.022	4.000	3.989	4.017	4.022	4.000	4.014	4.013	4.009	4.008	3.000
Mg#	68.1	76.4	63.7	86.6	70.7	68.5	76.2	49.8	80.7	45.3	83.3	76.1	83.9	25.6	78.4	78.1	37.1	1.9

Table 3. Representative pyroxene and spinel chemistry of basaltic rocks from Sites 765 and 766.

Note: The oxide values are normalized to total 100%. Fe₂O₃ of spinel was estimated so as to make cation total 3 on the 4 oxygen basis, assuming $R^{2+}R^{3+}_{2}O_{4}$ stoichiometry and $TiR^{2+} - 2R^{3+}$ exchange. Cpx = clinopyroxene, opx = orthopyroxene, gm = groundmass, ph = phenocryst, sv = segregation vesicle, Ti-mt = titanomagnetite.

Table 4. 87 Sr/86 Sr ratios of basaltic rocks from Sites 765 and 766.

Core, section, interval (cm)	Lith. unit	⁸⁷ Sr/ ⁸⁶ Sr (2σ)	Reference		
123-					
765D-19R-1, 72-73	15	0.702831 (20)	Intlab. STD	I	
765D-21R-1, 133-135	16	0.702694 (18)	Personal	#56	
766A-49R-5, 44-50	3	0.702976 (22)	Personal	#73	
766A-55R-3, 105-118	5	0.703255 (23)	Intlab STD	п	

Note: Intlab STD = interlaboratory standard sample.

fresh glass and the crystalline rocks and cannot be the result of an alteration process such as selective Mg leaching from primitive (Ti-poor) basalt. The correlation may have resulted from fractional crystallization, mixing/assimilation, or partial melting, or by any combination of these processes.

The first interpretation is a classic fractional crystallization model. If the increase of FeO^{*}/MgO is taken as a measure of the degree of fractionation, then TiO_2 in the magma may have been buffered or removed by a TiO_2 -rich crystalline phase. However, Na₂O and other incompatible elements regularly decrease with TiO_2 (e.g., Zr in Fig. 3), and the crystalline phase(s) must have had higher concentrations of incompatible elements than the magma, a highly unrealistic assumption. Thus, the FeO^{*}/MgO ratio must have decreased with fractionation. However, the fractionation of an Fe-rich and Ti-poor mineral, such as wüstite or Fe metal, is extremely unlikely under the normal oxygen fugacity in Earth's lithosphere. The fractionation of Ti-magnetite induces positive TiO_2 -FeO*/MgO correlations in the evolving melt. Moreover, the occurrence of Fe- and Ti-rich segregation vesicles and the intense compositional zoning of groundmass pyroxene with Fe-rich rims clearly indicate a normal FeO*/MgO increasing trend of the individual magma batch.

Another interpretation is that this correlation represents a mixing trend. One end-member may be N-MORB containing moderate TiO_2 (1.7 wt%), low FeO*/MgO ratio (1.2), and relatively abundant incompatible elements. The other end-member may be an unusual magma having low TiO_2 (1.2 wt%), high FeO*/MgO ratio (2.5), and extremely low abundances of the incompatible elements. This is a simple hypothesis, but how does the latter magma arise? This magma cannot be produced by fractionation of the former magma. A possible process is the remelting and assimilation of the mafic cumulates that form the lower part of the oceanic crust. These are depleted in incompatible elements and have a relatively high FeO*/MgO ratio. However, these cumulates are rich in plagioclase, and their remelting might produce a more aluminous magma, possibly with a positive europium anomaly, than was observed.

A third hypothesis assumes that the source mantle was heterogeneous in terms of the FeO*/MgO ratio and is relatively homogeneous in terms of incompatible elements. The Fe- and Mg-rich parts may have been a few 100 m or smaller in size and may have formed an irregular patchwork. If the patchwork body is brought above the solidus, the Fe-rich part (with a lower solidus temperature) undergoes higher degrees of melting than the Mg-rich part, and the incompatible elements are more diluted in the Fe-rich melt than in the Mg-rich melt. The unusual negative correlation among



Figure 6. Ca-Mg-Fe diagram for pyroxenes from basaltic rocks of Sites 765 and 766 (see inset for symbols). The Ca, Mg, and Fe apices are marked by representative pyroxene end-members, wollastonite (Wo), enstatite (En), and ferrosilite (Fs), respectively. Diopside (Di) and hedenbergite (Hd) are also marked.



Figure 7. TiO₂-Al₂O₃ diagram for clinopyroxenes from basaltic rocks at Sites 765 and 766 (see inset for symbols).

Site 765 basement basalts (Fig. 4) may have arisen through this process, provided that the degree of fractionation in the shallow depths is roughly uniform through all samples. The trend depicted in Figure 4 may thus represent a partial melting trend of the mantle, which was heterogeneous in terms of FeO*/MgO ratio. Note that the glass inclusions in plagioclase, a possible parental magma of Site 765 basalts, also indicate a negative trend (Fig. 4, triangles).

Other Basaltic Rocks from the Indian Ocean Floor

Both Sites 765 and 766 are underlain by the evolved NMORBs closely resembling each other. In the Ti-Zr diagram (Fig. 3A), together they form a linear trend along a Ti/Zr = 120 line, in spite of their different trends in the TiO₂-FeO*/MgO diagram (Fig. 4). Clearly, their Ti/Zr ratios are different from those of Southeast Indian Ridge basalts (about 90) and also from those of Southwest Indian Ridge basalts (about 45) (Fig. 3B). The Ti/Zr ratios of basement basalts from DSDP Sites 259, 260, and 261 are as high as those of Sites 765 and 766, suggesting that these high Ti/Zr ratios are common features in the Cretaceous basaltic rocks forming the eastern Indian Ocean floor.

The Ti/Zr ratio increases during advancing partial melting because of the differential incompatibility of Ti and Zr, as Zr is more incompatible at the beginning of partial melting. In this context, the Early Cretaceous basement basalt of the eastern Indian Ocean floor may have formed through large degrees of partial melting beneath fast-spreading ridges. More differentiated basalt tends to be erupted from a faster spreading ridge, because large permanent magma chambers are present at a shallow level beneath the fast-spreading ridges. Such magma chambers are also consistent with the differentiated nature of the basalts at Sites 765 and 766.

Implications for Early Cretaceous Rifting and Spreading

The basaltic rocks obtained from the basement sections of Sites 765 and 766 are evolved N-MORBs that were derived from a depleted mantle source. However, the basaltic pebbles encountered in the turbidites of the overlying sedimentary section include primitive but relatively enriched N-MORBs and alkalic E-MORBs having Ca-, Ti- and Al-rich clinopyroxene and slightly potassic plagioclase. Such an overall petrologic spectrum of the drilled sites resembles that of an area in the Afar Triangle-Bay of Aden Rift system, where temporal and spatial changes from pre-oceanic rift volcanism to oceanic ridge volcanism have been well-documented (Bizouard and Richard, 1980; Joron et al., 1980). For example, evolved, highly phyric, alkaline E-MORBs of the Asal Rift in the eastern Afar grade into slightly depleted T-MORBs of the Bay of Aden, and then into the typical N-MORBs of Carlsberg Ridge. In this African-Arabic rift system, the degree of fractionation decreases with the progress of "oceanization." However, this trend was not obvious in the Early Cretaceous volcanism studied here, and the N-MORBs of the ocean floor are more differentiated than those near the continent.

Magma Fractionation, Source Depletion, and Spreading Rate

In general, both the apparent degree of fractionation (increasing FeO*/MgO, TiO₂, decreasing Cr, etc.) and apparent degree of depletion ((La/Sm)_N, ⁸⁷Sr/⁸⁶Sr, etc.) of MORBs increase with spreading rate in the Atlantic and Pacific oceans (Scheidegger, 1973; Holness and Richter, 1989). For example, average (La/Sm)_N is about 1.25 at 3 cm/yr and 0.6 at 18 cm/yr (Holness and Richter, 1989). In this context, the evolved (FeO*/MgO = 1.8) and depleted ((La/Sm)_N<0.5) N-MORBs of the drilled sites may



Figure 8. The anorthite-Mg# relationship between coexisting plagioclase (Pl) and clinopyroxene (Cpx) in the basaltic rocks from Sites 765 and 766 (see inset for symbols). Island-arc tholeiite (IAT) and MORB fields, as well as Bushveld and Skaergaard trends, are based on well-known miscellaneous sources. Site 735 data were kindly provided by K. Ozawa of the University of Tokyo.



Figure 9. Chemical characteristics of the glass inclusions in the plagioclase megacrysts from the upper part of Site 765 basement. Data from Mid-Indian Ocean Ridge 70°E, Mid-Atlantic Ridge, and Bouvet Island are from Price et al. (1986) and Donaldson and Brown (1977). Pl, Ol, and Sp represent plagioclase, olivine, and spinel, respectively.

thus represent products of a fast-spreading ridge. However, this is not consistent with the relatively high Sr isotope ratio (0.7027 to 0.7033: generally about 0.7025 at a fast-spreading ridge) and the actual spreading rate during the Early Cretaceous, estimated from magnetic anomalies on the Indian Ocean floor (<6 cm/yr). These conflicting data prohibit simple interpretations with respect to spreading rate. Note that the Indian Ocean is generally excluded from the discussion about basalt chemistry–spreading rate correlations, possibly because of the presence of the Dupal anomaly.

CONCLUSIONS

1. Most basement basalts of Sites 765 and 766 are evolved N-MORBs (average FeO*/MgO = 1.8) derived from a depleted source ((La/Sm)_N<0.5 and Ti/Zr = 120). Their ⁸⁷Sr/⁸⁶Sr ratios are as low as those of the present MIORBs.

2. The wide mineralogic variation of megacrysts and gabbroic fragments included in the basaltic rocks of Site 765 are evidence of the extensive fractionation taking place in a shallow magma chamber.

3. The high-magnesian basaltic glass inclusions (12–15 wt% MgO) trapped in plagioclase megacrysts (An_{90}) indicate the primitive nature of the parental magma.

4. Site 766 basalts follow a normal tholeiitic trend on the TiO_2 -FeO*/MgO diagram, but Site 765 basalts indicate an unusual trend in which TiO_2 remains constant or even decreases with the increase of FeO*/MgO. This unusual trend may be made up of a bundle of normal fractionation trends that began with parental magmas having variable FeO*/MgO. This suggests fine-scale heterogeneity in the source mantle beneath Site 765 in terms of the FeO*/MgO ratio.

5. The basalt pebbles in the sedimentary sequence of Site 765 were derived from a slightly enriched source. These pebbles may have been transported from basement highs near the Australian passive margin and may represent earlier volcanism in the rifting–drifting history of the Australian continent.

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1 mm



2

1 mm

Plate 1. 1. Thin-section photomicrograph of segregation vesicles in Sample 123-765D-23R-2, 64–66 cm; open nicols. The largest vesicle in center is 1.7 mm in diameter. The meniscus-shaped filling in the vesicle is made up of an aggregate of needle-shaped quench minerals, such as Fe-rich augite, ilmenite, and plagioclase, crystallized from the Fe-Ti basaltic liquid segregated inward from the outer solidifying MORB magma. The gas-filled space is now occupied by green clay minerals. 2. Thin-section photomicrograph of glass inclusions in a euhedral plagioclase megacryst in Sample 123-765C-63R-2, 61–63 cm; crossed nicols. The plagioclase is 2.3×1.1 mm in size; this photograph covers only a zoned marginal part of the mineral. Tiny glass inclusions, 2 to 15 mm in diameter, are distributed in a concentrical zone passing the center of the photograph. Two dark horizontal bands in the middle are twins, and oblique irregular streaks are cracks.