3. PRIMARY MINERALOGY OF LEG 115 BASALTS[1]

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ABSTRACT

Basement rocks were recovered at four sites on Leg 115 along the Réunion hotspot track in the western Indian Ocean. Plate tectonic reconstructions indicate that the drilled structures formed in three different volcanic environments. Sites 706 and 713 from the eastern side of the Saya de Malha Bank and the northern end of the Chagos Bank, respectively, are on a large volcanic platform analogous to Iceland on the Mid-Atlantic Ridge. Lavas at Site 707 on the northwestern side of the Saya de Malha Bank erupted during the early stages of rifting of the Seychelles from India. Basalts from Site 715 were erupted onto an isolated oceanic island that was distant from ocean ridges and continents much as Réunion Island is today.

Many of the rocks were examined in thin section and found to be primarily augite-plagioclase basalts with minor olivine and rare opaque oxides. Site 715 is unusual in that it contains a variety of basalts including olivine-rich and aphyric Fe-Ti basalts. At each of the four sites the rocks were grouped into chemical types (units) on the basis of shipboard bulk-rock analyses and at least one thin section from each chemical unit was analyzed by electron microprobe. The plagioclase and augite chemistry reflects the bulk-rock chemistry and, in general, these minerals were in equilibrium with their host magmas at the time the basalts were quenched. Olivine was rarely preserved, but where it is still present it also appears to have crystallized in equilibrium with the host magma. At three of the drill sites plagioclase phenocrysts or megacrysts that crystallized from a primitive magma are also present. The one site (715) that does not contain these primitive plagioclase phenocrysts is also the site that appears to have been influenced the least by ocean-ridge or Deccan-type magmas. Site 715, furthermore, has a mineralogy that is dominated by olivine as compared with the plagioclase-rich lavas of the other sites.

INTRODUCTION

The Réunion hotspot track in the western Indian Ocean extends from the volcanically active island of Réunion through the deeply eroded volcanic Island of Mauritius, the Nazareth and Saya de Malha banks, and the Chagos-Maldive-Laccadive islands to the Deccan Traps, 5,000 km from Réunion (Fig. 1). The age progression of these features has now been established (Duncan, this volume; Duncan and Hargraves, this volume) and is shown in Figure 1.

The oldest known basalts from the hotspot track (Deccan Traps) have been extensively studied (Cox and Hawkesworth, 1985; Beane et al., 1986; Dewey and Lightfoot, 1986), as have those from the young end of the hotspot (Baxter, 1972; Upton and Wadsworth, 1972; Fisk et al., 1988). Until Leg 115, however, no samples from the intermediate-age volcanoes were available. Basalts from the Deccan Traps usually have more than 48 wt% SiO_2 and about 3 wt% total alkalis and are considered to be tholeiites (Macdonald and Katsura, 1964), whereas the basalts of Réunion Island are transitional between tholeiites and alkali basalts (Fig. 2). Preliminary major and trace element chemistry of selected lavas from all four sites (Backman, Duncan, et al., 1988; Fisk et al., 1989) show that they range in composition from primitive basalts to evolved Fe-Ti-rich basalts (Fig. 3A) and that tholeiites, transitional basalts, and alkali basalts are represented (Fig. 3B). These basalts cover nearly the same compositional range as the Réunion and Deccan lavas, combined. Extremely differentiated silicic or alkalic lavas that are commonly found in the waning stages of volcanism on oceanic islands (including Réunion) were not recovered at any of the sites.

Therefore, the recovered lavas at Sites 706, 713, and 715 represent the main shield-building stage of volcanism with tholeiitic to transitional chemistry. The lavas from Site 707 are basalts that are related to the rifting of the Seychelles platform from India during the waning stages of Deccan flood basalt activity. This relationship is inferred from the age of the basalts (64 Ma) and the plate reconstruction around the northwest Indian Ocean (Duncan, this volume).

Lavas along the Réunion hotspot track contain the usual suite of minerals found in basalts (olivine, plagioclase feldspar, and augite), but the proportions of these minerals are variable. Réunion and Deccan lavas are dominated by olivine phenocrysts, followed in abundance by plagioclase (Upton and Wadsworth, 1972; Beane et al., 1986), and the Leg 115 lavas are plagioclase-dominated, followed in abundance by augite (Backman, Duncan, et al., 1988). Olivine is present in many of the Leg 115 samples, but usually is less abundant than either plagioclase or augite. The mineralogical differences between basalts may be caused by small differences in bulk chemical composition of the magmas or by different physical conditions and kinetic processes during crystallization. In an attempt to understand the differences in mineralogy along the Réunion hotspot track, we made a detailed examination of the mineral chemistry of basalts from the four sites from Leg 115 that recovered basaltic basement.

At each site, lithologic units (flows) were identified aboard ship based on glassy or vesicular contacts and on the presence of interflow sediment. Additional flows were identified by changes in texture, mineralogy and color. The number of flows varied from 5 at Site 707 (77.4 m penetration) to 35 at Site 713 (63.2 m of basalt penetration). These flows were grouped into chemical units on the basis of shipboard whole-rock analyses. In spite of the diversity of flows, only three or four chemical *units* were identified at each site. These chemical units and their mineral chemistry are the subject of this report. (To avoid confusion, the term "unit" refers to a chemical unit and the term "flow" refers to the lithologic unit. The location of analyzed thin sections within chemical and lithologic units is shown in the Appendix.)
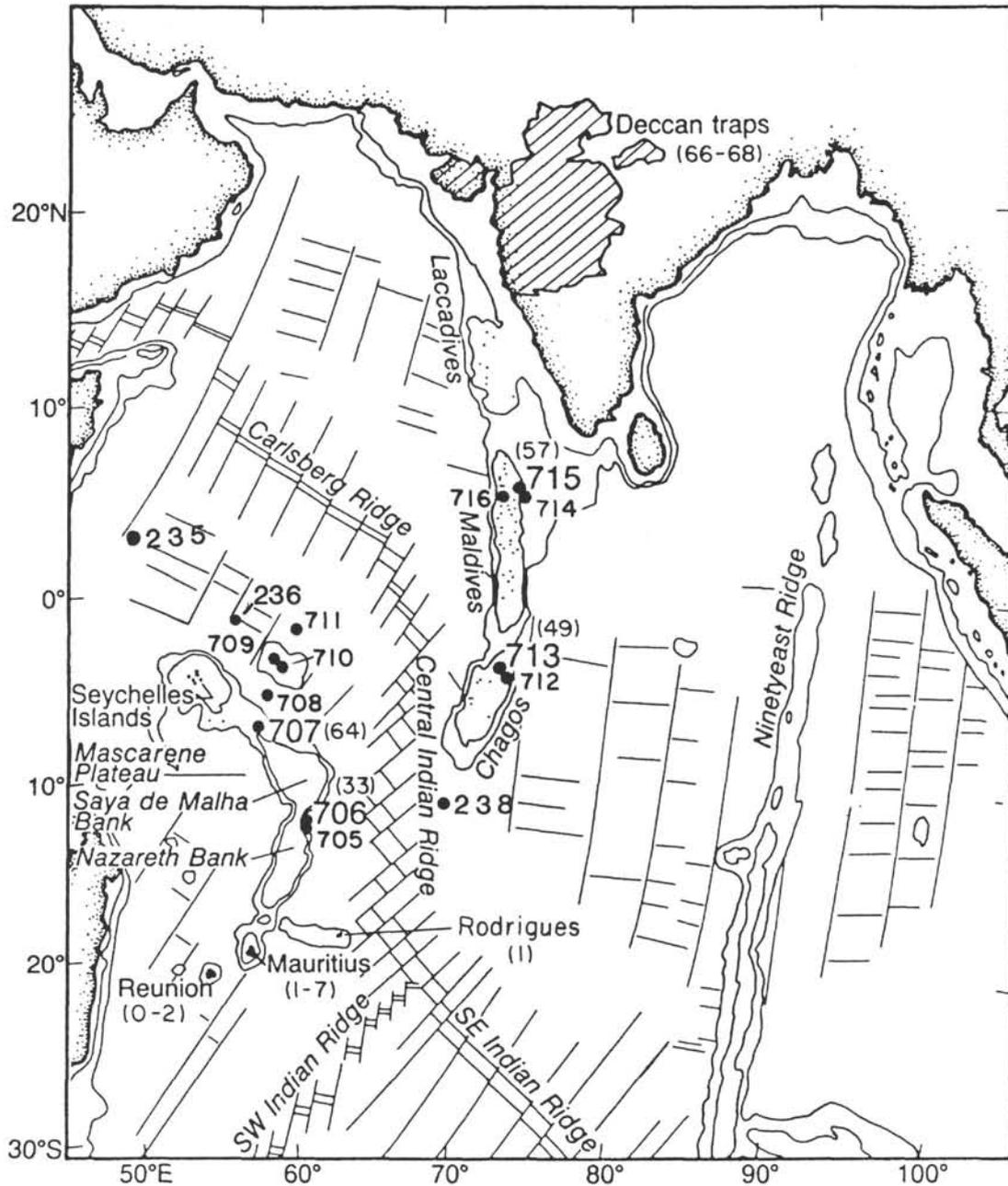
Figure 1. Map of the Indian Ocean showing the sites drilled during Leg 115. Sites 706, 707, 713, and 715 recovered basaltic basement; the age of the basement at these four locations is given in m.y. Basalts that were produced by the Réunion hotspot also include Réunion and Mauritius islands and the Deccan Traps; the ages of these basalts are also given. DSDP Leg 24 drilled three holes to basement in this area, and the position of these three holes are given (Sites 235, 236, and 238).

METHODS

Shipboard descriptions of the recovered samples were carried out by six petrologists as the cores were split and labeled. Polished thin sections were prepared from many of the flows and these were examined on board with petrographic microscopes to estimate modal abundances of phenocrysts, groundmass minerals and alteration (Backman, Duncan, et al., 1988). Samples for shipboard chemical analysis were carefully selected to be representative of the flows from which they came. Areas of heavy alteration were avoided but alteration or phenocrysts were *not* me-

chanically removed from the samples before they were crushed and prepared for analysis.

The flows were grouped into chemical units on the basis of downcore major and trace element variation. Examples of the chemical variation that were used to establish chemical units at each site are given in Figure 4. (Details of the major and trace element chemistry are given in Backman, Duncan, et al. (1988), and Fisk et al. (1989). The divisions between chemical units agree closely with divisions between lithologic units determined from hand specimens and petrographic examination of the basalts (Backman, Duncan, et al., 1988). Chemical unit 3 at Site
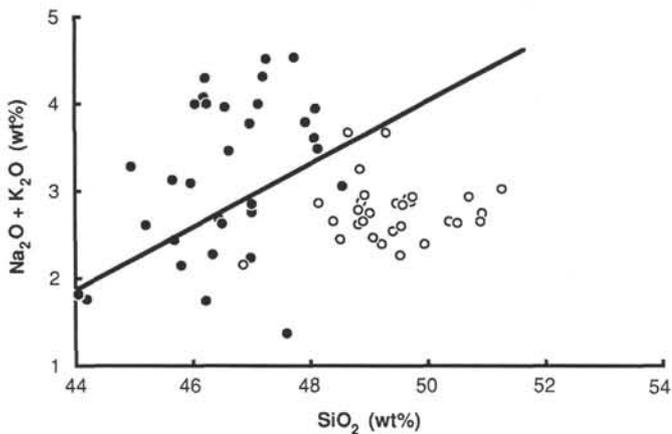
Figure 2. Silica-alkali diagram for Deccan (open circles; Cox and Hawkesworth, 1985) and Réunion lavas (filled circles; Fisk et al., 1988). The line divides the alkali and tholeiite basalt fields of Hawaii (Macdonald and Katsura, 1964).
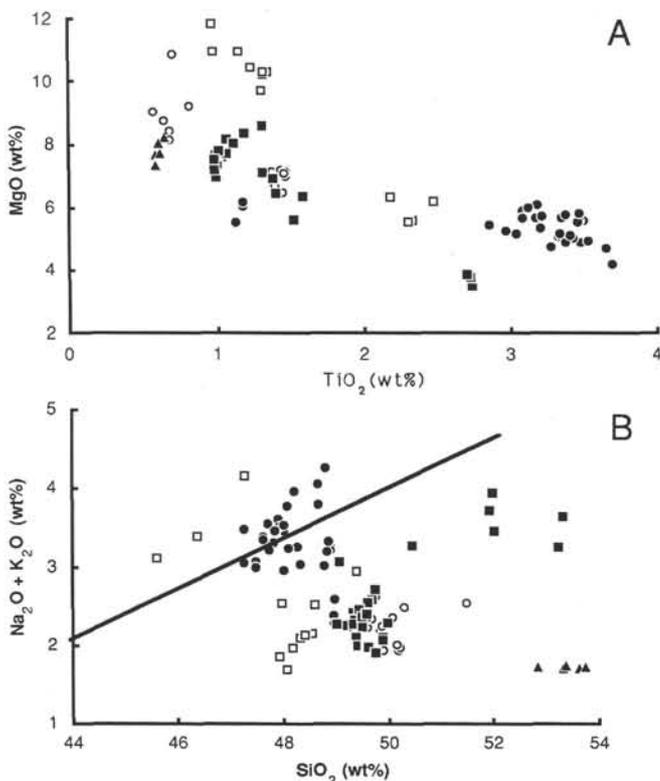
Figure 3. Variation diagrams of the major element chemistry of the bulk rocks and glass from Leg 115. **A.** MgO-TiO$_2$ for each drill site and for glass from DSDP Site 236 (Melson et al., 1977). Site 706, solid circles; Site 707, open circles; Site 713, solid squares; Site 715, open squares; DSDP Site 236, triangles. Bulk rocks from all Leg 115 sites except Site 713 have two distinct chemistries. The volcanic turbidite between chemical units 2 and 3 in Site 713 (solid squares) is distinct from the bulk-rock chemistry of Site 713. Glass analyses from other sites are not substantially different from the associated bulk rocks; therefore, these glasses have not been plotted. **B.** Total alkalis-SiO$_2$ for the bulk rocks from each site and for the glasses from Site 713 and DSDP Site 236. Alkali and tholeiite fields as in Figure 2. Symbols are the same as for Figure 3A.

715 has a single analysis that does not appear to be part of the unit; a second analysis, however, from lower in the same flow, is similar to the other five analyses of the unit, which is consistent with classifying these flows as a single chemical unit.

Thin sections from each of the chemical units at each site were selected for further analysis by electron microprobe. The microprobe analyses of glasses, olivine, feldspar, and pyroxene were performed on the University of Oregon ARL/EDX microprobe using 15-kV accelerating voltage and 0.15-μA sample current. The standards for major elements were well-characterized minerals and glass that were close in composition to the unknowns (e.g., Kakanui augite, anorthite, Lake County labradorite, Springwater olivine, and glasses made from basalt and diopside with 15% jadeite component). The minor elements Na, Ti, Cr, Mn, K, and Ni were standardized on mineral and glass standards that had high concentrations of these elements relative to the unknowns to obtain higher precision. Peaks and backgrounds were counted for 20 s and on-line data reduction followed standard procedures of Bence and Albee (1968) and Albee and Ray (1970). Statistical precision is ±2% or better for major elements and usually ±5% or better for minor elements.

Titanomagnetite analyses were performed on the University of Washington JEOL 733 microprobe using an accelerating voltage of 15-KV and a beam current of 25 nA. Standards for these analyses were chromite 52NL11, Elba hematite, Sawyer ilmenite, diopside jadeite, nickel olivine, and manganese silicate. Counting times were a maximum of 40 s, but counting ceased when precision based on total counts was better than 1%. The on-line correction procedure was the same as that for the ARL microprobe.

SAMPLE DESCRIPTIONS AND RESULTS

The following descriptions are based on the shipboard core and thin section descriptions and on the shipboard chemical analyses (Backman, Duncan, et al., 1988). Mineral amounts are estimates of modal abundance from the thin sections. Chemical units were defined on downhole XRF major and trace elements as described above and the microprobe mineral analyses are grouped by the chemical units shown in Figure 4.

Site 706 (Analogous to Iceland)

Basement rocks were recovered from all three holes of Site 706, which was located on the eastern margin of the Saya de Malha–Nazareth banks (Fig. 1). In Hole 706A, a single piece of basalt was found in the core catcher at the base of the hole, and in Hole 706B six basalt pieces were recovered from the 0.5 m of basement that was drilled. About 20 m of basalt was recovered from 77 m of basement at Hole 706C. The many glass contacts between 30 thin lithologic units (flows) suggests that the basalts were erupted underwater. Additional evidence for submarine eruption comes from the absence of oxidized contacts between flows; the high vesicularity (commonly as high as 35%), however, implies that this was a shallow-water environment.

Chemistry

These basalts form two distinct compositional groups (Figs. 3 and 4). One group includes the basalts from Holes 706A, 706B, and the upper 30 flows of 706C; they are high in TiO$_2$ (2.8–3.8 wt%) and are similar in chemistry to an unusual group of evolved lavas known as the giant plagioclase basalts in the lower part of the Deccan Traps (Beane et al., 1986). This high-titanium group from Site 706 is also similar to the lavas of Réunion Island (Fisk et al., 1988). Within the upper 30 flows of Site 706C, there is a subtle change in major element chemistry and a pronounced difference in Cr (Fig. 4) between flows 21 and

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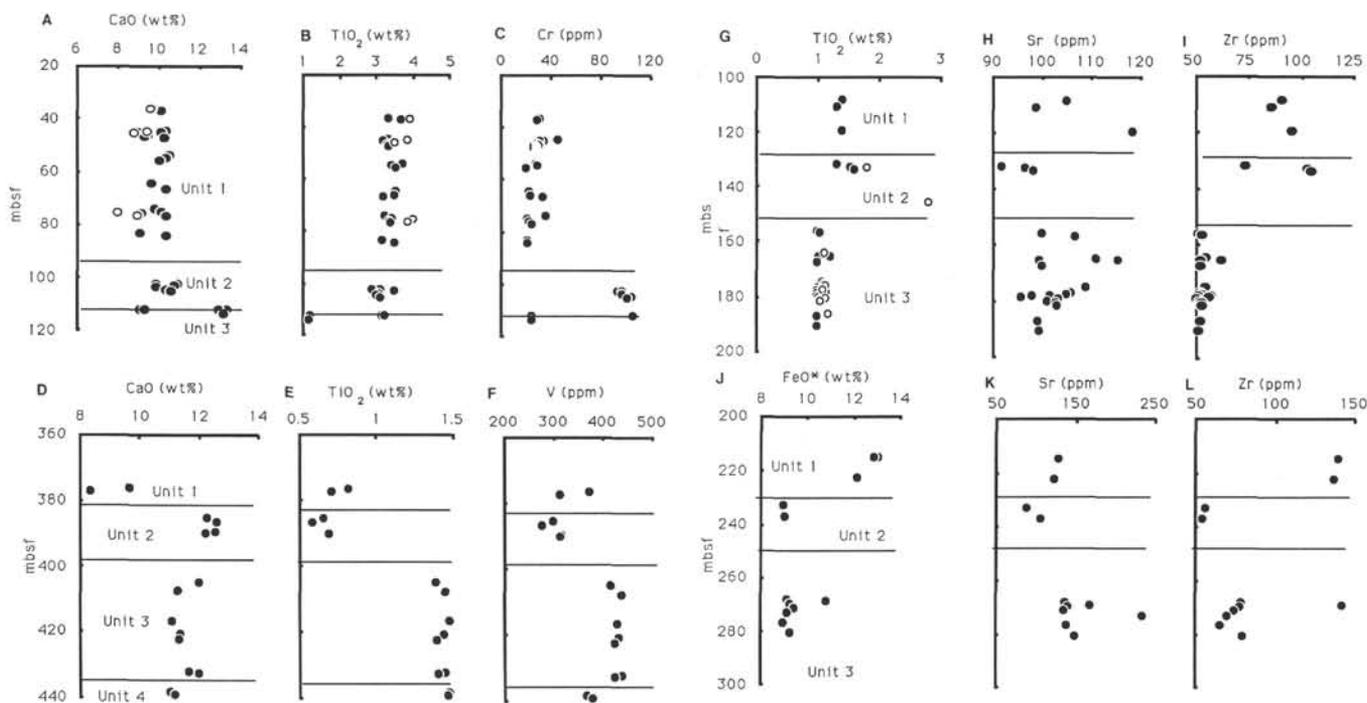
Figure 4. Downhole chemical variation for selected elements determined by X-ray fluorescence. **A–C.** Site 706. **D–F.** Site 707. **G–I.** Site 713. **J–L.** Site 715. Chemical units were defined by abrupt changes in chemistry. Glass analyses from Sites 706 and 713 are shown as open circles. The high-TiO_2 glass included with unit 2 of Site 713 is from a volcanic turbidite in sediment between units 2 and 3 and is clearly not part of unit 2.

26. We have separated these flows into chemical units 1 and 2. Chemical unit 3 from Site 706C was found in the lowest flows (31 and 32) and has low TiO_2 (1.1 wt%) and low total alkalis, but similar MgO content to the upper unit. Units 1 and 2, with a TiO_2 abundance that is three times that of unit 3, cannot be derived from the same parent magma as unit 3 by fractional crystallization. They could be derived, however, from distinct mantle sources based on different Nb/Y values (Fisk et al., 1989).

Mineralogy

The primary minerals of the two main chemical units at Site 706 are also distinctive. The upper high-titanium units have a uniform phenocryst mineralogy that is typical of evolved basalts; plagioclase and augite are always present, and olivine or pseudomorphs of olivine are sometimes present. The lower chemical unit is characterized by large (up to 30 mm) plagioclase phenocrysts (Backman, Duncan, et al., 1988, fig. 30).

In detail, chemical unit 1 has small (<2 mm) plagioclase phenocrysts that make up 10%–30% of the rock. Augite phenocrysts are never more abundant than plagioclase and make up 2%–25% of the rock. They are always less than 1 mm at their greatest dimension. Olivine phenocrysts, although mostly altered, composed up to 5% of some lavas but were entirely absent from others. They were originally present in 4 of 50 thin sections examined, but were preserved only in flows 17 and 19 (between 75 and 77 mbsf).

No magnetite phenocrysts were observed, even in the basalts with 15 wt% FeO and 3.3 wt% TiO_2, which is also typical of iron-titanium-rich, ocean-floor basalts such as those of the Galapagos Rift (Fisk et al., 1982; Perfit and Fornari, 1983). Chromites were not reported in the thin sections, but one chrome-rich magnetite was analyzed in unit 2. A small amount of Cr-rich magnetite could account for the higher Cr content in this unit (Fig. 4). The groundmass was either fine-grained plagioclase, augite, and oxides or a combination of these minerals with glass. Some of the quenched margins of pillows and flows contain substantial glass that has been devitrified and altered to clay.

Mineralogically, chemical unit 3 (flows 31 and 32) is not significantly different from the upper unit, except for the presence of large plagioclase phenocrysts that constitute 15 modal % of these flows. Augite (1%–10%) and olivine (1% or less) are also present in this lower chemical unit. The groundmass is plagioclase, augite, glass, and opaque oxides. No glass was preserved in this unit.

Alteration

In the thin sections examined from Site 706, alteration ranged from 3% to 85% (by volume). Olivine was usually altered to clay (Fisk and Howard, this volume), but plagioclase and augite phenocrysts and groundmass are untouched by alteration. The major alteration is concentrated in the quenched glass at the flow margins and in interstitial glass. In spite of this pervasive alteration, glass was preserved near the sediment-basalt interface as well as in three sections of the core from Hole 706C (at 37, 45–46, and 75–77 mbsf). Below 77 mbsf, all glass and olivine were altered to clay. Unit 3 has between 19% and 65% clay replacing olivine and glass.

Mineral Chemistry

We studied 12 thin sections in detail at this site. Plagioclase and augite were analyzed by microprobe in each chemical unit of Site 706, and glass and olivine were analyzed where they were preserved. Oxide minerals were not found as phenocrysts, but some groundmass titanomagnetites were probed in a few thin sections. In addition, glass, plagioclase, and pyroxene grains were analyzed in the sulfide-cemented sandstone found above unit 1 at Hole 706B. These analyses are included in histograms of the mineral compositions.

Representative microprobe analyses of minerals and glasses for Site 706 are given in Tables 1 through 5, and histograms of

Table 1. Microprobe analyses of plagioclase phenocrysts, Site 706.

Hole no.	706A			706B			706B			706C		
Unit no.	1			1			1			1		
Core, section	6H-4			7X-CC			7X-CC			2R-1		
Interval (cm)	20–24			17–20			20–27			76–80		
Depth (mbsf)	41.30			36.92			36.90			45.16		
Analysis no.	1	2	3	1	2	3	1	2	3	1	2	3
SiO_2	52.22	50.25	54.10	61.13	58.45	57.14	53.20	51.69	50.98	52.37	50.65	50.38
Al_2O_3	28.19	29.59	25.64	24.31	26.09	26.29	28.60	28.99	29.45	27.93	29.31	29.46
FeO	0.95	0.92	1.33	0.57	0.51	0.74	0.72	0.37	0.90	1.09	0.89	0.32
CaO	12.75	13.44	10.15	6.49	8.02	8.84	11.90	12.65	12.97	11.39	12.88	12.72
Na_2O	4.66	4.50	5.93	7.36	6.64	6.44	4.89	4.29	4.25	4.94	4.73	4.24
K_2O	0.33	0.25	0.45	0.50	0.42	0.39	0.37	0.32	0.31	0.39	0.23	0.25
Total	99.11	98.96	97.61	100.37	100.13	99.84	99.69	98.81	98.85	98.12	99.25	97.87
An	59.2	61.4	47.4	31.9	39.1	42.2	56.2	64.4	65.1	54.7	59.2	61.5
Notes	c	r	m	m	c	r	m	c	r	m	r	c

Hole no.	706C			706C		706C			706C			706C	
Unit no.	1			1		1			1			1	
Core, section	2R-2			2R-2		5R-1			5R-3			6R-1	
Interval (cm)	2–4			115–118		83–85			44–48			46–50	
Depth (mbsf)	46.00			47.13		74.03			76.64			83.36	
Analysis	1	2	3	1	2	1	2	3	1	2	3	1	2
SiO_2	49.18	50.84	52.31	53.48	52.59	52.86	51.82	55.70	50.30	54.18	53.34	51.44	53.88
Al_2O_3	31.81	29.41	29.14	28.22	29.01	27.56	28.49	25.38	29.68	27.13	28.05	29.90	27.17
FeO	0.80	1.00	1.02	0.86	0.98	0.97	0.88	0.99	0.86	1.00	0.97	0.76	0.75
CaO	15.15	12.39	11.85	11.88	12.01	11.69	12.19	9.29	14.44	11.71	11.41	15.09	11.71
Na_2O	2.87	4.08	4.33	4.00	4.64	4.67	3.98	6.04	2.97	4.55	4.62	2.74	5.12
K_2O	0.15	0.22	0.25	0.26	0.23	0.30	0.22	0.35	0.14	0.23	0.17	0.10	0.19
Total	99.96	97.94	98.90	98.71	99.47	98.05	97.58	97.76	98.37	98.80	98.56	100.03	98.82
An	74.3	61.9	59.4	61.2	58.0	57.1	62	45.1	72	58	57.2	75	55.2
Notes	c	r	m	c	r	r	c	r	c	r	m	c	r

Hole no.	706C			706C				
Unit no.	2			3				
Core, section	8R-2			9R-2				
Interval (cm)	43–45			36–38				
Depth (mbsf)	104.23			113.86				
Analysis	1	2	3	1	2	3	4	5
SiO_2	49.16	51.84	53.70	46.07	44.91	50.74	45.72	50.87
Al_2O_3	31.93	30.57	27.05	35.18	34.23	31.26	34.71	30.90
FeO	0.57	0.84	1.24	0.54	0.51	0.78	0.52	0.66
CaO	15.02	13.01	10.06	18.25	17.10	14.61	17.96	14.11
Na_2O	3.05	4.04	5.81	1.34	1.29	3.42	1.26	3.44
K_2O	0.16	0.24	0.37	0.04	0.08	0.08	0.07	0.09
Total	99.88	100.55	98.23	101.43	98.12	100.89	100.24	100.07
An	72.6	63.2	47.9	88.1	87.7	70	88.4	69
Notes	c	r	m	c	r	m	xc	xr

Notes: c = core, r = rim, m = microphenocryst, xc = xenocryst core, and xr = xenocryst rim.

all of the plagioclase and augite compositions are presented in Figures 5 and 6. The precision of the anorthite composition is ±2% or better on the basis of counting statistics made on calcium and sodium. One sample at the top of Hole 706B (Table 1) has low anorthite An_{32-42}; however, this feldspar is not from a flow but from a sandstone cemented with sulfide at the interface between the basalts and sediment.

The anorthite content of plagioclase in the thick upper unit has a mode of An_{61} (Table 1 and Fig. 5). There appears to be no systematic change in mineral chemistry with depth since all thin sections have phenocryst cores of An_{60-61}, except for those from the sandstone (115-706B-7X-CC, 17–20 cm), for which all of the feldspars are less than An_{43}. The equilibrium plagioclase composition is fixed at a specific anorthite content for a given magma composition and temperature, so the wide range of com-

positions observed in this upper unit indicates that several processes may have been active during the crystallization of these magmas. These include mixing of magmas and crystallization under a range of pressures and temperatures and water contents.

Even though there are minor differences in the bulk rock chemistry of units 1 and 2 the mineralogy of the two units are identical except for the presence of Cr-rich magnetite in unit 2 (Table 5). Unit 3, however, is significantly different from the upper units and contains plagioclase phenocryst cores that range from An_{83-88}. This high anorthite content can reflect a higher temperature and CaO/Na_2O of this magma compared to the upper units, or it may result from the incorporation of plagioclase xenocrysts in unit 3.

Augite phenocrysts (Table 2 and Fig. 6) have a wide range of compositions within the upper chemical unit (flows 1–17). Au-

Table 2. Microprobe analyses of clinopyroxenes, Site 706.

Hole no.	706A		706A		706B			
Unit no.	1		1		1			
Core, section	6H-4		7X-CC		7X-CC			
Interval (cm)	20–24		17–20		20–27			
Depth (mbsf)	41.30		36.92		36.90			
Analysis no.	1	2	1	2	1	2	3	4
SiO_2	48.00	46.72	52.02	49.16	48.34	47.67	47.97	50.88
TiO_2	1.89	2.29	0.70	0.80	1.79	1.34	1.67	0.92
Al_2O_3	5.23	5.19	1.26	1.08	5.19	4.78	4.41	2.56
FeO	11.21	12.60	13.42	13.37	9.76	9.71	10.64	9.48
MnO	0.24	0.30	0.47	0.45	0.21	0.18	0.22	0.25
MgO	14.25	12.75	12.18	12.69	13.84	14.09	13.69	15.61
CaO	19.36	19.17	19.98	20.08	19.86	20.09	19.91	18.89
Na_2O	0.32	0.35	0.29	0.32	0.40	0.47	0.41	0.35
Cr_2O_3	0.17	0.05	[a]0.04	[a]0.04	0.15	0.11	0.06	0.13
Total	100.66	99.42	100.34	98.00	99.55	98.44	98.97	99.06
Notes	c	r	c	r	c	r	c	r
Mg#	78	72	62	64	77	83	88	88

Hole no.	706C		706C		706C		706C			706C		
Unit no.	1		1		1		1			1		
Core, section	2R-1		2R-2		2R-2		5R-1			6R-1		
Interval (cm)	76–80		2–4		115–118		83–85			46–50		
Depth (mbsf)	45.16		46.00		47.13		74.03			83.36		
Analysis	1	2	1	2	1	2	1	3	4	1	2	
SiO_2	50.33	47.93	49.26	47.21	49.21	51.47	51.48	49.67	49.10	48.07	50.75	50.18
TiO_2	0.77	1.60	0.99	1.60	0.93	0.96	0.92	1.03	1.79	2.08	0.94	1.33
Al_2O_3	1.95	4.05	3.86	4.82	3.00	3.47	3.45	3.32	4.25	4.40	2.83	4.01
FeO	10.12	10.38	9.97	9.89	9.39	9.74	11.44	14.16	11.35	11.67	10.71	9.79
MnO	0.29	0.16	0.24	0.24	0.24	0.26	0.33	0.33	0.27	0.28	0.28	0.26
MgO	17.60	13.94	14.52	12.91	15.16	13.88	13.34	9.86	13.29	12.62	14.71	12.91
CaO	16.80	20.27	19.26	20.36	20.36	20.57	19.48	19.68	18.56	19.64	18.44	20.56
Na_2O	0.30	0.41	0.41	0.41	0.33	0.27	0.33	0.27	0.38	0.24	0.29	0.35
Cr_2O_3	0.11	0.05	0.14	0.12	0.10	0.10	[a]0.04	[a]0.04	0.09	0.05	0.09	0.09
Total	98.31	98.80	98.65	97.58	100.74	100.74	100.80	98.41	99.08	99.05	99.04	99.49
Notes	c	r	r	c	c	r	c	r	c	r	c	c
Mg#	76	70	88	88	74	72	68	55	69	69	72	70

Hole no.	706C		706C		
Unit no.	2		3		
Core, section	8R-2		9R-2		
Interval (cm)	43–45		36–38		
Depth (mbsf)	104.23		113.86		
Analysis no.	1	2	1	2	3
SiO_2	50.63	48.60	50.49	50.74	51.74
TiO_2	1.08	1.92	0.65	0.63	0.53
Al_2O_3	2.46	10.30	3.64	4.12	2.65
FeO	9.02	10.21	7.03	7.44	6.71
MnO	0.25	0.37	0.15	0.21	0.20
MgO	14.89	11.27	16.10	15.50	15.85
CaO	19.20	14.47	21.88	20.68	21.29
Na_2O	0.37	0.43	0.28	0.30	0.24
Cr_2O_3	0.28	0.05	0.05	0.05	0.05
Total	98.18	97.50	100.27	99.67	99.25
Notes	c	r	m	c	r
Mg#	76	66	91	83	84

Notes: c = core, r = rim, and m = microphenocryst.
[a]Minimum detection limit for Cr_2O_3 is 0.04 wt%.

gite in flow 1 has an Mg# ($100 Mg^{2+}/[Mg^{2+} + Fe^{2+}]$) range of 77–88; in flow 14 the Mg# range is 55–76; and in flow 17 the range is 73–79. These distinct augite compositions from separate flows suggest that although the flows have the same chemical composition they are not a single eruption of pillow basalts with many internal chilled margins, but they are, in fact, separate flows.

At Site 706 glass was preserved only in four flows of unit 1 and in the sulfide-cemented sandstone at the sediment/basalt interface in Hole 706B (Table 3). The glasses from the four flows in unit 1 are similar to their corresponding bulk-rock compositions with the exception that the glasses have lower MgO abundance (4.3–4.8 wt%) than the average of the bulk rock analyses for unit 1 (5.3 wt%; Fisk et al., 1989).

Table 3. Microprobe analyses of glasses, Site 706.

Hole no.	706B						706B	706C	706C	706C	706C
Unit no.	1						1	1	1	1	1
Core, section	7X-CC						7X-CC	2R-1	2R-2	5R-2	5R-3
Interval (cm)	[a]17–20						[a]20–27	76–80	2–4	102–105	44–48
Depth (mbsf)	36.87						36.90	45.06	46.00	75.72	76.64
Average (N)	1	1	1	1	1	1	8	8	5	5	5
SiO_2	48.73	49.29	50.34	50.64	47.65	54.70	47.95	48.15	45.24	48.84	48.75
TiO_2	3.26	2.54	3.63	2.84	3.38	2.36	3.94	3.87	3.53	4.02	3.86
Al_2O_3	13.89	13.11	14.64	14.26	14.08	14.76	12.71	12.93	12.18	12.26	12.49
FeO	14.36	12.95	12.78	12.90	14.11	11.60	15.62	15.34	13.28	15.53	15.30
MnO	0.25	0.24	0.24	0.26	0.25	0.25	0.26	0.25	0.23	0.29	0.28
MgO	4.65	6.56	4.00	3.53	4.74	2.32	4.70	4.76	4.45	4.33	4.38
CaO	9.35	10.66	8.12	7.50	9.28	6.85	9.64	9.41	8.84	7.99	8.93
Na_2O	3.42	3.18	3.44	3.77	3.23	3.50	2.95	3.04	3.01	2.40	2.49
K_2O	0.97	0.77	1.33	1.25	0.94	2.28	0.84	0.79	0.73	0.88	0.90
Total	98.92	99.34	98.57	97.00	97.70	98.65	98.65	98.58	91.53	96.58	97.42

[a] Glass in sulfide nodule between sediments and Unit 1.

Table 4. Microprobe analyses of olivine microphenocrysts, Site 706.

Hole no.	706C				706C		
Unit no.	1				1		
Core, section	5R-2				5R-3		
Interval (cm)	102–105				44–48		
Depth (mbsf)	75.72				76.64		
Analysis	1	2	3	4	1	2	3
SiO_2	37.20	37.38	37.85	36.06	36.90	36.75	36.54
FeO	28.52	28.97	28.29	28.38	28.65	27.78	28.35
MnO	0.43	0.50	0.48	0.47	0.46	0.40	0.45
MgO	32.07	31.69	31.94	32.65	32.47	32.59	32.05
NiO	0.11	0.11	0.11	0.12	0.17	0.11	0.11
Total	98.32	98.64	98.66	97.68	98.65	97.64	97.51
Fo	66.3	65.7	66.4	66.8	66.4	67.3	66.4

Olivine is preserved in two flows (17 and 19; Table 4), and these are two of the units in which glass was also preserved. This olivine has a restricted range (Fo_{66-67}), and the glasses from flows 17 and 19 have MgO/FeO ratios of 0.328–0.335. These glasses would be in equilibrium with an olivine of Fo_{66}, assuming that the Mg-Fe exchange coefficient for olivine and glass (K_D) is 0.306 (Roeder and Emslie, 1970) and 85 wt% of the total iron in the magma was FeO. The geothermometer of Ford et al. (1983) indicates that this olivine crystallized at 1135°C. The bulk-rock composition of flow 17, however, has a MgO/FeO ratio of 0.368, so the rock is enriched in MgO relative to the glass, indicating that the glass was more evolved than the bulk rock or that there was accumulated olivine or augite in the host rock. The thin sections of this flow contain 3%–5% olivine and 10% augite, which
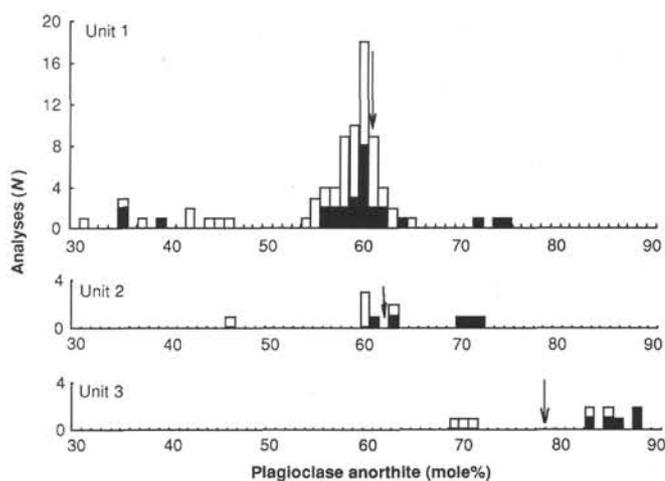
Figure 5. Histogram of anorthite content of plagioclase in each of the three chemical units from Site 706. Units 1 and 2 are chemically and mineralogically similar. The low anorthite plagioclases ($<An_{50}$) are from a sandstone at the top of the unit that is made of silicic ash cemented with iron sulfide. These feldspars are unrelated to those in the units below. Chemical unit 3 contains An_{83-88} megacrysts that are too anorthitic to have crystallized from the host magma. In this and subsequent histograms, core compositions are designated by solid bars, rim compositions by open bars, and arrows show the equilibrium plagioclase or pyroxene compositions at the liquidus temperature from Table 15.

Table 5. Leg 115 Opaque minerals, Sites 706, 707, 713, and 715.

Hole no.	706C	706C	706C	707C	707C	707C	707C	713A	715A	715A	715A	715A
Unit no.	1	2	2	1	2	3	4	1	1	1	2	3
Core, section	5R-2	8R-2	8R-2	22R-1	23R-1	26R-2	28R-3	15R-4	23R-3	23R-3	25R-3	30R-3
Interval (cm)	102–105	43–45	43–45	94–95	24–25	126–128	48–50	44–46	44–46	44–46	25–27	40–41
Analysis no.	1	1	2	1	1	1	1	1	1	2	1	1
SiO_2	0.09	0	0.19	0.39	0.64	0.54	0.26	0.16	0.15	0.08	0.12	0
TiO_2	17.43	5.65	17.22	14.50	17.95	21.76	17.11	19.73	25.60	52.76	27.05	47.51
Al_2O_3	3.82	8.03	4.00	2.79	2.51	2.10	2.41	1.36	1.88	0.12	1.22	0
FeO	69.52	48.54	68.33	77.97	74.35	71.82	75.48	74.11	64.98	41.94	68.77	49.84
MnO	0.37	0.35	0.40	0.27	0.33	0.44	0.37	0.56	0.64	0.42	0.52	0.51
MgO	4.60	5.52	3.74	0.13	0.52	0.82	0.44	0.33	1.12	1.74	1.70	1.09
Cr_2O_3	0.36	30.65	2.33	0.04	0.02	0.03	0.03	0.02	0.08	0	0	0.02
NiO	0.07	0.05	0.05	0	0.02	0.02	0.60	0	0.03	0	0.09	0.03
Total	96.39	98.86	96.44	96.22	96.37	97.72	96.24	96.45	94.52	97.20	99.47	99.22
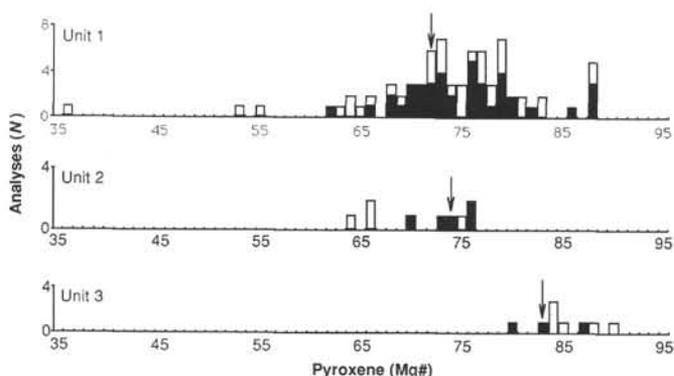
Figure 6. Histogram of the pyroxene Mg# ($Mg^{2+}/[Mg^{2+} + Fe^{2+}]$) of magnesium-augites from Site 706. The total iron content from the microprobe analysis has been recalculated to ferric and ferrous iron on the basis of pyroxene stoichiometry and tetrahedral site occupancy, and M1 and M2 site occupancy (Papike et al., 1974) before the Mg# was calculated. Augites in chemical unit 3 have higher Mg# than those in units 1 and 2, reflecting the higher Mg# of its host basalt.

is typical of this chemical unit and indicates that there is no significant accumulation of mafic phases in this flow.

Oxide minerals are not abundant at Site 706, but they were analyzed in flows 17 (chemical unit 1) and 28 (chemical unit 2). All analyses in both units were titanomagnetites (Table 5) except for the core of one grain in Flow 28, which was a spinel with 31 wt% Cr_2O_3.

Site 707 (Early Stages of Rifting)

These basalts appear to have erupted on the rifted margin of western India and, in contrast with Site 706, the Site 707 basalts erupted as only a few thick flows, possibly with long periods between eruptions given the presence of 1.09 m of shelly limestone between flows 3 and 4 and 0.36 m of carbonate sand between flows 4 and 5. Only five flows were identified in 63 m of section compared with the 32 flows in 77 m of section at Site 706.

Chemistry

The boundary between flows 2 and 3 is a 5-cm-thick vesicular zone, but the two flows could not be distinguished chemically. Therefore, they have been combined as chemical unit 2. The other three flows, which were identified by texture, mineralogy, and the presence of interflow sediments, could also be distinguished chemically (Fig. 4). The four chemical units have vesicular upper and lower margins and massive interiors. All the basalts from this site are characterized by their low K_2O content, and the upper units have extremely low TiO_2 (≤ 0.82 wt%), less than all other basalts from the Deccan Traps and from Réunion and Mauritius islands and even less than basalts erupted at the Central Indian spreading ridge.

Mineralogy

The basalts of Site 707 all contain plagioclase and augite phenocrysts, and minor amounts of relict olivine (<1 modal %) are found at the base of flow 3 (chemical unit 2), throughout chemical unit 3, and in chemical unit 4. Total phenocryst abundance varies from about 4 modal % in flow 1 to about 50 modal % in chemical unit 4. Plagioclase is always more abundant than augite, except in the top flow where there is 1% plagioclase and 5% augite. Unit 2 is characterized by abundant (7%–20%) plagioclase up to 5 mm across and subordinate augite (2%–15%) less than 1 mm across. Glomerocrysts of plagioclase and augite make up 30% of one thin section from unit 2.

Unit 3 is enormously thick (40 m); the mineralogy is dominated by plagioclase phenocrysts (7%–22%) and augite is significantly less abundant (1%–7%). Also found within unit 3 is 1%–3% magnetite. Unit 4 is similar to unit 3 except that the base of unit 4 has only plagioclase. All flows have a fine-grained groundmass of plagioclase, augite, and, in some cases, opaque oxides and black microcrystalline glass or altered glass.

Alteration

The four chemical units have undergone moderate degrees of alteration ranging from 10% to 70% in thin section. Primary minerals have been replaced with clays and carbonates, and vesicles are filled with these minerals. Chemical unit 3 appears to be the least altered, whereas chemical unit 1 is the most altered. Of the primary minerals, olivine is always converted to clay, and in unit 1, many of the augite phenocrysts and much of the groundmass are also converted to clay. In unit 2 the pyroxene and plagioclase phenocrysts have resisted alteration, but some of the groundmass pyroxene is altered to saponite (Fisk and Howard, this volume). In unit 3 plagioclase and augite are preserved, but olivine is converted to clay. In the groundmass about 25% of the minerals are altered to clay, although some thin sections have little or no alteration of phenocrysts or groundmass. Roughly 50% of unit 4 is also altered to clay, which replaces plagioclase and clinopyroxene in the groundmass. Details of the clay mineralogy and chemistry are given elsewhere (Fisk and Howard, this volume).

Mineral Chemistry

Nine thin sections from the four chemical units (5 flows) were analyzed by electron microprobe. Plagioclase and augite compositions are presented by unit in Tables 6 and 7 and in Figures 7 and 8. The plagioclase phenocryst cores in each unit have a wide range of composition, and all four units have two populations. Units 1, 2, and 4 have a high-anorthite group of phenocrysts with cores of An_{82-88} and another group with cores in the range of An_{60-72}. Unit 2 may have a distinct, third group of plagioclase phenocrysts that are An_{45-60}, but this group may be the result of zoning during slow cooling of the flow. The thickest unit (unit 3) has two distinct populations of plagioclase, but the most anorthitic are An_{76-79}. All of the units contain glomerocrysts of plagioclase and augite, and it is these glomerocrysts that contain the feldspars with the high anorthite content. Zoning of the feldspars is normal, with the highest anorthite values in the interiors of crystals and the lower values in the rims and groundmass.

Clinopyroxene compositions from units 2 and 3 (in particular, their Mg#) can be grouped into two or three distinct modes similar to those of the feldspars. There are not enough data for units 1 and 4 to say whether there is a bimodal distribution of Mg values (Fig. 8). The possibility that three populations of augite occur in unit 2 supports the observation that three populations of plagioclase phenocryst cores may also exist in this unit (Fig. 7). Pyroxene phenocryst cores with Mg#s of 88 or greater probably represent an earlier phase of crystallization from a more mafic liquid at higher temperatures than the host basalt.

Opaque oxide microphenocrysts were reported in unit 3 as minor constituents and in the groundmass (Backman, Duncan, et al., 1988). Skeletal and groundmass titanomagnetites were analyzed in the lower two units of the site, and they are typical of late-stage oxides with low chromium contents (Table 5). No ilmenite was found, however. Glass was not preserved in Site 707.

Site 713 (Near Ridge Volcanism)

At Site 713 on the northern edge of the Chagos Bank, about half of the 85 m of basement that was drilled was recovered. We

Table 6. Microprobe analyses of plagioclase phenocrysts, Site 707.

Hole no.	707C			707C		707C		707C			707C		
Unit no.	1			1		2		2			2		
Core, section	22R-1			22R-2		23R-1		23R-1			23R-3		
Interval (cm)	94–95			37–38		24–25		65–66			137–140		
Depth (mbsf)	376.54			377.57		385.54		385.95			389.67		
Analysis	1	2	3	1	2	1	2	1	2	3	1	2	3
SiO_2	46.44	49.36	53.27	50.76	55.29	45.60	45.12	56.41	49.42	50.82	47.66	50.46	54.18
Al_2O_3	34.09	31.00	28.28	30.22	27.52	34.02	33.36	25.82	30.55	29.12	33.51	30.23	27.23
FeO	0.62	0.87	1.14	0.68	1.84	0.61	0.74	1.05	0.69	1.00	0.63	0.82	1.02
CaO	18.35	15.15	12.06	14.51	11.45	18.42	17.84	9.52	14.63	12.86	17.22	15.33	11.28
Na_2O	1.36	3.27	4.88	2.79	4.86	1.41	1.67	6.58	2.91	4.31	1.92	3.07	5.76
K_2O	0.07	0.07	0.07	0.05	0.07	0.07	0.07	0.05	0.04	0.05	0.04	0.04	0.04
Total	100.92	99.71	99.69	99.01	101.03	100.12	98.81	99.42	98.24	98.17	100.98	99.95	99.51
An	88.0	71.7	57.6	74.0	56.4	87.6	85.3	44.3	73.4	62.1	83.1	73.3	51.9
Notes	c	r	m	c	r	c	r	r	c	r	c	r	m

Hole no.	707C		707C		707C		707C		
Unit no.	3		3		4		4		
Core, section	25R-3		26R-2		28R-1		28R-3		
Interval (cm)	0–1		126–128		27–29		48–50		
Depth (mbsf)	407.5		417.06		433.87		437.08		
Analysis	1	2	1	2	1	2	1	2	3
SiO_2	50.59	53.17	50.03	48.43	50.82	51.87	51.95	46.30	57.38
Al_2O_3	29.51	29.68	31.32	32.07	30.74	30.41	29.14	33.62	25.92
FeO	0.79	0.95	0.72	0.82	0.74	0.71	0.99	0.62	0.88
CaO	14.34	13.63	16.04	16.43	14.98	14.72	12.88	17.44	9.33
Na_2O	3.22	4.45	2.71	2.25	3.40	3.37	3.66	1.35	6.15
K_2O	0.11	0.07	0.06	0.05	0.06	0.05	0.04	0.04	0.05
Total	98.55	101.95	100.88	100.05	100.74	101.14	98.66	99.38	99.71
An	70.7	62.6	76.3	79.9	70.7	70.5	65.9	87.6	45.5
Notes	c	r	c	r	c	r	r	c	m

Notes: c = core, r = rim, and m = microphenocryst.

identified 35 flows; of these, the upper 11 flows extend from the basement/sediment contact at 107 m to 174 mbsf. The lower 23 flows make up only 17 m of the hole from 174 to 191 mbsf.

Chemistry

Three chemical units were identified in these flows based on major and trace element chemistry (Fig. 4). Units 1 and 2 have higher Fe_2O_3, TiO_2, P_2O_5, Zr, Ba, and Y values than unit 3, yet units 1 and 2 can be distinguished by their Al_2O_3 (not shown) and Sr abundances. The abundance of MgO is fairly constant (6–8 wt%) throughout all units (Backman, Duncan, et al., 1988), so the wide range in trace element abundances implies that the upper 2 units and lower unit are not simply related by fractional crystallization. Also present at Site 713 is an iron-titanium-rich glass from a turbidite between units 2 and 3. This glass can be considered a fourth chemical unit that was derived from the others by fractional crystallization.

Mineralogy

Plagioclase phenocrysts are usually the dominant mineral phase in the basalts at Site 713, and they vary from 2 to 25 modal % in the upper lavas and from 4 to 30 modal % in the lower flows. Pyroxene (1–40 modal % in units 1 and 2, and 3–13 modal % in unit 3) is the second most common phenocryst phase, except in some of the upper flows where it exceeds plagioclase in abundance. Olivine pseudomorphs are present in the majority of the flows for which thin sections were made, and they always represent <5% of the sample. The groundmass invariably consists of plagioclase, augite, and oxides, except in the chilled margins of flows where the groundmass can be entirely glass or a mixture of groundmass minerals and glass.

Alteration

As at Sites 706 and 707, alteration occurs throughout the section. At Site 713 the upper flows have experienced 1%–65% alteration based on visual estimates from thin sections. Samples with small amounts of alteration are glassy. In the lower flows, alteration varies from 10% to 85%, yet in some samples with 50% alteration, primary olivine and glass are preserved.

Mineral Chemistry

We analyzed 13 thin sections from the three units from Site 713, and the results are presented in Tables 5, 8, 9, 10, and 11. As in Sites 706 and 707, the feldspars have a wide range of anorthite content in all three units, and there appears to be at least two distinct chemical groups (Fig. 9). The high-anorthite plagioclase analyses are commonly found in the cores of the larger phenocrysts, and the lower anorthite plagioclase is found in the glomerocrysts. The few augite analyses do not appear to fall into groups based on Mg# (Fig. 10). The cores of the pyroxene phenocrysts have higher Cr_2O_3 and less TiO_2 and Al_2O_3 than the rims of the same grains (Table 9). The high Cr and Mg# suggest that the cores represent an earlier stage of crystallization at high temperatures, possibly from a magma with higher Cr_2O_3. The TiO_2 contents of the rims reach 1.6 wt%, which is typical of titanaugites from alkali basalts but not as high as the TiO_2 found in the rims of pyroxenes in the upper units of Site 706.

Glass was preserved in several of the flows at Site 713. No glass was found in chemical unit 1. In chemical unit 2 the only glass (Table 10) has low total abundance of the oxides, low Na_2O content, and a variable composition. This unit has only a small amount of alteration, but the glass may have started to de-

Table 7. Microprobe analyses of clinopyroxenes, Site 707.

Hole no.	707C		707C			707C	707C		707C		
Unit no.	1		1			2			2		
Core, section	22R-1		22R-2			23R-1	23R-1		23R-3		
Interval (cm)	94–95		37–38			24–25	65–66		137–140		
Depth (mbsf)	376.54		377.57			385.54	385.95		389.67		
Analysis	1	2	1	2	3	1	1	2	1	2	3
SiO$_2$	53.25	53.07	51.42	50.77	52.78	52.26	50.76	51.46	51.76	52.14	52.06
TiO$_2$	0.23	0.20	0.31	0.49	0.24	0.23	0.26	0.28	0.29	0.23	0.46
Al$_2$O$_3$	2.25	1.50	3.90	2.89	2.39	2.58	1.55	2.34	2.37	2.44	1.93
FeO	7.13	8.86	6.74	9.23	5.78	5.81	11.18	7.29	8.60	5.94	10.40
MnO	0.20	0.28	0.23	0.23	0.20	0.21	0.40	0.26	0.24	0.16	0.35
MgO	16.72	17.59	16.21	14.81	17.85	17.09	17.24	16.29	16.19	16.71	15.65
CaO	20.01	19.18	20.04	20.15	21.50	21.94	16.48	19.89	19.26	21.08	18.40
Na$_2$O	0.16	0.17	0.26	0.26	0.20	0.24	0.18	0.16	0.26	0.20	0.30
Cr$_2$O$_3$	0.22	0.05	0.33	0.04	0.23	0.49	0.05	0.11	0.06	0.51	0.07
Total	100.17	100.91	99.44	98.86	101.18	100.86	98.10	98.08	99.04	99.41	99.60
Notes	c	r	c	r	c	c	r	c	r	c	m
Mg#	81	82	83	88	92	92	73	80	80	86	75

Hole no.	707C			707C			
Unit no.	3			4			
Core, section	26R-2			28R-3			
Interval (cm)	126–128			48–50			
Depth (mbsf)	417.06			437.08			
Analysis	1	2	3	1	2	3	4
SiO$_2$	51.78	51.37	52.11	51.09	50.77	51.37	52.71
TiO$_2$	0.50	0.51	0.41	0.16	0.25	0.31	0.22
Al$_2$O$_3$	2.98	2.52	2.06	2.63	2.42	3.35	1.88
FeO	9.10	8.75	10.57	5.62	7.17	6.78	6.95
MnO	0.24	0.21	0.27	0.15	0.21	0.21	0.18
MgO	15.45	16.33	16.73	16.85	16.84	16.41	16.41
CaO	18.26	19.48	18.21	21.76	20.75	20.95	19.96
Na$_2$O	0.31	0.30	0.22	0.28	0.20	0.22	0.15
Cr$_2$O$_3$	0.07	0.23	0.08	0.34	0.05	0.24	0.05
Total	98.68	99.70	100.66	98.89	98.66	99.85	98.51
Notes	m	c	r	c	r	c	r
Mg#	75	82	88	94	89	87	81

Notes: c = core, r = rim, and m = microphenocryst.
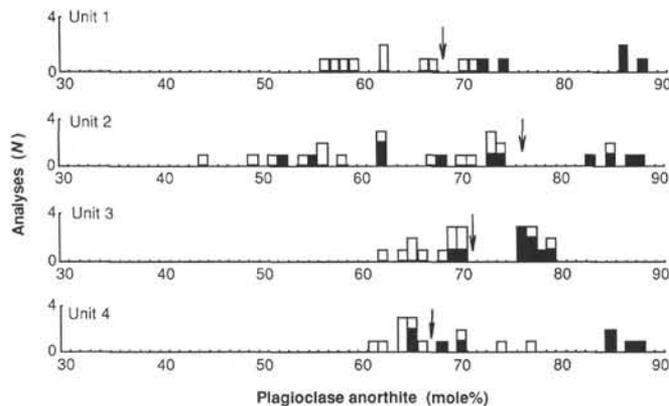
Figure 7. Histogram of the anorthite content of plagioclase in the four chemical units at Site 707. Units 1 and 2 have a wide range of compositions even though each unit is a single flow. All chemical units contain plagioclase with anorthite content too high to have crystallized from the host magma.

Figure 8. Histogram of magnesium-augite Mg# for Site 707 chemical units. The pyroxene analyses have a restricted range of compositions compared with plagioclase of the same units. All units have one or more pyroxene analyses with unusually high Mg# compared with that expected, given the composition of the host magmas.

vitrify and hydrate. In chemical unit 3, glass is preserved in many of the flows. This glass is chemically uniform throughout the 22 m of this unit, and the standard deviation of the average of most elements is within the analytical error of the micro-probe. The glass found in the volcanic turbidite between units 2 and 3 is clearly different from any of the other Site 713 units (Figs. 3 and 4) and could be classified as a Fe-Ti basalt. Quenched olivine (Fo$_{82}$; Table 11) is preserved in the glassy margins of the many thin flows in unit 3.

Table 8. Microprobe analyses of plagioclase phenocrysts, Site 713.

Hole no.	713A		713A	713A		713A			
Unit no.	1		2	2		2			
Core, section	13R-3		15R-4	15R-4		15R-4			
Interval (cm)	16–20		44–46	143–145		3–7			
Depth (mbsf)	110.86		131.64	132.63		132.73			
Analysis no.	1	2	1	1	2	1	2	3	4
SiO_2	45.80	46.11	58.20	51.29	50.13	46.89	51.15	45.27	51.80
Al_2O_3	33.98	32.03	25.79	30.42	30.51	33.46	30.22	33.56	30.21
FeO	0.67	0.73	0.68	0.88	0.91	0.66	1.00	0.47	0.98
CaO	17.73	16.38	8.57	14.04	14.81	16.37	13.94	17.30	13.18
Na_2O	1.71	3.56	7.63	3.98	3.64	2.06	4.07	1.59	4.27
K_2O	0.05	0.05	0.15	0.09	0.07	0.04	0.08	0.04	0.05
Total	99.94	97.87	101.01	100.70	100.07	99.49	100.46	98.23	100.49
An	85.1	77.8	38	65.8	69	81	65	85.6	63
Notes	c	r	r	c	r	c	r	r	m

Hole no.	713A			713A		
Unit no.	2a			3		
Core, section	17R-2			19R-1		
Interval (cm)	41–44			116–118		
Depth (mbsf)	147.61			165.56		
Analysis no.	1	2	3	1	2	3
SiO_2	53.49	47.19	46.39	50.67	47.93	44.75
Al_2O_3	26.74	32.49	32.56	29.85	31.91	34.37
FeO	1.08	0.68	0.76	0.88	0.80	0.54
CaO	10.77	16.45	16.52	13.85	16.15	18.24
Na_2O	5.56	1.70	1.56	3.51	2.72	1.39
K_2O	2.03	0.11	0.06	0.27	0.06	0.05
Total	99.66	98.62	97.85	99.03	99.57	99.34
An	46	84	85	67.6	76.5	87.8
Notes	m	c	r	m	r	c

Notes: c = core, r = rim, and m = microphenocryst.

Site 715 (Analogous to Réunion)

Site 715 was drilled on the eastern side of the Maldive Islands platform in 2266 m of water. About 75 m of basalt was drilled, and 21 flows were identified, some of which were separated by carbonate sediments.

Chemistry

Three units at Site 715 can be distinguished compositionally. The uppermost unit is made up of Fe-Ti basalts with greater than 12 wt% total FeO (Fig. 4) and with alkali abundance that places it in the alkali basalt field (Fig. 3B). This unit overlies 50 cm of carbonate sediment that separates it from units with lower FeO. The lower two units are made up of primitive flows with more than 9 wt% MgO, which are classified as tholeiites based on alkali and silica abundances (Fig. 3B). Flows 9 and 10 have subtle chemical signatures (in Zr, Sr, Nb, and Cr) that distinguish them from flows 12 through 21 (Fig. 4; Backman, Duncan, et al., 1988). These chemical differences could be caused by fractional crystallization, in which case, all of the magmas may be derived from a common parent.

Mineralogy

The upper flows (1–7; chemical unit 1), including the Fe-Ti basalts, are nearly aphyric and contain 1%–3% (modal) plagioclase phenocrysts, which are >2 mm at their greatest dimension. Olivine and augite are rare. Flows 9, 10, and 11 (chemical unit 2) are olivine phyric, with original olivine contents up to 15 modal %, but they do not contain any plagioclase or augite. In chemical unit 3, flow 12 has 10% olivine and 20% plagioclase, and flow 13 had 10% olivine. Flows 14 through 21 are mostly aphyric.

Throughout the site, the groundmass of these flows is either glass (flow 12) or plagioclase, augite, opaques, and olivine.

Alteration

The rocks throughout the hole are pervasively altered, and all glass and olivine are replaced with clay. Often the olivine is replaced by iddingsite. In some of the flows, plagioclase and augite are partially replaced by clays. The opaques, however, seem unaffected. Alteration products constitute 10%–90% of the flows studied in thin section.

Mineral Chemistry

Eight thin sections representing the three chemically distinct units were examined by microprobe (Tables 5, 12, 13, and 14), and it was found that their phenocrysts are also chemically distinctive. The cores of the feldspars in unit 1 have a maximum An_{70} content, whereas units 2 and 3 have phenocrysts with cores of An_{76} and An_{79}, respectively (Fig. 11). The feldspars in units 1 and 2 have normal zoning, but those in unit 3 have both normal and reversed zoning. Pyroxene from the three units at Site 715 is also distinctive (Fig. 12). Unit 1 does not contain the high-MgO phenocrysts that are found in units 2 and 3. The Cr_2O_3 in phenocryst cores from units 2 and 3 is as high as 0.9 wt%, whereas augite cores in unit 1 have 0.1 wt% or less.

Olivine was originally present in all three units, but it is preserved only in flow 18 of chemical unit 3; its composition is Fo_{72-81} (Table 14). Glass was originally present in the margins of some of the flows, but it was altered to clay in all of the thin sections that were examined. Groundmass oxide minerals in the upper unit are both magnetite and ilmenite, but in the lower two units they are primarily magnetite.

Table 9. Microprobe analyses of clinopyroxenes, Site 713.

Hole no.	713A	713A			713A		
Unit no.	1	1			1		
Core, section	13R-3	15R-4,			15R-4		
Interval (cm)	16-20	44-46			143-144		
Depth (mbsf)	110.86	131.64			132.63		
Analysis no.	1	1	2	3	1	2	3
SiO_2	49.96	50.15	48.54	47.85	49.92	51.37	50.57
TiO_2	0.43	0.44	0.79	0.83	0.46	0.43	0.46
Al_2O_3	3.52	2.04	2.74	1.79	2.63	2.80	3.46
FeO	6.83	8.30	13.14	18.26	10.94	7.91	7.96
MnO	0.21	0.26	0.36	0.53	0.33	0.22	0.21
MgO	17.36	16.59	14.28	11.28	15.32	16.14	17.09
CaO	20.28	19.87	17.81	16.62	18.29	19.94	20.24
Na_2O	0.22	0.34	0.36	0.23	0.28	0.28	0.20
Cr_2O_3	0.80	0.15	[a]0.04	[a]0.04	0.13	0.33	0.58
Total	99.60	98.15	98.06	97.44	98.31	99.42	100.77
Notes	m	xc	xr	m	xc	xr	c
Mg#	91	84	72	55	78	83	88

Hole no.	713A				713A		
Unit no.	2				3		
Core, section	15R-5				19R-1		
Interval (cm)	3-7				116-118		
Depth (mbsf)	132.73				165.56		
Analysis no.	1	2	3	4	1	2	3
SiO_2	51.13	51.09	53.25	52.35	51.42	51.34	49.91
TiO_2	0.42	0.54	0.34	0.45	0.41	0.26	0.81
Al_2O_3	2.31	2.82	2.45	2.88	4.07	2.58	5.31
FeO	7.51	8.82	7.98	8.70	5.75	5.55	7.44
MnO	0.20	0.29	0.25	0.26	0.15	0.13	0.17
MgO	16.55	15.22	17.13	16.38	16.86	16.62	15.09
CaO	19.32	18.32	18.18	17.73	20.43	21.50	20.51
Na_2O	0.29	0.32	0.33	0.28	0.24	0.23	0.26
Cr_2O_3	0.46	0.17	0.38	0.26	0.56	0.30	0.07
Total	98.19	97.58	100.31	99.30	99.90	98.51	99.58
Notes	c	r	c	r	c	r	m
Mg#	84	75	79	77	87	90	82

Notes: c = core, r = rim, m = microphenocryst, xc = xenocryst core, and xr = xenocryst rim.

[a] Minimum detection limit for Cr_2O_3 is 0.04 wt%.

DISCUSSION

Site 706

The chemistry of phenocrysts in Site 706 basalts is consistent with the bulk chemistry of the units. For example, chemical units 1 and 2 have lower average CaO/Na_2O and Al_2O_3 (Fig. 13) than unit 3. This corresponds to the lower anorthite content of the feldspars in units 1 and 2 (Fig. 5). The low MgO/FeO of the upper two units is also reflected in the lower average MgO/FeO of the pyroxenes in these units (Fig. 6).

The compositions of the majority of the phenocrysts in these rocks are close to the calculated equilibrium compositions based on the phase equilibrium model for basaltic magmas (Nielsen, 1988). The compositions of olivine, plagioclase, and augite at the liquidus temperature of each of the three chemical units at Site 706 are given in Table 15. Based on the ability of this model to predict the chemistry of minerals crystallizing from basalts (Nielsen, 1988), these calculated mineral compositions are accurate to within ±5% and are therefore useful in determining if minerals could have crystallized from the host magma or if they are xenocrysts or xenoliths.

In chemical units 1 (flows 1-21) and 2 (flows 22-30), the median value of plagioclase core and rim compositions is An_{60}, and the calculated equilibrium values are An_{61} and An_{62}, respectively. The similarity of the calculated equilibrium plagioclase

and the observed plagioclase of units 1 and 2 suggests that, for the most part, these 30 flows erupted from a magma chamber with temperatures as high as 1143°C. This is possible if the influx of parental magma is balanced by the amount of crystallization and eruption.

The few plagioclase phenocrysts that are An_{70} or greater are in the cores of rare, large phenocrysts from flow 3 near the top of chemical unit 1, or from flows 18 and 20 near the base of unit 1. Only one thin section from chemical unit 2 (flow 28) was analyzed, but it also had rare, large plagioclase phenocrysts with cores of An_{70-72}. All of these phenocrysts are strongly zoned to rims of about An_{60}. These cores must have crystallized from a magma that was more primitive than the bulk of the magma at this site.

It appears from the plagioclase and bulk-rock compositions of the upper two units that the magma chamber and mineralogy remained at a steady state while the uppermost 30 flows were erupted. The presence of plagioclase phenocryst cores (An_{70} or greater) in several flows indicates that these flows contained an admixed component that was either another magma of a different composition (and higher temperature or water content) or that the plagioclase was picked up from the magma chamber walls, from the conduit during eruption, or from a region of the magma chamber that had a higher temperature than the bulk of the erupted magma.

The chemical composition and mineralogy of chemical unit 3 (flows 31 and 32 and Fig. 4) distinguishes it from the 30 flows above it. Unit 3 is noted for its abundant (15%), large, plagioclase phenocrysts (Backman, Duncan, et al., 1988) with cores of An_{83-88} and rims of An_{70}. The anorthite content of the cores is higher than the equilibrium value calculated for the bulk composition of the unit (An_{77}; Table 15). This difference could be caused by the mixing of a magma that contained high-An plagioclase (An_{83-88}) with a magma that was crystallizing plagioclase of An_{70}. The bulk composition of the resulting mix could have a composition that would crystallize An_{77} plagioclase.

The calculated equilibrium pyroxene composition for chemical units 1 and 2 are nearly identical (Table 15). The Mg^+ (100 En/[En + Fs]) of these pyroxenes is 72 and 74, respectively. Because the model assumes all the iron in the pyroxene is FeO, this value will be slightly lower than the Mg# of the pyroxene analyses plotted in Figure 6, because the ferrous iron in the microprobe analyses has been adjusted for the stoichiometry of the pyroxenes and for preferred site occupancy based on the model of Papike et al. (1974). Even though there are slight differences in calculating the Mg# of the microprobe analyses and the pyroxenes discussed above, we conclude that the majority of the pyroxene phenocrysts and microphenocrysts crystallized near the liquidus temperature of their host magmas.

Some augite phenocrysts in unit 1 (Fig. 6) have an exceptionally high Mg# (86 or 88). These occur in the topmost sample in Hole 706B as well as in flow 3 near the top of chemical unit 1. This same flow has plagioclase phenocryst cores with high anorthite content (Fig. 5), which supports the hypothesis that some of the flows represent magmas with an admixed mafic component. Whether this admixed component is a second magma with high-temperature plagioclase and pyroxene phenocrysts or is a disrupted gabbroic cumulate from the margins of the magma chamber is not clear.

The similarity of the plagioclase and pyroxene equilibrium temperatures for units 1 and 2 (Table 15) supports the hypothesis that these two phases crystallized together in a steady-state magma chamber at 1130°-1143°C. The order of crystallization of primitive Réunion Island magmas at 1 atm is olivine first, followed by plagioclase, and then augite (Fisk et al., 1988). At 1150°-1160°C all three phases crystallize together, but below

Table 10. Microprobe analyses of glasses, Site 713.

Hole no.	713A	713A	713A
Unit no.	2	2	—[a]
Core, section	15R-5	15R-5	17R-2
Interval (cm)	3–7	3–7	41–44
Depth (mbsf)	133.00	146.11	
Average (N)	2	2	5
SiO_2	44.59	51.02	52.50
TiO_2	2.22	1.80	2.72
Al_2O_3	12.18	12.70	12.85
FeO	17.20	14.22	14.44
MnO	0.33	0.29	0.27
MgO	7.62	5.98	3.63
CaO	9.34	8.29	7.70
Na_2O	1.24	1.16	2.90
K_2O	0.41	0.27	0.70
Total	95.19	95.77	97.75

Hole no.	713A	713A	713A	713A	713A	713A	713A	713A	713A
Unit no.	3	3	3	3	3	3	3	3	3
Core, section	19R-1	20R-2	20R-2	20R-3	20R-5	20R-6	21R-2	Unit 3	Unit 3
Interval (cm)	15–20	37–39	89–91	64–66	98–99	22–24	130–132	Ave.	SD
Depth (mbsf)	164.55	175.77	176.29	177.54	180.88	181.62	186.10		
Average (N)	6	7	8	6	6	7	6	7	—
SiO_2	49.24	49.09	49.55	49.92	49.53	48.53	48.90	49.25	0.46
TiO_2	1.10	1.10	1.12	1.09	1.12	1.05	1.18	1.11	0.04
Al_2O_3	13.95	14.07	14.32	14.04	14.03	13.95	13.87	14.03	0.14
FeO	11.42	11.53	11.66	11.40	11.35	11.42	11.40	11.45	0.11
MnO	0.23	0.22	0.24	0.21	0.23	0.22	0.22	0.22	0.01
MgO	7.43	7.44	7.55	7.42	7.47	7.35	7.28	7.42	0.09
CaO	12.61	12.82	11.93	12.71	12.86	12.42	12.44	12.54	0.32
Na_2O	2.44	2.38	2.39	2.38	2.40	2.38	2.46	2.40	0.03
K_2O	0.20	0.14	0.14	0.13	0.13	0.20	0.21	0.16	0.04
Total	98.66	98.83	98.95	99.34	99.16	97.56	98.00		

Note: Ave. = average and SD = standard deviation.
[a] Glass in turbidite between units.

this temperature olivine reacts with the residual melt and leaves only plagioclase and augite to crystallize until the appearance of magnetite and/or ilmenite.

Figures 6 and 14A show the pyroxene Mg# and quadrilateral components for augite from Site 706, and the chemical unit 3 (flows 31 and 32) augites reflect the high-MgO content of these rocks. The high-MgO contents of the augites also agree with the enstatite and ferrosilite components calculated for this unit (Table 15). The temperature at which these pyroxenes are expected to crystallize (1167° ± 20°C) is well below the crystallization temperature calculated for plagioclase, but it is the same as the olivine crystallization temperature (1152°C ± 20°C). This indicates that the large amount of plagioclase that was found in the magma, and which appears to be out of equilibrium with the host magma, was added to the magma. The plagioclase xenocrysts are strongly zoned from An_{70-85}, which also supports the hypotheses that these feldspars are an added component. These xenocrysts, however, have euhedral shapes and either must have overgrowths of equilibrium plagioclase or they must have been introduced into the magma shortly before the magma was quenched.

Olivine was originally present in only a few of the flows of units 1 and 2, but calculation of the equilibrium mineralogy shows that olivine is not expected to crystallize at any temperature from a magma that had a composition equivalent to the average of the 30 flows at the top of the hole (Table 15). This contradiction can be explained if the magma chamber contained a magma with only plagioclase and augite on the liquidus and this magma chamber was occasionally recharged with a primitive magma that brought olivine onto the liquidus with plagioclase

and augite. Maintaining a magma chamber close to the olivine out-phase boundary long enough to erupt 30 flows (equivalent to about 70 m of section) requires the presence of a steady-state magma chamber. The high-An plagioclase and high-MgO pyroxene in some of the flows indicates that this magma chamber occasionally contained primitive magma that was mixed with the more evolved bulk composition, or that these plagioclase and augite xenocrysts were added to the magma by another mechanism.

Site 707

Although four chemical units can be distinguished among the five flows at Site 707 (Fig. 4), there appears to be a major change in chemistry between chemical units 2 and 3. The upper three flows (units 1 and 2) have extremely low TiO_2 content (Figs. 3A and 4E), lower than any of the Deccan lavas (Beane et al., 1986). The lower two flows (units 3 and 4) have comparatively higher TiO_2 and lower MgO contents, similar to the Bushe flows of the Deccan province (Beane et al., 1986; Cox and Hawkesworth, 1985). The mineralogy and mineral chemistry of these units, to some extent, reflect this abrupt change in chemistry.

All units exhibit bimodal distribution of anorthite compositions (Fig. 7). The calculated equilibrium feldspar composition at the liquidus temperature is given in Table 15, and these calculated compositions are similar to the low-An plagioclase in each unit. The high-An plagioclase appears to be out of equilibrium with the bulk rock. In units 1, 2, and 4 the maximum An content of the plagioclase is 88, but in the 40-m-thick flow (unit 3) the maximum is An_{79}. Perhaps because of the thickness of the

Table 11. Microprobe analyses of olivine phenocrysts, Site 713.

Hole no.	713A		713A				713A						
Unit no.	3		3				3						
Core, section	19R-1		20R-2				20R-2						
Interval (cm)	15–20		37–39				89–91						
Depth (mbsf)	164.55		175.77				176.29						
Analysis No.	1	2	1	2	3	4	1	2	3	4	5	6	7
SiO_2	39.27	37.81	39.73	39.28	39.00	39.01	39.69	39.73	39.51	39.40	39.29	39.31	39.45
FeO	17.25	16.93	16.76	16.90	16.98	16.97	17.06	17.40	17.45	17.69	17.27	17.22	17.67
MnO	0.26	0.27	0.29	0.26	0.22	0.32	0.30	0.32	0.30	0.27	0.31	0.32	0.30
MgO	43.29	41.99	43.60	43.59	44.25	43.88	43.53	43.17	43.06	43.16	43.06	43.17	42.70
NiO	0.09	0.12	0.12	0.13	0.15	0.14	0.12	0.14	0.09	0.11	0.09	0.10	0.14
Total	100.16	97.13	100.50	100.08	100.60	100.32	100.70	100.74	100.41	100.63	100.02	100.12	100.26
Fo	81.8	81.6	82.3	82.3	82.3	82.2	82	81.6	81.5	81.4	81.7	81.7	81.2
Notes	c	r	c	r	c	r	m	c	r	c	r	r	c

Hole no.	713A			713A								713A	
Unit no.	3			3								3	
Core, section	20R-3			20R-5								20R-6	
Interval (cm)	64–66			98–99								22–24	
Depth (mbsf)	177.54			180.88								181.62	
Analysis no.	1	2	3	1	2	3	4	5	6	7	8	1	2
SiO_2	39.44	39.89	39.44	39.96	40.18	39.01	40.18	40.11	40.32	38.88	39.47	37.94	37.85
FeO	16.83	16.61	16.79	16.91	16.86	16.59	16.80	16.93	16.42	17.08	16.94	16.57	16.92
MnO	0.31	0.29	0.30	0.30	0.29	0.26	0.26	0.28	0.23	0.25	0.28	0.35	0.29
MgO	42.59	42.73	42.35	42.39	41.89	42.22	42.46	42.51	42.95	42.03	42.32	43.58	43.57
NiO	0.11	0.09	0.12	0.12	0.19	0.10	0.13	0.15	0.12	0.15	0.19	0.19	0.16
Total	99.28	99.61	99.00	99.67	99.41	98.18	99.83	99.98	100.04	98.38	99.21	98.63	98.79
Fo	82	82	81.8	82	79	82	82	82	82	81.7	81.7	82.4	82.1
Notes	c	r	m	m	c	r	c	r	c	r	m	c	c

Notes: c = core, r = rim, and m = microphenocryst.
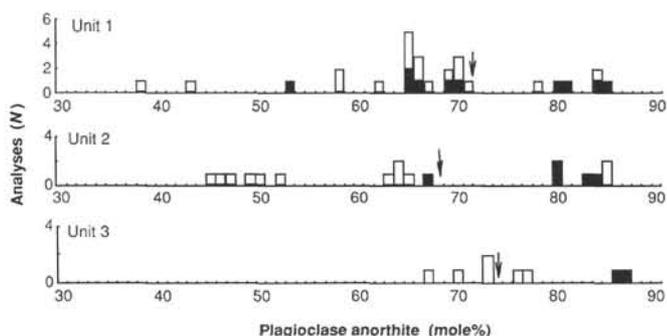
Figure 9. Histogram of anorthite content of plagioclase in Site 713 chemical units. An_{45-52} in unit 2 are from a volcanic turbidite between chemical units 2 and 3 and are plotted with unit 2 for convenience. Glass from this same turbidite are plotted in Figures 3A and 3B.
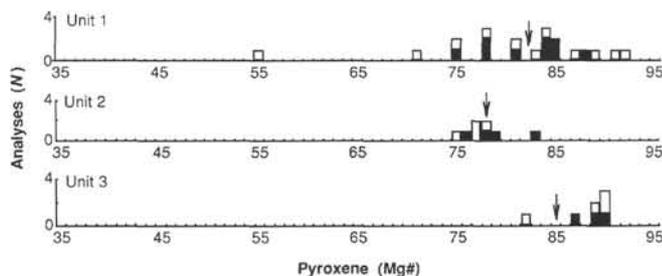
Figure 10. Histogram of magnesium-augite Mg# from the three chemical units of Site 713.

flow and its long cooling time, the plagioclase re-equilibrated during cooling, whereas the thinner flows (chemical units 1, 2, and 4) would have had their plagioclase phenocryst compositions quenched at the time of eruption.

The bimodal distribution of plagioclase compositions and the presence of plagioclase "xenocrysts" or megacrysts in all of the units implies that all of the flows have an admixed component from either a second unerupted magma or from plagioclase xenocrysts located in the magma chamber or conduit walls. If the admixed component is a magma, it will have a CaO/Na_2O (wt%) greater than 8 (Fisk, 1984), but in all lavas at this site the ratio is less than 6. Upper Paleocene magmas from the Indian Ocean (DSDP Site 236) with exceptionally high CaO/Na_2O (7.6) have been reported (Melson et al., 1977), and other areas of the Indian Ocean have basalts with a CaO/Na_2O of 9.5 (Melson et al., 1977). The rift that produced the basalts at DSDP Site 236 (Fig. 1) is also probably the source of the basalts at Site 707, so the primitive magmas from Site 236 could be similar to the magmas that produced the high-anorthite plagioclase in the Site 707 magmas. It is not necessary, however, that the admixed component be a magma; it could originate from the plagioclase phenocrysts that crystallized from a high-CaO/Na_2O magma (such as those from DSDP Site 236) and were separated from it. One mechanism for plagioclase separation could have been the plating of the magma chamber roof by floating of the feldspar because of its low density relative to the magma.

The high CaO/Na_2O and high MgO/FeO of the Site 236 magmas (Melson et al., 1977) indicates that they are high-temperature, primitive magmas that are capable of crystallizing the An_{85-88} plagioclase found in Site 707 magmas. The Site 236 glasses are similar in MgO and TiO_2 contents to some rocks from Site 707 (Fig. 3A), but they cannot be the parents of the

Table 12. Microprobe analyses of plagioclase phenocrysts, Site 715.

Hole no.	715A	715A			715A	715A		
Unit no.	1	1			2	2		
Core, section	23R-2	23R-3			25R-3	25R-6		
Interval (cm)	26–28	44–46			25–27	37–38		
Depth (mbsf)	212.51	214.13	214.13	214.13	233.25	237.87	237.87	237.87
Analysis no.	1	1	2	3	1	1	2	3
SiO_2	54.24	51.14	51.88	49.93	52.81	49.41	53.25	51.66
Al_2O_3	27.75	30.29	29.71	31.41	30.06	32.01	28.21	30.01
FeO	1.03	0.65	0.93	0.58	0.82	0.78	0.91	0.92
CaO	11.20	14.28	13.54	15.13	12.37	14.97	11.93	13.80
Na_2O	4.72	3.69	4.11	3.28	4.19	2.84	4.15	3.67
K_2O	0.27	0.13	0.17	0.11	0.17	0.10	0.25	0.13
Total	99.21	100.17	100.34	100.44	100.43	100.11	98.70	100.19
An	55.9	67.7	64	71.4	61.4	74.0	60.5	67.0
Notes	m	c	r	c	m	c	r	m

Hole no.	715A		715A	715A				715A
Unit no.	3		3	3				3
Core, section	29R-1		29R-1	30R-3				31R-2
Interval (cm)	1–2		116–118	40–41				94–95
Depth (mbsf)	267.71		268.86	274.10				280.64
Analysis no.	1	2	1	1	2	3	4	1
SiO_2	49.33	48.24	58.39	47.46	48.81	53.67	51.05	58.15
Al_2O_3	29.97	30.82	25.13	31.11	30.61	29.19	29.80	24.55
FeO	0.72	0.64	0.65	0.55	0.59	0.85	0.69	0.91
CaO	13.80	16.32	8.97	15.29	14.41	12.66	14.20	7.26
Na_2O	3.96	2.45	6.90	2.75	3.28	4.45	4.00	6.69
K_2O	0.14	0.09	0.41	0.12	0.16	0.22	0.15	0.56
Total	97.92	98.57	100.46	97.28	97.86	101.03	99.89	98.12
An	65.3	78.3	40.9	75	70.2	60.4	65.8	36.3
Notes	c	r	r	c	r	r	c	m

Notes: c = core, r = rim, and m = microphenocryst.

Site 707 magmas because of their high silica contents and low total alkalis (Fig. 3B) relative to the Site 707 basalts. Site 236 basalts are distinct from those of Site 707 and represent magmas produced by different melting conditions in the mantle, by melting of a distinct mantle composition, or by a different set of magmatic processes (magma chamber dynamics and assimilation). If magmas like those at Site 236 were involved in the generation of Site 707 magmas, then none of these magmas erupted at Site 707 and the only evidence that they could have existed is the high-An plagioclase that could have passed through the magma chamber without being assimilated.

The pyroxene compositions of chemical units 2 and 3 have a bimodal distribution in Mg#, but in units 1 and 4 there are not enough analyses to demonstrate this. The majority of analyses from each flow have Mg#s close to the equilibrium values given in Table 15. (The range of Mg# values in Figure 8 is caused in part by the calculation of ferrous iron in the sample, which is sensitive to the accuracy of the SiO_2 determination.)

Some augites in chemical unit 3 have the lowest MgO content (Mg# 74) of augites from all four units, which may be caused by the re-equilibration of the pyroxenes as the unit cooled, as was also suggested by the low anorthite content of the plagioclase. The augite phenocrysts with the highest Mg# are found near the top and bottom of this thick unit. These phenocrysts also have a high Cr_2O_3 content (0.3–0.5 wt%), implying that they crystallized from a magma rich in chromium. The decrease in Cr_2O_3 and Mg# is the normal chemical change during cooling of augite in a magma and indicates that the augites in the center of the flow re-equilibrated as the unit cooled. Elevated concentrations of Al_2O_3 and Na_2O in pyroxenes are often considered an indication of high-pressure crystallization of pyroxene (Thompson, 1975). The Na_2O and Al_2O_3 concentrations in the high-

Cr_2O_3, high-MgO augite cores, however, are not different from the rims, which implies that the high-temperature cores of the augites crystallized close to the same pressure as the rims. The high-MgO augite cores may also represent xenocrysts from a more primitive magma that was mixed with the host magma, or they could originate from gabbroic cumulates from margins of the magma chamber that were incorporated before the eruption of this flow.

The trace element chemistry of basalts from the three Leg 24 sites in the old oceanic crust of the western Indian Ocean (Sites 235, 236, and 238) and present-day Indian Ocean Ridge basalts have unusually low Ba, Ti, and Zr abundances (Engel et al., 1974; Price et al., 1986) compared with lavas from the hotspot track (Duncan, Backman, et al., 1989) and compared with other ocean ridge basalts (Engel et al., 1974). Of the Réunion hotspot track basalts, however, those from chemical units 1 and 2 of Site 707 have the lowest abundances of these three elements (Duncan, Backman, et al., 1989), which implies that similar degrees of melting of the same mantle source accounts for the generation of the magmas at Sites 707 and 236.

The ratios of trace elements (e.g., BaO/TiO_2) from the older oceanic crust (Sites 235, 236, and 238) are the same as the present-day Indian Ocean Ridge basalts (Price et al., 1986) and are also the same as those for Site 707; but they are distinctly different from Sites 706, 713, and 715 and Réunion and Mauritius islands, which implies that the old and young ocean-floor basalts had the same mantle source as Site 707.

Site 713

As in the previous two sites, there appears to be several populations of plagioclase compositions within each chemical unit (Fig. 9). The calculated equilibrium plagioclase content for each

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Table 13. Microprobe analyses of clinopyroxenes, Site 715.

Hole no.	715A	715A				715A				715A	
Unit no.	1	1				2				1	
Core, section	23R-2	23R-3				25R-3				25R-6	
Interval (cm)	26–28	44–46				25–27				37–38	
Depth (mbsf)	212.51	214.13				233.25				237.87	
Analysis no.	1	1	2	3	4	1	2	3	4	1	2
SiO_2	48.17	51.62	51.04	51.85	50.01	51.37	50.96	49.75	51.47	51.28	52.17
TiO_2	1.17	0.40	0.68	0.59	0.87	0.53	0.77	1.00	0.63	0.98	0.56
Al_2O_3	4.40	1.79	2.01	2.11	2.47	3.92	1.80	2.22	2.41	2.27	2.70
FeO	11.08	9.48	10.00	9.56	11.48	6.56	13.50	19.42	9.05	12.25	7.24
MnO	0.25	0.21	0.24	0.23	0.26	0.18	0.38	0.53	0.23	0.40	0.15
MgO	14.63	14.93	15.27	15.04	14.45	15.82	15.24	11.05	15.32	15.98	16.39
CaO	18.01	21.09	19.17	20.61	18.29	20.67	16.37	13.85	19.95	16.91	21.00
Na_2O	0.34	0.26	0.21	0.25	0.23	0.22	0.23	0.25	0.27	0.28	0.25
Cr_2O_3	0.05	0.05	0.26	0.10	0.08	0.92	[a]0.04	[a]0.04	0.06	[a]0.04	0.24
Total	98.11	99.82	98.88	100.34	98.13	100.19	99.30	98.11	99.39	100.39	100.71
Notes	c	c	r	c	r	c	r	r	c	r	c
Mg#	70	79	76	77	72	82	69	50	78	73	84

Hole no.	715A		715A		715A		715A		
Unit no.	3		3		3		3		
Core, section	29R-1		29R-1		30R-3		31R-2		
Interval (cm)	1–2		116–118		40–41		94–95		
Depth (mbsf)	267.71		268.86		274.10		280.64		
Analysis no.	1	2	1	2	1	2	1	2	3
SiO_2	52.02	51.56	49.01	49.14	51.81	50.59	50.52	50.26	49.47
TiO_2	0.77	0.71	1.02	1.32	0.64	0.89	2.00	1.50	1.74
Al_2O_3	3.01	3.19	2.55	1.96	1.35	0.78	1.14	3.55	2.87
FeO	7.56	7.84	11.24	17.86	6.55	13.61	17.24	9.68	12.89
MnO	0.16	0.19	0.23	0.37	0.15	0.43	0.56	0.22	0.30
MgO	14.97	14.82	14.91	9.56	16.63	15.07	11.41	14.62	12.58
CaO	20.72	20.04	18.29	19.04	20.63	16.57	16.19	19.93	19.76
Na_2O	0.21	0.17	0.35	0.16	0.27	0.31	0.29	0.32	0.30
Cr_2O_3	0.51	0.66	0.12	[a]0.04	0.73	[a]0.04	[a]0.04	0.27	[a]0.04
Total	99.92	99.17	97.72	99.45	98.76	98.30	99.39	100.34	99.95
Notes	r	m	c	r	c	r	r	c	r
Mg#	78	77	75	49	83	67	54	76	66

Notes: c = core, r = rim, and m = microphenocryst.
[a] Minimum detection limit for Cr_2O_3 is 0.04 wt%.

Table 14. Microprobe analyses of olivines, Site 715.

Hole no.	715A							
Unit no.	3							
Core, section	30R-3							
Interval (cm)	40–41							
Depth (mbsf)	274.10							
Analysis no.	1	2	3	4	5	6	7	8
SiO_2	38.43	38.58	38.49	36.86	38.58	37.71	37.91	37.50
FeO	17.94	21.35	19.17	24.98	19.27	22.11	20.53	23.72
MnO	0.29	0.34	0.31	0.39	0.27	0.29	0.32	0.38
MgO	42.29	39.18	41.09	36.45	41.07	38.60	39.66	37.64
NiO	0.25	0.20	0.19	0.20	0.21	0.16	0.13	0.16
Total	99.19	99.65	99.24	98.89	99.41	98.87	98.56	99.40
FO	80.8	76.6	79.3	72.2	79.2	75.7	77.5	73.9
Notes	c	r	c	r	c	r	c	r

Notes: c = core, r = rim, and m = microphenocryst.

Figure 11. Histogram of anorthite content of plagioclase from the three chemical units of Site 715. This is the one site that does not have the high-anorthite plagioclase.

of the units (Table 15) is within 5 mole % of An_{70}, which corresponds to the rims of the phenocrysts and the groundmass plagioclase, but plagioclase of An_{80-87} is found in the cores of all of the large phenocrysts or xenocrysts.

The plagioclase analyses from the volcanic turbidite that separates units 2 and 3 are clearly more evolved (lower temperature) than those above or below it, and they must be derived from an evolved lava that did not extend to the drill site. The glass in this same turbidite (115-713A-17R-2, 41–44 cm; Table 10) had high Na_2O and low CaO and could have been the host magma for these feldspars.

The pyroxene megacryst cores in unit 1 have high Mg#, but they do not appear to be distinguished by high TiO_2, Cr_2O_3, or Al_2O_3. Unlike the plagioclase megacrysts, the cores of the augites seem to have crystallized from a magma that was chemically similar to the host magma except that it had a higher MgO content and, therefore, a higher temperature. Unit 3 contains
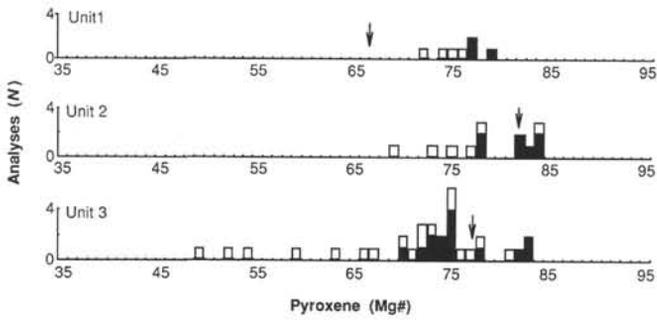
Figure 12. Histogram of magnesium-augite Mg# of phenocrysts cores and rims in groundmass in Site 715 basalts.
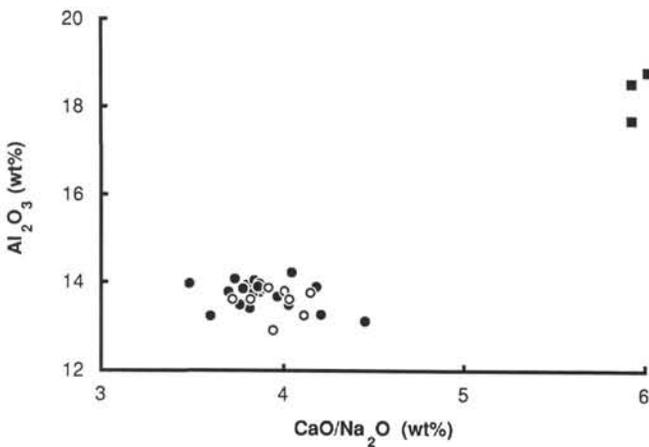
Figure 13. CaO/Na$_2$O vs. Al$_2$O$_3$ for chemical units from Site 706. Chemical unit 1, filled circles; chemical unit 2, open circles; and chemical unit 3, squares.

Table 15. Equilibrium mineralogy of chemical units.

Site	Unit	Olivine		Plagioclase		Augite				
		T°C	Forsterite	T°C	Anorthite	T°C	Wo	En	Fs	Mg#
706	1	[a]—	—	1143	61	1130	39	44	17	72
706	2	[a]—	—	1143	62	1133	39	45	16	74
706	3	1152	78	1246	77	1167	41	48	10	83
707	1	1262	86	1184	68	1148	35	47	18	85
707	2	1194	85	1212	76	1185	40	50	10	83
707	3	1167	79	1192	71	1163	38	48	14	77
707	4	1168	79	1178	67	1159	38	48	14	77
713	1	1172	82	1194	71	1172	40	49	11	82
713	2	[a]—	—	1170	68	1157	42	47	13	78
713	3	1174	82	1210	74	1183	41	50	9	85
715	1	1142	72	1167	65	1126	34	44	[b]22	66
715	2	1259	89	1195	76	1175	39	50	11	82
715	3	1229	87	1187	71	1155	37	47	15	76

Note: Mineral compositions and crystallization temperatures by methods of Nielsen (1988).
[a] Olivine does not appear on the liquidus even after 60% crystallization.
[b] Low calcium pyroxene (Wo 4 En 69 Fs 27) appears at 1129°C.

crystallized augite with uniformly high Mg#s that are close to values expected for the composition of the magma (Table 15).

Olivine is preserved in fresh glass in chemical unit 3 (below the ash-chalk layer) and is virtually unzoned; all but one of the analyses fall within the range of Fo$_{81.7-82.5}$. This absence of zoning indicates that the olivine grew isothermally and was then quenched rapidly. The presence of many thin lithologic units with glassy contacts in the lower part of the hole indicates that
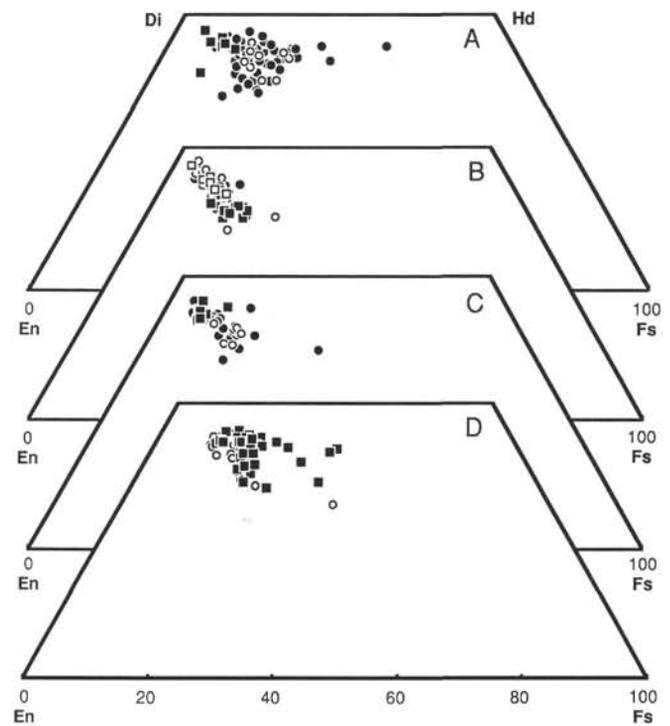
Figure 14. Pyroxene quadrilateral diagrams for all pyroxene analyses from Leg 115. **A.** Site 706: chemical unit 1, solid circles; chemical unit 2, open circles; chemical unit 3, solid squares. **B.** Site 707. Symbols for chemical units 1, 2, and 3 are the same as for Site 706; chemical unit 4, open squares. **C.** Site 713. Symbols are the same as for Site 706. **D.** Site 715. Symbols are the same as for Site 706.

these lavas were submarine and could have been quenched quickly, thus preserving the original mineralogy. The olivines found in these flows (Table 11) have compositions that agree with the calculated equilibrium olivine compositions (Table 15), and there do not appear to be any high-Fo olivines that correspond to the primitive plagioclase (An$_{86-87}$). This could result from the fact that olivine re-equilibrates with basaltic magma much more quickly than does plagioclase, so the olivine may have had time to equilibrate at lower temperatures in the magma chamber and the plagioclase did not. Alternatively, the magma that produced the An$_{86-87}$ plagioclase could have been free of olivine or contained olivine that was Fo$_{82}$.

In chemical unit 3, however, augite is found primarily as megacrysts with high Mg# (assuming stoichiometry and recalculating total iron to Fe^{2+} and Fe^{3+}). It is possible that the augite represents the remnants of the high-temperature parent magma to unit 3. Some of the augite cores have a high Cr$_2$O$_3$ content, which also implies that they crystallized from a more primitive magma. The oxide minerals at Site 713 are found only in the groundmass and are typical of the magnetites that are found in the other sites on Leg 115.

Site 715

The feldspars at Site 715 do not have the characteristic bimodal character observed at the other sites along the Réunion hotspot track (Fig. 11), and in all three units the calculated equilibrium composition of the plagioclase (arrows) are within 5 mole % anorthite of the most abundant phenocryst core compositions. Chemical unit 3 is made up of many flows and has a wide range of plagioclase compositions (Fig. 11), and the feldspar is normally as well as reversely zoned. The phenocryst cores range

from An_{47-78}, and the rims cover much of the same range. The microphenocrysts have lower An contents (An_{35-45}) and probably represent late-stage crystallization.

Using the classification of Papike et al. (1974), the pyroxenes are Mg-augites throughout the section and have a similar distribution of Mg# as the An contents of the feldspars. There is a hint of bimodal Mg# in chemical unit 2, and the wide scatter in Mg# in chemical unit 3 is much like the scatter in the An content of plagioclase from the same unit. The Mg#s agree fairly well with the calculated equilibrium augites (Table 15), except in unit 1 where pigeonite is predicted to crystallize before augite and the augite has an Mg# of 66. No pigeonite was found in this unit, and the predicted augite Mg# is well below that observed in unit 1.

The similarity of the calculated crystallization temperatures of the four phases (olivine, plagioclase, and two pyroxenes) in unit 1 suggests that this magma is close to four-phase saturation. The presence of augite with considerably higher Mg# than predicted with the computer model implies that the augites are xenocrysts. This upper unit is also one of the most alkaline from Leg 115 (Fig. 3B).

Mineralogical Variation along the Réunion Hotspot Track

In the Deccan, Réunion, and Mauritius lavas, olivine is the dominant phenocryst (Beane et al., 1986; Upton and Wadsworth, 1972; Baxter, 1976), whereas the lavas from intervening locations (Sites 706, 707, and 713) are primarily dominated by plagioclase phenocrysts. The exception to this is Site 715, in which olivine is usually more abundant than plagioclase or augite. The reason for the abundance of plagioclase and augite at Sites 706, 707, and 713 is not clear, and a number of alternatives are possible.

1. The lavas at Sites 706, 707, and 713 are volcano-capping, evolved lavas, similar to the Differentiated Series lavas of Réunion (Upton and Wadsworth, 1972), and are not typical, therefore, of the remainder of the volcanic products from each site.
2. The primary magmas that fed the magma chambers at Sites 706, 707, and 713 may have been a mixture of an olivine-rich magma and a more evolved magma similar to Indian Ocean mid-ocean ridge basalts (MORB).
3. The recharge rate of the magma chambers for these three sites may have been low compared with Deccan, Réunion, Mauritius, and Site 715.

Comparison of Réunion Differentiated Series and Sites 706, 707, and 713

We will only know if the lavas from Sites 706, 707, and 713 are typical of the volcanoes from which they came when additional samples are obtained. We may speculate, however, that the lavas represent a cap of differentiated basalts like those that are found on Réunion. Piton des Neiges on Réunion Island, for example, is covered with feldspar-phyric lavas known as the "Differentiated Series" (Upton and Wadsworth, 1965). The Differentiated Series, however, is dominated by lavas with less than 5.0 wt % MgO; 81 out of 94 published and unpublished analyses of Differentiated Series lavas have less than 5.25 % MgO (Fisk and Nielsen, 1989), but all of the units from Sites 706, 707, and 713 have more than 5.25% MgO (Fisk et al., 1989). It does not appear that the basalts collected at these three sites are plagioclase-phyric simply because they are evolved caps of their individual volcanos.

Magma Mixing

Basalts at Sites 706, 707, and 713 were erupted on or close to a spreading ridge, and the chemistry of their basalts may be explained by the mixing of two magma types, one typical of the ocean islands and one typical of an ocean rift (Fisk et al., 1989). A mixed magma may stabilize plagioclase relative to olivine if the ocean-rift magmatic component has high Al_2O_3 and possibly high SiO_2, CaO/Na_2O, and FeO/MgO, similar to the glasses found in the Paleocene ocean-floor lavas at DSDP Site 236 (Melson et al., 1977).

The bimodal distribution of plagioclase phenocryst compositions in Sites 706, 707, and 713 (Figs. 5, 7, and 9) may also provide evidence of mixing. The high-anorthite content plagioclase could not have crystallized from the host magma but was probably derived from a primitive magma that was not sampled at any of the sites. It can be argued that these high-anorthite plagioclase "xenocrysts" resulted from the random incorporation of previously crystallized plagioclase into an erupting basalt. Preserving and erupting the xenocrysts but not the primitive magmas from which they crystallized requires that certain special conditions be met. The high-temperature plagioclase phenocrysts must be separated from their parent magma and the co-crystallizing olivine and they must be stored (possibly, as a crystal mush) at the top or sides of a magma chamber so that they can be easily disrupted and incorporated into an erupting magma.

Plagioclase gravitationally separates from olivine because of their different densities (2.7 for An_{88} and 3.3 for Fo_{85}) relative to mafic silicates. Plagioclase would sink slowly (less than 5 cm/hr) or possibly float, depending on the composition of the host magma, whereas olivine would sink at more than 50 cm/hr (Kushiro, 1980). The low density of the plagioclase may allow them to plate the walls and top of the magma chamber, making them easy to assimilate by an erupting magma.

The fact that the plagioclase chemistry exhibits a bimodal distribution complicates this explanation because a bimodal distribution requires that out of the continuum of plagioclase compositions that crystallize from a cooling magma, only a portion of them are reincorporated into the evolved magmas. For example, in chemical unit 1 of Site 707 (Fig. 7), the magma that produced the An_{86-88} xenocrysts did not also produce An_{75-85} plagioclase unless there was some mechanism for destroying or removing these intermediate composition plagioclase "xenocrysts."

The bimodal character of the plagioclase compositions could be produced if a primitive magma with high-anorthite plagioclase phenocrysts mixed with the pre-existing magma in the chamber and triggered an eruption at the same time. In this way no intermediate plagioclase compositions would ever be produced unless the volume of the primitive magma was greater than half of the magma chamber volume. Recharge volumes for the Réunion Island magma system, however, are thought to be about 3%–5% of the magma chamber volume (Fisk and Nielsen, 1989).

Magma Chamber Dynamics

A third explanation of the presence of the more evolved, augite-plagioclase basalts at Sites 706, 707, and 713 depends on the magma supply rate (recharge rate) and magma chamber volume. O'Hara (1977) developed a model of major and trace element chemical evolution of magmas that was dependent on the rate of magma recharge into the magma chamber, on the amount of crystallization within the magma chamber, on the amount of assimilation, and on the amount of magma erupted. This model can also be applied to the study of the mineralogy of the erupted basalts.

The order of silicate mineral crystallization with descending temperature of a tholeiite magma is almost always olivine, followed by plagioclase, followed by augite. In alkali basalts, again olivine is the first mineral to crystallize, but augite sometimes precedes plagioclase as the second most abundant mineral. Higher pressures will favor augite formation relative to plagioclase (Bender

et al., 1978). In general, the more evolved, cooler magmas will have a low abundance of olivine and a high abundance of plagioclase and augite phenocrysts, and the high-temperature, primitive magmas will have a high proportion of olivine. A magma chamber that is maintained at a high temperature will, therefore, erupt more magmas that have abundant olivine. This will happen if the magma chamber is recharged frequently and the volume of the recharge is a large fraction of the volume of the magma chamber. The large volume and short interval for the eruption of the majority of the Deccan lavas indicates that these magma chambers were frequently recharged with large volumes of magma. Under these conditions, the erupted magmas are expected to contain abundant olivine, which proves to be the case (Beane et al., 1986).

If the less voluminous eruptions along the hotspot are the result of low recharge rate, then these magmas would be expected to be dominated by plagioclase and/or pyroxene, and this is the case for lavas from Sites 706, 707, and 713 but not for the islands of Réunion (Upton and Wadsworth, 1972) or Mauritius (Baxter, 1975, 1976) or for Site 715, which are all dominated by olivine phenocrysts. It is interesting that Sites 706, 707, and 713 not only have similar mineralogy but also have similar incompatible trace element abundance ratios (Fisk et al., 1989). This is also true of the lavas from Site 715, Réunion, and Mauritius, which form a group distinct from lavas at Sites 706, 707, and 713.

Réunion, Mauritius, and Site 715 are isolated volcanoes with a single magma supply (the hotspot). As such, they might be expected to have low magma supply rates relative to Sites 706, 707, and 713, which are located near a mid-ocean rift and may have two magmatic sources: the ridge and the hotspot. The critical factor, however, is not the absolute supply rate but the supply rate relative to the magma chamber volume. If magma chambers at or near the rifts (Sites 706, 707, and 713) are large relative to those at Réunion, then even with a high magma supply rate the magmas could be more evolved than those found at Réunion and the mineralogy of magmas could be dominated by plagioclase.

CONCLUSIONS

Basalts collected from four drill sites in the western Indian Ocean along the Réunion hotspot track range in composition from tholeiites to alkali basalts similar to those found in the Deccan Traps and at Réunion and Mauritius islands. The dominant minerals in the basalts are plagioclase and augite, in contrast to the olivine-dominated lavas of Deccan and Réunion. Basalts of Site 715 are most like Réunion lavas in chemistry and mineralogy; this may be a result of the similar plate tectonic environment of volcanism at Réunion and Site 715. The other three drill sites (706, 707, and 713) appear to have bimodal distributions of plagioclase composition that could be the result of mixing of rift and hotspot magmas.

ACKNOWLEDGMENTS

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Appendix. Thin sections probed on samples from Leg 115.

Core, section, interval (cm)	Phases analyzed	Lithologic unit (flow)	Chemical unit
115-706A-6H-4, 20–24	Pl, Px	1	1
115-706B-7X-CC, 17–20	Pl, Px, Gl	—	—
115-706B-7X-CC, 20–27	Pl, Px, Gl	1	1
115-706C-2R-1, 76–80	Pl, Px, Gl	1	1
115-706C-2R-2, 2–4	Pl, Px, Gl	3	1
115-706C-2R-2, 115–118	Pl, Px	8	1
115-706C-5R-1, 83–85	Pl, Px	14	1
115-706C-5R-2, 102–105	Pl, Px, Gl, Ol, Ox	17	1
115-706C-5R-3, 44–48	Pl, Gl, Ol	19	1
115-706C-6R-1, 46–50	Pl, Px	20	1
115-706C-8R-2, 43–45	Pl, Px, Ox	28	2
115-706C-9R-2, 36–38	Pl, Px	32	3
115-707C-22R-1, 94–95	Pl, Px, Ox	1	1
115-707C-22R-2, 37–38	Pl, Px	1	1
115-707C-23R-1, 24–25	Pl, Px, Ox	2	2
115-707C-23R-1, 65–66	Pl, Px	2	2
115-707C-23R-3, 137–140	Pl, Px	3	2
115-707C-25R-3, 0–1	Pl, Px	4	3
115-707C-26R-2, 126–128	Pl, Px, Ox	4	3
115-707C-28R-1, 27–29	Pl	5	4
115-707C-28R-3, 48–50	Pl, Px, Ox	5	4
115-713A-13R-3, 16–20	Pl, Px	2	1
115-713A-15R-4, 44–46	Pl, Px, Ox	3	1
115-713A-15R-4, 143–145	Pl, Px	4	2
115-713A-15R-5, 3–7	Pl, Px, Gl	5	2
115-713A-17R-2, 41–44	Pl, Gl	—	[a] —
115-713A-19R-1, 15–20	Gl, Ol	8	3
115-713A-19R-1, 116–118	Pl, Px	10	3
115-713A-20R-2, 37–39	Gl, Ol	12	3
115-713A-20R-2, 89–91	Gl, Ol	13	3
115-713A-20R-3, 64–66	Gl, Ol	15	3
115-713A-20R-5, 98–99	Gl, Ol	21	3
115-713A-20R-6, 22–44	Gl, Ol	23	3
115-713A-21R-2, 130–132	Gl	32	3
115-715A-23R-2, 26–28	Pl, Px	4	1
115-715A-23R-3, 44–46	Pl, Px, Ox	7a	1
115-715A-25R-3, 25–27	Pl, Px, Ox	9	2
115-715A-25R-6, 37–38	Pl, Px	10	2
115-715A-29R-1, 1–2	Pl, Px	12	3
115-715A-29R-1, 116–118	Pl, Px	13	3
115-715A-30R-3, 40–41	Pl, Px, Ol, Ox	16	3
115-715A-31R-2, 94–95	Pl, Px	21	3

Note: Pl = plagioclase, Px = pyroxene, Gl = glass, Ol = olivine, and Ox = oxide.

[a] Volcanic ash in sediment between Units 2 and 3.