# **19. PETROLOGY OF BASALT RECOVERED DURING DSDP LEG 39B**

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### ABSTRACT

Basaltic basement rock (7.5 m core; 78.1  $\pm$ 9m.y. old) from the Brazil Basin, and a basaltic pebble in a Cretaceous chalk from the São Paulo Plateau were recovered during Leg 39B. Brazil Basin basalt is typical ocean-ridge tholeiite and is characterized by intergranular plagioclase (An<sub>86-31</sub>), clinopyroxene (mainly augite), and titaniferous magnetite, and low bulk K<sub>2</sub>0 content (0.07 wt % in the freshest sample); relict olivine is also present in the upper, more altered core samples. Compositional changes attributable to seawater alteration are higher K<sub>2</sub>0 (and possibly Cr) and lower Ni contents when comparing the lowermost (freshest) to uppermost (most altered) core samples.

The basaltic pebble from the São Paulo Plateau is extremely altered, but high  $K_20$  in feldspar, and interstitial alkali feldspar indicate that it may represent oceanic alkalic basalt or alkalic basalt transitional to tholeiite. It was probably derived by slump from the São Paulo Ridge, which, based on the pebble's composition, may be composed of former oceanic islands bordering the São Paulo Plateau.

## INTRODUCTION

Basaltic basement rock was recovered from the Brazil Basin, Site 355, during Leg 39B (Figure 1). This material was located between magnetic anomalies 33 and 34 (Pitman et al., 1975) and is the oldest basaltic unit cored from the South Atlantic Ocean ( $78.1 \pm 9$  m.y.; McKee and Fodor, this volume). The 7.5 meter core length provides an opportunity to describe petrologic characteristics with reference to both vertical variation within the core and to younger oceanic basalt located closer to the Mid-Atlantic Ridge. This report presents the detailed chemistry and mineralogy of basalt samples at four vertical intervals throughout the core.

Drilling on the São Paulo Plateau, Site 356 (Figure 1) (near the São Paulo Ridge), yielded a basaltic pebble ( $\sim$ 3 cm) from a Cretaceous marly chalk. A petrologic description of this material is also presented to help characterize the type of basaltic material present in the São Paulo plateau region.

# ANALYTICAL PROCEDURES

Whole-rock analyses of basalt were obtained by the following techniques: Silica was determined gravimetrically. Total Fe,  $Al_2O_3$ , MgO, CaO, Na<sub>2</sub>O, K<sub>2</sub>O, TiO<sub>2</sub>, and MnO were determined by atomic absorption using calibration curves prepared from U.S. Geological Survey standard basalt, BCR-1. For determination of P<sub>2</sub>O<sub>5</sub>, an adaptation of the Molybdenum Blue spectrophotometric method was employed. Water was determined by ignition loss, but

the amount of Fe oxidation was taken into account by  $K_2Cr_2O_7$  titration of ferrous iron in both the ignited and unignited sample. The trace elements Rb, Ba, Sr, Co, Cr, Ni, and V were also determined by atomic absorption, using larger sample weights than for the major elements. Mineral compositions were determined with an ARL-EMX-SM electron microprobe operated at 15 keV accelerating voltage and 0.015 to 0.020  $\mu$ A sample current. Corrections for differential matrix effects were made according to Bence and Albee (1968).

#### **GENERAL DESCRIPTIONS**

Basalt in the Brazil Basin was reached about 450 meters below the sea floor in 4900 meters water depth. The contact between basalt and overlying sediment was not recovered nor was the basalt drilled extensively enough to indicate whether it is a sill or true basement.

The upper 10 cm of the core ranges in color from dark gray to yellowish-gray and consists almost entirely of clay minerals produced by seawater alteration. The remaining portion of the core is medium to dark gray in color and highly fractured and veined with calcite. At least four altered, glassy zones were observed and these may represent the tops of separate flows. They are generally thin ( $\leq 1$  cm) and often mixed with calcite. Local brecciated zones are sometimes associated with the altered glass. The basalt is essentially aphyric, although plagioclase laths are visible in certain areas.

At the São Paulo Plateau, a sedimentary marly chalk containing a basaltic pebble was cored at about 660 meters below the sea floor in about 3175 meters water depth. The pebble is about 3.5 cm long and 2 cm thick,



Figure 1. Map of the South Atlantic Ocean showing the locations of Sites 355 and 356, and other sites drilled during Leg 39.

dark gray in color, and contains phenocrysts of oxidized olivine (reddish in color), clinopyroxene, and plagioclase. A distinct weathering rim about 5 mm thick is visible in a cut cross-section. The pebble was recovered from a core of Santonian (Cretaceous) marly calcareous chalk containing black shale and *Inoceramus* fragments. Altered basaltic pebbles (0.2mm to 1 cm) were also observed in conglomeratic zones, mudstones, and graded zones lying 20 to 50 meters below the pebble, indicating extensive deposition of coarse material during Santonian time, presumably by slump from a nearby ridge (Figure 2).

# PETROGRAPHY

Thin-section examination of the Brazil Basin basalt reveals a large range in the degree of alteration; the freshest samples with closest to original textures are from near the base of the core. Texture is intergranular and consists of plagioclase phenocrysts, microphenocrysts, and groundmass laths (1 mm to 0.1 mm) intimately associated with microphenocrysts and groundmass clinopyroxene (0.4 to 0.1 mm) (Figure 3); they sometimes occur in glomerocrysts, or clots (Figure 4). In the upper half of the core, most of the groundmass pyroxene has been altered to brownish clay minerals and highly oxidized remnants of olivine are present as rare phenocrysts. No olivine was observed in the lower parts of the core. Present in the groundmass of the lowermost and freshest core samples are angular, sometimes skeletal, oxides ( $\sim 0.05$  mm), but they are absent from the more altered upper core. Crystallization of clinopyroxene in part preceded plagioclase as indicated by some microphenocrysts of pyroxene enclosed by feldspar (Figure 5). Where olivine remnants are present, it may have been the liquidus phase. Plagioclase appears to have been the phase most resistant to alteration as indicated by the presence of at least a few remaining laths even in the most intensely altered samples.

A thin section of the São Paulo Plateau basaltic pebble shows an extreme alteration of the original texture that probably consisted of intergranular feldspar and clinopyroxene. Present now are plagioclase laths, oxides, and clay minerals forming the groundmass and phenocrysts of plagioclase, clinopyroxene, and highly oxidized relict olivine (Figure 6). Of the plagioclase and clinopyroxene phenocrysts, grain margins are altered, but fresh cores remain.

## **BULK COMPOSITION**

Whole-rock analyses and normative mineralogy of four samples from the Brazil Basin basalt core are presented in Table 1. Areas of the core sampled for analyses are illustrated in Figure 7; systematic sampling, however, was hampered somewhat by fractures, veins, and secondary mineralization present in the core.

Samples throughout the core are remarkably similar in major element concentrations, indicating that the entire core either represents one flow or, more likely, several flows from the same source. There is variation, however, in K<sub>2</sub>O content, where a very low (0.07 wt %) concentration is present in the lowermost sample (22-5) and values closer to 0.5 wt % are measured higher in the core. Because samples farthest from the basaltsediment interface are expected to be least affected by seawater alteration, the low K<sub>2</sub>O of the bottom sample is probably closest to the original concentration, whereas higher K2O contents in the upper samples probably resulted from seawater alteration (Hart, 1970; Hart et al., 1974). This is in agreement with textural observations, but curiously, is not apparent from H2O contents (Table 1); the bottom sample has more H<sub>2</sub>O than the highly altered upper core samples.

Trace element contents (Table 1) show a general trend of increasing Cr and decreasing Ni and V contents from the bottom to the top of the core (freshest to most altered); V, however, greatly increases again near the top. The change in Ni agrees with data reported by others for the alteration effects in basalts (e.g., Hart et al., 1974), but nothing conclusive is known about the changes in Cr and V contents. Here, changes in V may be related to weathering of titaniferous magnetite in the upper samples, as opposed to primary fractionation, whereas there is no apparent reason attributable to weathering for the ~20% increase in Cr.

Comparison of bulk compositions to those of dredged Mid-Atlantic Ridge basalts shows that the Brazil Basin core is typical mid-ocean ridge basalt



# 356 40-3

Figure 2. A Cretaceous conglomerite composed partly of basaltic fragments from the São Paulo plateau. This sample is from one of many conglomeratic zones that the basaltic pebble (356-38-378) is associated with. Scale is provided by the typewritten numbers. Photo provided by J. Thiede.



Figure 3. Intergranular texture of plagioclase and clinopyroxene in the Brazil Basin basalt (22-5). Crossed nicols; scale bar equals 0.5 mm.

(Table 1). Unlike many oceanic tholeiites, however, the Brazil Basin basalts are highly quartz normative (Table 1; Figure 8), but this characteristic is largely the result of the degree of oxidation (i.e., Fe<sub>2</sub>O<sub>3</sub>/FeO). When normative mineralogy is calculated after normalizing Fe<sub>2</sub>O<sub>3</sub> to 1.5 wt % and omitting CO<sub>2</sub>, there is a compositional shift into or closer to the field of olivine tholeiites (Figure 8). This is consistent with the relict olivine observed in the uppermost samples. Relatively low P<sub>2</sub>O<sub>5</sub>, TiO<sub>2</sub>, Rb, Ba, and Sr contents also characterize the Brazil basalt as ocean-ridge basalt (Table 1). The São Paulo basalt pebble is highly altered as indicated by exceedingly high H<sub>2</sub>O (6.5 wt %) and CO<sub>2</sub> contents (Table 1). This presents difficulty in establishing the true character of the basalt, whether tholeiitic or alkalic. Some oxide contents, such as low SiO<sub>2</sub> and high K<sub>2</sub>O, suggest that the pebble has alkalic characteristics, although they are not entirely conclusive because alteration of ocean-ridge tholeiite can result in material that closely resembles true oceanic alkalic-basalt in composition (Hart, 1970). The high K<sub>2</sub>O content, however, appears too high to have resulted from an alteration of low-K (tholeiitic)



Figure 4. A cluster, or glomerocryst, of plagioclase and clinopyroxene in the Brazil Basin basalt (22-5). Crossed nicols; scale bar equals 0.5 mm.



Figure 5. Clinopyroxene enclosed by plagioclase in the Brazil Basin basalt (22-2). Crossed nicols; scale bar equals 0.2 mm.

material. For example, Bass et al. (1973) showed analyses of highly altered basalts with 4.7 and 6.5 wt % H<sub>2</sub>O that contain only about 0.5 wt % K<sub>2</sub>O. Also, Matthews (1971) showed that alteration of an oceanic basalt (7.2 wt % H<sub>2</sub>O), which is comparable in

alteration to that of the São Paulo pebble, increased  $K_2O$  by about three times initial  $K_2O$  content. In comparison, to account for  $K_2O$  of 2.5 wt % in the pebble from an original  $K_2O$  of <0.5 wt % (tholeiitic) would require an increase by about five times.

![](_page_4_Picture_1.jpeg)

Figure 6. Plagioclase phenocrysts with corroded margins in the highly altered basaltic pebble from the São Paulo plateau. Groundmass consists of clay minerals and plagioclase laths. Crossed nicols; scale bar equals 1 mm.

Although alteration effects cannot be expected to produce the same results everywhere, the changes in K<sub>2</sub>O contents due to alteration observed in other rocks make it seem unlikely that the basaltic pebble was originally tholeiitic. High Rb, Sr, and Ba in the pebble possibly also represent true alkalic-basalt concentrations (Table 1). Although Rb and Ba concentrations increase with seawater alteration, they are not known to increase more than a few parts per million under moderate alteration (Hart et al., 1974).

Normative mineralogy has substantial quartz (Table 1; Figure 8), but that is largely a function of high  $Fe_2O_3/FeO$ . When  $Fe_2O_3$  is normalized to 1.5 wt % and  $CO_2$  omitted, the composition is much closer to the plane of undersaturation (O1-Di of Figure 8).

# MINERALOGY

Mineral compositions were determined in three of the four bulk compositionally analyzed Brazil Basin basalt samples, representing top, middle, and bottom portions of the core, and for the São Paulo basaltic pebble.

# Clinopyroxene

Microphenocrysts and groundmass clinopyroxene are present in each of the sections analyzed of the Brazil Basin basalts, although intense alteration of the top sample, 21-1, left only rare and exceedingly small (~1 to  $2\mu$ m) grains. One phenocryst was also observed in 21-1. Average compositions (Table 2) and the compositional trend (Figure 9) of increasing FeO and MnO attended by a decrease in CaO and SiO<sub>2</sub> from phenocryst, to microphenocryst, to groundmass are similar to those of clinopyroxene typically found in tholeiitic basalts (Fodor et al., 1975). Throughout the core, there are no significant compositional differences in clinopyroxene. Compositional zoning occurs in the microphenocrysts, and groundmass pyroxene is highly variable with respect to Fe and Ca (Figure 9). Groundmass compositions presented for 21-1, however, are subject to some question because of intense alteration in this sample and difficulty in avoiding overlap onto clay minerals with the electron beam when analyzing the small grains of remaining pyroxene.

Attending the changes in grain size from phenocryst to groundmass clinopyroxene, there is a substantial increase in TiO<sub>2</sub> (Figure 10). Between microphenocrysts and groundmass, Al<sub>2</sub>O<sub>3</sub> content is nearly constant or appears to decrease slightly with increasing TiO<sub>2</sub>, as illustrated by the freshest sample, 22-5 (Figure 10, Table 2) (the high Al<sub>2</sub>O<sub>3</sub> values shown for 21-1 may be due to particularly high alteration in that sample). A slight decrease in Al<sub>2</sub>O<sub>3</sub> probably reflects simultaneous crystallization of groundmass pyroxene and plagioclase. The increase in TiO<sub>2</sub> from microphenocryst to groundmass indicates that titaniferous magnetite probably crystallized after groundmass pyroxene; this is also suggested by texture.

Fresh cores of otherwise altered clinopyroxene phenocrysts in the São Paulo basalt pebble (Table 2; Figure 9) have compositions (Fs11En49W040) common to pyroxene phenocrysts in tholeiitic basalt. This composition, however, is also observed for some alkalic basalts and alkalic basalts transitional to tholeiites (Fodor et al., 1975).

#### TABLE 1

#### Bulk Compositions and Molecular Norms of Four Brazil Basin Basalt Samples (Columns 1-4; Top to Bottom of Core; Figure 7) and a Basaltic Pebble from the São Paulo Plateau (Column 5), Western South Atlantic Ocean, Compared to Average Compositions of 33 and 6 Dredged MAR Basalts (Columns 6, 7; after Melson and Thompson, 1971, and Kay et al., 1970, Respectively)

	1	2	3	4	5	6	7
SiO <sub>2</sub>	48.88	49.26	49.28	50.14	46.06	49.21	48.55
TiO <sub>2</sub>	1.78	1.70	1.87	1.88	2.24	1.39	1.57
Al <sub>2</sub> O <sub>3</sub>	15.42	14.75	15.15	14.96	14.10	15.81	15.20
Fe <sub>2</sub> O <sub>3</sub>	5.42	5.86	4.49	3.78	6.92	2.21	
FeO	5.65	5.69	5.32	6.45	5.20	7.19	10.72
MnO	0.17	0.16	0.19	0.16	0.05	0.16	0.18
MgO	6.35	6.50	6.97	7.00	6.22	8.53	7.55
CaO	10.74	10.75	10.60	10.40	5.08	11.14	10.93
Na <sub>2</sub> O	2.51	2.38	2.69	2.70	2.81	2.71	2.61
K <sub>2</sub> O	0.57	0.49	0.46	0.07	2.61	0.26	0.21
H2O-	0.82	0.96	1.50	1.16	3.75	-	-
$H_2O^+$	0.85	1.04	1.04	0.81	2.66		1.01
P2O5	0.17	0.14	0.16	0.15	0.28	0.15	0.15
CO <sub>2</sub>	0.66	0.38	0.57	0.65	1.92	—	<u>+12</u> 10
Total	99.99	100.06	100.29	100.31	99.90	98.76	98.68
q	4.27	5.34	3.42	4.59	5.48		
or	3.46	3.00	2.79	0.42	16.60		
ab	23.18	22.12	24.84	24.82	27.16		
an	29.98	29.12	28.71	29.18	12.09		
wo	7.75	9.06	8.24	7.37			
Di en	6.71	7.91	7.19	5.86	_		
fs	1.06	1.15	1.05	1.51			
Hy en	11.33	10.66	12.60	13.92	18.48		
fs	1.78	1.55	1.84	3.59	0.21		
il	2.55	2.45	2.68	2.68	3.36		
mt	5.83	6.34	4.83	4.05	7.79		
ap	0.37	0.30	0.34	0.32	0.63		
с		-	-		2.98		
cc	1.72	0.99	1.48	1.68	5.23		
Rb (ppm)	<10	<10	<10	<10	40	10 <sup>a</sup>	
Ba	<40	<40	<40	<40	250	14	
Sr	100	100	120	112	320	130	
Co	50	57	72	57	29	32	
Cr	231	238	226	188	139	297	
Ni	50	50	80	85	60	97	
v	390	240	390	440	260	292	

Note: DSDP sample numbers; Column 1, 355-21-1, 102 cm; Column 2, 355-22-2, 44 cm; Column 3, 355-22-3, 12 cm; Column 4, 355-22-5, 120 cm; Column 5, 356-38-8, 78 cm.

<sup>a</sup>Average for tholeiitic basalts; after Engel et al. (1965).

#### Feldspar

Phenocrysts, microphenocrysts, and groundmass feldspar in the Brazil Basin basalt (Table 3; Figure 11) range in composition from calcic bytownite to sodic labradorite and are exceedingly low in  $K_2O$  contents (<0.11 wt %). Compositional changes from phenocryst to groundmass include an increase in Na<sub>2</sub>O, K<sub>2</sub>O, FeO, and SiO<sub>2</sub> and a decrease in Al<sub>2</sub>O<sub>3</sub>, whereas MgO remains nearly constant. No high-K rims on large feldspar grains nor interstitial material were observed. All of these features are characteristic of feldspar in tholeiitic basalts (Keil et al., 1972).

Fresh cores in phenocrysts of the São Paulo basalt pebble are also bytownite in composition, but higher in  $K_2O$  relative to feldspar in the Brazil Basin basalt (Table 3). The groundmass feldspar is labradorite in composition and higher in  $K_2O$  relative to labradorite in the Brazil Basin basalt. Most notably, there is interstitial material in the groundmass very high in  $K_2O$ 

![](_page_6_Figure_1.jpeg)

Figure 7. Schematic diagram showing the sampling areas (arrows) in the Brazil Basin basalt core.

content, some reaching An2Ab10Orss. The presence of 2.1 wt % Or end member in the groundmass laths and the high-K interstitial material are characteristic for alkalic basalt (Keil et al., 1972). Whether or not the enrichment in K in the feldspar is innate or a result of the intense alteration is essential to interpreting the true character of the rock. Seawater alteration increases the K content of basaltic material by forming clay minerals (Melson and Thompson, 1973) and K-feldspar cores in plagioclase, but to have K enter plagioclase without obvious alteration (optically, the plagioclase cores appear fresh) and to form interstitial material that is stoichiometrically high-K feldspar seems highly unlikely. Although replacement of plagioclase by stoichiometric orthoclase has occurred in deep-sea basalts (Matthews, 1971; Bass et al., 1973; Steward et al., 1973), no incipient or partial alteration, such as

![](_page_6_Figure_4.jpeg)

Figure 8. Normative mineralogy plotted on a diopside (Di)hypersthene (Hy)-olivine (01)-quartz (Q)-nepheline (Ne) diagram. Closed circles represent norms listed in Table 1 and open circles represent norms recalculated after  $CO_2$ is omitted and  $Fe_2O_3$  normalized to 1.5 wt%.

only a small (<1.0 wt %) increase in K<sub>2</sub>O throughout plagioclase, has been reported. Therefore, the alkalic characteristics of the feldspar and interstitial material are thought to be real.

The coexistence of pyroxene having tholeiitic affinities and feldspar that is typically alkalic has previously been reported for a Hawaiian tholeiite that was classified by Keil et al. (1972) and Fodor et al. (1975) as transitional between tholeiitic and alkalic basalt. On the basis of pyroxene and feldspar compositions, the São Paulo pebble may be a basalt transitional between tholeiitic and alkalic basalt, but highly altered by seawater.

# Oxides

The only oxide present in the Brazil Basin basalt is titaniferous magnetite in the lowermost portion of the core (22-5). Its composition (Table 4) is similar to that of titaniferous magnetite in other tholeiitic basalts, such as of Hawaii (Fodor et al., 1972).

In the São Paulo basalt pebble, titaniferous magnetite and ilmenite coexist, both as individual grains and in the same grain (Table 4). The ulvöspinel content of the magnetite is lower than that of magnetite in the Brazil Basin basalt. Equilibration temperature and oxygen fugacities estimated from the coexisting Fe-Ti oxides (Buddington and Lindsley, 1964) are 925°C and  $10^{-12}$  atm, respectively.

## PERTINENT OBSERVATIONS AND SUMMARY

Aside from small compositional differences in major elements that can be attributed to seawater alteration (increasing K, Fe<sup>+3</sup>), bulk and mineral compositions are consistent throughout the 7.5-meter core of Brazil Basin basalt. Absence of significant chemical fractionation suggests that the core represents one basaltic source. The basalt is characterized by intergranular plagioclase and clinopyroxene, and in the TABLE 2

Average Compositions of Clinopyroxene Phenocrysts (ph), Microphenocrysts (m), and Groundmass (g) in Basalt from the Brazil Basin (21-1; 22-2; 22-5) and in a Basaltic Pebble from the São Paulo Plateau (28-3), Western South Atlantic Ocean. Compositions are Averages of 20 to 50 Spot Analyses (in wt %)

21-1			23	2-2	23	38-3		
	ph	m	g	m	g	m	g	ph
SiO <sub>2</sub>	52.3	51.6	48.8	52.2	49.5	51.4	49.7	52.0
TiO <sub>2</sub>	0.39	0.82	1.8	0.80	1.6	0.97	1.3	0.58
Al <sub>2</sub> O <sub>3</sub>	3.9	4.3	6.1	4.1	4.4	4.2	3.6	2.4
Cr2O3	0.90	0.47	0.07	0.37	<.01	0.34	0.03	0.29
FeO	4.6	6.6	10.9	6.9	14.7	7.7	14.3	7.0
MnO	0.17	0.20	0.31	0.21	0.37	0.22	0.37	0.22
MgO	17.9	17.4	14.1	16.8	12.4	16.8	13.9	16.8
CaO	19.4	18.0	16.6	18.1	15.7	17.8	16.1	19.4
Na <sub>2</sub> O	0.30	0.32	0.40	0.26	0.35	0.31	0.30	0.19
Total	99.86	99.71	99.08	99.74	99.02	99.74	98.60	98.88
Number	of Ions or	n the Basis	of 6 (0)					
Si	1.903	1.890	1.833	1.911	1.886	1.891	1.884	1.932
Aliv	0.097	0.110	0.167	0.089	0.114	0.109	0.116	0.068
Alvi	0.070	0.076	0.103	0.088	0.084	0.073	0.045	0.037
Ti	0.011	0.023	0.051	0.022	0.046	0.027	0.037	0.016
Cr	0.026	0.014	0.002	0.011	-	0.010	0.001	0.009
Fe	0.140	0.202	0.342	0.211	0.468	0.237	0.453	0.217
Mn	0.005	0.006	0.010	0.007	0.012	0.007	0.012	0.007
Mg	0.971	0.950	0.789	0.917	0.704	0.921	0.785	0.930
Ca	0.756	0.706	0.668	0.710	0.641	0.701	0.654	0.772
Na	0.021	0.023	0.029	0.018	0.026	0.022	0.022	0.014
x	2.000	2.000	1.994	1.984	1.981	1.998	2.009	2.002
Sum	4.000	4.000	3.994	3.984	3.981	3.998	4.009	4.002
Molecula	ar End Mer	mbers						
Fs	7.5	10.9	19.0	11.5	25.8	12.7	24.0	11.3
En	52.0	51.1	43.9	49.9	38.8	49.6	41.5	48.5
Wo	40.5	38.0	37.1	38.6	35.4	37.7	34.5	40.2

![](_page_7_Figure_4.jpeg)

Figure 9. Pyroxene electron-microprobe spot analyses plotted in terms of mole percent enstatite (En; Mg<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>), ferrosilite (Fs; Fe<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>), and wollastonite (Wo; Ca<sub>2</sub>Si<sub>2</sub>O<sub>6</sub>). Di=diopside (CaMgSi<sub>2</sub>O<sub>6</sub>) and Hd=hedenbergite (CaFeSi<sub>2</sub>O<sub>6</sub>). Brazil Basin basalt is indicated by Site 335 (top to bottom of core; 21-1; 22-2; 22-5) and the São Paulo pebble by Site 356.

uppermost portions, by minor olivine (relict). Restriction of olivine to the top may indicate an inverted magma chamber where an olivine-enriched bottom portion was the last material to be extruded on the sea floor; magma-chamber zoning, however, is not apparent from the bulk compositions. Whether or not the basalt is a sill or true basement cannot be determined because of the relatively shallow

![](_page_8_Figure_1.jpeg)

Figure 10. Plot of  $TiO_2$  versus  $Al_2O_3$  for clinopyroxene electron-microprobe spot analyses of the Brazil Basin basalt (top to bottom of core, 21-1; 22-2; 22-5). High  $Al_2O_3$  in pyroxene of Sample 21-1 may partly be due to alteration of most pyroxene to clay minerals in that sample.

penetration depth and no recovery of upper contact; the age of  $78.1 \pm 9$  m.y. (McKee and Fodor, this volume), however, indicates that it is probably basement. Mineral compositions and textural observations show that Mg-rich clinopyroxene crystallization was attended by, and partly succeeded, calcic plagioclase. Groundmass-pyroxene crystallization was attended by intermediate

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	Average Compositions of Feldspar	Phenocrysts (ph), Microp	henocrysts (m), and	Groundmass Laths (g)
i	n Basalt from the Brazil Basin (21-1	;22-2;22-5) and in a Basal	tic Pebble from the	São Paulo Plateau (38-3),
	Western South Atlantic Ocean.	Compositions are Average	s of 20 to 50 Spot	Analyses (in wt%)

TABLE 3

		21-1		22	2-2		22-5			38-3	
	ph	m	g	m	g	ph	m	g	ph	g	Hi-K <sup>a</sup>
SiO <sub>2</sub>	49.4	50.4	53.0	50.0	53.2	49.1	51.5	53.8	50.1	53.2	65.5
Al2O3	32.1	30.7	29.4	30.7	28.5	31.6	30.0	28.7	31.9	29.7	18.3
FeO	0.73	0.85	1.0	0.83	1.3	0.77	0.94	1.3	0.59	0.95	0.77
MgO	0.43	0.47	0.51	0.44	0.41	0.38	0.45	0.43	0.23	0.15	0.09
CaO	16.2	14.8	13.0	15.1	11.8	16.3	13.3	11.1	15.0	12.1	0.92
Na <sub>2</sub> O	2.4	3.2	3.2	3.0	4.8	2.5	3.9	5.3	2.8	4.2	1.9
к <sub>2</sub> õ	0.04	0.06	0.11	0.07	0.09	0.04	0.06	0.09	0.14	0.34	12.8
Total	101.30	100.48	100.22	100.14	100.10	100.69	100.15	100.72	100.76	100.64	100.28
Number	of lons on	the Basis of	32 (0)								
Si	8.956	9.191	9.600	9.156	9.682	8.969	9.387	9.718	9.094	9.609	11.969
AI	6.859	6.598	6.276	6.625	6.113	6.803	6.444	6.110	6.824	6.322	3.941
Fe	0.111	0.130	0.151	0.127	0.198	0.118	0.143	0.196	0.090	0.143	0.118
Mg	0.116	0.128	0.138	0.120	0.111	0.103	0.122	0.116	0.062	0.040	0.025
Ca	3.147	2.891	2.523	2.962	2.301	3.190	2.597	2.148	2.917	2.341	0.180
Na	0.844	1.131	1.124	1.050	1.694	0.885	1.378	1.856	0.985	1.471	0.673
K	0.009	0.014	0.025	0.016	0.021	0.009	0.014	0.021	0.032	0.078	2.984
Z	15.815	15.789	15.876	15.781	15.795	15.772	15.831	16.542	15.918	15.931	15.910
x	4.227	4.294	3.961	4.290	4.325	4.305	4.254	4.337	4.086	4.073	3.980
Sum	20.042	20.083	19.837	20.056	20.120	20.077	20.085	20.165	20.004	20.004	19.890
Weight l	Percent End	Members									
An	79.7	72.8	69.9	74.4	58.7	79.1	66.4	54.8	75.2	61.5	4.7
Ab	20.1	26.8	29.4	25.2	40.8	20.7	33.2	44.7	24.0	36.4	16.7
Or	0.2	0.4	0.7	0.4	0.5	0.2	0.4	0.5	0.8	2.1	78.6

<sup>a</sup>Groundmass interstitial feldspar.

![](_page_9_Figure_1.jpeg)

Figure 11. Ternary feldspar diagrams where individual feldspar electron-microprobe spot analyses are plotted in terms of weight percent anothite (An; CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub>), albite (Ab; NaAlSi<sub>3</sub>O<sub>8</sub>), and orthoclase (Or; KA1Si<sub>3</sub>O<sub>8</sub>). Brazil Basin basalt is indicated by Site 355 (top to bottom of core, 21-1; 22-2; 22-5) and the São Paulo pebble by Site 356.

TABLE 4 Average Compositions of Titaniferous Magnetite and Ilmenite in Basalt from the Brazil Basin (22-5) and in a Basaltic Pebble from the São Paulo Plateau (38-3) Western South Atlantic Ocean. Compositions are Averages of 30 to 50 Spot Analyses (in wt %)

	22-5				
	mt	mt	ilm	(Range)	ilm <sup>a</sup>
SiO <sub>2</sub>	0.95	1.1	0.77		1.0
TiO <sub>2</sub>	22.4	17.3	47.8	(46.1-51.9)	47.5
Al <sub>2</sub> O <sub>3</sub>	3.2	1.7	1.1	(0.75-1.5)	1.6
Cr2O3	0.03	0.10	0.06		0.01
V2O3	0.27	0.57	0.27		0.18
FeO	67.7	71.5	45.2	(37.2-46.1)	45.2
MnO	0.74	0.26	0.88		0.57
MgO	0.88	0.91	2.4	(1.4-3.1)	2.6
CaO	0.71	0.37	0.16		0.31
ZnO	0.29	0.02	0.15		0.09
Sum	97.17	93.83	98.79		99.06
Recalculated					
FeO	48.7	43.8	38.4		38.2
Fe <sub>2</sub> O <sub>3</sub>	21.1	30.8	7.5		7.7
Total	99.27	96.93 <sup>b</sup>	99.49		99.96
Usp (mol %)	66.6	51.4	2 <u>00</u>		100
Hem	-	-	8.1		8.4

<sup>a</sup>Coexisting with magnetite.

<sup>b</sup>Total may be low due to more Fe being Fe<sup>3+</sup> than calculated stoichiometrically.

plagioclase, but preceded titaniferous magnetite. Bulk compositions border between quartz and olivine tholeiites. The compositions show that ocean-ridge basalt was essentially the same in upper Cretaceous time, shortly after initial rifting of the South Atlantic Ocean, as many basalts that were only recently erupted at the Mid-Atlantic Ridge (Table 1). Compositionally, such material represents extensive melting of mantle material at relatively shallow depth (e.g., Kay et al., 1970). Consistent compositions over at least 80 m.y. indicate no major temperature changes beneath the Mid-Atlantic Ridge.

The São Paulo Plateau basaltic pebble (recovered from Cretaceous sediments) has been extensively altered by seawater. Concentrations of certain elements, however, such as K, Rb, Ba, and Sr, are indicative of initial alkalic-basalt characteristics, somewhat modified by alterations, and indicate that the pebble was not typical ocean-ridge basalt. This suggestion is supported by the relatively high K in plagioclase and the interstitial alkali feldspar, which are characteristic of alkalic basalt, or alkalic basalt transitional to tholeiite.

The large size (3.5 cm) of the pebble precludes the possibility of long transport (i.e., continental source) and suggests that its source was local. In addition, substantial amounts of basaltic pebbles in conglomerites (Figure 2) associated with mudstones and graded zones underlying the pebble indicate extensive deposition of coarse material from a local source during Santonian time. The most likely source for such slump deposits is the nearby São Paulo Ridge, of east-west trending feature that bounds the São Paulo Plateau on the south (see, for example, Levden et al., 1971).

The implications, then, are that the São Paulo Ridge (the presumed source of the pebble) is not composed of typical ocean crust (tholeiitic basalt), at least in part. It more closely resembles oceanic alkalic basalt (or transitional basalt), which almost invariably is associated with seamounts and volcanic islands (e.g., Engel et al., 1965) and commonly represents posttholeiitic activity. This in turn, suggests that the eastwest-trending São Paulo Ridge bordering the São Paulo Plateau may be composed of a continuous or semicontinuous chain of volcanos that developed during early Cretaceous time along the east-west fracture zone that bounds the Rio Grande Rise on the north, or by a "hot spot" on the Mid-Atlantic Ridge.

## NOTE ADDED IN PROOF

The following analyses have been provided by Dr. Roman Schmidt for Samples 355-22-5, 120 cm, using **INAA** techniques:

Sc (ppm)	43.9
Hf	3.4
La	3.5
Ce	14.0
Sm	4.0
Eu	1.6
Tb	1.1
Yb	4.0
Lu	0.59

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