15. PETROLOGY AND GEOCHEMISTRY OF BASALTIC ROCKS FROM RIO GRANDE RISE, SOUTH ATLANTIC: DEEP SEA DRILLING PROJECT LEG 72, HOLE 516F[1]

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ABSTRACT

Basalts from Hole 516F, DSDP Leg 72 on the Rio Grande Rise are tholeiitic in character but differ from normal mid-ocean ridge basalts in the South Atlantic in higher concentrations of incompatible elements such as Ti, K, V, Sr, Ba, Zr, Nb, and light rare-earth elements and in lower concentrations of Mg, Cr, and Ni. They contrast with previously reported basalts from the Rio Grande Rise, which were highly alkalic in character. The Rio Grande Rise basalts from Hole 516F (age 84.5 Ma) are generally similar to basalts from the eastern end of the Walvis Ridge (80–100 Ma). It is suggested that they either originated, like the Walvis Ridge, from a mantle hot spot that is different from the present-day hot spot (Tristan da Cunha) and that has changed composition with time, or from a spreading center that was shallow and chemically influenced by the adjacent hot spot, similar to the present-day Mid-Atlantic Ridge near the Azores and Tristan da Cunha.

INTRODUCTION

The Rio Grande Rise is one of the world's major aseismic ridges; it rises more than 3 km above the ocean floor. In reconstructions of the South Atlantic opening, the Rio Grande Rise in the western basin and the Walvis Ridge in the eastern basin have been explained as aseismic ridges related to passage of the plates over a hot spot (Dietz and Holden, 1970; Morgan, 1971). The island of Tristan da Cunha is thought to be the present-day expression of that hot spot. Morphologically the Rio Grande Rise is less well developed than the Walvis Ridge, but because of its east-west orientation across the water mass pathways of the western boundary current and because of the presence of the Vema Channel cutting through the Rise, it has played a major role in paleocirculation and paleoenvironments in the past. Recent seismic studies have shown that the Rio Grande Rise is bounded by major fracture zones, and it has been suggested that the Rise is related to volcanism along these fracture zones (LePichon and Hayes, 1971).

Before Leg 72 of the Deep Sea Drilling Project (DSDP), attempts to core the basement of the Rio Grande Rise had failed (Maxwell et al., 1970; Perch-Nielsen et al., 1977). Drilling at DSDP Site 357 during Leg 39 recovered basaltic fragments in a breccia in calcareous middle Eocene sediments. These fragments were found to be alkalic basaltic rocks probably erupted from an alkali-rich seamount in shallow water during the Eocene (Fodor and Thiede, 1977). Igneous rocks were also recovered by dredging in 1973 and were composed largely of basaltic fragments. These samples, composed of alkalic basalt, trachybasalt, and trachyandesite, are similar to rock types found on Tristan da Cunha (Fodor, Husler, et al., 1977). This dredge site at 30°26′S, 36°01′W is just west of Hole 516F (30°16.59′S, 35°17.11′W) and Site 357 (30°00.25′S, 35°33.59′W) where the volcanic breccia was recovered. These locations are shown in Figure 1.

On the basis of their studies of the Site 357 breccia and the dredged rocks, Fodor, Husler, et al. (1977) suggested that the Rio Grande Rise represented a series of alkalic-basalt islands that formed and eventually subsided during rifting of the South Atlantic. Thiede (1977) has suggested that the Rio Grande Rise was a large island 2–3 km above sea level during Santonian to Campanian times (85–75 Ma). Fodor, Husler, and Kumar (1977) noted similarities between the dredged basalts and drilled breccias and suggested they might be from similar sources. They further noted that these samples were unlike mid-ocean ridge basalts but more like those recovered from the South Atlantic islands such as Tristan da Cunha and Gough. Samples previously reported from the Walvis Ridge (Hekinian, 1972) had alkaline characteristics similar to the Rio Grande Rise rocks; however, they also contained some rocks with tholeiitic affinities, suggesting differences between these two aseismic ridges. Frey and others (1974) and Schilling (1975) reported on basalts recovered from the South Atlantic basin at 30°S during DSDP Leg 3 (Fig. 1). They noted that these basalts, ranging in age up to 60 Ma, were typical mid-ocean ridge basalts.

In contrast to the previous studies of rocks from the Rio Grande Rise, preliminary work on the igneous rocks recovered at DSDP Site 516F, Leg 72 (Barker et al., 1981) suggested that these samples had tholeiitic affinities but with higher concentrations of incompatible elements such as Ti, P, Zr, Nb, Y, La, and Ce in comparison to typical mid-ocean ridge basalts (MORB). A Santonian-Campanian age (84.5 Ma) for basement is inferred from the age of overlying sediments and identifi-

[1] Barker, P. F., Carlson, R. L., Johnson, D. A., et al., *Init Repts. DSDP*, 72: Washington (U.S. Govt. Printing Office).

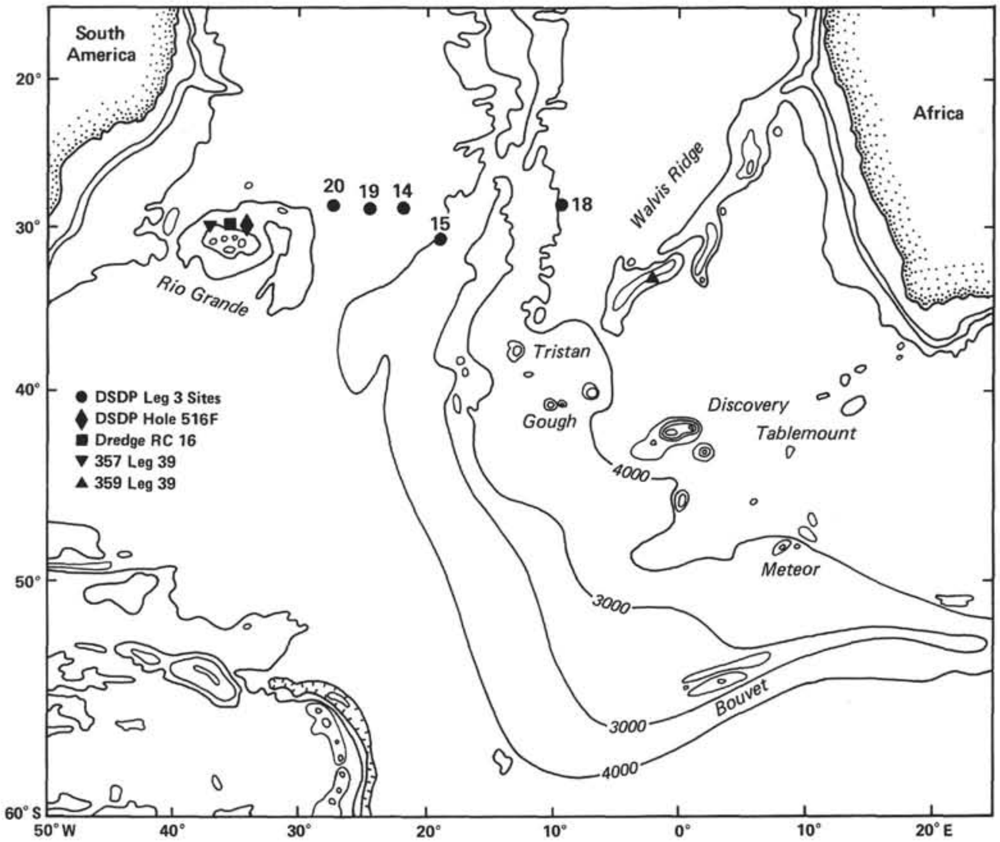

Figure 1. Map of the South Atlantic showing the position of Discovery Tablemount, DSDP Leg 3 sites, Dredge RC16, DSDP Leg 39 Sites 357 and 359, and DSDP Leg 72 Hole 516F.

cation of Magnetic Anomalies 33 and 34 to the east of the site (site chapter, Site 516, this volume).

In this paper, we present detailed petrologic and geochemical studies of 14 igneous rock samples from different stratigraphic levels in the cored basement of Hole 516F. The objectives of our study are (1) to understand the compositional variation within the flows recovered by drilling at this site; (2) to compare these rock compositions with those from the mid-ocean ridge at this latitude, with rocks recovered from the Walvis Ridge (the geographic counterpart of the Rio Grande Rise), with rocks from the South Atlantic islands, and with samples previously described from the Rio Grande Rise; and (3) to suggest a possible origin and history for this major oceanographic feature.

PETROGRAPHY

The principal minerals in the basalts from Leg 72 are plagioclase, clinopyroxene, and iron oxides; plagioclase is dominant. The rocks are generally glomerophyric, with plagioclase and occasional clinopyroxene phenocrysts occurring in small clusters within a fine-grained groundmass. Vesicles are rare in these samples, but those present are commonly filled with bright green clay minerals or calcite. Most of the samples studied were selected to avoid vein or vesicle contents.

Plagioclase phenocrysts are commonly euhedral or lath-shaped, and often show quite complex zoning. Optical properties suggest that they are labradorite. Pyroxene phenocrysts are less common, often making up only about 1% by volume. They are euhedral to subhedral and display simple twinning, as well as zoning. In the more weathered samples, both types of phenocrysts are partially replaced by calcite.

The groundmass consists of microlites of plagioclase, granular pyroxene, opaque minerals, and possibly glass in varying proportions. Much of what might be considered glass is replaced, mainly by calcite, although clay minerals are present in some samples.

The samples we have studied may be divided into two groups on the basis of the degree of crystallinity of the groundmass and the proportions of the constituent minerals. The upper unit extends from Sample 516F-126-2, 143–146 cm down to Sample 516F-127-4, 44–48 cm inclusive. It consists of basalts in which the groundmass is mainly plagioclase microlites and fine-grained, altered material dominated by calcite; clinopyroxene is minor. Fine-grained, subhedral to anhedral iron oxides are scattered throughout the groundmass and comprise up to 4% by volume. The lower unit extends from Sample 516F-127-4, 60–63 cm to the bottom of the hole. The groundmass in samples from the lower unit consists of plagioclase microlites and granular pyroxene with minor amounts of interstitial altered material. The iron oxides are coarser grained than in the upper unit and are often euhedral or needle-shaped. This unit appears less weathered than the upper unit, but they are extremely similar and could represent a single basaltic flow.

The petrographic character of these samples differs markedly from typical MORB and shows none of the typical quench structures of lavas erupted on the deep sea floor (Bryan, 1972). The fine-grained altered groundmass may represent a chilled interstitial glass consistent with eruption in shallow water. However, the pervasive nature of the alteration and its dominance by calcite preclude definitive statements on the origin of the flow.

METHODS

The samples were selected at different levels in the core; we tried to avoid samples with obvious major alteration or veining. The samples were ground in agate and analyzed by X-ray fluorescence spectrometry. Accuracy for major elements is in the 0.5–3% range; for trace elements, it is in the 1–5% range, based on analysis of reference rocks. Details of the X-ray fluorescence technique have been described by Schroeder et al. (1980). The rare earth elements (REE) and Sc were determined by instrumental neutron activation analysis (INAA). Details of the technique have been described by Schilling and Ridley (1976).

CHEMICAL ANALYSIS

In Table 1, Part 1, we present the analyses for major elements. Because of the large amount of alteration, these analyses are presented on a volatile-free basis to make comparisons easier. Analyses of the volatiles are also presented so that the analyses may be recast into their original form if required. Trace element analyses are presented in Table 1, Part 2.

DISCUSSION

Within-Site Variation

Both the chemical analyses and petrographic studies of the Hole 516F samples show that there are differences between samples from the upper part of the core and those lower in the core. The upper samples, up to and including 516F-127-4, 44–48 cm, are marked by higher concentrations of CO_2 and H_2O^+ and higher Fe_2O_3/FeO. Other distinct chemical differences indicate that it is not merely the degree of alteration that distinguishes the two groups. In Table 2, we show the average compositions of these two groups. Sample 516F-127-2, 83–88 cm has been omitted from the average of the upper group because it contains a high quantity of a green smectite, an alteration product that was carefully avoided in the other samples. Although this affects only the K_2O and Rb contents, it clearly acts as a dilutant on the other element concentrations.

The concentration differences between the two groups are not large. They are within experimental errors for the rare earths. The slightly higher concentrations of TiO_2, Na_2O, V, Zr, and Nb in the Group 1 samples could argue that this upper flow (if indeed these two groups represent two distinct flows) is more evolved in terms of fractional crystallization. However, this simple apparent enrichment in incompatible elements is accompanied by lower SiO_2, K_2O, Rb, and Y contents and higher concentrations of incompatible elements such as Cr, Co, and Ni in the upper flow. Some of these differences are shown in Figures 2 and 3. It should be noted that the differences are not great between the two groups and these lavas are characterized by their high degree of crystallinity. Some of the chemical differences reflect alteration effects, some reflect differences in degree of crystal fractionation, and others probably reflect differences in modal content of individual minerals. Thus, although the differences are somewhat complex to explain, they are too small to affect the relative chemical characterization of the rocks of this hole compared to other rocks from the Rio Grande Rise or other parts of the South Atlantic.

Regional Comparison

On a standard alkalies versus silica diagram, Hole 516F basalts are all found in the field of Hawaiian tholeiites (Fig. 4). Symbols representing previously recovered dredged rocks from the Rio Grande Rise (Fodor, Husler, et al., 1977) occur well into the field of Hawaiian alkali basalts, as do basalts from Tristan da Cunha, the Discovery Tablemount basalts, and many, but not all, of the Walvis Ridge basalts. Basalts from the Mid-Atlantic Ridge, including DSDP Leg 3 basalts, apparently have tholeiitic affinities similar to Hole 516F, although most have less total alkalies because of their very low K_2O content.

However, the Rio Grande Rise basalts of Hole 516F, although they have tholeiitic major element affinities, are quite markedly enriched in incompatible trace elements compared to normal MORB and thus have many alkaline affinities, as shown in Table 3, which summarizes the comparative analyses of some of these South Atlantic basalts. Figure 5 clearly shows the marked enrichment in TiO_2 and Zr of the Hole 516F Rio Grande Rise basalts compared to normal MORB. Also, in Figure 6, the chondrite-normalized light rare-earth element (LREE) enrichment of the Rio Grande Rise basalts is quite distinctive compared to the flat or typically LREE-depleted MORB. Figure 6 indicates that the Rio Grande Rise basalts, although not quite as LREE-enriched, have REE distribution similar to the Walvis Ridge and Gough Island basalts. Data on some of the trace elements of the dredged alkaline basalts from the Rio Grande Rise are given in Table 4, and Figures 5 and 7. These analyses were done in our laboratory on splits of the powders analyzed by Fodor, Husler, and Kumar (1977) for major elements and kindly made available to us by Dr. Fodor.

Humphris and Thompson (1982) in their study of Walvis Ridge basalts noted a wide range of compositions from tholeiitic to alkaline. However, they did find systematic differences in composition in the different parts of the ridge. In particular, they noted that the eastern end of the Walvis Ridge (80–100 Ma) was quite distinct from the central and western sections and from the present-day hot spot at Tristan da Cunha. Figure 7 shows this feature best in a plot of Nb versus Zr. These two elements are not markedly affected by alteration (Thompson, 1973), and their ratio is not markedly affected by fractional crystallization. Rather, they are good markers of the source region of the basalts (Erlank and Kable, 1979). The Hole 516F basalts are distinct from the Mid-Atlantic Ridge basalts, which have a Zr/Nb ratio usually greater than 20. These Rio Grande Rise

Table 1. Basalt analyses from Hole 516F.

	Core-section (interval in cm)													
Element	126-2 143–146	126-3 6–9	126-3 41–44	127-2 83–88	127-3 68–72	127-3 97–102	127-4 44–48	127-4 60–63	128-1 25–28	128-1 122–126	128-2 51–56	128-2 130–135	128-3 44–48	128-3 73–75
Major element analyses (on a volatile-free basis after ignition at 1000°C; in wt.%)														
SiO_2	49.64	50.26	50.43	48.92	49.45	49.96	48.68	51.05	51.86	51.25	51.77	49.20	51.81	51.62
TiO_2	2.69	2.72	2.82	2.45	2.63	2.63	2.51	2.27	2.30	2.23	2.37	2.50	2.41	2.35
Al_2O_3	16.24	16.46	16.19	16.86	16.45	15.66	15.84	13.89	14.16	13.93	14.13	14.84	13.77	13.99
FeO^a	13.33	10.87	11.32	14.66	12.76	12.32	13.77	13.25	12.55	13.40	12.65	14.37	13.02	12.74
MnO	0.17	0.13	0.14	0.19	0.11	0.12	0.20	0.23	0.19	0.23	0.19	0.25	0.20	0.19
MgO	4.66	3.93	4.21	4.41	4.99	5.08	5.55	5.91	5.66	5.85	5.70	5.88	5.51	5.60
CaO	10.18	11.96	11.13	8.11	10.04	10.81	10.29	10.53	10.63	10.44	10.64	10.14	10.47	10.57
Na_2O	2.92	3.00	2.99	2.46	2.95	2.90	2.61	2.29	2.39	2.27	2.32	2.26	2.30	2.35
K_2O	0.23	0.30	0.23	1.12	0.26	0.22	0.22	0.32	0.34	0.31	0.32	0.23	0.39	0.34
P_2O_5	0.22	0.11	0.15	0.38	0.24	0.20	0.25	0.21	0.20	0.22	0.18	0.26	0.20	0.20
Sum	100.28	99.74	99.61	99.56	99.88	99.91	99.92	99.95	100.28	100.13	100.27	99.93	100.08	99.95
Other analyses[b]														
FeO	8.35	5.75	6.51	7.60	7.70	8.02	9.96	9.87	9.13	10.07	9.34	9.38	9.42	9.39
Fe_2O_3	5.53	5.69	5.35	7.85	5.62	4.79	4.23	3.76	3.80	3.70	3.68	5.55	4.00	3.72
H_2O^+	1.65	1.44	1.40	1.52	1.44	1.34	1.18	0.84	0.83	0.88	0.81	1.00	0.80	0.81
H_2O^-	4.50	3.89	3.57	3.61	3.63	3.22	2.48	1.22	0.93	1.25	1.07	1.92	0.72	0.82
CO_2	7.69	6.19	5.56	9.35	7.91	6.52	7.71	3.91	3.07	4.03	2.92	5.24	2.56	2.55
Trace element analyses (on a dried 110°C basis; in ppm)[c]														
XRF														
Rb	3.5	7.4	4.6	25.3	4.2	3.6	2.9	9.4	9.8	8.9	8.4	3.8	11.3	9.3
Sc	38		41		39			37		35		39		36
V	400	405	416	385	400	393	379	364	356	341	369	373	358	366
Cr	40	36	34	39	35	34	30	28	32	28	32	30	29	28
Co	50	40	44	54	62	57	64	43	41	47	46	47	46	49
Ni	54	51	49	61	57	52	58	48	48	51	52	50	48	50
Cu	199	219	198	123	226	198	195	185	188	182	187	202	198	186
Zn	114	101	103	118	104	113	129	102	130	113	112	117	107	103
Sr	410	686	446	291	387	403	351	278	271	266	272	281	269	266
Ba	276	131	178	91	157	168	126	192	165	157	207	158	171	202
Y	35	37	38	41	34	37	35	40	42	40	41	35	43	39
Zr	185	189	187	152	181	186	184	172	176	168	172	181	182	169
Nb	14.4	14.1	14.0	12.8	13.2	14.7	14.2	13.2	12.9	13.4	12.7	14.6	13.6	13.3
INAA														
La	14.2		15.6		14.6			15.2		15.2		13.3		14.3
Ce	36.0		37.9		36.1			36.8		35.2		34.0		36.9
Nd	21.0		21.3		19.3			18.9		20.3		19.7		19.7
Sm	6.3		7.0		6.6			6.5		6.5		6.4		6.1
Eu	2.2		2.3		2.2			2.1		2.1		2.3		2.1
Gd	7.9		8.7		10.0			7.7		7.3		9.0		8.2
Tb	1.1		1.3		1.1			1.4		1.2		1.2		1.2
Dy	7.3		7.4		6.7			7.0		7.6		6.8		7.8
Tm	0.58		0.59		0.55			0.63		0.63		0.46		0.58
Yb	3.1		2.8		3.0			3.3		3.4		2.8		3.3
Lu	0.38		0.37		0.38			0.44		0.43		0.37		0.43
Co	45		39		57			39		42		43		43
Cr	42		37		38			30		33		40		31
Na_2O (wt.%)	2.83		3.02		3.00			2.74		2.70		2.82		2.70

Note: Blanks indicate "not analyzed."
[a] Total Fe as FeO.
[b] On a dried (110°C) basis, except H_2O^-.
[c] XRF = X-ray fluorescence; INAA = instrumental neutron-activation analysis.

basalts (Zr/Nb about 13) are similar to the basalts of the eastern end of the Walvis Ridge with a Zr/Nb of about 10. These basalts were erupted at approximately the same period.

Barker et al. (1981) noted that the Hole 516F basalts were enriched in incompatible elements compared to typical MORB (i.e. the normal or N-type of Sun et al., 1979, or Group I of Bryan et al., 1976). However, they did compare them to some of the MORB that are markedly enriched in incompatible elements (the plume or P-type of Sun et al., 1979, or Group II of Bryan et al., 1976), particularly those on the Reykjanes Peninsula recovered during Leg 49. Wood and others (1979) compared enriched MORB from 63°N, 45°N, and 36°N and noted that each was distinctive, particularly in Zr/Nb content (63°N about 8, 45°N about 5, 36°N about 3). These LREE-enriched MORB have been characterized by Schilling (1973) as plume-type basalts. However,

Table 2. Average composition for upper and lower parts of DSDP Hole 516F.

Element	Group 1[a] average (upper)	Group 2[b] average (lower)
Major elements (in wt.%)		
SiO_2	49.74	51.22
TiO_2	2.67	2.35
Al_2O_3	16.14	14.10
FeO^c	12.39	13.14
MnO	0.14	0.21
MgO	4.74	5.73
CaO	10.74	10.49
Na_2O	2.90	2.31
K_2O	0.24	0.32
P_2O_5	0.20	0.21
FeO	7.72	9.51
Fe_2O_3	5.20	4.03
H_2O^+	1.41	0.85
CO_2	6.95	3.47
Trace elements (in ppm)		
Rb	4.4	8.7
Sc	39	37
V	399	361
Cr	35	30
Co	53	46
Ni	54	50
Cu	206	190
Zn	111	112
Sr	447	272
Ba	173	179
Y	36	40
Zr	185	174
Nb	14.1	13.4
La	14.8	14.5
Ce	36.7	35.7
Nd	20.3	19.7
Sm	6.6	6.4
Eu	2.2	2.1
Gd	8.9	8.1
Tb	1.2	1.2
Dy	7.1	7.3
Tm	0.57	0.57
Yb	3.0	3.2
Lu	0.38	0.42

[a] Average of 6 samples (core-section, depth in cm): 126-2, 143; 126-3, 6; 126-3, 41; 127-3, 68; 127-3, 97; 127-4, 44. Sample 127-2, 83 cm has been omitted from the average of Group 1 because it contains a high quantity of green smectite (see text for further explanation).

[b] Average of 7 samples (core-section, depth in cm): 127-4, 60; 128-1, 25; 128-1, 122; 128-2, 51; 128-2, 130; 128-3, 44; 128-3, 73. Rare earth elements and Sc are average of 3 samples for Group 1, and 4 for Group 2 (see Table 1, Part 2).

[c] Total Fe as FeO.

in detail there are significant differences in rare-earth (RE) patterns among hot spots as well (Schilling et al., 1982). The RE pattern of Hole 516F basalts are similar to Mid-Atlantic Ridge basalts over the Azores platform in terms of light and heavy RE enrichments, but are slightly higher in the middle RE (Sm-Eu-Gd). In a recent study of the Mid-Atlantic Ridge axis about 30–45°S, Schilling and others (1981) noted that most of the basalts were typical MORB. Those recovered from the axis at the latitude of Tristan da Cunha, however, were slightly enriched in incompatible elements (Zr/Nb about 16, slight LREE enrichment), although the enrichment was neither so great nor so distinctive as that of the Rio Grande Rise basalts.

Origin of Rio Grande Rise

The age of Hole 516F basalts is compatible with an origin at a spreading center about 84 Ma ago. However, unlike the Mid-Atlantic Ridge basalts at about 30°S (DSDP Leg 3), these basalts are not typical MORB. The shallow water origin, the probable past history of the Rio Grande Rise as a complex of subaerial volcanoes (Thiede, 1974), and the presence of typical alkaline volcanic material at least through to the Eocene (Fodor and Thiede, 1977) all suggest that the Rio Grande Rise may have followed a pattern typical of other large volcanoes in Hawaii, Iceland, or Piton de la Fournaise of Réunion Island, which started with tholeiitic eruptives in the early stages and then changed to alkaline basalts in the later stages.

The similarity of the Hole 516F basalts to the eastern Walvis Ridge basalts suggests that the two basalts may have had similar origins. At the opening of the Atlantic from 80–100 Ma, the hot spot (which was the origin of the Walvis and Rio Grande rises) apparently was mildly tholeiitic in character. As the spreading continued, the hot spot has grown more alkaline; Tristan da Cunha is the present-day expression. Alternatively, one might argue that the eastern Walvis and the Rio Grande Rise at Site 516 were not direct expressions of the hot spot but rather of a spreading center influenced by a nearby hot spot such as the present-day Mid-Atlantic Range axis adjacent to Tristan da Cunha (Schilling et al., 1981).

Another possible origin is volcanism associated with the large fracture zones bounding the Rio Grande Rise (and the Walvis Ridge) (LePichon and Hayes, 1971). Kempe and Schilling (1976) related the Discovery Tablemount chemistry to a possible hot-spot origin, and noted that, because it was much younger than the surrounding sea floor, it had an origin not directly connected with spreading. The basement age for Hole 516F is consistent with a spreading model, but the Eocene breccia in Site 357 and the Eocene tuff at Site 359 on the Walvis Ridge (Fodor, Keil, et al., 1977) suggest that volcanism continued on these aseismic ridges until they were well away from the spreading centers.

The chemistry, the morphology, and the age relationships strongly suggest an origin either adjacent to a hot spot or related to spreading at a hot spot. The comparison with the corresponding part of the Walvis Ridge suggests the hot-spot influence has continued through time, producing a linear series of volcanoes that continued their activity and development as they moved away from the spreading center. The strongly alkaline character of the present-day Tristan da Cunha volcanism, with its unusually potassic eruptives, suggests that the hot-spot activity may have intensified with time.

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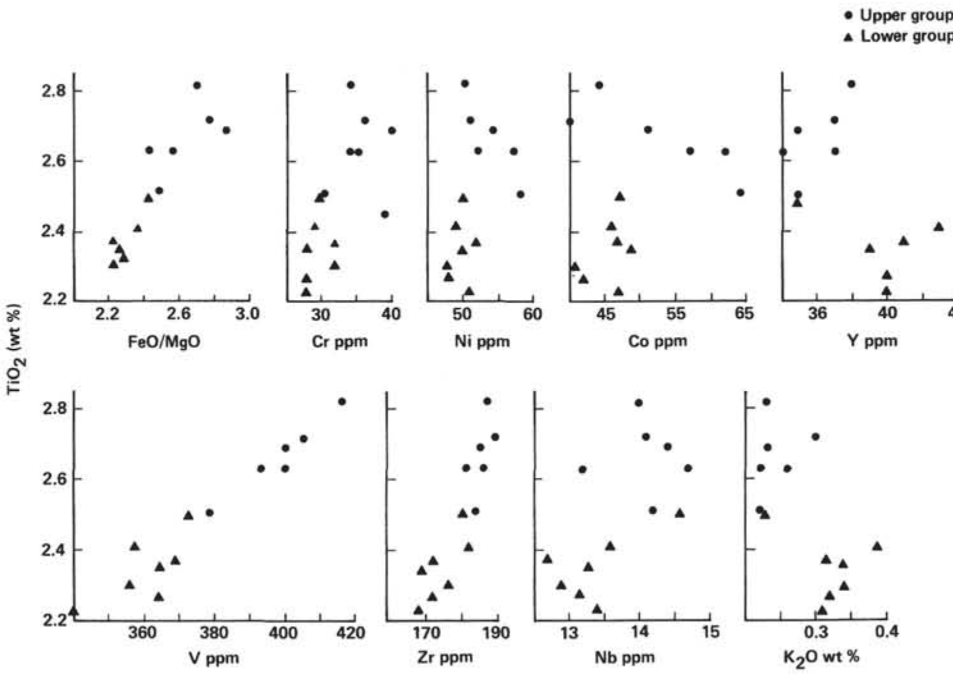

Figure 2. Plot of TiO_2 versus FeO/MgO, Cr, Ni, Co, Y, V, Zr, Nb, and K_2O for upper and lower groups of DSDP Leg 72 Hole 516F. Upper group = samples from 516F-126-2, 143–146 cm to 516F-127-4, 44–48 cm; lower group = samples from 516F-127-4, 60–63 cm to the bottom of the hole.

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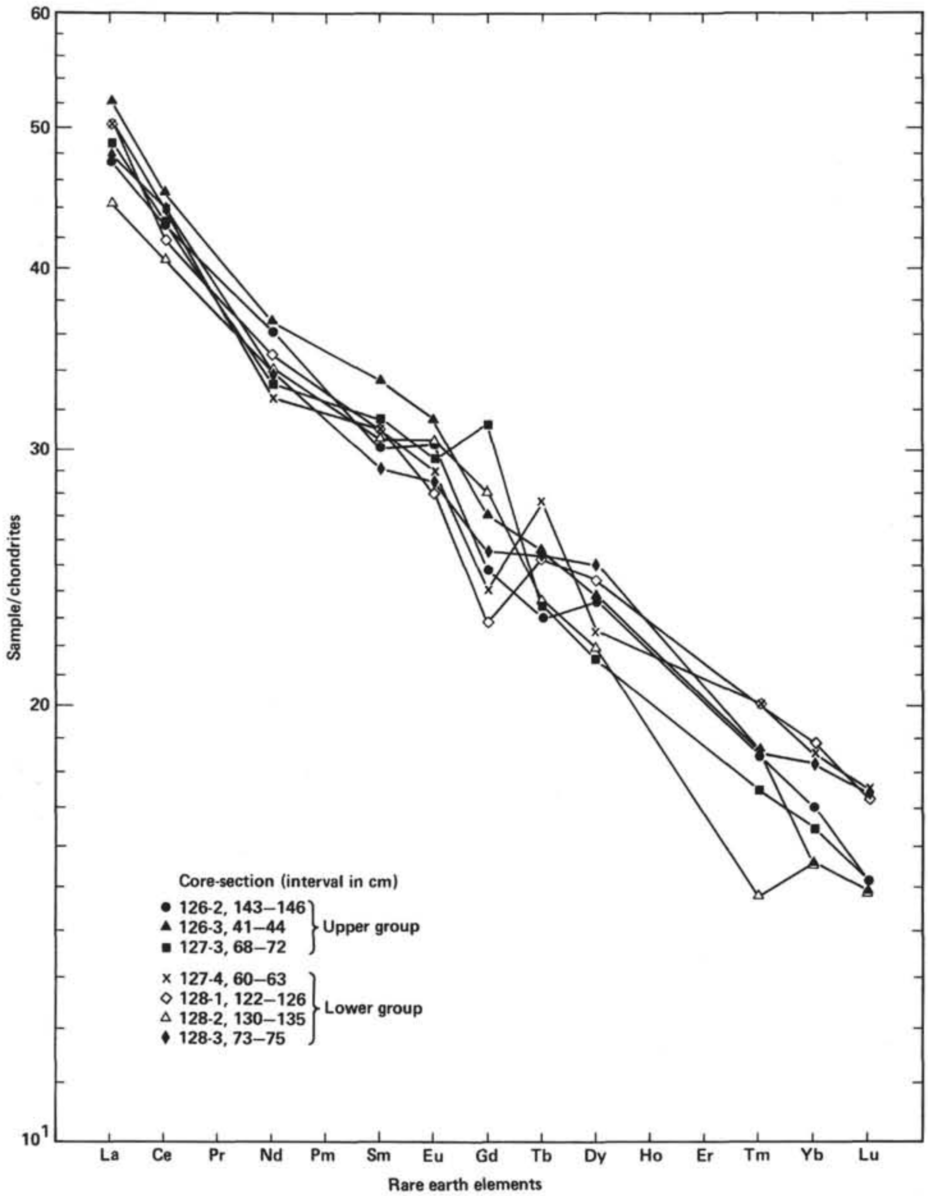

Figure 3. Plot of chondrite-normalized rare-earth element abundances for Hole 516F.

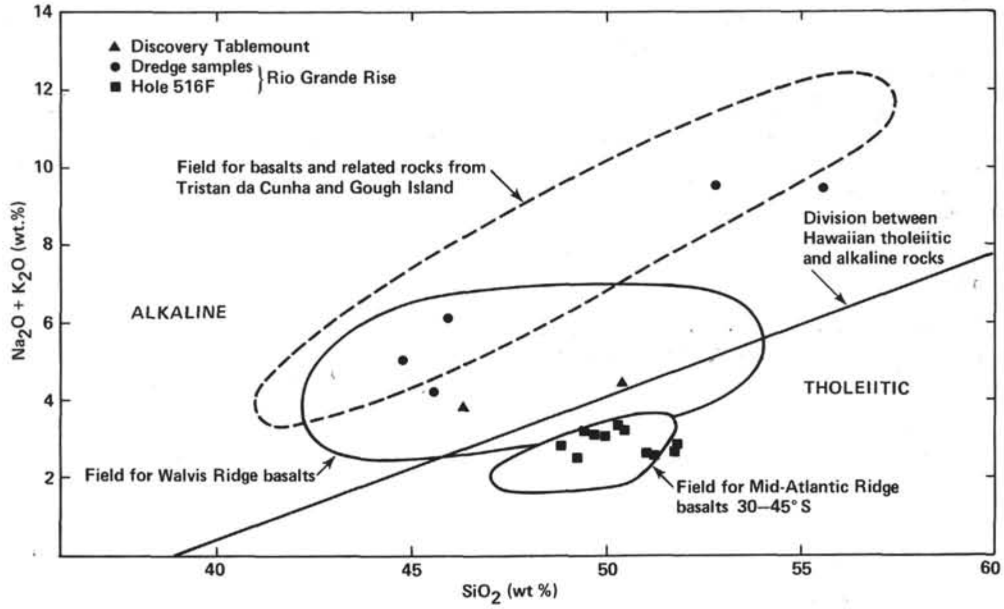

Figure 4. $Na_2O + K_2O$ versus SiO_2 diagram showing the fields of alkaline and tholeiitic basalts (after Macdonald and Katsura, 1964). The field for basalts from Tristan da Cunha and Gough Island are from data of Baker et al. (1964), LeMaitre (1962), and Humphris and Thompson (1982); the data for the Walvis Ridge are from Hekinian (1972) and Humphris and Thompson (1982); the data for Mid-Atlantic Ridge basalts are from Frey and others (1974), Humphris and Thompson (1982), and Schilling and others (1981); Discovery Tablemount data are from Kemp and Schilling (1974); data for dredge samples are from Fodor, Husler, and Kumar (1977); and data for Hole 516F are from this paper.

Table 3. Comparative analyses of Hole 516F basalts with other basalts from the South Atlantic.

Element	Hole 516F Rio Grande Rise	Dredge RC16 Rio Grande Rise	Discovery Tablemount	E. Walvis Ridge	Tristan da Cunha	Mid-Atlantic Ridge, S. Atlantic
Major element oxides (in wt. %)						
SiO_2	50.48	47.33	51.53	51.14	46.7	50.74
TiO_2	2.51	3.25	2.75	3.03	3.6	1.03
Al_2O_3	15.12	14.90	15.86	16.53	17.3	15.83
FeO	12.76	9.60	9.82	11.96	10.4	9.05
MnO	0.17	0.17	0.16			0.15
MgO	5.23	7.19	4.99	2.37	4.7	8.78
CaO	10.61	10.15	9.28	7.08	9.7	12.20
Na_2O	2.61	3.57	3.10	2.91	4.1	2.32
K_2O	0.28	1.73	1.43	2.19	3.0	0.06
P_2O_5	0.21	0.75	0.43			
Trace elements (in ppm)						
Rb	6.5	2.8	22		173	
Sc	38		22.5			42
V	380	271	400	437	230	233
Cr	32	146	50	73	28	500
Co	49	45	40	62	18	49
Ni	52	106	100	55	10	174
Cu	198	55	225	110		102
Zn	112	103	227			
Sr	360	928	>1000	318	1167	124
Ba	176	1156	600	384	913	13
Y	38	25	50	46	45	35
Zr	180	293	250	200	325	91
Nb	13.7	70			112	
La	14.7		29.4	25.1	196	2.2
Ce	36.2			65		7.1
Nd	20.0			35.2		7.2
Sm	6.5		7.8	8.3		2.41
Eu	2.2		2.4	2.5		0.93
Gd	8.5					
Tb	1.2		1.0	1.2		0.69
Dy	7.2					
Tm	0.57					
Yb	3.1		1.5	3.3		2.8
Lu	0.40		0.29	0.53		0.49

Note: Hole 516F column = mean of Groups 1 and 2, Table 2 (this paper). Dredge RC16 column = mean of 3 basalts, D11A, D12C, and D12A (Fodor, Husler, et al., 1977); trace element data previously unpublished. Discovery Table-mount column = fresh basalt (Kemp and Schilling, 1974). E. Walvis Ridge column = mean of 7 basalts (Hekinian, 1972; Hekinian and Thompson, 1976; REE from Frey, unpublished). Tristan da Cunha column = average of 10 analyses (Baker et al., 1964). Mid-Atlantic Ridge column = average of 7 basalt glass analyses, DSDP Leg 3 (Frey et al., 1974).

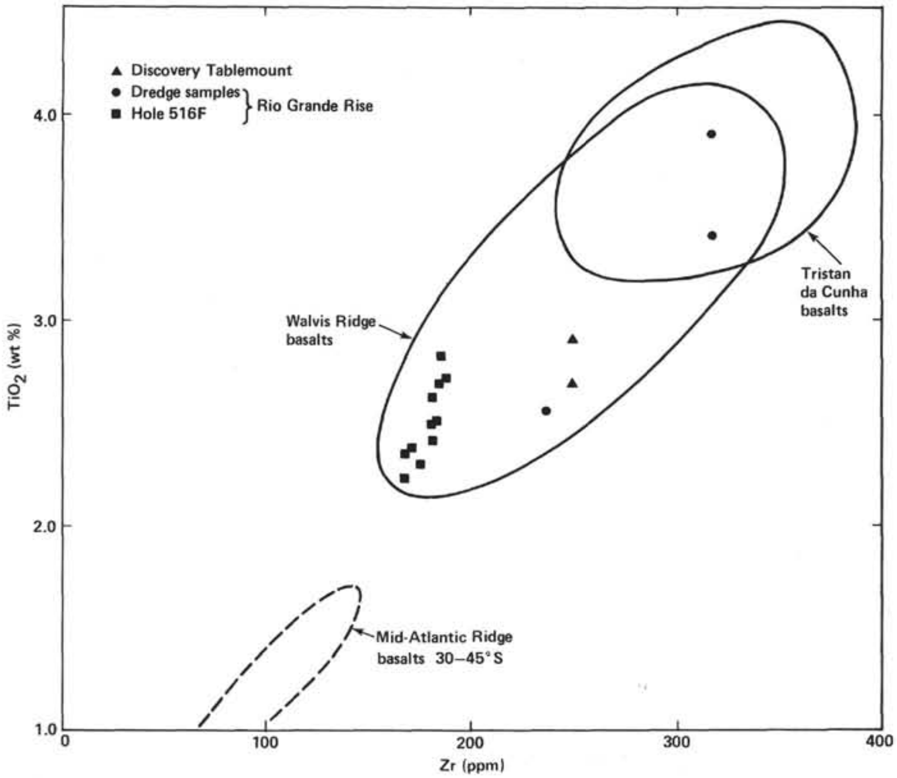

Figure 5. Plot of TiO_2 versus Zr for Hole 516F and other basalts. Data sources as in Figure 4.

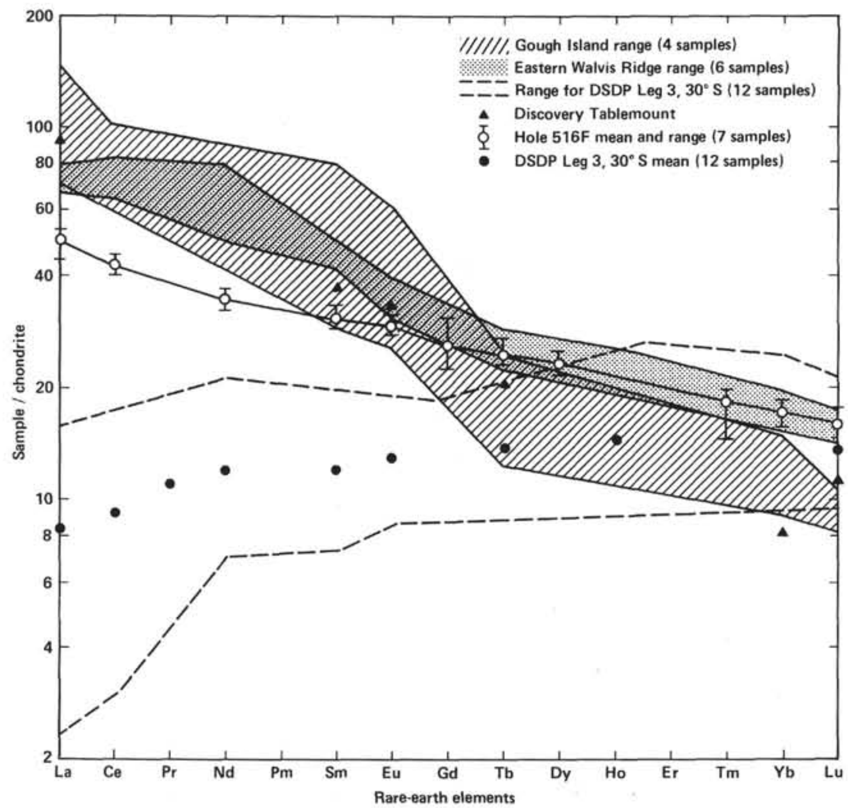

Figure 6. Chondrite-normalized REE data for Hole 516F basalts and other basalts. Data for Gough Island are from Zielinski and Frey (1970); for the Walvis Ridge the data are for the dredge samples described by Hekinian (1972) for the eastern end of the Walvis Ridge and are from Frey (personal communication); the remainder of the data sources as in Figure 4.

Table 4. Trace element analyses of dredged samples from Rio Grande Rise (in ppm)

Element	D11A	D12C	D12A	D12B	D12D
Rb	33	30	20	84	97
V	235	268	309	180	96
Cr	246	36	157	< 2	4
Co	48	46	42	13	17
Ni	139	83	102	14	14
Cu	52	38	76	3	20
Zn	75	130	105	111	92
Sr	878	1028	879	1211	1045
Ba	927	1197	1345	1615	2727
Y	23	30	23	34	34
Zr	236	322	322	450	417
Nb	43	73	95	77	83

Note: Major element analyses presented by Fodor, Husler, et al. (1977); trace element analyses on splits from those samples.

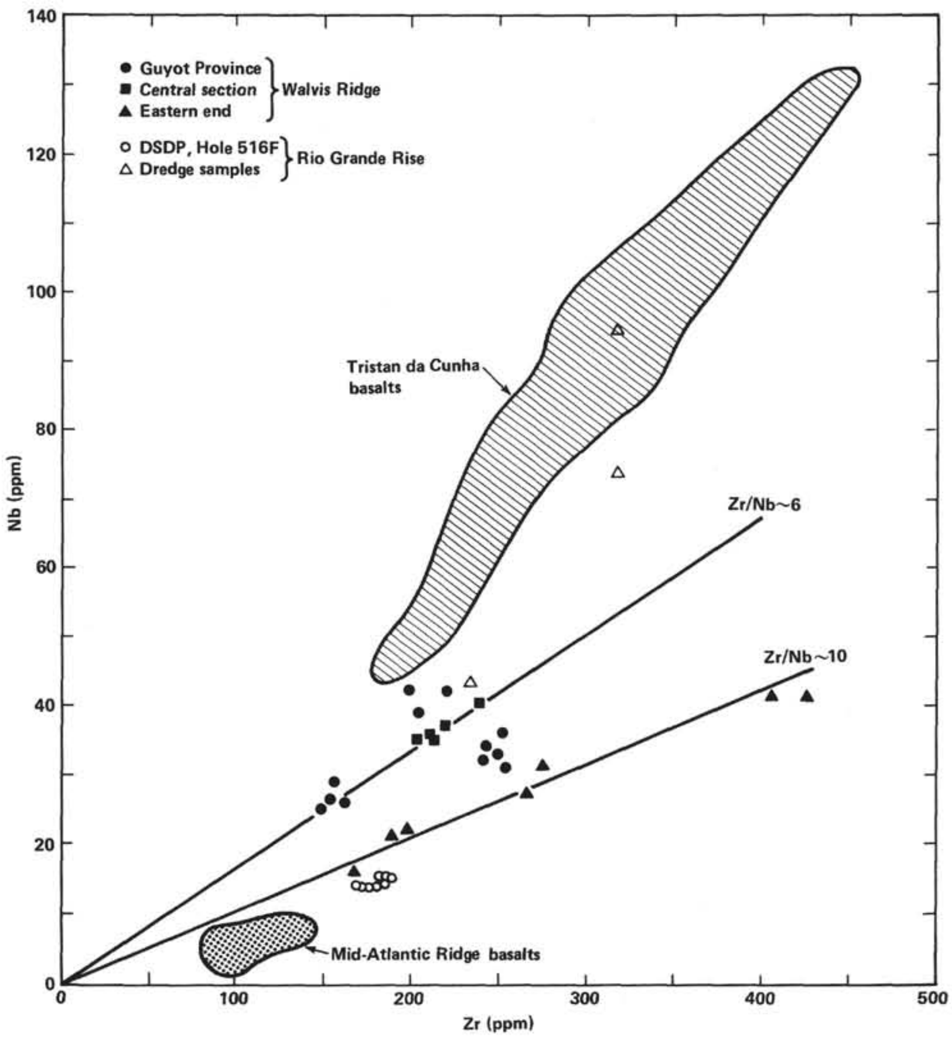

Figure 7. Plot of Nb versus Zr for Hole 516F basalts and other basalts. Data for Tristan da Cunha and the Walvis Ridge are from Humphris and Thompson (1982); the remainder of the data sources as in Figure 4.