Petrology of basaltic rocks from the Ceará and the Sierra Leone aseismic rises in the equatorial Atlantic Ocean

Basalt chemistry
Mineral chemistry
Aseismic rises
Chimie des basaltes
Chimie minérale
Rides aséismiques

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ABSTRACT

The Ceará rise and the Sierra Leone rise are paired, aseismic structural features in the equatorial Atlantic. Basalt drilled at the Ceará rise (DSPD site 354) is altered, but whole-rock TiO_2 (>3.0 wt.%), P_2O_5 (0.32 wt.%), and Zr (>200 ppm) contents, and clinopyroxene composition (Wo_{42}; TiO_2 1.2-2.3 wt.%; Al_2O_3 3-4.8 wt.%; SiO_2 48-51 wt.%) indicate that the rock is of alkalic basalt parentage. Similarly, basaltic fragments recovered in sediment cores from the Sierra Leone rise suggest the presence of basaltic rock different from those erupted on recent accreting plate-boundary regions; namely, they have clinopyroxene of Wo_{41-45} (Al_2O_3=1.8-5 wt.%; TiO_2=0.7-2.2 wt.%; and SiO_2<51 wt.%); and one occurrence of anorthoclase was observed. From their whole-rock and mineral compositions, plus their geographic setting and morphology, it is inferred that these aseismic rises represent an original large accumulation of volcanic material (probably of many individual volcanoes) at the mid-Atlantic ridge during Cretaceous time. Subsequently, they were divided by sea-floor spreading into two structural features, now buried by sediment.

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RÉSUMÉ

Pétrologie des roches basaltiques des rides aséismiques Ceará et Sierra Leone de l'Océan Atlantique équatorial

Les rides Ceará et Sierra Leone constituent un ensemble de deux structures aseismiques de l'Océan Atlantique équatorial.
Le basalte, prélevé par forage (DSDP site 354) sur la ride Ceará, est fortement altéré et ne conserve que très peu des caractères représentatifs de sa structure originelle. Les teneurs en TiO_2 (>3,0 %), P_2O_5 (0,32 %), Zr (>200 ppm) et la composition du clinopyroxène (Wo_{42}, TiO_2>1 %) caractérisent un basalte d'affinité alcaline. De la même manière, les fragments de roches basaltiques, récupérés dans une carotte sédimentaire de la ride Sierra Leone, ont une composition de basalte différente de celle que l'on retrouve dans les roches des dorsales océaniques récentes; elles contiennent un pyroxène de composition Wo_{41-45} (Al_2O_3=1.8-5 %; TiO_2=0.7-2.2 %; SiO_2<51 %).
La composition des basaltes de ces deux rides, leur morphologie et leur situation géographique suggèrent que ces deux structures ont été constituées par une accumulation importante de produits volcaniques (probablement un assemblage de plusieurs volcans) sur l'axe de la dorsale médio-atlantique au Crétacé, qui fut ensuite divisée par l'expansion océanique en deux parties (maintenant recouvertes par les sédiments).

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INTRODUCTION

The Ceará and the Sierra Leone aseismic rises are twin features in the equatorial Atlantic-Ocean equidistant from the mid-Atlantic ridge that separates them (Fig. 1). They are approximately equal in area and rise about 1,500 m above the surrounding abyssal plains. Studies to unravel the geologic history of the Atlantic Ocean have proposed that the Ceará and the Sierra Leone rises represent thick accumulations of ocean crust that had a common origin at the mid-Atlantic ridge about 80 M.Y. ago (Kumar, Embley, 1977; Hortz *et al.*, 1977; Kumar, 1979). A variation of this hypothesis puts the origin of these features at 110 to 127 M.Y. ago and in a structural gap between Africa, South America, and North America (Sibuet, Mascle, 1978).

These twin features resemble another pair of aseismic rises in the South Atlantic: the Rio Grande rise and the Walvis ridge. The composition of the volcanic rocks from each of these features and their structural settings suggest that they are composed of a network of isolated volcanic centers active during the opening of the South Atlantic Ocean and now deeply buried by sediments (Hekinian, 1972; Fodor *et al.*, 1977 *a; b*). The same perhaps holds true for the Ceará-Sierra Leone pair. Not only does their morphology suggest this, but an initial study of the mineral phases in basaltic fragments in sediment pistoncores from the Sierra Leone rise indicated the presence of nearby basaltic material, perhaps from isolated volcanoes now buried (Hekinian *et al.*, 1979) (Fig. 1).

To investigate the possibility of the Ceará and the Sierra Leone aseismic-rise pair representing sites of former volcanic centers, a detailed study of the whole-rock composition and mineralogy was undertaken for the basaltic rock drilled from the Ceará rise during Leg 39A of the Deep Sea Drilling Project. Also, a further look was made into the compositions of the minerals in the basaltic rock fragments recovered during piston coring of the Sierra Leone rise by the research vessel, "Jean Charcot" (Hekinian *et al.*, 1979).

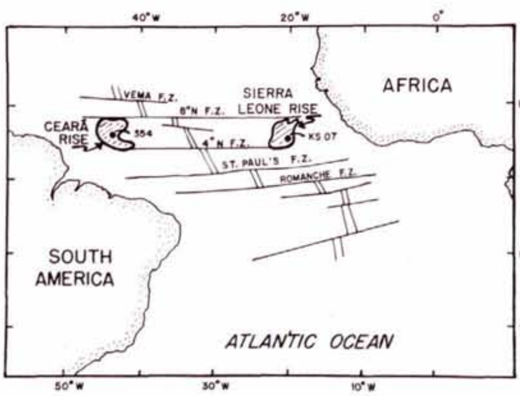

Figure 1

Location map for the Ceará and the Sierra Leone rises, equatorial Atlantic Ocean, and for the sample localities, DSDP site 354 and piston core site KS07 (F.Z. = fracture zone).

ANALYTICAL RESULTS

Descriptions

The Ceará rise rock examined is from 9.5 m of basaltic core recovered from beneath 886 m of sediment on the western part of the structural feature. The location is site 354 of the DSDP, 5°54′N, 44°12′W (Fig. 1).

In general, the rock is gray to gray-black in color, but mottled yellow and light-green in places due to alteration and sea-water weathering. Portions of the core have veins of calcite up to 1 cm in thickness.

Thin section examination shows that substantial clinopyroxene has been altered to layer-lattice silicate phases, and that much of the interstices of the groundmass have brown clay-like phases and calcite. Plagioclase laths remain abundant in the groundmass, however, and in the freshest samples are associated with remnant clinopyroxene and opaque phases in a relationship that was probably originally intergranular (Fig. 2*a*). Average grain sizes observed for plagioclase were 0.8 mm, for clinopyroxene, 0.3 mm, and for oxides, 0.15 mm.

Figure 2*a*

The weathered groundmass of Ceará rise sample 354-19-6 *showing intergranular plagioclase, clinopyroxene, and oxides. Abundant layer-lattice silicate phases occupy the groundmass as weathering products. Crossed nicols; scale bar equals* 1 *mm.*

Whether or not the Ceará rise basalt core represents true basement rock is not known. The initial report of the texture by the Shipboard Scientific Party of Leg 39A suggested that its rather coarse-grained nature indicated a possible origin as a sill or as a flow intercalated with sediment. This interpretation is supported by seismic reflection data at site 354 (Shipboard Scientific Party, 1977), and is quite plausible when considering the numerous occurrences noted during deep-sea drilling where the uppermost basaltic rocks are interbedded with sediments rather than representing true basement.

Basaltic fragments, about 3 cm in size, in sediment from the Sierra Leone rise are composed of crystals of plagioclase, up to 0.75 mm, clinopyroxene, 1 mm, and one crystal (0.5 mm) of anorthoclase, in a brown layer-lattice silicate matrix (Fig. 2*b*). Hekinian *et al.*, (1979) noted remnant feldspar laths in the matrix from what may have originally been a trachytic texture.

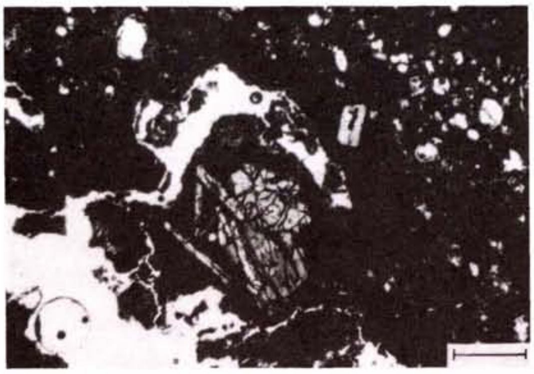

Figure 2 *b*

An assemblage of plagioclase and clinopyroxene crystals in the weathered basaltic fragments from the Sierra Leone rise. Much of the white area is holes in the polished thin section. Black is a layer-lattice silicate weathering product. Crossed nicols; scale bar equals 1 mm.

Whole-rock composition

Two samples of Ceará rise basaltic rock were analyzed chemically: one from an intermediate zone of the core, 354-19-4, and a second from near the base and presumably the freshest material, 354-19-6. The compositions are presented in Table 1.

The high H_2O^+ content of each sample points to the extreme alteration and weathering these basaltic rocks have undergone, particularly the upper sample, 354-19-4. Similarly, the exceedingly low SiO_2 reflects the abundances of calcite and hydrous phases in these rocks.

Table 1

Whole-rock compositions (in wt. %) for two basaltic samples from a 9.5 m core drilled from the Ceará rise, equatorial Atlantic Ocean (DSDP site 354).

	354-19-4 (15-17)	354-19-6 (100-102)
SiO_2	39.25	44.50
TiO_2	3.15	3.44
Al_2O_3	11.30	12.10
Fe_2O_3	4.49	5.57
FeO	7.93	7.41
MnO	0.23	0.21
MgO	3.72	4.80
CaO	12.00	8.08
Na_2O	2.47	2.56
K_2O	1.01	0.80
* H_2O^+	13.20	8.82
H_2O^-	1.08	1.26
P_2O_5	0.32	0.33
Total	100.15	99.88
Rb (ppm)	9	17
Ba	236	197
Sr	363	367
V	246	221
Cr	<4	<4
Ni	13	7
Cu	12	14
Zn	151	148
Y	16	15
Zr	204	213

* *Includes CO_2.*
Analysts: Major elements by wet chemistry and AA, J. W. Husler; trace elements by XRF, T. J. Bornhorst; both University New Mexico.

The intense alteration of this basaltic core was previously noted by Kharin *et al.*, (1977).

Because of the alteration, little can be evaluated as representative of the original basalt. The K_2O, for example, is relatively high for oceanic basalt, but in all probability is not present in its original amounts due to the affects of sea-water alteration. If TiO_2 and P_2O_5 can be considered relatively immobile oxides, their relatively high abundances of >3 wt. % and >0.3 %, respectively, suggest alkalic affinities for these rocks (e. g. Floyd, Winchester, 1975; Winchester, Floyd, 1977).

Among the trace elements, Zr concentrations are thought by most geochemists to be quite immobile and a good indicator of magma parentage. Accordingly, the values of over 200 ppm Zr for the Ceará rise basalts are too high to be compatible with oceanic tholeiites, such as the basalts at ocean ridges (e. g. Floyd, Winchester, 1975; Kay, Hubbard, 1978). On the other hand, these values are not unequivocally alkalic either (e. g. Floyd, Winchester, 1975; Winchester, Floyd, 1977; Miyashiro, 1978). At best, the Zr contents can be stated as indicating alkalic rock, but somewhat transitional to tholeiitic. Similarly, if the Sr content of 365 ppm can be treated as representing original values, they too suggest basalt transitional in nature (Engel *et al.*, 1965; Miyashiro, 1978; Kay, Hubbard, 1978).

Mineral compositions

Remnant clinopyroxene and feldspar were analyzed by electron microprobe in the lowermost sample of the Ceará rise core, and in the basaltic fragments from the Sierra Leone piston cores. In addition, partial analyses were made of the opaque phases in the Ceará rise basalt. The analytical data are listed in Tables 2 and 3.

The average composition of clinopyroxene in Ceará rise basalt resembles that found in basalts having alkalic affinities. Namely, it has an average of 42 mole percent wollastonite (Wo) content, which is greater than that in groundmass pyroxenes in tholeiitics rocks (tholeiitic clinopyroxene typically has Wo_{40} or less; Fodor *et al.*, 1975), and relatively high Al_2O_3 (>3.5 wt. %) and TiO_2 (>1.5 %) contents. The Fe-Ca-Mg compositional variation in the groundmass pyroxenes is illustrated in Figure 3.

Three distinctive clinopyroxene crystals (occurring as phenocrysts to microphenocrysts) were observed in the Sierra Leone fragments. One type is compositionally close to the Ceará clinopyroxene, having average values of Wo_{45}, Al_2O_3 4.9 wt. %, and TiO_2 2.2 %. A second type contains Wo_{42} and less Al_2O_3 and TiO_2 (2.6 and 2.2 wt. %, respectively), and a third grain has Wo_{40} and substantially lower Al_2O_3, 1.8 wt. %, and lower TiO_2, 0.71 %. Moreover, the third type is much richer in FeO, having Fs_{26} (Fig. 3). Whereas the first two clinopyroxene types are more compatible with alkalic rocks and rocks transitional to tholeiitic, this latter pyroxene in the Sierra Leone fragments agrees best with tholeiitic parentage.

In order to show compositional differences between alkalic and tholeiitic suites, Le Bas (1962) used the silica

Table 2

Clinopyroxene compositions (by electron microprobe; in wt. %) as groundmass (g) and phenocrysts (p) in basalt from the Ceará rise, and basaltic fragments from the Sierra Leone rise, equatorial Atlantic Ocean.

	1	2	3	4	5
	Ceará rise		Sierra Leone rise		
	g (range)	g (range)	p	p	p
SiO_2	49.5 (48.3-50.2)	49.3 (48.1-50.8)	49.1	51.1	50.2
TiO_2	1.7 (1.3-2.0)	1.9 (1.2-2.3)	2.2	1.3	0.71
Al_2O_3	3.7 (2.8-4.5)	4.1 (2.8-4.8)	4.9	2.6	1.8
Cr_2O_3	<0.01	<0.01	0.19	0.07	<0.01
FeO	9.6	10.0	7.7	8.9	15.1
MnO	0.20	0.20	0.22	0.38	0.10
MgO	14.3	14.2	14.4	14.9	11.6
CaO	19.9	20.5	21.6	20.3	19.3
Na_2O	0.40	0.36	0.34	0.32	0.42
Total	99.00	100.56	100.65	99.85	99.23
Molecular end members					
Fs	15.9	16.2	12.6	14.5	25.0
En	42.3	41.1	42.0	43.2	34.2
Wo	41.8	42.7	45.4	42.3	40.8

Col. 1, avg. of 10 points; DSDP 354-19-6 (100-102). 2, avg. of 8 points; DSDP 354-19-5 (147-150). 3, avg. of 5 points; CH77KS07; 4, avg. of 4 points; CH77KS07; 5, avg. of 3 points; CH77KS07.

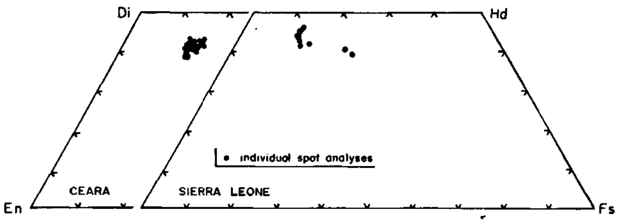

Figure 3

Pyroxene quadralateral showing the compositions (by electron microprobe) for groundmass pyroxene in the Ceará rise samples and pyroxene phenocrysts (and microphenocrysts) in the Sierra Leone basaltic fragments.

and alumina contents of clinopyroxene from subaerial volcanic rocks. A similar diagram is used here in Figure 4 to illustrate representative clinopyroxene compositions in basaltic rocks from spreading centers and aseismic ridges. In general, the clinopyroxene compositions of volcanic rock from aseismic ridges vary from tholeiitic to alkalic (Fig. 4). More significant is that clinopyroxene in aseismic ridge volcanic rocks, such as at Ninety-east and Walvis ridges, depart from typical accreting plate-boundary basalts with respect to their clinopyroxene compositions (Fig. 4). The pyroxenes from basalts erupted on recent spreading ridges (mid-Atlantic ridge and East Pacific rise) are somewhat higher in SiO_2 (51-53 wt. %) than those in basaltic rocks from aseismic ridges (SiO_2=46-51%) (Fig. 4). Using these criteria, clinopyroxene in the Ceará and Sierra Leone basaltic rocks have compositions distinctive from those in basalts at recent accreting plate-boundaries and are more compatible with pyroxene in other aseismic ridge rocks (Fig. 4). This is true even for the more typically tholeiitic pyroxene in the Sierra Leone fragments.

Table 3.

Average feldspar compositions (by electron microprobe; in wt. %) for microphenocrysts (m) and groundmass grains (g) in basalt from the Ceará rise, and basaltic fragments from the Sierra Leone rise, equatorial Atlantic Ocean.

	Ceará rise			Sierra Leone rise			
	m	m	g	m	m	g	m
SiO_2	51.6	55.3	58.3	52.0	56.4	59.5	67.9
Al_2O_3	30.1	27.2	25.5	30.0	26.6	24.0	19.3
FeO	0.80	0.53	0.59	0.78	0.80	0.80	0.33
MgO	0.13	0.05	0.01	0.09	0.12	0.08	0.01
CaO	13.5	10.5	8.1	13.7	10.1	7.3	0.50
Na_2O	3.8	5.2	6.3	3.6	5.8	6.0	8.3
K_2O	0.14	0.23	0.32	0.18	0.29	0.67	4.3
Total	100.07	99.01	99.11	100.35	100.11	98.35	100.63
Molecular and members							
An	65.8	52.1	40.8	67.1	48.4	36.3	2.4
Ab	33.4	46.5	57.3	31.8	49.9	59.7	72.7
Or	0.8	1.4	1.9	1.1	1.7	4.0	24.9

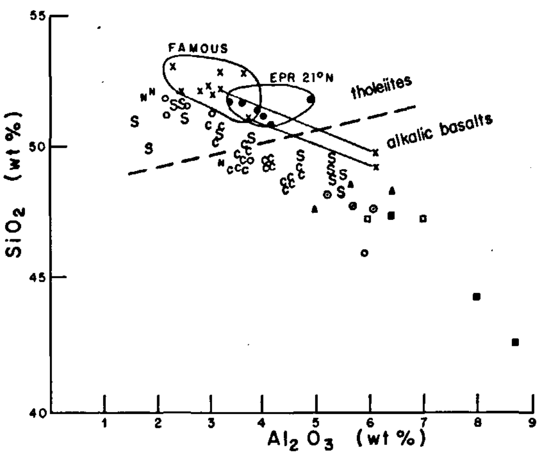

Figure 4

Al_2O_3-SiO_2 wt % diagram of clinopyroxene composition from various structural settings. The samples from aseismic ridges such as the Sierra Leone Rise (S), the Ceará rise (C), the Walvis ridge (O) (Hekinian unpublished data), the Ninety East Ridge (N) (Hekinian unpublished data), are compared with the clinopyroxene from alkali basalts of Annobon island (O, Cornen and Maury, 1980) from the M.A.R. 43°N (□) (Shibata et al.*, 1979) and from Site 211, leg 22 (■) (Whorton basin, Indian Ocean) (Hekinian, unpublished data). The tholeiitic basalts from the Famous area near 36°50'N on the M.A.R. and those from the East Pacific Rise (Cyana samples) are also reported for comparison. The tie-lines connect the composition of zoned clinopyroxenes. The cores of the pyroxenes are enriched in SiO_2 instead the corresponding margins are enriched in Al_2O_3 content.*

The plagioclase in both the Ceará and the Sierra Leone samples has K_2O content more characteristic of alkalic samples than tholeiitic. In particular, the groundmass grains of intermediate plagioclase have relatively high molecular orthoclase; or is 1.9 and 4.0 mole percent, respectively. In contrast, intermediate plagioclase typically observed as groundmass laths in tholeiitic basalt have $Or_{1.1}$ or less (Keil *et al.*, 1972). However, it should be noted that even if the feldspar grains analyzed look fresh in thin section, too much emphasis cannot be placed on their Or content because of the strong susceptibility of K_2O alteration by sea-water and hydrothermal solutions. In addition to plagioclase, one twinned grain of anorthoclase was observed in a Sierra Leone basaltic fragment. It is in the same rock chip as the plagioclase and clinopyroxene grains analyzed and appears to be a true phenocryst rather than an alteration product.

Opaque phases analyzed in the Ceará rise basalt are pyrite (Fe 44 wt.%), ilmenite (TiO_2 58 wt.%), and titaniferous magnetite (TiO_2 18 wt.%, FeO 60%, Al_2O_3 4%, MgO 3%). The titaniferous magnetite is actually low in TiO_2 and FeO, even when all FeO is recalculated as Fe_2O_3. This possibly indicates incipient hydration of this oxide phase.

DISCUSSION AND CONCLUSIONS

The basalt cored at DSDP site 354 provides the only igneous material representing basement rock of the Ceará rise. On the basis of whole-rock compositions, namely the high TiO_2, P_2O_5, and Zr contents, and on the basis of mineral chemistry, namely the clinopyroxene, the Ceará rise rock has affinities with an alkalic magma parentage. These data appear to be characteristic of aseismic ridges (Hekinian, 1972; Hekinian, Thompson, 1976; Fodor *et al.*, 1977 *a*) and are unlike those of typical oceanic tholeiite at mid-ocean ridges.

The same can be said for the basaltic material from the Sierra Leone rise. Based on its mineral chemistry, mainly clinopyroxene and the one grain of anorthoclase observed, these basaltic fragments are different from recent spreading-ridge rocks. In fact, when both the mineral compositions of the Ceará and the Sierra Leone basalts and the whole-rock composition of Ceará basalt are compared with those of other aseismic ridges, it could be inferred that similar magmatic processes were responsible for forming all of these volcanic features.

The Sierra Leone fragments can be interpreted as representing underlying alkalic (and tholeiitic) igneous rocks that compose the main mass of the rise. Such an inferrence is viable and was demonstrated for the Rio Grande rise and the Walvis ridge. At the Rio Grande rise, for example, clinopyroxene in basaltic fragments in sediments drilled during DSDP Leg 39 from above the igneous basement indicated nearby basalt with alkalic affinities, probably as basement rock (Fodor, Thiede, 1977). And there, too, an alkali feldspar grain ($An_2Ab_{17}Or_{81}$) was found associated with the basaltic fragments. Indeed, subsequent examination of dredged samples from the Rio Grande rise confirmed the alkalic make-up of the basement rock (Fodor *et al.*, 1977 *a*).

Pertinent to the origin of the Ceará and Sierra Leone rises is that alkalic basaltic rocks in ocean provinces are almost invariably associated with islands and seamounts (e. g., Engel *et al.*, 1965; Aumento, 1968; Baker, 1973), and in some cases at island centers known to have previously erupted tholeiitic basalt (there are, however, occurrences of alkalic basalt in fracture zones, e. g., Melson *et al.*, 1967; Fodor *et al.*, 1980). Accordingly, the compositional data for the Ceará rise lend support to the hypothesis that it represents a geologic feature that originated on the mid-Atlantic ridge as a thick volcanic pile perhaps up to 2 km thick, probably bounded by fractures zones at 4 and 8°N (Kumar, 1979). In all likeliness, the Sierra Leone rise shared this spot of "abnormal" volcanic activity at the ridge crest, contributing to one massive accumulation of basalt. One or both rises are probably composites of several volcanic centers, some of which may have been represented by subaerial volcanoes at one time. It should be noted here that if the Sierra Leone rise extends beyond the 4°N fracture zone to the St. Paul's fracture zone (e. g., Emery *et al.*, 1975), then the volcanic rocks reported here may have some relationship to the alkalic basalt dredged from the St. Paul's fracture zone at 29°W (Melson *et al.*, 1967).

The splitting up of the proposed volcanic mass that formed during Cretaceous time into east and west structural parts resulted from subsequent ocean-floor spreading at that region. And that was probably followed by the change to more recent spreading ridge type of volcanic activity at the crest (i. e., morphologically there is no evidence for a chain of volcanoes to indicate that a "hot spot" persisted since Cretaceous). However, because the basalt cored may represent a sill or a flow interbedded with sediment, sporadic volcanism may have occurred on the Ceará rise after substantial sediments had already accumulated on the submerged structural rise.

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