

MINERAL CHEMISTRY AND PETROGRAPHY OF PASSIVE-MARGIN BASALT, SOUTHEASTERN BRAZIL

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ABSTRACT Mineral chemistry and textures of Jurassic-Cretaceous basaltic rocks from the southeastern Brazil margin (coastline and offshore) depict the geochemical diversity of these rocks. For example: (1) some low-K basalts (N- and T-type MORB equivalents) have intergranular and subophitic textures (hypabyssal emplacement), while those with CFB-like compositions (high K and LREE) have granular, hyaloophitic, and plagioclase – and clinopyroxene-phyric textures compatible with subaerial and subaqueous emplacement of evolved basalt on rifted continental crust; (2) most diagnostic is Or in plagioclase, where $An_{60}Or_{0.8}$ and $An_{60}Or_2$ compositions distinguish low-K basalt from CFB; (3) some samples are altered and the positive correlation between Or and whole-rock K_2O enables estimating that seawater weathering increased K_2O by >1 wt%; (4) augite compositions also parallel whole-rock compositions, Fs correlating with FeO^*/MgO , whereas pyroxene Ti-Al relationships distinguish N-type MORB from CFB. Phase compositions and textures corroborate the observation (Fodor & Vetter 1985) that CFB, N-type MORB, and basalt transitional between these types mark the change from continental to oceanic magmatism along the southeastern Brazil margin.

RESUMO Notável diversidade geoquímica é mostrada pelas rochas basálticas Jurássicas-Cretácicas da margem continental (borda e plataforma) do SE brasileiro, com reflexos na mineralogia e textura das rochas. Identificam-se algumas características significativas. (1) Alguns basaltos pobres em K (equivalentes aos basaltos de cadeias meso-oceânicas, MORB, tipos normal N e transicional T) mostram texturas intergranulares e subofíticas (compatíveis com colocação hipoabissal), enquanto que as rochas comparáveis geoquimicamente aos derrames basálticos continentais intrabacia (“continental flood basalts”, CFB), com teores altos de K e de Terras Raras leves, exibem texturas granulares e hialofíticas, com fenocristais de plagioclásio e piroxênio, identificando possíveis ambientes subaéreos e subaquosos de deposição, colocando-se sobre crosta continental em processo de “rifting”. (2) Como característica diagnóstica, basaltos pobres em K tem plagioclásio pobre em Or ($An_{60}Or_{0.8}$), enquanto que os aparentados aos CFB mostram plagioclásio com $An_{60}Or_2$. (3) Em alguns basaltos, mostra-se incremento no teor total de K_2O em mais de 1%, por provável alteração por água do mar. (4) As composições da augita refletem a composição da rocha total; o teor de ferrossilita correlaciona-se com FeO^*/MgO da rocha, enquanto que o conteúdo de Ti e Al da augita permite diferenciar os tipos basálticos N (MORB) dos CFB. Textura e mineralogia confirmam a observação (Fodor & Vetter 1985) de que a passagem química de CFB para os tipos N (MORB) identifica paralelamente a transição entre magmatismo continental para oceânico, ao longo da margem continental do SE brasileiro.

INTRODUCTION Geochemistry of late Jurassic-early Cretaceous basaltic rocks from the passive margin of southeastern Brazil (South Atlantic rift zone) marks the transition of continental to oceanic lithosphere (Fodor *et al.* 1983, Fodor & Vetter 1985). Magma types are tholeiitic and correspond to: (1) incompatible-element and light rare-earth element (LREE), enriched basalts that resemble continental flood basalts (CFB); (2) ordinary mid-ocean ridge basalt (N-type MORB); and (3) transitional basalt (T-type MORB) with flat REE patterns and composition similar to North Atlantic margin rift-zone basalt from eastern North America and northwestern Africa. The first category (CFB-like samples) can be subdivided: those compositionally enriched due only to their source-areas, and those enriched due partly to continental-crust component added after magma generation (*i.e.* crustal contamination).

This study presents phase compositions and petrography of these compositionally diverse Brazil margin rocks. Our objectives include determining: 1) if mineral compositions reflect the various whole-rock compositions, distinguishing, for example, N-type MORB from CFB; 2) if any rocks are enriched due only to alteration; 3) if seemingly-contaminated

basalts reflect crustal histories in their mineral compositions or petrography; 4) if highly evolved basalts that approach alkalic-basalt compositions (having $K_2O > 2$ wt.%; $TiO_2 > 3$ wt.%) have mineralogy transitional from tholeiitic to alkalic affinities; and 5) if textures of basalts in a passive-margin environment compare with textures in oceanic and continental basalts. To achieve these objectives, we determined the petrography of 31 Brazil passive-margin basaltic rocks that Fodor & Vetter (1985) described geochemically, and determined the mineral chemistry by electron microprobe for 17 of those rocks.

SAMPLE LOCATIONS AND DESCRIPTIONS The samples are from 12 Petrobrás drill sites on the coastline and offshore in the Santos, Campos, and Espírito Santo sedimentary-tectonic basins along southeastern Brazil (Fig. 1). Geologic details of these basins are in Asmus & Ponte (1973), Ponte & Asmus (1976), Asmus (1978), Asmus & Guazelli (1981), and Ojeda (1982). The offshore samples are from sites located up to 150 km from the shoreline, but mostly from between 50 and 100 km offshore. Figure 1 illustrates drill-site locations, and Table 1 lists their

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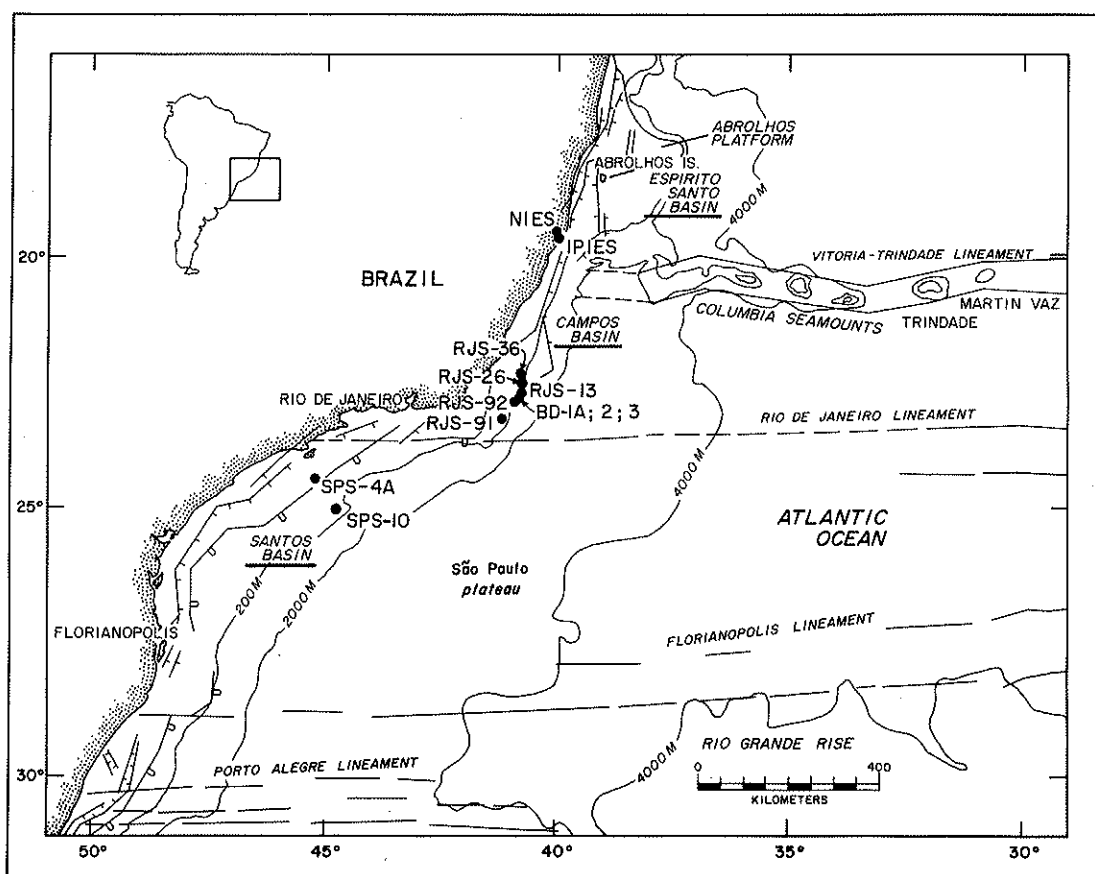


Figure 1 – Index map showing locations, labeled according to Petrobrás drill sites. Base map from Asmus & Guazelli (1981).

Table 1. Core locations, top-of-core depths* below sealevel, core-sampling intervals, and K-Ar ages* for basaltic rock from the southeastern Brazil margin

Basin; core	Lat., Long.	Depth (m)	Sampling intervals (m) (relative or absolute)	K-Ar age ⁺ (Ma)
Espirito Santo				
IPIES	19.5°S, 39.95°W	3293	3294, 3366, 3635, 3637, 3702, 4056	129.8 ± 7.0; uppermost sample
NIES	19.4°S, 40.0° W	3176	0.2, 0.5, 13 ⁺⁺	123.3 ± 3.0
Campos				
RJS-13	22.73°S, 40.83°W	3257		
RJS-26	22.57°S, 40.87°W	2585		
RJS-36	22.35°S, 40.9° W	3472	1, 6, 8	112.3 ± 4.0
RJS-91	22.35°S, 41.1° W			104.9 ± 2.6
RJS-92	22.83°S, 40.84°W	2981	1, 9, 15, 24, 30, 37, 45	123.8 ± 3.0
BD-1A	22.75°S, 40.84°W			
BD-2	22.78°S, 40.88°W	3159	1, 7, 18	
BD-3	22.76°S, 40.76°W		1, 4, 9, 17	115.8 ± 3.5
Santos				
SPS-4A	24.5° S, 45.35°W	2840		138.1 ± 3.5
SPS-10	24.95°S, 44.95°W	3586		

* where known

+ from Fodor et al. (1983)

++ no recovery between these intervals

latitude and longitude and K-Ar ages of the rock recovered. Because more than one sample was examined from most cores, Table 1 also presents intrasite sampling intervals. In general, samples were recovered from 3000 to 4000 m below sealevel, whether coring was offshore or onshore.

Samples of offshore basalt (Campos and Santos basins) generally appear unaffected by seawater, but some have obvious alteration features that include reddish oxidation color, carbonate veins, and vesicles filled with either carbonate or green layer-lattice silicate minerals. Alteration

of onshore basalt (Espírito Santo basin) is visible as rare fracture and vesicle fillings of dark layer-lattice silicates.

Table 2 lists modes of selected samples. Almost every sample contains plagioclase, clinopyroxene, and Fe-Ti oxides, but olivine (now altered) was observed in only eight samples. Several samples contain pigeonite, detected only by microprobe.

Sample numbers in this report are Petrobrás identifica-

tions: drill site, core number, and core-box number. For brevity in the text, however, we use only site and core-box references; tables list full sample I.D.'s. To enable relating petrography and mineral compositions to the whole-rock compositions in Fodor & Vetter (1985), we present variation diagrams in Fig. 2 and a summary of our geochemical classification of these Brazil margin rocks in Table 3.

Table 2 – Selected modes* of basaltic rocks from the southeastern Brazil margin

	IPIES		NIES	RJS-92		BD-2	BD-3
	19– 1/1	23– 2/3	58– 1/1A	3– 1/2	5– 7/11	5– 7/7	4– 4/17
Phenocrysts and microphenocrysts							
PLG	–	42.5	34.0	4.0	13.6	21.3	11.7
CPX	–	17.2	24.5	–	2.5	5.1	2.2
OLV	–	–	–	0.5	–	–	–
Groundmass							
PLG and CPX	83.3	–	–	28.8	50.7	42.8	58.9
OLV	0.6	–	0.1	0.2	–	–	–
Opaque OX	4.7	0.3	12.0*	0.2	2.5	1.4	2.7
Remainder (glass and alteration and devitrification products)	11.4	40.0	29.4	66.3	30.7	29.4	24.5

+ in volume percent; based on 1100-1500 points

* includes some microphenocrysts

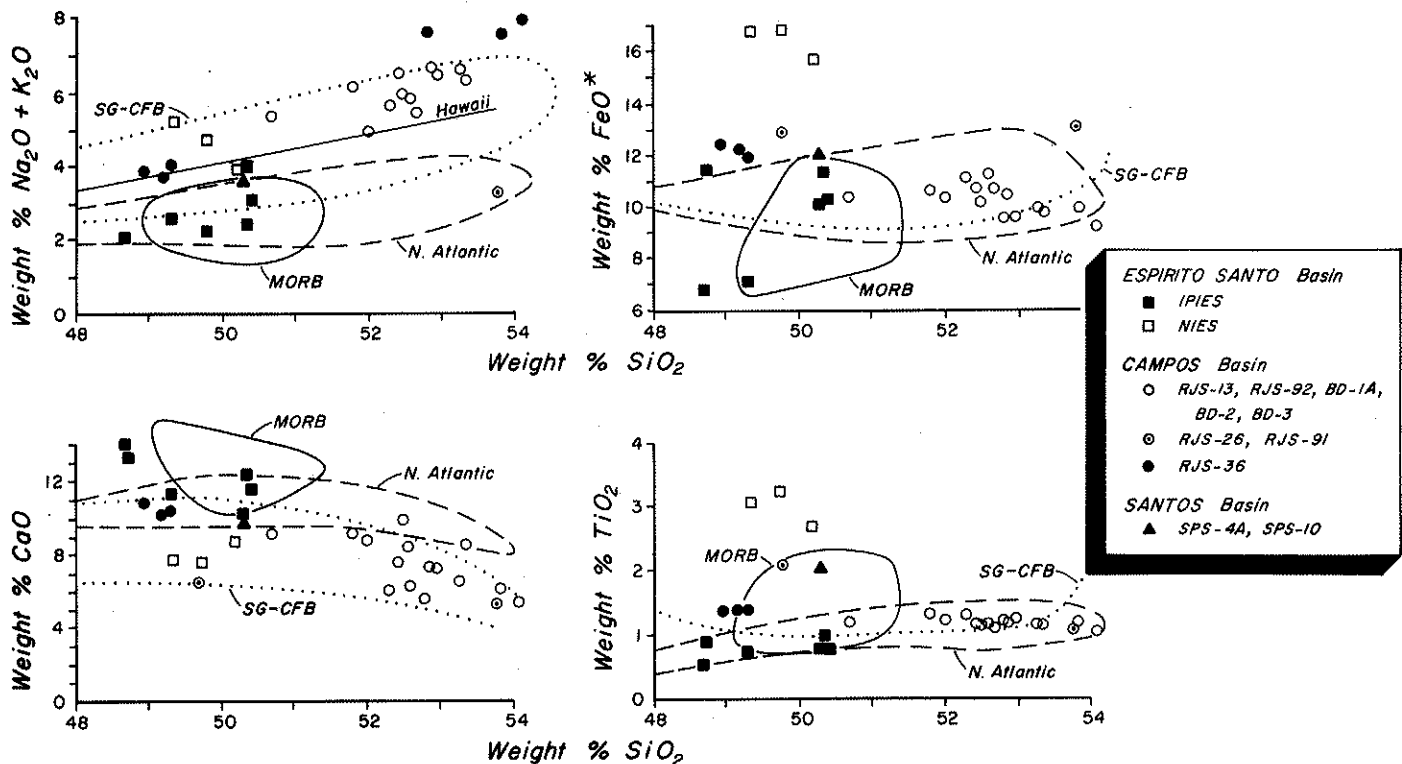


Figure 2 – SiO_2 -variation diagrams for basaltic rocks recovered from three basins along the southeastern Brazil margin (from Fodor & Vetter, 1985). Squares, Espírito Santo basin; circles, Campos basin; triangles, Santos basin. For comparison, fields are shown for N-type MORB (Frey et al. 1974, Bryan et al. 1981), and basalt associated with opening of the N. Atlantic (Weigand & Ragland 1970, Bertrand et al. 1981), and Serra Geral CFB (Ruegg 1976). Hawaii line refers to division between Hawaiian tholeiitic and alkalic basalts (McDonald & Katsura 1964). Note: SG-CFB field open ended at top in FeO^* and TiO_2 diagrams; sample SPS-10 has SiO_2 43.5 wt.% and is not plotted here.

Table 3 – Summary of basalt types from the passive-margin of southeastern Brazil, based on geochemical data in Fodor & Vetter (1985)

Basin and Petrobrás drill site	Incompatible-element Abundances			
	Relatively-low		Relatively-high	
	N-type MORB Ce/Yb _(n) = 0.7	T-type MORB Low-K (<0.40%) Ce/Yb _(n) ≈ 1-1.2	source-area characteristics Ce/Yb _(n) ≈ 3-4	includes continental crust component* Ce/Yb _(n) ≈ 4.5
Espírito Santo basin				
IPIES (5 samples)		x		
IPIES (1 sample; # 3/4)	x			
NIES			x	
Campos basin				
RJS-13				x
RJS-26		x		
RJS-36		x		
RJS-91 ⁺⁺				x?
RJS-92				x
BD-1A				x
BD-2				x
BD-3				x
Santos basin				
SPS-4A			x	
SPS-10 ⁺			x	

* crustal contamination proposed by Fodor & Vetter 1985

+ Ce/Yb_(n) = 6

++ spilitized

Espirito Santo Basin *SITE IPIES.* Six samples from discontinuous cores represent a vertical distance of 765 m (see Table 1) and basalt intercalated with terrigenous sediment. Whether they were hypabyssal rocks intruding rift-zone sediment or flows burying sediment remains undetermined. The uppermost and lowermost samples, 1/1 and 1/2, are equigranular (~ 0.4 mm) plagioclase, clinopyroxene, olivine (smectite), and Fe-Ti oxides in an intergranular to intersertal texture (Fig. 3). Original glass is either devitrified or altered to brown smectite. Rare vesicles (< 0.5 mm) contain orange smectite and calcite. Second and third samples from the top, 3/4 and 2/4, are diabasic and subophitic (~ 1 mm grains) textures (Fig. 3). Brown smectite and chlorite are present in 3/4 and 2/4, respectively, and are possibly pseudomorphic after olivine. Plagioclase in 2/4 is considerably altered. Next lowest basalt is 4/4, a microcrystalline rock from within two meters of 2/4. It consists mainly of plagioclase and clinopyroxene devitrification products; rare clinopyroxene microphenocrysts are present, and chlorite patches and calcite veins represent secondary mineralization. Finally, sample 2/3, second from the bottom, is coarse-grained (2 mm) plagioclase and clinopyroxene in texture that approaches vitrophyric (Fig. 3). Much original glass, however, is now smectite.

SITE NIES Basalt in this core, like in IPIES, is associated with terrigenous sediment (see Leyden *et al.* 1971). Three samples representing about 10 m of core have textures gradational between vitrophyric and hyaloophitic (Fig. 3), where plagioclase, clinopyroxene, and Fe-Ti oxides are 1-4 mm. Rare olivine grains (<0.5 mm) are now smectite. Glass is gray-black, partly devitrified, or altered to brown smectite. Opaque oxides (up to 0.5 mm) and relict olivine are in glass and clinopyroxene.

Campos basin *SITE RJS-13* One sample examined has microphenocrysts of plagioclase, clinopyroxene, and olivine altered to smectite in a fine-grained intergranular groundmass of clinopyroxene, plagioclase, and Fe-Ti oxide grains. Centers of some plagioclase microphenocrysts are altered but the groundmass appears free of alteration.

SITE RJS-26 The single sample examined is a medium-grained (~ 1 mm) intergranular assemblage of plagioclase and clinopyroxene (cpx now altered to smectite). It is the most oxidized of all samples studied, and reddish areas in the assemblage may represent olivine replaced by smectite. Carbonate and chlorite occupy portions of the groundmass.

SITE RJS-36 Three samples examined are aphyric and have medium-grained intergranular to subophitic textures (grains up to 1 mm) of plagioclase, clinopyroxene, and Fe-Ti oxides (Fig. 3). Chlorite replacements of some glass occupies interstices, forms patches (0.5 mm), and fills vesicles. Fe-Ti oxide grains are mainly in the glass.

SITE RJS-91 A single sample displays a plagioclase-microphyric texture where spilitization produced albite from original plagioclase. The matrix is intersertal and comprised of plagioclase laths, clinopyroxene (mainly altered), and Fe-Ti oxides. Where glass appears fresh, it is gray or light brown. Ample patches of carbonate and chlorite are in the matrix.

SITE RJS-92 Seven samples taken at 6- to 9-m intervals from a 45-m continuous core demonstrate an intersertal to hyaloophitic groundmass of plagioclase, clinopyroxene, Fe-Ti oxide grains, and glass, with microphenocrysts and phenocrysts (0.5 to 2 mm) of plagioclase and clinopyroxene (Fig. 3). The uppermost sample differs by containing rare

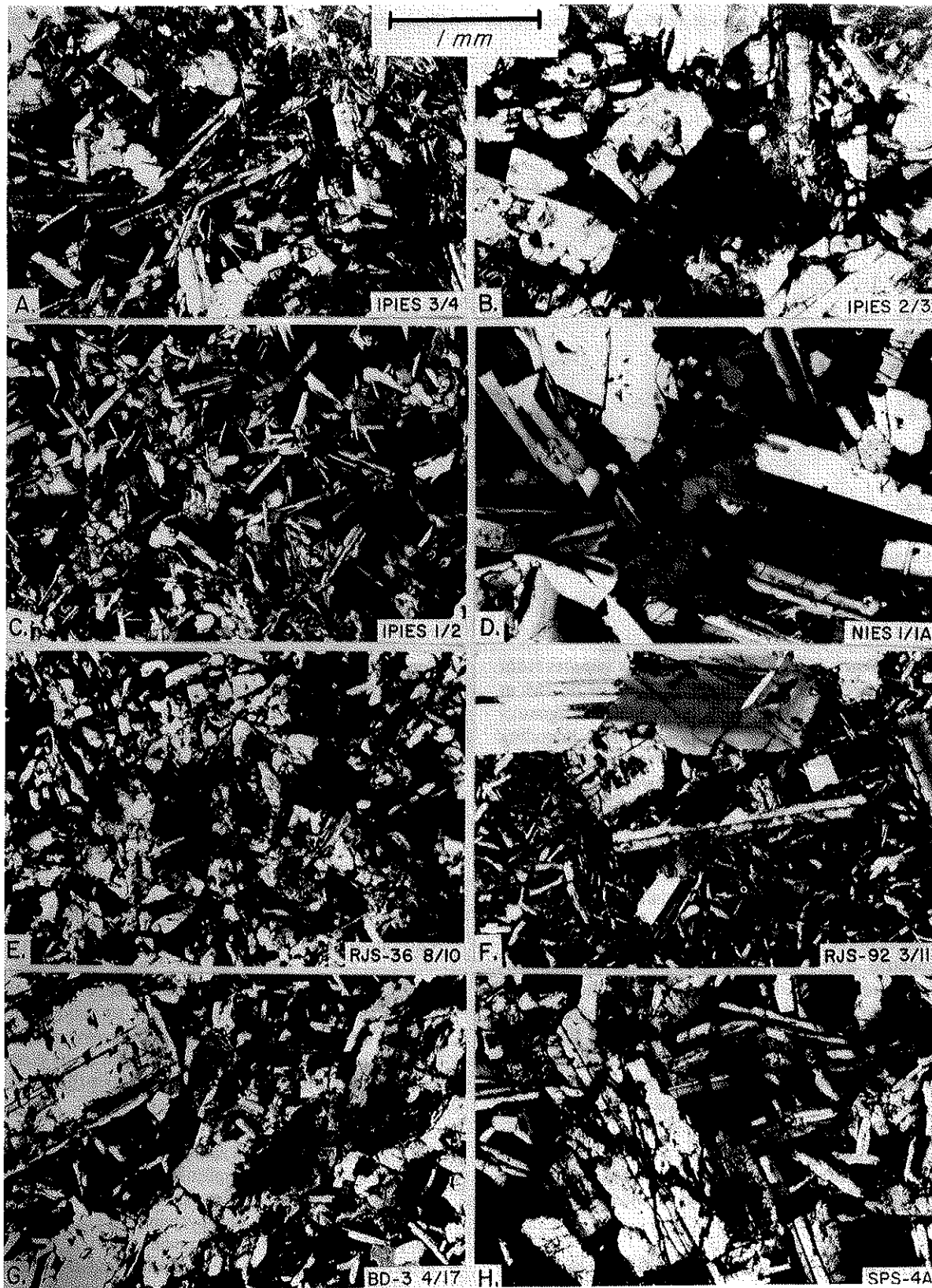


Figure 3 – Photomicrographs of representative basaltic rocks from the southeastern Brazil margin. The 1 mm scale bar applies to all photos. Sample numbers are in lower right corner of each photo; all photos in crossed nicols. A, B, and C are Espírito Santo basin basalts, drill site IPIES, with mainly plagioclase, clinopyroxene, Fe-Ti oxides and glass in variations of intergranular, subophitic, and subvitrophyric textural relationships. D, basalt from Espírito Santo site NIES, shows a cluster of plagioclase and clinopyroxene in an otherwise vitrophyric rock. E, F, and G are Campos basin basalts that have variations of intergranular, intersertal, and hyaloophitic textures; F and G are plagioclase- and clinopyroxene-phyric. H is a Santos basin basalt with largely plagioclase and clinopyroxene in an intergranular to dictytaxitic texture.

microphenocrysts and groundmass grains of altered olivine. Phenocrysts and microphenocrysts occur individually and as glomerocrysts. Plagioclase crystals occupy 4-17 volume percent, exceeding phyrlic clinopyroxene by factors of 4 to 8 (Table 2). Alteration affected plagioclase phenocrysts and microphenocrysts in most samples, as well as groundmass laths in many, where grain centers appear sericitized. Some clinopyroxene crystals are altered to protoceladonite and groundmass pyroxene grains in certain samples are now smectite. Glass ranges from fresh gray-black and light brown, to partly devitrified and birefringent, to altered to smectite. Fe-Ti oxide grains are generally in the glass. Proceladonite and carbonate occupy vesicles.

SITE BD-1A Like neighboring RJS-92 basalt, this basalt is plagioclase – and clinopyroxene-microphyric and hyaloophitic. Plagioclase, however, and groundmass pyroxene grains, show substantial alteration to chlorite and smectite. Most glass is altered to smectite.

SITE BD-2 Three samples mineralogically and petrographically resemble RJS-92 basalt; clinopyroxene, however, is scarce. Phyrlic plagioclase is altered (microprobe analyses detected portions that are nearly pure Ab and Or), and although fresh clinopyroxene microphenocrysts are present, most groundmass pyroxene is altered. Opaque oxides are in glass as dendritic crystals and subhedral grains. Veins and vugs of chlorite and carbonate are common.

SITE BD-3 Three examined samples contain plagioclase and clinopyroxene microphenocrysts (to 1.5 mm) and glomerocrysts in matrices of plagioclase crystals and crystallites surrounded hyaloophitically by glass (Fig. 3). Centers of phyrlic plagioclase are altered (pure Ab and Or detected) whereas rims are fresh. Calcite replaced some plagioclase and clinopyroxene, and chlorite replaced some phyrlic clinopyroxene. Glass is fresh and gray-black or altered to orange-brown smectite. Opaque oxides are subhedral to dendritic and mainly in the glass. Vugs contain chlorite and carbonates.

Santos basin SITE SPS-4A One examined sample is equigranular (~ 1 mm) and comprised of an intergranular to diktytaxitic arrangement of plagioclase, clinopyroxene, Fe-Ti oxides, and glass, where original glass is either partly devitrified or altered to smectite (Fig. 3).

SITE SPS-10 One examined sample was originally glassy with crystallites of plagioclase and clinopyroxene. The glass is now hydrated, altered, and partly devitrified. Most plagioclase appears fresh but nearly all clinopyroxene is altered. Calcite grains are abundant.

SUMMARY OF PETROGRAPHY Relevant about petrography is that some samples that geochemically correspond to N-type and T-type MORB—namely, IPIES and RJS-36 basalts have medium to coarse-intergranular and subophitic textures that agree with hypabyssal emplacement. That is, they are comparable to North Atlantic margin rift-zone basalts in both petrography and whole-rock compositions. Although most remaining samples have CFB-like compositions (largely, the Campos basin basalts),

textures are too glassy to be typical of continental flood basalts. In this regard, these basalts may have been emplaced subaqueously (either marine or lacustrine; e.g. Asmus & Guazelli 1981), but on continental crust and subsequent to crustal subsidence due to rifting.

The plagioclase— and pyroxene-phyric character of these Campos basalts implies crustal residence during which phenocrysts precipitated. This situation is compatible with the crustal contamination history proposed for these rocks by Fodor & Vetter (1985) on the basis of whole-rock compositions (e.g. $\text{SiO}_2 > 52$ wt.%; $\text{TiO}_2 < 1.3\%$, $\text{K}_2\text{O} > 2\%$, $\text{La}/\text{Sm}_{(n)} \sim 3$, $\text{Ti}/\text{Zr} 40-53$); that is, magma-chamber residence is an environment amenable to crustal assimilation and assimilation-induced crystallization. Also, by equating the petrography of these rocks to that observed and interpreted for abyssal tholeiites, the preponderance of phyrlic plagioclase over pyroxene and the absence of olivine would imply an advanced shallow-level crystallization history (e.g. Bryan & Dick 1982; Mg#s in these samples are < 53).

Finally the intergranular-diktytaxitic texture of Santos basalt SPS-4A is like that of actual Serra Geral CFB (e.g. Fodor *et al.* 1985) and other continental tholeiitic flows (e.g. Lipman 1969, Swanson & Wright 1981). This agrees with subaerial emplacement as indicated by an age that precedes landmass separation (138 Ma.; Table 1).

ANALYTICAL RESULTS AND DISCUSSION We determined mineral compositions using ARL-SM-EMX electron microprobes at North Carolina State University and the University of New Mexico. Operating conditions were 15 keV at 0.015-0.018 microamps samples current. We used mineral standards compositionally similar to the unknown phases and made Bence & Albee (1968) matrix corrections.

Pyroxene Samples from the Espirito Santo and Santos basins have both high-Ca (augite) and low-Ca (pigeonite) pyroxenes, whereas those of the Campos basin have only augite (Table 4; Fig. 5). Where pigeonite occurs, host rocks have $\text{Mg}\# < 47$ (where $\text{Mg}\#$ is $\text{Mg} \times 100/(\text{Fe}+\text{Mg})$). The augites of all samples have Fe-Ca-Mg contents that vary within and between grains. The wide compositional scatter of the augite (increasing Fe, decreasing Ca) in many of the samples is typical of augite in tholeiitic basalts (e.g. Carmichael 1967, Frey *et al.* 1974, Fodor *et al.* 1975, Bryan 1979, Perfit & Fornari 1983), as are the concentrations of CaO, TiO_2 , Cr_2O_3 , Al_2O_3 , and Na_2O in the Brazil margin pyroxenes reported here (Table 4).

The major pyroxene components, Fe, Ca, and Mg, therefore do not distinguish among the various geochemical types of Brazil-margin basaltic rocks. Even pyroxenes in samples enriched in incompatible elements, such as NIES basalts, offer no indications in their Fe-Ca-Mg that host-rock compositions approach alkalic basalt affinities (Fig. 2). Only magma evolution (*i.e.* increasing FeO^*/MgO) appears to influence Fe, Ca, and Mg contents in these tholeiitic pyroxenes ($\text{FeO}^* = \text{total Fe}$). For example, low Fs content in augite of IPIES basalts correlates with low whole-rock FeO^*/MgO ; the pyroxene with least Fs (9%) and most W_0 (43.8%) is in IPIES 3/4, the most primitive basalt ($\text{FeO}/\text{MgO} 0.7$; $\text{Mg}\# 71$) (Fig. 4). In contrast, the high FeO^*/MgO (~ 4) NIES samples have Fs in phenocrysts > 20 mol %. This pyroxene-rock relationship accounts not

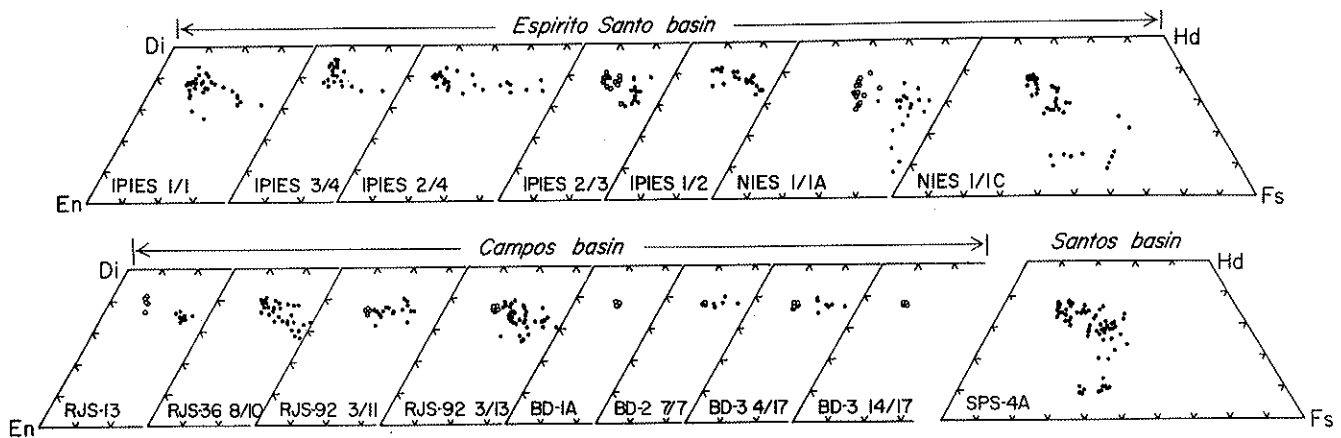


Figure 4 – Quadrilaterals illustrating Fe, Ca, and Mg contents in pyroxenes of the Brazil margin basaltic rocks in terms of molecular percent En (enstatite, $MgSiO_3$), Fs (ferrosillite, $FeSiO_3$), Di (diopside, $CaMgSi_2O_6$), and Hd (hedenbergite, $CaFeSi_2O_6$). Each data point represents one point-analysis by electron microprobe. Open circles, phenocrysts; closed circles groundmass.

Table 4 – Representative pyroxene compositions (in weight %, by electron microprobe) for phenocrysts (p) and groundmass (g) in basaltic rocks from the southeastern Brazil margin. Analyses represent averages of 3 to 7 points on individual grains.

Espírito Santo Basin													
	IPIES						NIES						
	19– 1/1	20– 3/4	22– 2/4	23– 2/3	24– 1/2		58– 1/1A	59– 1/1C					
	g	g	g	g	p	g	g	p	g	g	g	g	
SiO ₂	51.7	52.1	50.5	48.2	52.2	50.0	51.5	51.0	49.8	50.9	50.4	50.9	49.1
TiO ₂	0.54	0.38	0.70	0.90	0.66	1.4	0.59	0.94	1.0	0.65	1.0	0.77	0.74
Al ₂ O ₃	2.8	4.2	3.2	3.8	2.0	2.8	1.9	2.0	1.6	0.58	2.6	2.4	1.1
Cr ₂ O ₃	0.03	0.42	0.80	0.01	0.18	0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.04	0.02
FeO*	8.7	5.6	12.0	20.4	9.2	13.6	13.1	15.1	23.4	29.5	13.2	18.6	32.3
MnO	0.31	0.15	0.28	0.55	0.29	0.40	0.35	0.43	0.66	0.88	0.39	0.50	0.90
MgO	16.8	16.5	14.5	9.5	16.8	14.4	14.2	14.0	9.7	13.2	14.4	14.0	11.4
CaO	19.0	21.3	18.0	16.1	18.1	16.6	18.1	16.6	15.1	4.9	18.1	14.0	4.7
Na ₂ O	0.20	0.17	0.22	0.25	0.23	0.28	0.26	0.20	0.17	0.03	0.26	0.18	0.06
Total	100.08	100.82	100.20	99.71	99.66	99.49	100.00	100.27	101.43	100.64	100.35	100.39	100.32
Fs	13.8	9.0	19.7	35.2	14.8	22.5	21.2	24.6	39.0	49.7	21.3	30.2	55.1
EN	47.5	47.2	42.4	29.2	48.0	42.4	41.1	40.7	28.8	39.7	41.3	40.6	34.6
Wo	38.7	43.8	37.9	35.6	37.2	35.1	37.7	34.7	32.2	10.6	37.4	29.2	10.3

Campos Basin										Santos Basin				
	RJS-13	RJS-36	RJS-92				BD-1A	BD-2	BD-3		SPS-4A			
	9– 3/3	4– 8/10	4– 3/11	6– 3/13	5– 1/2	5– 7/7	4– 4/17	4– 14/17						
	p	g	p	g	p	g	p	g	p	g				
SiO ₂	52.1	51.1	52.9	51.8	52.0	50.8	49.3	51.9	52.6	50.7	51.9	50.4	52.2	51.7
TiO ₂	0.43	0.66	0.41	0.62	0.51	0.67	1.1	0.46	0.35	0.96	0.37	0.81	0.33	0.76
Al ₂ O ₃	2.4	2.2	2.1	2.3	2.1	2.1	2.2	1.9	2.1	3.1	2.0	2.2	2.1	2.2
Cr ₂ O ₃	0.90	0.03	0.17	0.07	0.09	0.05	0.03	0.11	0.28	0.05	0.26	0.01	0.01	0.06
FeO*	6.5	10.7	8.2	11.7	9.0	12.5	17.9	8.0	7.6	10.6	8.0	13.1	7.9	11.7
MnO	0.18	0.34	0.26	0.31	0.31	0.26	0.44	0.23	0.18	0.25	0.22	0.26	0.23	0.32
MgO	17.4	15.9	17.7	16.3	17.5	16.2	13.1	17.5	17.7	15.7	17.8	14.5	17.7	15.4
CaO	19.4	18.4	18.1	16.7	18.1	16.3	15.1	18.4	18.9	18.4	18.3	18.1	18.6	17.6
Na ₂ O	0.24	0.25	0.18	0.22	0.19	0.28	0.22	0.23	0.19	0.24	0.17	0.32	0.20	0.23
Total	99.55	99.58	100.02	100.02	99.80	99.16	99.39	98.73	99.90	100.00	99.02	99.70	99.47	99.97
Fe	10.4	17.1	13.0	18.8	14.2	20.1	29.5	12.7	12.0	17.0	12.07	21.1	12.5	19.0
EN	49.7	45.2	50.1	46.7	49.2	46.3	38.5	49.7	49.8	45.0	50.2	41.6	49.8	44.5
Wo	39.9	37.7	36.9	34.5	36.6	33.6	32.0	37.6	38.2	38.0	37.1	37.3	37.7	36.5

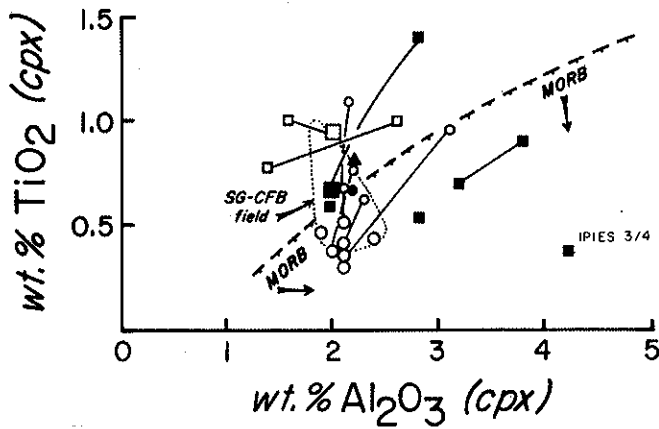


Figure 5 – Pyroxene compositions expressed in wt.% TiO₂ and Al₂O₃, where each data point represent an average of 6-8 point-analyses per grain per sample. Tie lines connect coexisting pyroxene. Symbols same as in Figure 2; larger sizes represent phenocrysts. Field below dashed boundary is where Ca-pyroxenes in N-MORB and Famous fall; (Bryan 1979, Bryan et al. 1981, Perfit & Fornari 1983). Dotted field is for Serra Geral CFB (Fodor & Corwin, 1985).

only for the trend of increasing Fe and decreasing Mg in high-Ca pyroxene, but also for the occurrence of pigeonite in the groundmasses of the more evolved rocks.

Only TiO₂ and Al₂O₃ contents in pyroxenes distinguish basalt types.

Figure 5 shows that sample IP1ES 3/4, which has N-type MORB whole-rock composition, contains pyroxene that plots apart from the main mass of samples in terms of TiO₂ and Al₂O₃; it is far into the field defined by mid-ocean ridge basalts. Most other samples fall in or near the field for pyroxene in actual Serra Geral basalts and basaltic andesites of southern Brazil. Exceptions include two IP1ES samples that are compositionally unlike CFB and closer to low-K rift-zone basalt.

Plagioclase Plagioclase K contents (Table 5) of fresh grains in the Brazil margin basalts mirror whole-rock incompatible-element abundances. Plots of anorthite (An) versus orthoclase (Or) contents for plagioclase in samples IP1ES 3/4, 2/4, and 1/2, and in RJS-36 show low Or content, close to N-MORB plagioclase compositions (Fig. 6). Three of these basalts have low whole-rock K₂O contents (0.05, 0.16, 0.50 wt.%) but one (IP1ES 2/4) has high

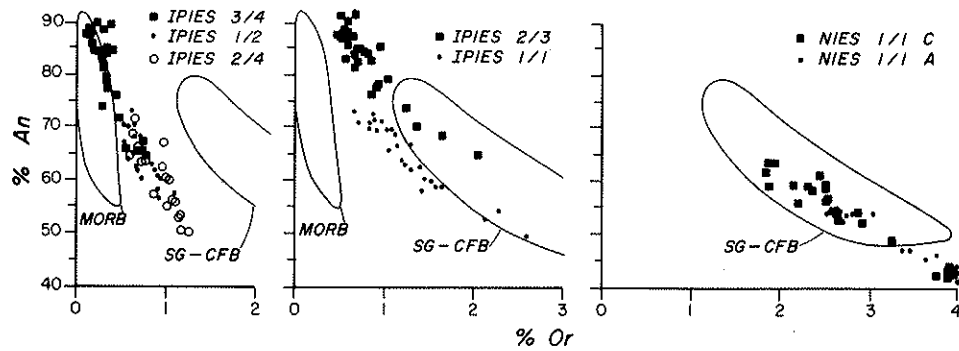
Table 5 – Representative plagioclase compositions (in weight %; by electron microprobe) for phenocrysts (p), microphenocrysts (mp), and groundmass laths (g) in basaltic rocks from the southeastern Brazil margin. Analyses represent averages of 4 to 5 points on individual grains

Espírito Santo Basin										
	IP1ES						NIES			
	19- 1/1	20- 3/4	22- 2/4	23- 2/3	24- 1/2	58- 1/1A	59- 1/1C			
	g	p	g	g	p	g	g	p	g	g
SiO ₂	53.4	48.6	51.1	53.5	48.5	55.5	52.7	55.4	60.0	52.7
Al ₂ O ₃	29.4	32.3	30.3	29.0	32.5	28.0	29.4	27.1	25.1	28.2
FeO*	1.0	0.62	0.95	1.1	0.60	1.1	1.1	0.88	0.75	0.80
CaO	13.0	17.0	14.3	12.6	16.8	11.0	12.9	11.2	8.1	11.7
Na ₂ O	3.7	2.0	3.4	4.3	2.1	4.9	4.0	4.8	6.0	4.4
K ₂ O	0.18	0.05	0.09	0.17	0.13	0.37	0.12	0.44	0.74	0.39
Total	100.68	100.57	100.14	100.67	100.63	100.87	100.22	99.82	100.69	98.19
An	65.3	82.2	69.6	61.2	81.0	54.2	63.7	54.9	40.9	58.2
Ab	33.6	17.5	29.9	37.8	18.3	43.6	35.6	42.5	54.7	29.5
Or	1.1	0.3	0.5	1.0	0.7	2.2	0.7	2.6	4.4	2.3

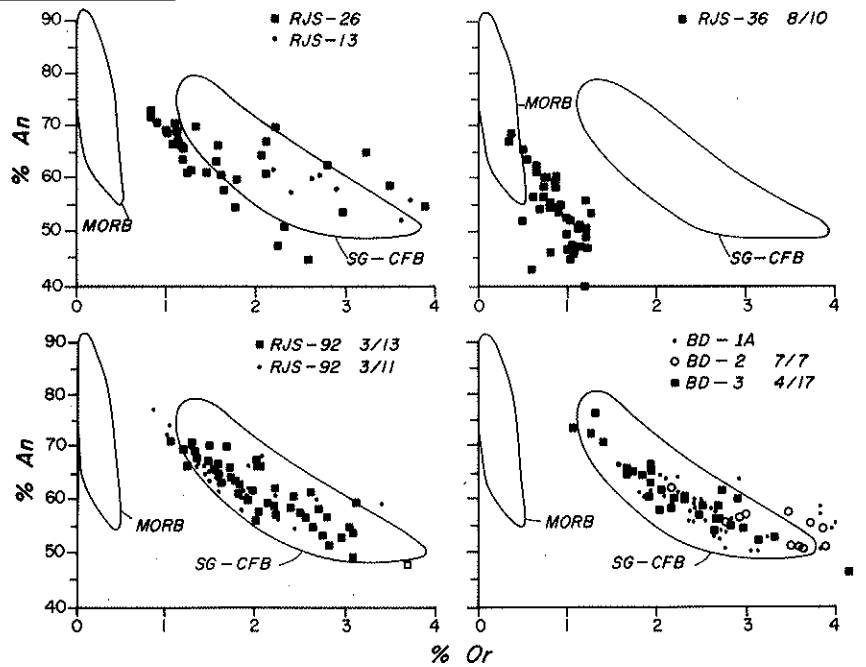
+ Some areas are altered to Ab or Or
 ++ phenocrysts altered to Ab and Q

Campos Basin											Santos Basin		
RJS-13	RJS-26	RJS-36	RJS-92				BD-1A	BD-2	BD-3		SPS-4A		
9- 3/3	4- 1/1	4- 8/10	4- 3/11	6- 3/13	5- 1/2	5- 7/7	4- 4/17	4- 14/17					
mp	g	g	p	g	p	g	p ⁺	g ⁺	g ⁺	p	g	g ⁺⁺	g
53.6	52.8	55.0	52.2	54.4	51.0	55.0	51.1	53.5	55.9	52.0	56.3	57.2	53.9
29.6	28.9	26.5	30.0	28.3	29.9	26.6	29.1	27.6	27.1	29.7	27.3	26.4	28.6
1.0	0.9	1.1	0.87	1.2	0.86	1.1	0.85	1.0	1.1	0.80	1.0	1.3	0.80
12.2	12.7	10.5	14.1	12.3	13.8	10.3	12.9	11.9	10.6	13.6	10.9	10.2	12.1
4.0	3.6	5.2	3.5	4.1	3.2	4.9	3.8	4.2	5.0	3.6	4.7	5.0	4.6
0.30	0.21	0.16	0.23	0.34	0.24	0.61	0.30	0.36	0.53	0.25	0.58	0.64	0.28
100.70	99.11	98.46	100.90	100.64	99.00	98.51	98.05	98.56	100.23	99.95	100.78	100.74	100.28
61.7	65.3	52.3	68.1	61.2	69.5	51.8	64.1	59.7	52.3	66.7	54.3	51.0	58.3
36.4	33.4	46.8	30.6	36.8	29.1	44.5	34.1	38.1	44.6	31.9	42.3	45.2	40.6
1.8	1.3	0.9	1.3	2.0	1.4	3.7	1.8	2.2	3.1	1.4	3.4	3.8	1.6

ESPIRITO SANTO BASIN



CAMPOS BASIN



SANTOS BASIN

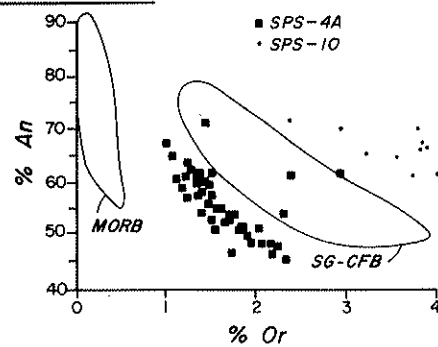


Figura 6 – Plagioclase compositions expressed in terms of molecular percent An (anorthite, $\text{CaAl}_2\text{Si}_2\text{O}_8$) and Or (orthoclase, KAlSi_3O_8). Each data point represents one point-analysis by electron microprobe. Reference fields are shown for MORB (includes N-type from Bryan et al. 1981, and Frey et al. 1974) Famous (Bryan 1979) and Serra Geral (SG-CFB, Fodor & Corwin, 1985).

K₂O, 1.06%. This can only mean that much of the K₂O in IP1ES 2/4 is secondary and that this rock originally had K₂O comparable to that of the other IP1ES basalts (≤0.25 wt%). Petrography and microprobe analyses indicate that groundmass alteration is responsible for the high K₂O contents (alteration phase contains 8-9 wt.% K₂O).

In contrast, plagioclase compositions for RJS-92, N1ES, and BD basalts are largely similar to those found in plagioclase of the Serra Geral CFB of southern Brazil (Fig. 6). This confirms the whole-rock compositions that identify these samples as CFB (Fodor & Vetter 1985) and as basalts with relatively high original incompatible-element abundances. Fresh matrix glass in these samples contains ~ 10 wt.% K₂O and further confirms their enriched character (Table 6). (Glass compositions are essentially sanidine and indicate probable incipient devitrification to alkali feldspar.)

Samples SPS-4A and IP1ES 1/1 have plagioclase transitional between that of N-MORB and CFB plagioclase. Whole-rock compositions of these samples respectively agree with low-K rift-zone basalt (transitional, T-type MORB) and moderately LREE-enriched CFB (La/Sm_(n) = 2).

Overall, there is positive correlation between Or content in plagioclase and the enrichment in incompatible-elements of host rocks. A plot of whole-rock K₂O against Or in representative grains shows this relationship (Fig. 7). However, a comparison with the Or-K₂O field for actual Serra Geral CFB indicates that some Campos basin samples probably have more K₂O than indicated by their plagioclase Or content (Fig. 7). The Or-K₂O relationship for Hawaiian tholeiitic and alkalic basalts, which forms a field similar to that of Serra Geral CFB, supports this suggestion (Fig. 7). The amount of excess K₂O over Or in the Brazil margin rocks (when compared to the field for SG-CFB in Fig. 7) provides a measure of the magnitude by which alteration, presumably by seawater, increased original K₂O. Apparently some Campos basin basalts have over 1 wt.% K₂O more than their original magmatic values. Nevertheless, Fig. 7 and Table 6 indicate that whole-rock K₂O before alteration was high. This, plus whole-rock geochemical characteristics such as immobile-element abundances (and those pointed out in the summary of petrography) led Fodor & Vetter (1985) to propose igneous histories that include crustal assimilation.

Table 6 – Representative compositions (in wt.%) of fresh glass in the matrices of Campos basin basaltic rocks

	RJS-92 6– 3/13*	RJS-13 9– 3/3†	
SiO ₂	59.0	62.8	64.4
Al ₂ O ₃	17.5	17.9	17.8
FeO	5.2	0.80	0.68
CaO	2.6	1.4	0.68
Na ₂ O	2.7	2.3	1.5
K ₂ O	9.4	11.8	14.2
Total	96.4	97.0	99.26

* average of 3 slightly broadened-beam analyses; K₂O range, 8.6-10.1%; "broad" beam apparently incorporated Fe-oxide in analyses

† each column one point-analysis

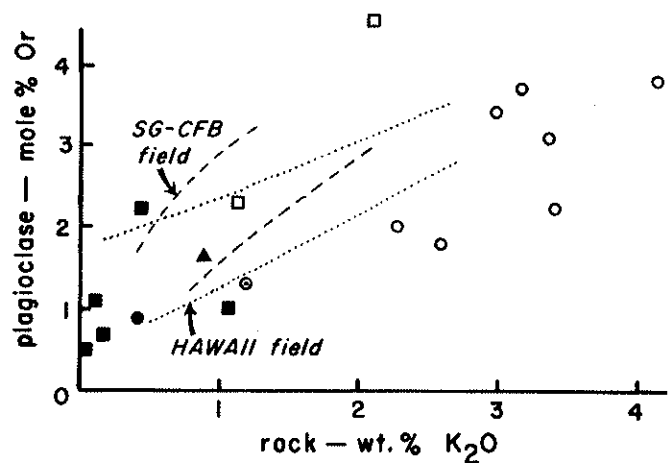


Figure 7 – Covariation between plagioclase Or and whole-rock K₂O for Brazil margin basaltic rocks. Each data point represents an average of 6-8 point analyses. Symbols as in Fig. 2; larger symbols are for phenocrysts. Tie lines connect coexisting plagioclase. Dashed reference field for groundmass plagioclase in Serra Geral CFB (Fodor & Corwin 1985) and dotted field for groundmass plagioclase of Hawaiian tholeiitic and alkalic basalts, including hawaiite and mugearite (Keil et al. 1972). K₂O data from Fodor & Vetter (1985).

If indeed Campos basin RJS-92 and BD basalts represent low-K basaltic magma to which Brazilian crust contributed K₂O content, contamination occurred prior to phenocryst crystallization because the plagioclase contains >1 mol % Or. That is, plagioclase crystallizing as phenocrysts from low-K (i.e. uncontaminated) basalt typically has Or <1% (e.g. Keil et al. 1972, Bryan 1979).

Oxides and Sulfides Titaniferous magnetite was observed in nearly every sample and ilmenite in some. Analytical summations, however, even after stoichiometrically converting FeO* to FeO and Fe₂O₃, are low (Table 7). Presumably, excess Fe³⁺ is present, plus additional elements (e.g. Si, Ca, Zn) not analyzed for. Samples with evidence of submarine alteration have oxides particularly low in analytical summations and the grains may have undergone incipient hydration. Another analytical problem encountered was severe intragrain inhomogeneity with respect to TiO₂, which ranges from 15 to 25 wt.%, probably due to both alteration and mixed lamellae of ilmenite and titaniferous magnetite. There is also intergrain heterogeneity as shown in the RJS-92 and BD-3 analyses in Table 7. (This table lists the best Fe-Ti oxide analyses acquired.)

Ti-magnetite contains Al₂O₃ in 0.5 to 2.3 wt.%, with highest values in the high-FeO N1ES rocks, but MgO is below detection in some grains. When present, MgO ranges from 0.2 to 0.5 wt.%. The MnO content varies unsystematically from 0.2 to 4.5 wt.%. Relative amounts of Fe and Ti expressed as molecular ulvospinel (usp) in the Espirito Santo basin sample is between 50 and 72 mol%, where the highly evolved N1ES basalts fall into the upper half of that mol% usp range. For comparison, we analyzed Ti-magnetite in two actual SG-CFB samples and found 55 and 66 mol% usp and MnO and Al₂O₃ contents similar to those in the

Table 7 – Representative compositions of titaniferous oxides (in weigh %; by electron microprobe) in basaltic rocks of the southeastern Brazil margin. For Espírito Santo samples, columns are averages of 5 to 6 grains; for Campos basin samples, columns are points or representative grains. Unusually low totals may reflect hydration and alteration of oxides.

	Espírito Santo Basin					Campos Basin					
	19– 1/1	IP1ES 20– 3/4	24– 1/2	N1ES 58– 1/1A 59– 1/1C		RJS-92 4– 3/11			BD-3 4– 4/17		
TiO ₂	18.5	17.8	18.5	24.2	21.8	20.0	18.3	24.0	6.2	16.1	20.6
Al ₂ O ₃	1.9	1.7	1.8	2.3	2.1	2.0	1.9	1.8	0.37	1.7	1.5
Cr ₂ O ₃	<0.01	<0.01	0.02	0.03	0.17	<0.01	0.03	0.02	0.03	0.08	0.06
V ₂ O ₃	0.23	0.37	0.50	0.48	0.75	0.42	0.52	0.47	0.58	0.54	0.20
FeO*	68.9	70.1	71.6	66.5	69.7	68.3	66.1	59.8	75.1	70.4	64.3
MnO	4.5	3.2	1.3	1.7	1.4	2.5	4.2	4.3	0.27	5.4	7.1
MgO	<0.01	<0.01	0.21	0.15	0.31	0.50	0.34	0.18	0.13	0.02	0.01
Sum	9.403	93.17	97.93	95.36	96.23	93.72	91.39	90.57	82.68	94.24	93.76
Usp	52.2	51.3	54.7	72.2	63.9	58.3	53.0	73.7	20.0	43.2	57.0
FeO ⁺	41.0	42.1	44.7	49.6	47.8	44.2	40.5	45.4	32.1	38.9	41.1
Fe ₂ O ₃ ⁺	29.2	30.2	29.1	17.8	23.3	25.9	27.6	15.2	47.5	34.2	25.1
Total	96.23	95.31	96.09	96.21	97.61	95.51	93.35	91.34	87.17	96.92	95.68

* all Fe as FeO

+ calculated stoichiometrically

Table 8 – Representative compositions (in wt.%) of pyrite, pyrrhotite, and chalcopyrite grains in Brazil margin basaltic rocks

	Espírito Santo basin			Campos basin					
	IP1ES 19– 1/1	N1ES 59– 1/1C		RJS-36 4– 8/10	RJS-91 4– 2/2	RJS-92 6– 3/13	BD-2 5– 7/7	BD-3 4– 4/17	
Cu	33.8	0.09	33.4	34.3	<0.01	<0.01	<0.01	<0.01	0.05
Ni	0.13	0.34	0.15	0.12	0.06	<0.01	<0.01	<0.01	0.02
Fe	30.1	60.5	30.1	29.6	46.8	46.6	46.9	46.7	46.7
S	34.5	38.4	34.6	34.8	53.2	53.7	53.1	53.3	54.5
Total	98.53	99.33	98.25	98.82	100.06	100.3	100.0	100.0	101.27
S:Fe	2.0	1.11	2.0	2.05	1.98	2.01	1.97	1.99	2.03

magnetite of the Brazil margin basalts. Also, magnetite in N-MORB generally has 60-70 mol% usp (e.g. Mazullo & Bence 1976, Fodor *et al.* 1977, Perfit & Fornari 1983). The opaque oxides therefore offer little to characterize the Brazil-margin basaltic rocks.

Sulfide minerals are present in many samples as grains that are generally a few microns in size. Pyrite is the most abundant sulfide, although pyrrhotite and chalcopyrite also occur (Table 8). Both pyrrhotite and chalcopyrite contain trace amounts of Ni.

CONCLUSIONS 1) Brazil margin rocks that geochemically correspond to Atlantic margin rift-zone basalt and to continental flood basalts have textures appropriate for either hypabyssal, subaerial, or subaqueous emplacement during the rifting of the South American and African landmasses.

2) Aspects of phase compositions useful in discerning various geochemical basalt types of the Brazil margin (*i.e.* South Atlantic margin rift-zone) are TiO₂-Al₂O₃ in augite and K₂O in plagioclase. In each case, basalt depleted in

incompatible elements and compositionally similar or close to N-MORB basalt compositions can be separated from continental flood basalt.

3) Fs, Wo, and En contents in pyroxenes only measure basalt evolution and do not distinguish the geochemical types of Brazil margin rocks.

4) Mineral compositions give no clues to crustal contamination of basalts, however, if contamination occurred, it was before plagioclase crystallization.

5) On the other hand, whole-rock alteration can be evaluated. Knowing the Or-K₂O relationship for mafic samples of the Serra Geral CFB province enables estimating effects that seawater had on K₂O in the CFB-like Brazil-margin basalts.

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MANUSCRITO

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Enriquecemo-nos pela utilização pródiga de nossos recursos naturais e podemos, com razão, orgulhar-nos do nosso progresso. Chegou porém o momento de refletirmos seriamente sobre o que acontecerá quando as nossas florestas tiverem desaparecido, quando o carvão, o ferro e o petróleo se esgotarem, quando o solo estiver mais empobrecido ainda, levado para os rios, poluindo as suas águas, desnudando os campos e dificultando a navegação.

Theodore Roosevelt, 1908, Conferência sobre a Conservação dos Recursos Naturais