

# Isotopic and trace-element indications of lithospheric and asthenospheric components in Tertiary alkalic basalts, northeastern Brazil

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## Abstract

Plate reconstructions at 30 Ma place northeastern Brazil over the Fernando de Noronha hotspot, presently ~ 250 km offshore northeastern Brazil. Tertiary basaltic centers in northeastern Brazil may therefore be products of the Fernando de Noronha hotspot. We examined alkalic basalt from seven ~ 30–13 Ma old centers in Rio Grande do Norte and Pernambuco states to assess this possible link. Compositions are primitive, where MgO concentrations range from 12.5 to 17 wt.%, and SiO<sub>2</sub> from ~ 41 to 48 wt.%. Trace-element abundances and Sr, Nd, and Pb isotopic compositions compare well with those of ocean island basalt: <sup>87</sup>Sr/<sup>86</sup>Sr = ~ 0.7038–0.7051, <sup>143</sup>Nd/<sup>144</sup>Nd = ~ 0.51266–0.51280, and <sup>206</sup>Pb/<sup>204</sup>Pb = ~ 18.52–19.35. There are correlations among SiO<sub>2</sub>-undersaturation, incompatible-element abundances, relative percentages of partial melting (based on La/Yb and La/Y ratios), and the degree of isotopic ‘enrichment’ inherited from mantle sources. There is also a negative correlation for La/Nb (~ 0.6–0.86) vs. Ba/Nb (6.6–10.6), where lower La/Nb samples represent larger percentages of melting of a source comparatively enriched in radiogenic Sr. We attribute these compositional relationships to the lavas representing mixing of melts mainly from asthenosphere of largely HIMU plus DM characterization, probably the Fernando de Noronha plume, with melts from subcontinental lithosphere that was isotopically closer to EM1. Isotopic and trace-element compositions of the northeastern Brazil basalts are generally similar to those of Fernando de Noronha lavas (12–2 Ma), and some minor trace-element differences observed (e.g., more Zr, Nb, and less Th compared to northeastern Brazil basalts) are probably due to heterogeneity within the asthenospheric plume and to melt contributions from delaminated subcontinental lithosphere that may underlie Fernando de Noronha. © 1998 Elsevier Science B.V. All rights reserved.

**Keywords:** Basalt; Brazil; Trace-elements; Isotopes; Mineral compositions

## 1. Introduction

Plate reconstructions for the South Atlantic (Morgan, 1983; O’Connor and Duncan, 1990) place

northeastern Brazil over or near the oceanic Fernando de Noronha hotspot about 30 Ma ago. The ~ 30–13 Ma old alkalic-basalt centers in the northeastern corner of Brazil at ~ 5°30’S and 35°W may therefore have overlain or been in the proximity of the Fernando de Noronha hotspot, presently ~ 250

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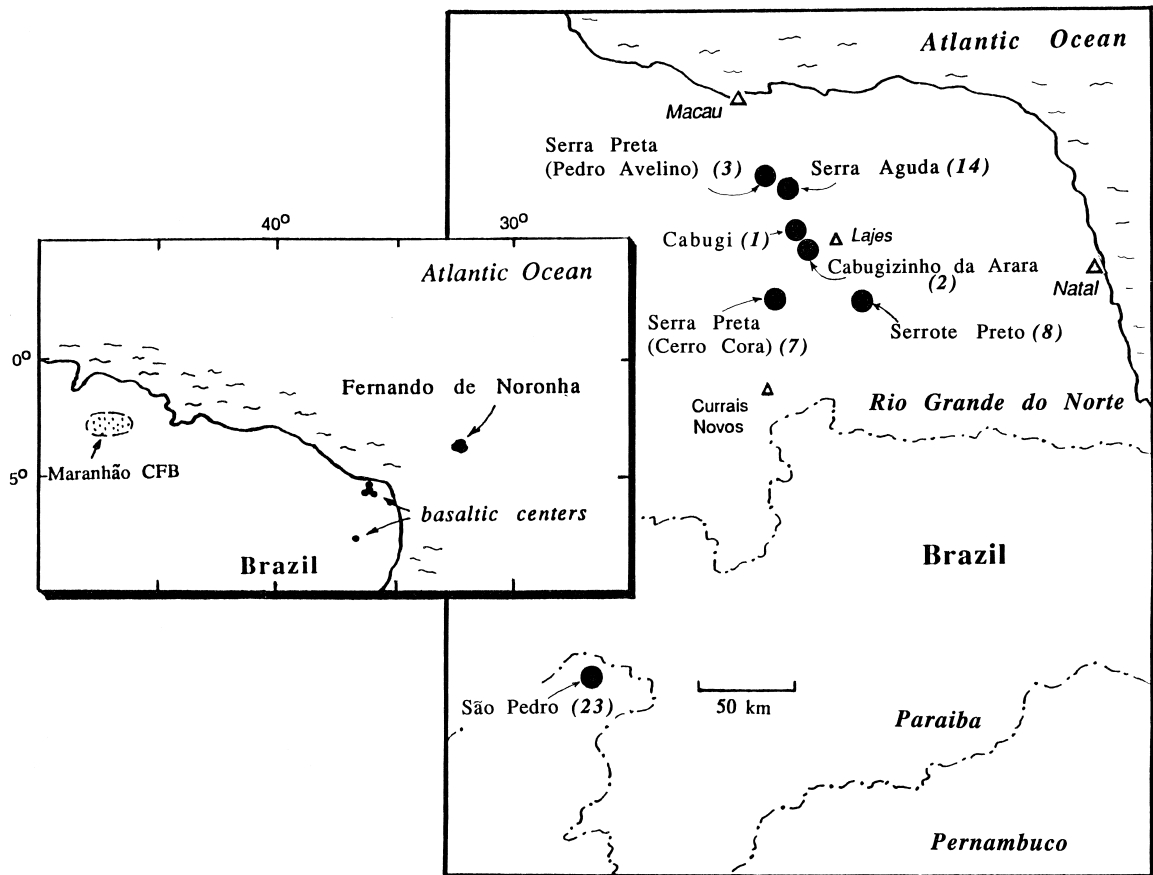


Fig. 1. Locations and names of seven Tertiary alkalic basalt centers in northeastern Brazil, relative to the Fernando de Noronha alkalic basalt province (Gerlach et al., 1987) and the Mesozoic Maranhão low-TiO<sub>2</sub> continental flood basalt province (Fodor et al., 1990). Numbers in parentheses are the sample site numbers used in text and in Table 1.

km offshore at 4°S (Fig. 1). The juxtaposition of the northeastern Brazil and the Fernando de Noronha alkalic-basalt provinces and the inference from plate reconstruction that the two provinces originated over a common mantle regime afford an opportunity to evaluate crustal, subcontinental lithospheric, and asthenospheric contributions to magmas emplaced in northeastern Brazil from ~ 30 to 15 Ma ago.

Our assessment of the continental alkalic-basalt centers utilizes new petrographic, mineralogic, trace-element, and isotopic data for northeastern Brazil lavas and existing compositional data for Fernando de Noronha (Gerlach et al., 1987; Weaver, 1990) lavas cropping out in an oceanic setting. We also use comparative data (Fodor et al., 1990) for

Mesozoic continental flood basalts (CFB) of northern Brazil (Maranhão province) because, like the Parana CFB in southern Brazil (e.g., Hergt et al., 1991; Turner and Hawkesworth, 1995; Turner et al., 1996), they represent to some extent subcontinental lithosphere (Fodor et al., 1990) and therefore specify precedence for northern Brazil lithospheric mantle having contributed to basaltic magmatism.

## 2. Background information

We studied seven alkalic centers—six in Rio Grande do Norte state and one in Pernambuco state. Fig. 1 shows the locations and names of these basaltic

centers, and the numbers (1, 2, 3, 7, 8, 14, and 23) we assigned to these centers. The Rio Grande do Norte basaltic centers were originally described in the work of Sial (1977) and Sial et al. (1981). Their field exposures are limited to essentially circular outcroppings < 1-km diameter around topographic highs (e.g., small plugs and necks; Sial, 1977; Sial et al., 1981). The K–Ar ages of two, Serra Preta at Cerro Cora (center 7) and Serrote Preto (8), are 30.4 and 29.3 Ma, respectively (Sial et al., 1981), and therefore coincide with origins near the present latitude and longitude of Fernando de Noronha when lithospheric plates are reconstructed for Tertiary time. A third center, Serra Preta at Pedro Avelino (3), is 13.0 Ma (Sial et al., 1981), corresponding to the time when northeastern Brazil was about halfway between its present location and Fernando de Noronha. Ages for the other three Rio Grande do Norte basaltic centers—Cabugi (1), Cabugzinho da Arara (2), and Serra Aguda (14)—are unknown but we infer from their geographic and geologic associations (and petrographic similarities) that they, too, erupted between ~ 30 and 13 Ma ago. Supporting this inference that all northeastern Brazil alkalic magmatism occurred within ~ 15-Ma time frame is the newly acquired K–Ar age of  $20.0 \pm 0.6$  Ma (E.H. McKee, US Geological Survey) for the previously unstudied basaltic center, São Pedro (23), in Pernambuco state (Fig. 1).

The continental crust underlying the basaltic centers is diversified with surface rocks comprising Precambrian mica schists, gneisses, amphibolites, and migmatites, and early Paleozoic granitoids. These rock types are overlain by Mesozoic sandstones, shales, and conglomerates that accumulated in tectonic basins (e.g., Mabeoone et al., 1981; Petri and Campanha, 1981; Caby et al., 1991). Gravity and isostasy studies show that the Rio Grande do Norte crust is ~ 30-km thick (Castro et al., 1997a,b).

The Fernando de Noronha compositional data we use for comparison are for nephelinites and basanites of the Quixaba formation, 2–6 Ma, and for basanites and alkalic basalts of the Remedios formation, 8–12 Ma (Gerlach et al., 1987; Weaver, 1990). Accordingly, the oldest Fernando de Noronha lavas are penecontemporaneous with the youngest known northeastern Brazil basaltic center, Serra Preta at Pedro Avelino (center 3; Fig. 1). Published isotopic

data for Fernando de Noronha (Gerlach et al., 1987) represent all rock types and the full range of ages, but the trace element data available represent only youngest lavas, the Quixaba formation (Weaver, 1990).

Compositions selected to represent other northern Brazil magmatism for comparative purposes are for the ~ 190 Ma low-TiO<sub>2</sub> Maranhao basin continental flood basalts (Fodor et al., 1990). This province is ~ 1000 km west of Rio Grande do Norte state (Fig. 1).

### 3. Analytical techniques

We acquired mineral compositions by ARL-SEM-Q electron microprobe, and analyzed whole rock samples for major- and trace-elements (Sr, Ba, Zr, Nb, Y, Ni) by X-ray fluorescence spectrometry; both laboratories are at North Carolina State University. We determined rare-earth element and Th, Hf, and Sc abundances by neutron activation at the Oregon State University radiation center, and obtained radiogenic isotopic compositions by using VG Sector multicollector thermal ionization mass spectrometers at the University of Michigan and the University of North Carolina; analytical procedures are in the work of Mukasa et al. (1994), and data for standards are given in Table 4. Our oxygen isotope data are from the University of Georgia stable isotope laboratory.

### 4. Petrography

Lavas at each center have abundant (~ 7 to 18 vol.%) olivine phenocrysts and microphenocrysts (0.5–5 mm), and at most centers also contain subhedral clinopyroxene grains (0.5–2 mm). Some clinopyroxenes are strongly zoned and have sieved-cores (e.g., spongy-textures) (Fodor et al., 1995). Some lavas also have subhedral plagioclase microphenocrysts (0.5–1 mm) with sieved-cores. The groundmasses of lavas from basaltic centers 1, 7, 8, and 14 are assemblages of plagioclase laths and olivine, clinopyroxene, and Fe–Ti oxide grains with interstitial glass or feldspar. Groundmasses of lavas from centers 2, 3, and 23 have microlites of olivine and clinopyroxene and Fe–Ti oxide grains within

Table 1  
Whole-rock compositions of Tertiary alkalic basalts, Rio Grande do Norte and Pernambuco, Brazil (in order of decreasing MgO)

	Serra Preta at Pedro Avelino 3		Cabugi 1		Serra Aguda 14		Cabugizi nho da Arara 2		Serra Preta at Cerro Cora 7		Sao Paulo 23		Serrote Preto 8	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
	SiO <sub>2</sub>	41.52	41.07	45.35	43.39	45.65	44.97	45.85	45.98	45.52	45.09	45.19	44.89	48.44
TiO <sub>2</sub>	2.67	2.64	2.13	2.18	2.57	2.49	2.79	2.86	2.40	2.33	2.23	2.20	1.86	1.75
Al <sub>2</sub> O <sub>3</sub>	10.15	11.27	11.68	11.45	12.35	11.77	11.36	11.81	12.37	11.86	12.52	12.37	13.14	12.78
FeO	10.70	10.98	10.66	11.44	11.06	11.39	11.08	11.62	11.37	11.05	10.76	10.60	9.73	9.69
MnO	0.20	0.20	0.18	0.21	0.19	0.19	0.17	0.17	0.19	0.18	0.18	0.18	0.17	0.17
MgO	17.11	16.91	15.32	15.48	13.20	14.40	12.64	12.27	13.05	12.88	12.44	12.57	12.70	13.05
CaO	12.60	12.15	9.07	9.95	10.12	9.36	9.86	10.19	9.94	9.91	10.14	10.22	8.85	9.21
Na <sub>2</sub> O	2.88	2.99	3.25	3.26	2.90	2.92	4.03	3.90	3.06	2.95	4.06	4.41	2.74	2.75
(Na <sub>2</sub> O)	2.85		2.87		2.70		3.66		2.84		3.92		2.81	
K <sub>2</sub> O	0.63	0.81	1.52	1.71	1.63	1.62	0.87	0.85	1.72	1.83	1.65	1.58	1.59	1.56
P <sub>2</sub> O <sub>5</sub>	1.47	1.42	0.73	1.07	0.71	0.67	0.83	0.87	0.75	0.73	0.78	0.78	0.46	0.41
Total	99.93	100.44	99.89	100.14	100.38	99.78	99.48	100.52	100.37	98.81	99.95	99.80	99.68	99.13
Mg#	78.1	77.4	76.2	75.1	72.7	73.8	71.8	70.2	71.9	72.2	72.0	72.5	74.4	75.0
LOI	2.40	2.64	0.55	1.46	1.19	0.96	1.03	1.39	0.84	1.05	1.34	1.56	1.22	0.61
Rb	17	22	31	43	43	38	18	19	44	47	49	45	45	42
Sr	1330	1485	970	1250	825	780	790	830	850	790	875	845	690	540
Ba	839	900	615	733	586	594	536	565	589	579	733	690	470	476
Zr	291	303	176	217	202	207	242	251	214	228	174	171	158	150
Hf	6.62		4.13	4.61	5.10		5.54		5.20		4.00		3.60	
Nb	127	124	67	84	61	63	75	73	71	72	69	67	53	48
Th	13.7		6.4	7.9	6.2		7.0		7.0		5.9		5.1	
Y	30	31	30	32	31	30	25	25	30	30	26	25	28	27

Ni	425	458	507	501	354	413	439	418	323	334	305	282	308	375
Sc	20.7		21.3	21.7	22.1		19.2		21.8		17.5		20.0	
La	106.0	95.0	52.9	65.0	44.7	46.0	55.1	63.0	48.6	51.0	41.5	43.0	33.4	29.0
Ce	202.0		100.0	115.0	89.5		107.0		95.3		77.1		66.6	
Nd	83.70		42.90	52.40	41.80		49.20		43.70		34.80		31.70	
Sm	13.10		9.06		8.89		8.73		9.14		7.31		6.18	
Eu	3.88		2.84	3.44	2.73		2.76		2.74		2.37		1.92	
Tb	1.37		1.12	1.32	1.10		0.97		1.08		0.86		0.80	
Yb	2.42		2.00	3.10	2.14		1.65		2.21		1.56		1.77	
Lu	0.35		0.30		0.28		0.24		0.25		0.19		0.24	
Zr/Nb	2.3	2.4	2.6	2.6	3.3	3.3	3.2	3.4	3.0	3.2	2.5	2.6	3.0	3.12
La/Nb	0.83	0.77	0.79	0.77	0.73	0.73	0.73	0.86	0.68	0.71	0.60	0.64	0.63	0.60
Zr/Y	9.7	9.8	5.9	6.8	6.5	6.9	9.7	10.0	7.1	7.6	6.7	6.8	5.6	5.6
La/Yb	43.8		26.5		20.9		33.4		22.0		26.6		18.9	
Ba/Nb	6.6	7.3	9.2	8.7	9.6	9.4	7.1	7.7	8.3	8.0	10.6	10.3	8.9	9.9
K–Ar age	13.0 ± 1								30.4 ± 1		20.0 ± 0.6		29.3 ± 2	
Modes (vol.%; based on 1500–2000 counts)														
Olivine	18.1		12.6		11.9		10.1		7.1		10.7		8.9	
cpx			0.5		2.2		0.2		6.0		0.2		0.2	
Plagioclase			0.1		0.3		<sup>b</sup>		0.3				0.2	
Groundmass	81.9		86.8		85.6		89.7 <sup>a</sup>		86.6		89.1 <sup>a</sup>		90.7	

<sup>a</sup>Contains nepheline.

<sup>b</sup>Trace of plagioclase xenocrysts.

1, 7, 8, 14, and 23 contain quartz xenocrysts.

Sample numbers correspond to localities illustrated in Fig. 1; 'a' and 'b' refer to two lavas analyzed from each center.

Major-element abundances are volatile-free, determined after igniting samples to 1000°C.

Na<sub>2</sub>O by xrf; (Na<sub>2</sub>O) by neutron activation.

Mg# = 100 × atomic Mg / (Mg + Fe<sup>2+</sup>), where Fe<sup>2+</sup> / (Fe<sup>2+</sup> + Fe<sup>3+</sup>) = 0.80.

L.O.I. = loss on ignition; by weight difference on 1-g powder after 1000°C ignition, but not accounting for weight gain due to Fe oxidation during ignition.

Reproducibility as percentages of amounts present: SiO<sub>2</sub> 0.75%; TiO<sub>2</sub> 1%; Al<sub>2</sub>O<sub>3</sub> 1.2%; FeO 1.2%; MgO 1.7%; CaO 0.57%; Na<sub>2</sub>O 2.5%; K<sub>2</sub>O 3%; P<sub>2</sub>O<sub>5</sub> 4%; Sr 1.6%; Zr 2.5%; Y 5%; Nb 9%; Ni 2.5%.

dark, cryptocrystalline matrices. Lavas of localities 2 and 23 contain groundmass nepheline.

All basaltic centers contain peridotite xenoliths, and some contain pyroxene megacrysts (Sial, 1977; Fodor et al., 1991). The peridotite xenoliths are generally 1–4-cm long but occur up to  $\sim 10$  cm, and the pyroxene megacrysts observed at three centers are up to several centimeters in size and with reaction rims. Five centers (1, 7, 8, 14, 23) have rare quartz xenocrysts  $\leq 2$  cm across, also with reaction rims, and one center (2) has lava with plagioclase xenocrysts ( $\leq 0.5$  mm; identified as xenocrysts by microprobe analyses) with resorbed margins.

Modal percentages of olivine and clinopyroxene in the lavas at each center vary between different samplings, and Table 1 provides representative values for each. Whereas the modes do not include xenolithic fragments, they may include any olivine crystals that disaggregated from peridotite xenoliths because olivine xenocrysts cannot unequivocally be optically discerned from olivine phenocrysts and omitted from modal analyses.

Plagioclase and clinopyroxene grains are fresh, but olivines show varying stages of alteration. Some lavas have olivine with substantial iddingsite component, such as those from center 2, whereas others have olivine with varying amounts of layer-lattice silicate (serpentine?) veins, such as lavas from centers 8 and 23; olivine in lavas from 1, 3, 7, and 14 have incipient formation of secondary-mineral veins. In general, loss-on-ignition values, which range from  $\sim 0.55$  to 2.6 wt.% (Table 1) reflect the extent of olivine alteration; a notable exception is that basalt

center 3 lavas have only mildly altered olivine but yield the highest volatile contents.

## 5. Analytical results

### 5.1. Mineral compositions

Olivine phenocrysts have forsterite (Fo) values between 80 and 88 mol.% (Table 2). We distinguished *phenocrystic* from *xenocrystic* olivine on the basis of olivine grains derived from peridotite xenoliths typically having  $> \text{Fo}_{88}$  (Table 2 and unpublished data). Information on representative zoned-clinopyroxene compositions may be found in the work of Fodor et al. (1995), where it is shown that clinopyroxenes are largely diopside with  $\text{Al}_2\text{O}_3$  contents ranging from 3 to 7 wt.% and Mg#s from 86 to 73.

The sieved-core, or spongy, plagioclase microphenocrysts that occur in some lavas have a compositional range of  $\text{An}_{48-61}$  (Table 3). The grains display small compositional variations as rims that are  $\sim 5-7$  mol.% An more calcic than spongy interiors. These rim compositions correspond closely to those of the groundmass plagioclase laths, which have average compositions of  $\text{An}_{58-62}$  (Table 3). In contrast, the plagioclase microphenocrysts in a center 2 lava are xenocrysts judging by their distinctive compositions—one grain is  $\text{An}_{85}$  and another is  $\text{An}_{39}$  (Table 3)—and by their resorbed margins and solid crystal forms (rather than sieved). Table 3 includes the compositions of groundmass nepheline in lavas from centers 2 and 23.

Table 2

Representative compositions<sup>a</sup> for olivine as phenocrysts (ph), rims on phenocrysts (r), groundmass (gnd), and as xenocrysts (xeno) (from peridotite) in lavas from seven Tertiary alkalic basalt centers in northeastern Brazil

	1			2		3		7			8		14	23
	ph	gnd	xeno	ph	ph	ph	r	gnd	ph	gnd	ph	ph		
SiO <sub>2</sub>	37.8	37.3	39.8	39.3	38.9	40.2	38.2	38.1	38.7	38.0	39.6	39.0		
FeO	19.5	21.8	9.3	12.2	13.1	12.0	22.0	23.7	18.7	22.2	12.3	17.1		
MnO	0.37	0.46	0.12	0.20	0.21	0.15	0.35	0.41	0.34	0.46	0.13	0.33		
MgO	41.3	38.8	50.2	46.9	46.3	47.4	39.7	37.6	42.1	39.1	47.8	42.0		
CaO	0.11	0.38	0.02	0.05	0.21	0.05	0.30	0.45	0.11	0.36	0.16	0.37		
NiO	0.27	0.22	0.42	0.33	0.29	0.36	0.34	0.36	0.30	0.26	0.42	0.20		
Total	99.35	98.96	99.86	98.98	99.01	100.16	100.87	100.62	100.25	100.38	100.41	99.00		
Fo	79.0	76.0	90.6	87.3	86.3	87.5	76.3	73.9	80.1	75.8	87.4	81.4		

<sup>a</sup>In wt.%, by microprobe, and in order by sample number; each column is the average of 10–15 point analyses.

Table 3

Representative plagioclase and nepheline compositions for microphenocryst (mph), groundmass lath (gnd), and xenocrystic (xeno) occurrences in six Tertiary alkalic basalt lavas in northeastern Brazil

	1		2			7		8		14		23
	mph <sup>b</sup>	gnd	gnd	xeno	xeno	mph	gnd	mph	gnd	mph	gnd	gnd neph
SiO <sub>2</sub>	54.9	52.6	48.4	58.4	46.0	52.3	53.0	53.3	52.4	53.5	52.8	52.7
Al <sub>2</sub> O <sub>3</sub>	28.5	29.2	32.8	27.0	35.7	30.7	30.0	29.7	30.2	30.3	29.6	28.2
FeO	0.42	0.78	0.54	0.22	0.15	0.89	0.77	0.75	0.90	0.54	0.67	0.93
CaO	9.0	11.7	0.84	7.5	16.9	12.4	12.0	11.6	11.8	11.7	12.9	0.69
Na <sub>2</sub> O	5.1	4.4	15.1	6.1	1.6	4.1	4.2	4.4	4.1	4.3	4.2	14.2
K <sub>2</sub> O	0.62	0.41	3.2	0.78	0.06	0.34	0.37	0.53	0.48	0.38	0.32	1.8
Total	98.54	99.09	100.88	100.00	100.41	100.73	100.34	100.28	99.48	100.72	100.49	98.52
An	47.5	58.1		38.6	85.1	61.4	59.9	57.5	59.7	58.7	61.8	
Or	3.9	2.4		4.8	0.36	2.0	2.2	3.1	2.9	2.3	1.8	

<sup>a</sup>In wt.%, by microprobe and in order by sample number.

<sup>b</sup>Analyses of mph, or microphenocrysts, are for the 'sieved-cores' of plagioclase grains. Each column is the average of 10–15 point analyses.

## 5.2. Basalt compositions

We analyzed two samples of lava from each center to serve as representatives of the magmas erupted at the seven sites (Table 1). Fig. 2a shows the compositional variations of the basaltic centers with respect to alkalic and SiO<sub>2</sub>-undersaturation characteristics. Collectively, northeastern Brazil lavas are MgO-rich, having ~12.5 to 17 wt.% (Fig. 3). They accordingly contrast with the low-MgO, SiO<sub>2</sub>-saturated compositions of the low-TiO<sub>2</sub> Mesozoic continental flood basalts of Maranhão province in northern Brazil (Fig. 1).

Whereas MgO contents in the northeastern Brazil alkalic basalts are high, we cannot state that they precisely represent *original* magma values. The reason is that while peridotite xenoliths were avoided during sample preparation, small fragments of xenoliths and olivine grains broken therefrom may have been (unavoidably) included in the rock chips powdered for analyses, thereby contributing slightly to whole-rock MgO contents. Also, the somewhat compositionally evolved olivine phenocrysts (i.e., Fo<sub>86–80</sub>; Table 2) in most of these lavas and the complexly-zoned clinopyroxenes (Fodor et al., 1995) in some identify these lavas with magmas that experienced at least some compositional differentiation before erupting.

Basalt center 3, with lowest SiO<sub>2</sub> (~41 wt.%) and highest MgO (~17 wt.%), has lavas with the highest amounts of Zr, Nb, La, and P, matching or exceeding those in Fernando de Noronha lavas (e.g., P<sub>2</sub>O<sub>5</sub> ~1.5 wt.%; Fig. 3). Lavas from five other centers—1, 2, 7, 14, and 23—have similar overall major-element compositions (Table 1), which include SiO<sub>2</sub> contents of ~45 wt.% (Fig. 3). Lavas from center 8 have higher (48 wt.%) SiO<sub>2</sub> and the lowest incompatible-element abundances (e.g., P<sub>2</sub>O<sub>5</sub> ~0.46 wt.%). Compositions of the two lavas analyzed from some centers are essentially identical, but those from center 1 (Cabugi) differ in incompatible-element abundances, and those from center 14 differ in MgO contents (Table 1; Fig. 3).

Na<sub>2</sub>O among all lavas ranges at ~3–4 wt.% (Table 1) and is highest at centers 2 and 3, where it is reflected by groundmass nepheline. Five centers have comparable K<sub>2</sub>O, 1.5–1.8 wt.%, and those from centers 2 and 3 are notably low, ~0.6–0.8 wt.% (Fig. 3). The same comparison holds for Rb, where five centers have 30–50 ppm, and lavas from centers 2 and 3 have the lowest Rb, ~20 ppm (Table 1). These low K<sub>2</sub>O and Rb abundances, particularly in center 3 lavas, can be interpreted as reflecting weathering/alteration processes. On the other hand, when K and Rb are plotted in abundance ratios with Nb and Sr, there is a correlation among

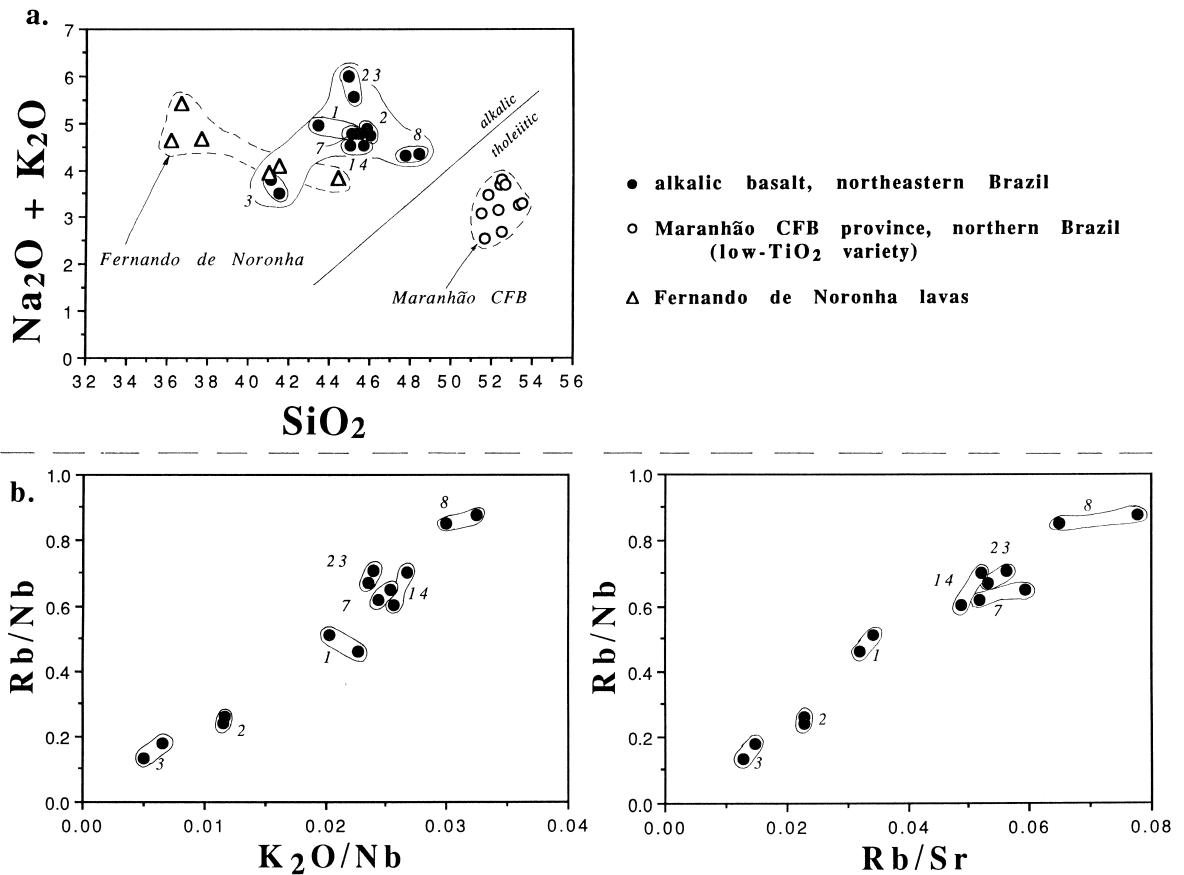


Fig. 2. (a)  $\text{SiO}_2$  vs. total alkalis diagram for alkalic basalts of northeastern Brazil compared to Fernando de Noronha alkalic basalts (Weaver, 1990) and Mesozoic Maranhão low- $\text{TiO}_2$  continental flood basalts of northern Brazil (Fodor et al., 1990) (Fig. 1). The tholeiitic–alkalic reference line is based from the work of Macdonald and Katsura (1964). (b) Variations in ratios among Rb, Nb, Sr, and  $\text{K}_2\text{O}$ ; data points are numbered according to sample sites (Fig. 1). Linear correlations among the northeastern Brazil basalts, collectively, demonstrate that alteration-sensitive elements Rb and K likely remain in their original values and have not been noticeably increased or reduced by alteration or weathering.

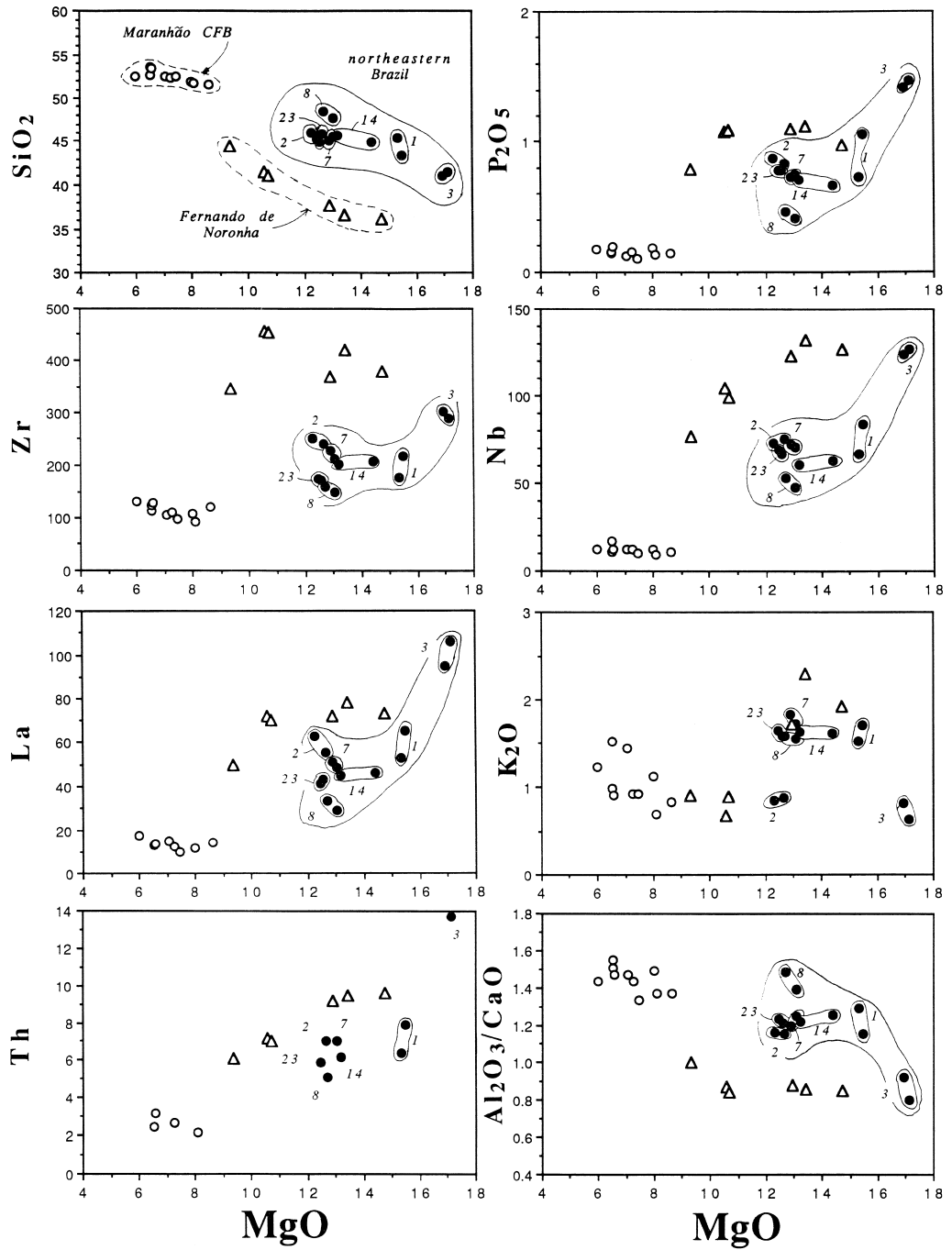
all samples analyzed to suggest that original K and Rb abundances of the lavas were not altered (Fig. 2b).

Fig. 4 shows compositions normalized to that of ‘average’ ocean-island basalt (OIB). It shows that lavas from centers 1, 7, 14, and 23 have essentially identical trace-element patterns and close compositional correlations with OIB (Fig. 4a,b). Center 8 and

center 2 lavas have overall patterns similar to those of 1, 7, 14, and 23 except for K and Rb, which are, respectively, enriched in 8 and depleted in 2 (Fig. 4a–c). Center 3 lava, the most incompatible-element enriched, has pronounced K and Rb depletions (Fig. 4c). Overall, Fernando de Noronha lavas have patterns similar to those of the northeastern Brazil basalts, including some K and Rb depletions in

Fig. 3.  $\text{MgO}$  variation diagrams for alkalic basalts of northeastern Brazil compared to Fernando de Noronha alkalic basalts (Weaver, 1990) and Mesozoic Maranhão low- $\text{TiO}_2$  continental flood basalts of northern Brazil (Fodor et al., 1990) (Fig. 1). Data points are numbered according to sample centers (Fig. 1).





- alkalic basalt, northeastern Brazil
- Maranhão CFB province, northern Brazil (low-TiO<sub>2</sub> variety)
- △ Fernando de Noronha lavas

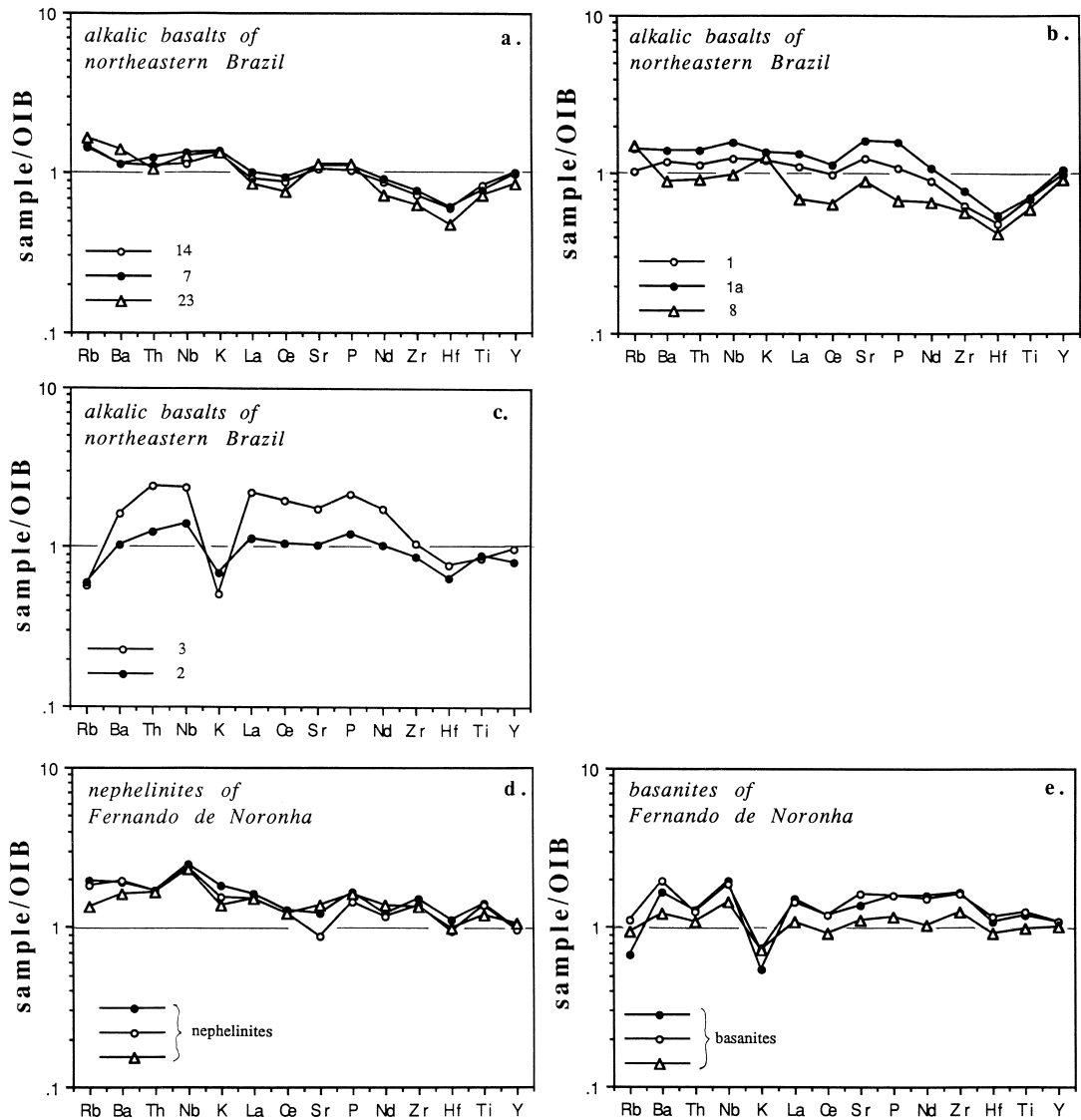


Fig. 4. Ocean-island basalt normalization diagrams for trace-element abundances in the alkalic basalts of northeastern Brazil (panels a, b, c) compared to Fernando de Noronha nephelinites and basanites (d, e) (Weaver, 1990). Normalization values from Fitton et al. (1991). The horizontal lines at '1' are for visual reference; two sample compositions (1 and 1a) are shown for basaltic center 1.

basanites (Fig. 4e), but they additionally have slightly positive Nb and Zr anomalies and slightly negative Th anomalies (Fig. 4d,e).

Rare-earth element (REE) patterns for all lavas except sample 3 are similar to one another and show slightly lower REE abundances than representatives of Fernando de Noronha (Fig. 5). Lava 3 has higher

REE abundances and is comparable in that regard to Fernando de Noronha lavas.

Sr and Nd isotopic compositions (Table 4) for the northeastern Brazil lavas plot in a field that extends from the isotopically 'depleted' side to the isotopically 'enriched' side of present-day bulk earth composition (Fig. 6a). There is a correlation between

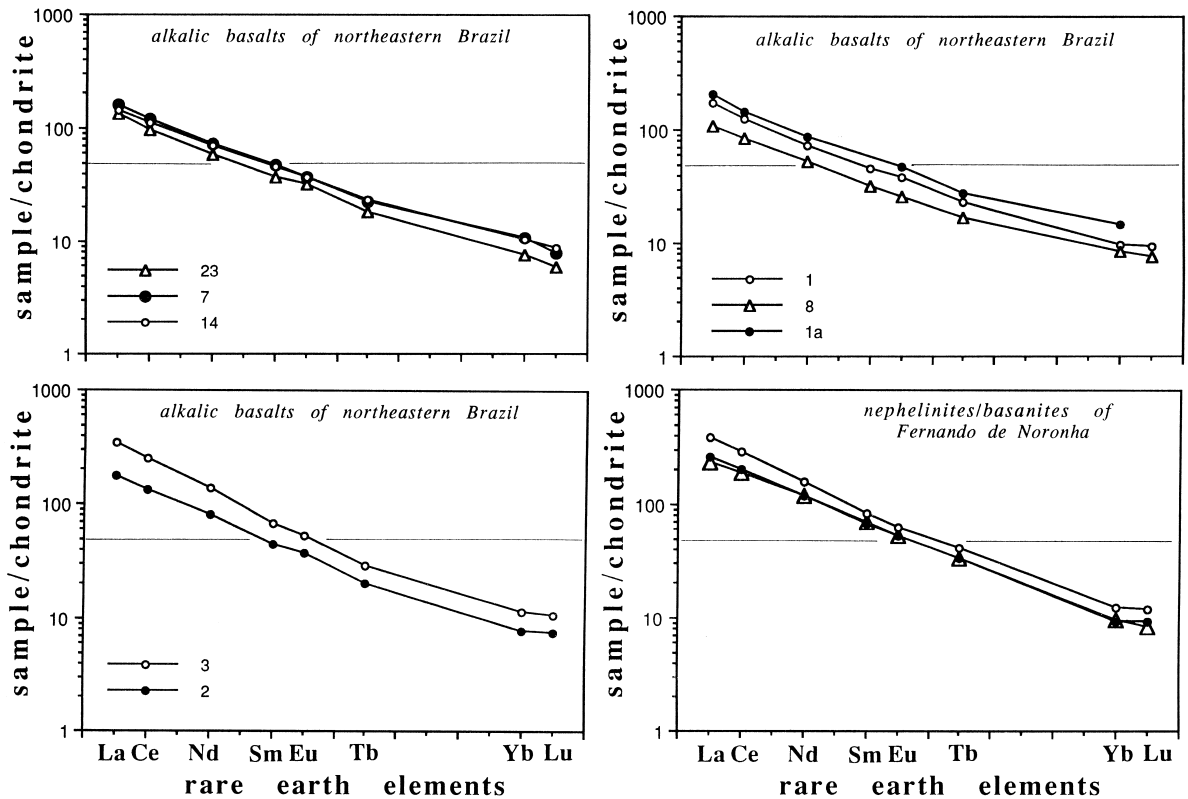


Fig. 5. Rare-earth element patterns for alkalic basalts of northeastern Brazil compared with nephelinites and basanites of Fernando de Noronha (Weaver, 1990). Lava 3 provides the best overlap with the rare-earth element patterns of Fernando de Noronha lavas. Horizontal lines at '50' are for visual reference; two sample compositions (1 and 1a) are shown for basaltic center 1.

isotopic compositions and whole-rock compositions. For example, center 8 lava has the highest  $\text{SiO}_2$ , the lowest incompatible-element abundances, and the most enriched isotopic compositions (i.e., rich in radiogenic Sr and poor in radiogenic Nd) (Figs. 3 and 6). In contrast, center 3 lava has the lowest  $\text{SiO}_2$ , the highest incompatible-element abundances, and among the most depleted isotopic composition (Figs. 3 and 6).

The  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$ , and  $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic compositions of the northeastern Brazil basalts overlap those of Fernando de Noronha, though in detail there are some notable distinctions between these two provinces. For example, some Fernando lavas have greater  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios at similar  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Fig. 6a), and the northeastern Brazil lavas as a group have higher  $^{208}\text{Pb}/^{204}\text{Pb}$  ratios (Fig.

6e). On the other hand,  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios of the northeastern Brazil lavas largely overlap those of Fernando de Noronha lavas (Fig. 6d,e), but lava from center 8 is notably lower in both  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  than the other northeastern Brazil alkalic basalts as well as those of Fernando de Noronha.

The Mesozoic low- $\text{TiO}_2$  CFB of northern Brazil (Maranhão province) plot in the Sr–Nd isotopically enriched field, and are therefore easily distinguished from alkalic basalts of either northeastern Brazil or Fernando de Noronha (Fig. 6a). Also, the  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios for the Maranhão CFB are lower than for most northeastern Brazil lavas (Fig. 6c–e).

Clinopyroxene separated from a lherzolite xenolith in a lava from center 8 falls among the lavas with the most 'depleted' Sr–Nd isotopic composi-

Table 4

Measured and initial isotope ratios for Tertiary alkalic basalts and lherzolite clinopyroxene, northeastern Brazil

Sample	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{meas}}$	$^{87}\text{Sr}/^{86}\text{Sr}_{\text{init}}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\delta^{18}\text{O}$
1	$0.70458 \pm 1$	0.70454	$0.51269 \pm 1$	18.949	15.617	39.336	
2	$0.70389 \pm 1$	0.70386	$0.51280 \pm 1$	19.347	15.661	39.577	
3	$0.70378 \pm 1$	0.70377	$0.51278 \pm 1$	19.166	15.589	39.171	
7	$0.70426 \pm 1$	0.70420	$0.51278 \pm 2$	19.166	15.628	39.202	7.18
8	$0.70508 \pm 2$	0.70500	$0.51266 \pm 3$	18.517	15.475	38.983	7.06
14	$0.70435 \pm 2$	0.70429	$0.51274 \pm 2$	19.178	15.686	39.304	7.13
23	$0.70431 \pm 2$	0.70426	$0.51274 \pm 3$	18.915	15.619	39.067	7.89
Cpx(8)	$0.70402 \pm 1$	—	$0.51285 \pm 2$	18.988	15.561	38.899	
Cpx(14)	—	—	—	—	—	—	5.89

Samples 1, 2, 3 analyzed at University of North Carolina isotope lab; samples 7, 8, 14, 23, and cpx(8) analyzed at University of Michigan isotope lab; cpx(14) analyzed at University of Georgia oxygen isotope lab. Clinopyroxenes are separates from lherzolite xenoliths in samples 8 and 14.

Pb isotopic compositions are corrected for fractionation using a factor of  $0.12 \pm 0.02\%$ /amu, based on replicate analyses of NIST NBS-981. Nd and Sr ratios were normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.721900$  and  $^{86}\text{Sr}/^{88}\text{Sr} = 0.119400$ . Measurements for NIST SRM-987 give  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710245 \pm 10$ , and for the La Jolla Nd standard values of  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511852 \pm 10$ . Total blanks average 0.04 ng for Pb, 0.02 ng for Nd, 0.02 for Sm, 0.07 ng for Rb, and 0.1 ng for Sr.

tions (Fig. 6a). Its Pb isotopic ratios are also generally consistent with those for the northeastern Brazil lavas (Fig. 6).

Whole-rock oxygen-isotopic compositions for four lavas have  $\delta^{18}\text{O}$  values of 7.1–7.9 (Table 4), which are at the high end of the range known for continental alkalic basalts (e.g., Harmon and Hoefs, 1995). Clinopyroxene from a lherzolite xenolith from center 14 is  $+5.9 \delta^{18}\text{O}$ . This isotopic value is consistent with those typically observed for mantle peridotite (Kyser et al., 1982).

## 6. Discussion

### 6.1. Relationships among the northeastern Brazil basalt centers

Based on variation diagrams such as  $\text{SiO}_2$  vs.  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  (Fig. 2a) and  $\text{SiO}_2$  vs.  $\text{MgO}$  (Fig. 3a), the lavas from the seven centers are not related by differentiation processes within a parental magma type that was common to northeastern Brazil. Moreover, the Nb variation diagrams (Fig. 7) show that trace-element abundance ratios, such as  $\text{Zr}/\text{Nb}$ ,  $\text{P}_2\text{O}_5/\text{Nb}$ , and  $\text{La}/\text{Nb}$ , are generally similar but nonetheless differ in detail among the basaltic centers. This implies that while their sources did not have grossly different trace-element abundances from one locality to another, there were at least some

heterogenities among the basalt sources for northeastern Brazil Tertiary magmatism. For example, there are slightly lower  $\text{P}_2\text{O}_5/\text{Nb}$  and  $\text{La}/\text{Nb}$  ratios at center 8 and lower  $\text{Zr}/\text{Nb}$  at centers 1, 3, and 23. On the other hand, nearly identical incompatible-element/Nb ratios in lavas from centers 7 and 14 suggest that they shared a common source (Table 1).

The plots of  $\text{La}/\text{Yb}$  and  $\text{La}/\text{Y}$  vs. Nb in Fig. 7 suggest that the lavas with highest incompatible-element abundances (namely, center 3) represent magmas that originated by the smallest percentages of partial melting. Conversely, these plots also suggest that lavas with lowest incompatible-element abundances, such as from center 8, represent the highest percentages of partial melting.

Before all of these trace element relationships—and additionally, isotopic compositions—can be incorporated into petrogeneses for these lavas, we first consider the possibility of upper crustal contamination. For example, the correlation between  $\text{SiO}_2$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  (Fig. 8a) suggests that some lavas reflect crustal contributions to both  $\text{SiO}_2$  and Sr isotopic compositions. If crustal contamination indeed occurred, in spite of implied short residence times for the magmas (i.e., lavas contain peridotite nodules and are not strongly  $\text{MgO}$ -fractionated), then contamination increased  $\text{SiO}_2$  abundances while not identifiably increasing or decreasing incompatible-element abundances. That is, lavas from center 8

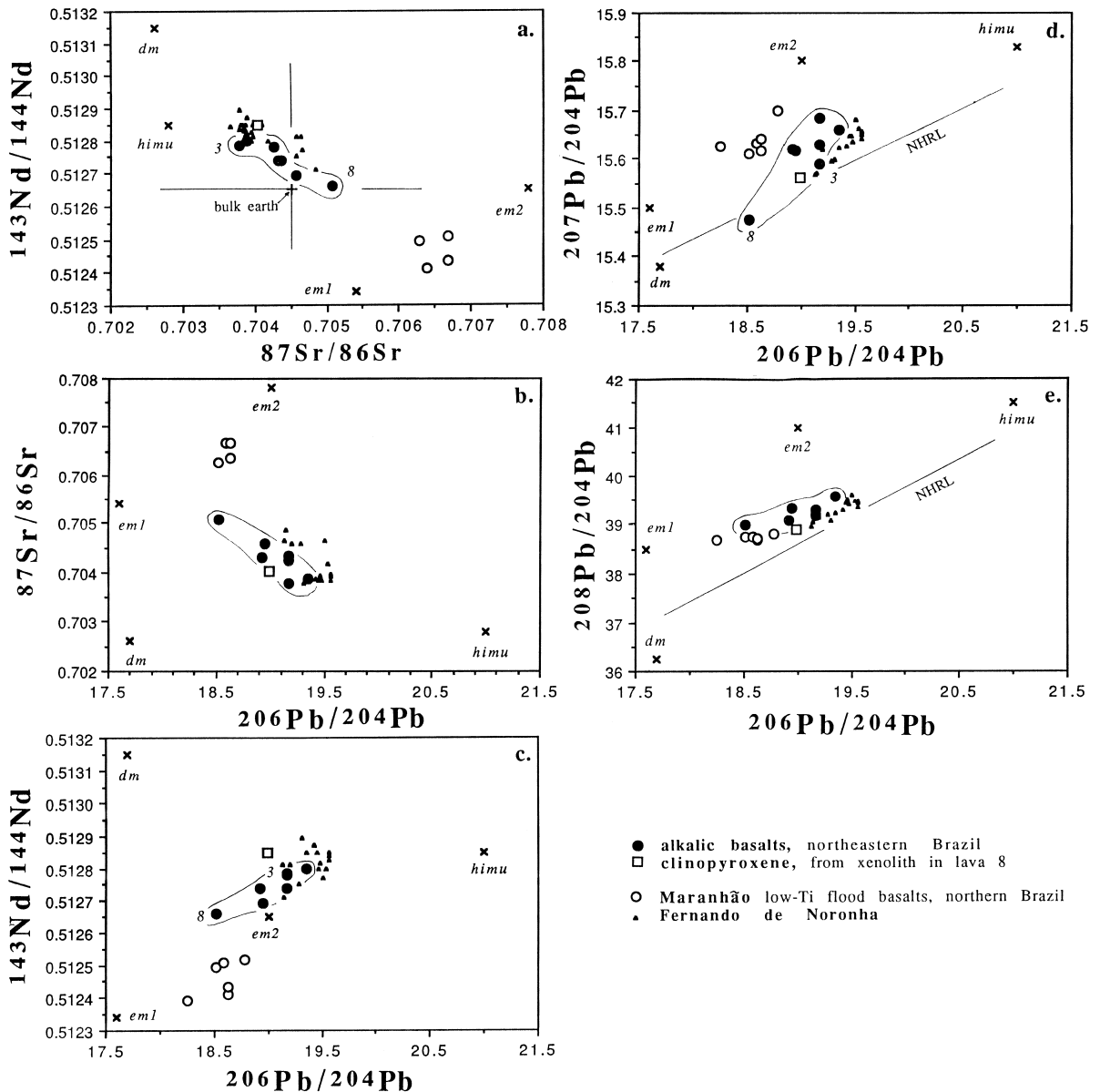
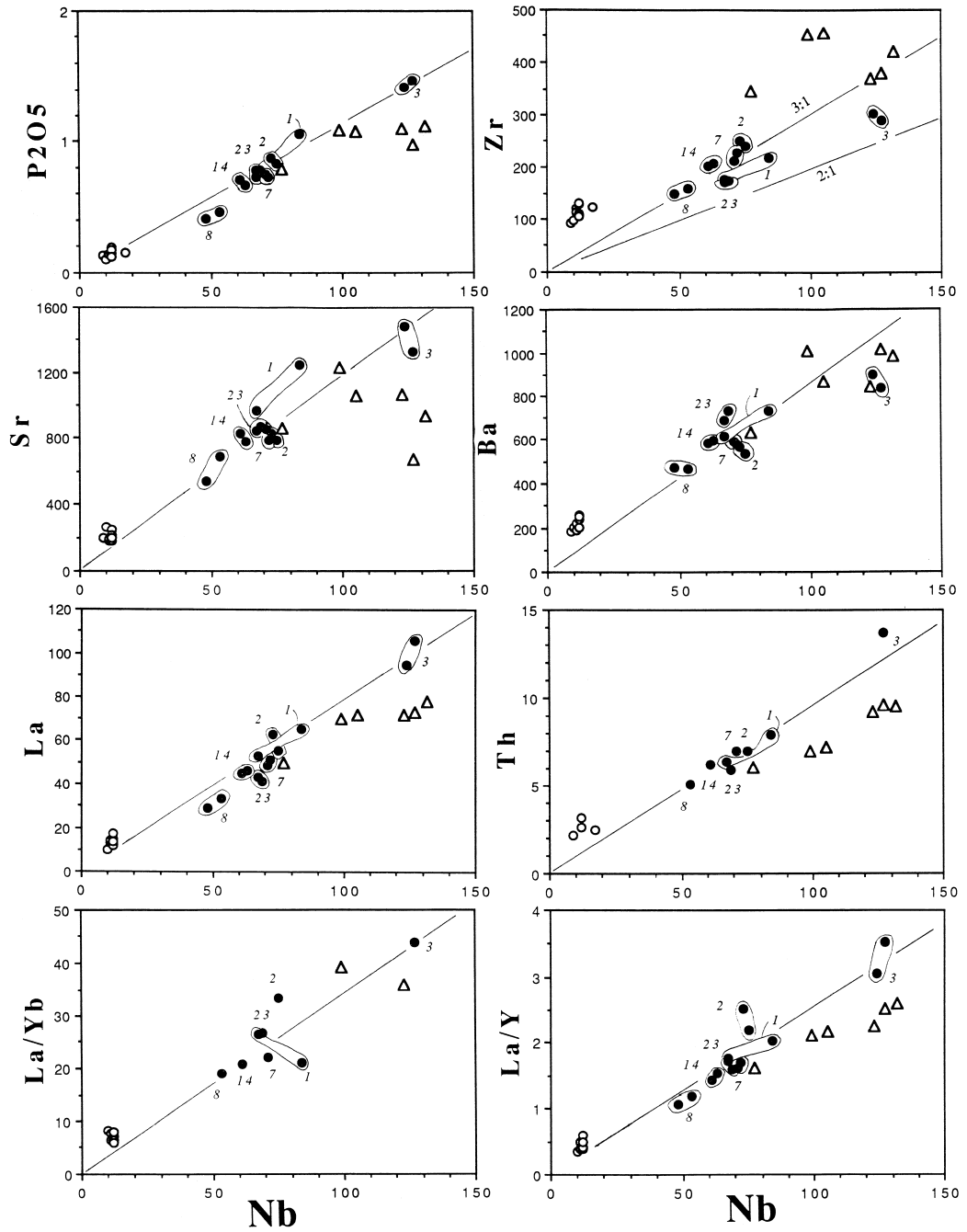


Fig. 6. Isotopic compositions for alkalic basalts of northeastern Brazil and for clinopyroxene from a peridotite xenolith in lava 8, all compared to those for Fernando de Noronha (Gerlach et al., 1987) and Mesozoic low-TiO<sub>2</sub> flood basalt of the Maranhão province, northern Brazil (Fodor et al., 1990). Lavas 3 and 8 are denoted in panels a, c, and d. Some panels appear to have six instead of seven alkalic basalt samples plotted due to overlapping data points. DM, HIMU, and EM, respectively refer to approximate compositions (× symbols) of the mantle endmembers depleted mantle, high mu (U/Pb), and enriched mantle (e.g., Hart, 1988). NHRL in panels d and e marks the northern hemisphere reference line, a characterization of mid-ocean ridge basalts (Hart, 1988).

have incompatible-element/Nb ratios reasonably consistent with those of the other lavas (Fig. 7). Moreover, lavas of center 8 have the lowest La/Nb

ratios (~0.60; Table 1; Figs. 7 and 8b), which is counter to comparatively high La/Nb of crustal rocks (e.g., > 1.2; Taylor and McLennan, 1985).



- alkalic basalt, northeastern Brazil
- Maranhão CFB province, northern Brazil (low-TiO<sub>2</sub> variety)
- △ Fernando de Noronha lavas

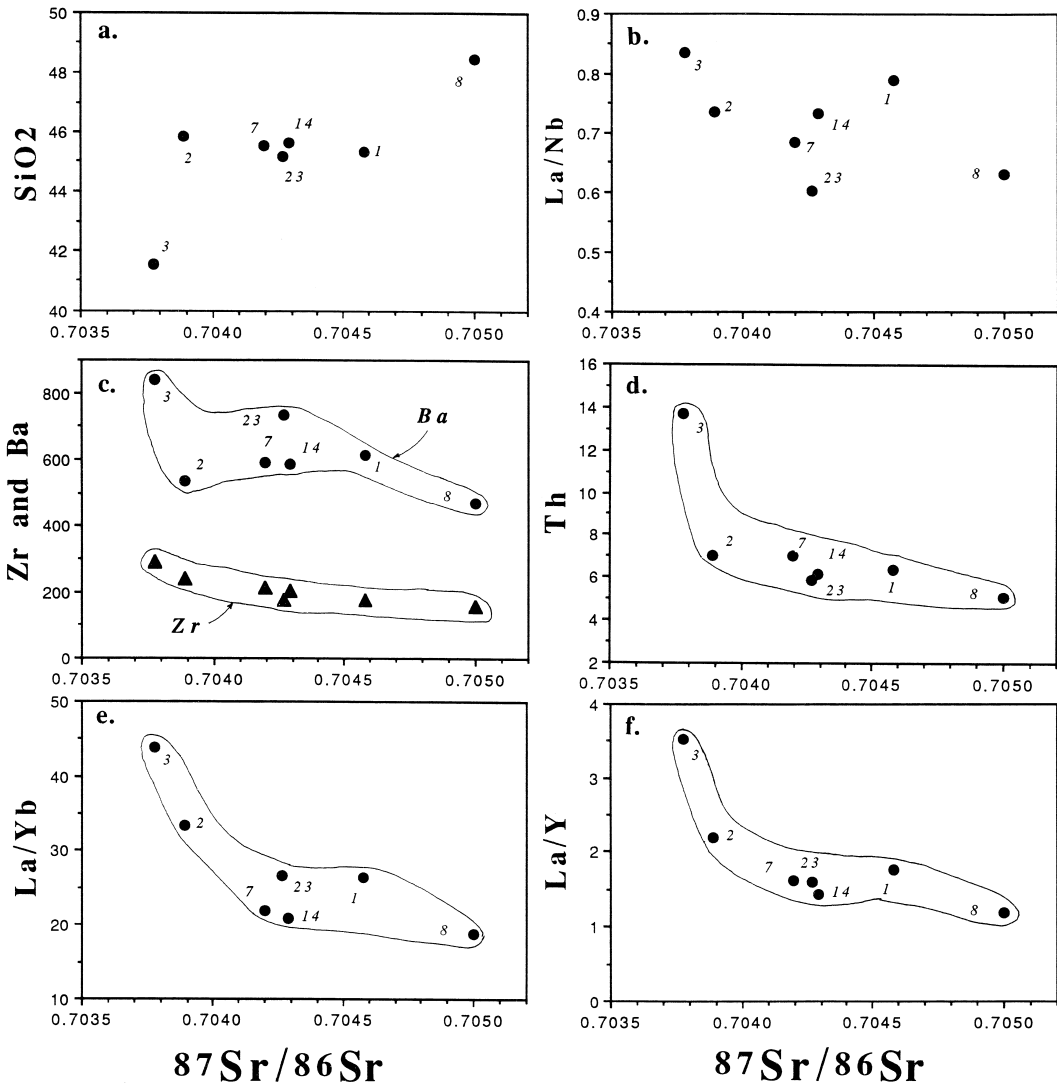


Fig. 8. Variation in  $\text{SiO}_2$ , Zr, Ba, and Th abundances and La/Yb and La/Nb ratios with Sr isotopic compositions for the alkalic basalts of northeastern Brazil. Data points are labeled according to samples sites (Fig. 1). In general, higher  $\text{SiO}_2$  and lower incompatible-element abundances and greater melting percentages (i.e., lower La/Yb and La/Y) correspond to higher  $^{87}\text{Sr}/^{86}\text{Sr}$ .

Comparatively high  $\text{SiO}_2$  without obvious enrichments in trace-element abundances are compatible with sandstone assimilation—particularly in view of quartz xenocrysts in the lavas at center 8. Sandstone,

however, would not elevate Sr isotopic ratios unless it was impure (e.g., contained feldspar and had a reasonably low melting eutectic; a quartz + Na–K feldspar assemblage), such that small amounts of

Fig. 7. Nb variation diagrams for incompatible elements and La/Yb and La/Y ratios for the alkalic basalts of northeastern Brazil compared with Fernando de Noronha alkalic basalts (Weaver, 1990) and Mesozoic low- $\text{TiO}_2$  flood basalts of the Maranhão province, northern Brazil (Fig. 1) (Fodor et al., 1990). The diagonal lines are to visually aid evaluating element/Nb ratios, but two Zr/Nb ratio lines are specifically identified. Data points for the various sample centers (Fig. 1) are numbered.

high Sr-, high  $^{87}\text{Sr}/^{86}\text{Sr}$ -bearing components were ‘rapidly’ assimilated during magma ascent. This is unlikely, however, because center 8 lavas have the lowest abundances of Ba, Sr, and Th (Figs. 7 and 8c,d), elements characteristic of  $\text{SiO}_2$ -rich granitoid crust. Also, there is an overall negative correlation between  $^{87}\text{Sr}/^{86}\text{Sr}$  and elements likely to be enriched in the crust (Ba, Zr, Th) (Fig. 8c,d).

From another perspective, the plagioclase xenocrysts (resorbed) in lavas from basaltic center 2 might be remnants of crustal contaminants, but these lava hosts for the plagioclase xenocrysts have among the lowest of the observed  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (Fig. 8). Moreover, lavas from four other centers contain quartz xenocrysts, but do not have  $\text{SiO}_2$  abundances as high as those in lavas at center 8. Therefore, quartz xenocrysts do not assure that  $\text{SiO}_2$  contents became elevated due to their incorporation. All of these lavas, however, do have seemingly high oxygen isotope values. These may be related to the quartz xenocrysts and/or to secondary alteration; but on the other hand, the  $\delta^{18}\text{O}$  values (Table 4) are within the range of values observed for continental intraplate basalts worldwide and may reflect their sources (e.g., Harmon and Hoefs, 1995). Our assessment, then, of the radiogenic isotopic and trace-element compositions is that they closely represent the source(s) for these lavas and do not reflect assimilated crust.

## 6.2. Mantle source beneath northeastern Brazil

The similarity of trace-element and isotopic compositions to those of ocean island basalts (Figs. 3–5) points to a largely asthenospheric mantle source for the basaltic centers of northeastern Brazil (Fig. 1). In terms of mantle isotope-endmember components HIMU (high U/Pb), EM (enriched mantle, types 1 and 2), and DM (depleted mantle) (e.g., Zindler and Hart, 1986; Hart, 1988), Fig. 6a shows that the northeastern Brazil lavas, as a group, plot between a variety of EM and a combination of HIMU and DM components. The Sr–Pb and Nd–Pb isotopic plots (Fig. 6b,c) further illustrate that the samples can be expressed as mixtures of varying amounts of endmembers that compositionally approach HIMU plus DM and EM1 mantle components. The general relationships are that lavas with greatest incompatible-

element abundances and  $\text{SiO}_2$  undersaturation have a relatively high proportion of HIMU + DM isotopic component. In contrast, lavas with low abundances of incompatible elements and  $\text{SiO}_2$  saturation (Fig. 2) have less HIMU + DM and more EM1 components (center 8 lavas). Because we believe that the isotopic and trace-element compositions were not noticeably affected by incorporation of quartz and feldspar xenocrysts, we accept the relative proportions of HIMU, DM, and EM1 components in these basalts as characteristics of their sources.

Trace elements that describe ‘oceanic’ mantle domains—namely, ratios among Ba, Nb, and La (e.g., Weaver, 1991)—only weakly support the isotopic assessment for the northeastern Brazil basalts representing a compositional continuum that extends largely from HIMU generally toward EM1. That is, the collective data for La/Nb and Ba/Nb ratios trend at angles to the HIMU–EM1 transition based on trace elements (Fig. 9a). Nonetheless, the high La/Nb portion of the correlation corresponds to a largely HIMU composition with some DM component (Fig. 9a), comparable to observations for isotopic compositions. Additionally, the overall data field describing La/Nb and Ba/Nb ratios for northeastern Brazil basalts is not unique to this continental alkalic province. Continental provinces in China (Zhi et al., 1990), northern Tanzania (Paslick et al., 1995), Slovakia (Dobosi et al., 1995), and in Cameroon (Fitton and Dunlop, 1985) are all believed to have largely asthenospheric sources, and all have La/Nb and Ba/Nb ratios like those of northeastern Brazil basalts (Fig. 9b). The northeastern Brazil basalts differ, however, by their notable negative correlation of decreasing La/Nb with increasing Ba/Nb (Fig. 9a,b).

Because Ba, Nb, and La are highly incompatible, the continuum of La/Nb–Ba/Nb (Fig. 9a) reflects mantle heterogeneity rather than varying percentages of melting of a homogeneous source. But because La/Nb and Ba/Nb each correlate with La/Y (Fig. 9e,f), the ratios do appear to be related to melting percentages. For example, samples with lower La/Nb correspond to greater source melting (e.g., lower La/Y; Fig. 9e). Additionally, because the variable  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic compositions (Fig. 6) correlate with La/Yb and La/Y (Fig. 8e,f), higher melting percentages associate with source material



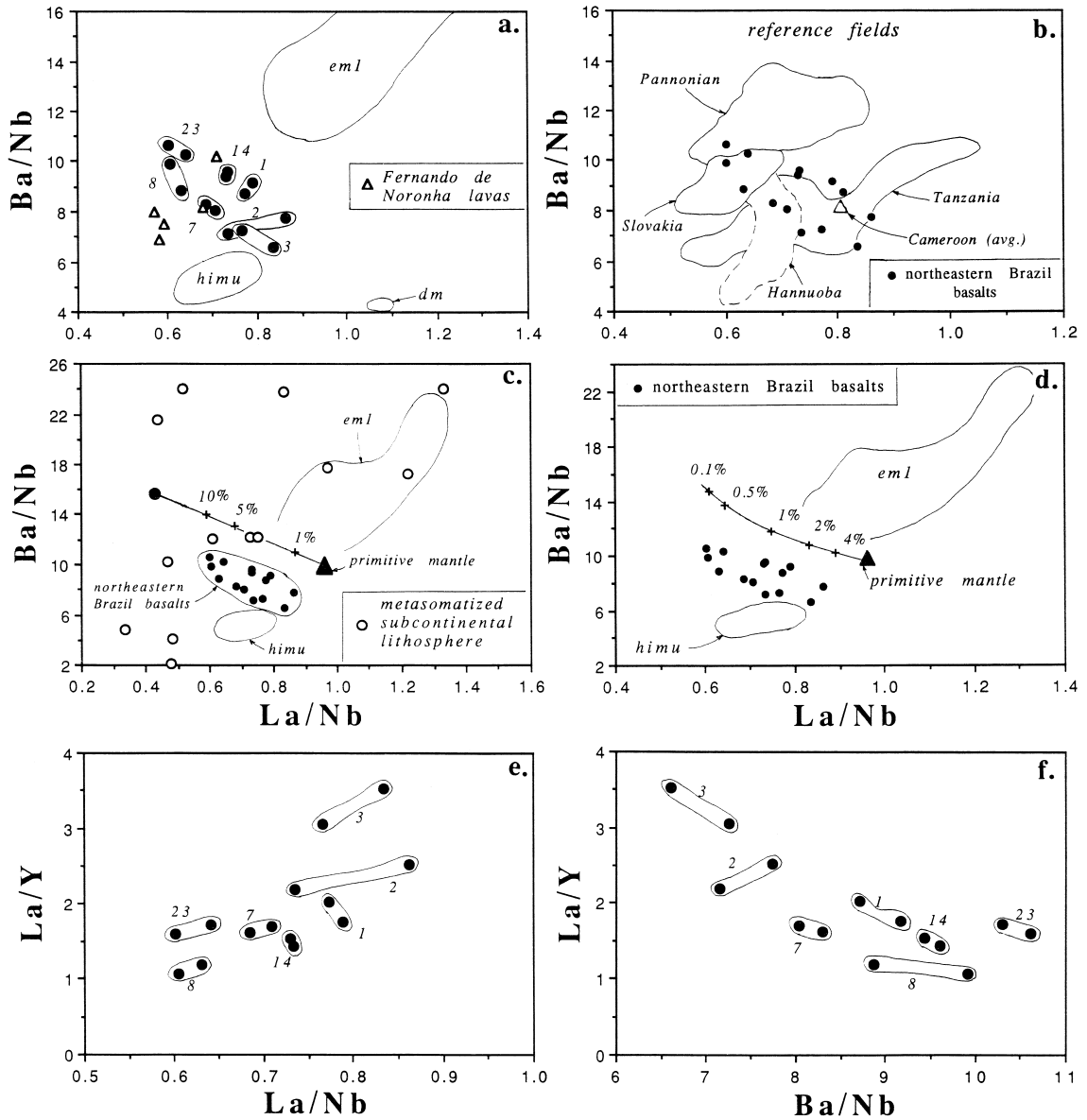


Fig. 9. La/Nb and Ba/Nb relationships for northeastern Brazil alkalic basalts compared to: (a) oceanic isotopic endmembers HIMU, EM1, and DM (fields after Weaver, 1991) and Fernando de Noronha lavas (Weaver, 1990), where data points are labeled according to sample sites (Fig. 1); (b) continental alkalic basalts from Pannonian basin, Hungary (Embey-Isztin et al., 1993), Slovakia (Dobosi et al., 1995); Hannuoba, China (Zhi et al., 1990), Tanzania (Paslick et al., 1995) and Cameroon average composition (Fitton and Dunlop, 1985); (c) compositions of xenoliths representing subcontinental lithosphere (Menzies et al., 1987; Erlank et al., 1987), and a mixing curve for melts from asthenosphere (represented by primitive mantle; Sun and McDonough, 1989) and from metasomatized subcontinental lithosphere (Ba 250 ppm, Nb 16 ppm, La 7 ppm; after Menzies et al., 1987); percentages refer to proportion of lithosphere in mixture; and (d) melt compositional trends for modal partial melting of primitive mantle (Sun and McDonough, 1989) using partitioning coefficients for La and Nb from Kelemen et al. (1993) and using zero for Ba (all phases) for ‘melting’ 60% olivine, 25% orthopyroxene, 10% clinopyroxene, and 5% garnet. (e and f) Variations in La/Nb and Ba/Nb ratios with indicators of degrees of partial melting (e.g., lower La/Y equates with relatively higher melting). Data points are labeled according to sample sites.

having higher  $^{87}\text{Sr}/^{86}\text{Sr}$ . The straightforward reconciliation of all these relationships, then, is that they reflect varying melt proportions of a compositionally heterogeneous source or mixtures of compositionally different sources.

Although the northeastern Brazil basalts have an OIB characterization (Fig. 5), their continental setting requires additionally evaluating trace-element and isotopic variations in terms of melt contributions from subcontinental lithosphere. Trace element abundances for subcontinental lithosphere are not easily specified due to compositional heterogeneity acquired during incompatible-element enrichments and depletions, as interpreted from samplings (e.g., McDonough, 1990; McDonough and Frey, 1990). But by and large, consensus has that it is a regime of trace element and  $^{87}\text{Sr}/^{86}\text{Sr}$  enrichments from long histories of metasomatism by small-degree asthenospheric melts (e.g., McKenzie, 1989; Hawkesworth et al., 1990). Also, as determined from analyses of whole xenoliths from subcontinental lithosphere, this domain can have low La/Nb and high Ba/Nb ratios (Fig. 9c). Accordingly, if the La/Nb–Ba/Nb trend (Fig. 9a) represents mixing of two components, the lower La/Nb ratios—which represent greater melting (Fig. 9e) than higher La/Nb ratios—appropriately represent subcontinental lithosphere. Moreover, because lithosphere is, in general, isotopically enriched relative to asthenosphere (e.g., McKenzie, 1989; McDonough, 1990), the  $^{87}\text{Sr}/^{86}\text{Sr}$  relative enrichment in the basalts with low La/Nb (Fig. 8b) is consistent with these samples representing lithospheric component. Our one xenolith representation of subcontinental mantle (from center 8 lava) does not show such  $^{87}\text{Sr}/^{86}\text{Sr}$  enrichment, but it is, on the other hand, in isotopic agreement with the bulk of northeastern Brazilian lavas (Fig. 6). The high La/Nb end of the trend, generally consistent with isotopic and trace-element HIMU(+DM) component, represents asthenosphere, presumably the Fernando de Noronha plume.

In view of the trace-element observations, the relatively low La/Nb ratios of some northeastern Brazil lavas may represent La/Nb of lithosphere that was modified by underplating of small-degree asthenospheric melts (e.g., Paslick et al., 1995). For instance, because < 1% melts can fractionate highly-incompatible elements (e.g., Sun and Mc-

Donough, 1989) to create La/Nb ratios lower than in mantle material melting, any small-degree asthenospheric melts added to lithosphere would lower the overall La/Nb ratio of potential lithospheric source. In particular, a 0.5% melt of primitive mantle will have La/Nb  $\sim$  0.64, compared to a source ratio of  $\sim$  0.96 (Fig. 9d). Particularly relevant for this study is that such small-degree melting yields a La/Nb–Ba/Nb trend that parallels the data set for the northeastern Brazil basalts (Fig. 9d).

Our interpretation, then, is that the northeastern Brazil alkalic basalts collectively represent mixtures of melts from two mantle components. One was asthenosphere characterized by isotopic and trace-element signatures that are close to those of HIMU plus DM, which probably represented the Fernando de Noronha plume. The second source had isotopic signatures closer to EM1 than HIMU and lower La/Nb and higher Ba/Nb than the asthenospheric source. We suggest that this comparatively  $^{87}\text{Sr}/^{86}\text{Sr}$  Sr-enriched ‘second’ component was subcontinental lithosphere. Based on La/Y and La/Yb relationships, the lithospheric components in the mixtures represent larger melting percentages than those from the asthenosphere. Also, based on a La/Nb and Ba/Nb mixing curve for approximate endmember-source compositions (Fig. 9c)—namely, plume component represented by primitive mantle (Sun and McDonough, 1989) and metasomatized lithosphere represented by xenoliths (e.g., Menzies et al., 1987)—we show that mixtures comprise < 10% of the lithosphere component (Fig. 9c).

### 6.3. Magma crystallization histories *vis-a-vis* magma mixing

Fodor et al. (1995) describe the complexly-zoned clinopyroxene phenocrysts in lavas from two centers (7 and 14) and suggest that their magmas differentiated, accounting for clinopyroxene Mg#s of 86–73. Because  $\text{Al}^{\text{iv}}/\text{Al}^{\text{vi}}$  site ratios vary among the clinopyroxene compositional zones, and because some grains have sieved cores, differentiation was probably polybaric and attended by magma mixing (Fodor et al., 1995). Mixing of phenocrysts into different magmas, perhaps replenishment magmas, can account for incipient dissolution, or sponginess, of clinopyroxene crystals. The overriding interpreta-

tion (Fodor et al., 1995), then, based on clinopyroxene crystallization histories, is that the magmas represented by the northeastern Brazil alkalic basalts experienced various igneous processes, such as differentiation and mixing, within mantle regimes. Evidence from clinopyroxene for magma mixing is consistent with our proposal for mixing of melts from asthenospheric and lithospheric sources.

In this study, we identify sieved-core plagioclase microphenocrysts to further document mixing processes. The 'spongy' plagioclase grains are innate to the magmas because compositions overlap with and are slightly less calcic than the compositions of groundmass plagioclase laths (Table 2). (Grains identified as xenocrysts, Table 3, lava 2, are not spongy-textured.) Identical or slightly lower An in early-formed plagioclase compared to groundmass plagioclase is consistent with liquidus and solidus temperatures and compositions adjusting during change from high- to low-pressure crystallization regimes as magma ascends. Because of the limited pressure under which plagioclase crystallizes ( $\leq 9$  kbar), microphenocryst growth should have been at no greater than  $\sim 30$ -km depth. This depth to mantle is in accordance with crust–mantle interface studies by Castro et al. (1997a,b). The presence of mantle xenoliths that were entrained during ascent also indicate that the distinctive sieved-cores of plagioclase and clinopyroxene in many of the northeastern Brazil alkalic basalts formed within the mantle.

#### 6.4. Comparison to Fernando de Noronha

To a large extent, isotopic compositions and trace-element abundance ratios for Fernando de Noronha lavas of all ages (i.e.,  $\sim 12$ –2 Ma; Gerlach et al., 1987) overlap those of the northeastern Brazil lavas (Figs. 3, 6 and 9a). Detailed differences between the overall lava compositions of northeastern Brazil and Fernando de Noronha, such as the apparent Zr and Nb enrichments and Th depletion and the slightly higher  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios in the Fernando lavas (Fig. 4d,eFig. 6), suggest, however, that while the alkalic basalts of northeastern Brazil and those of Fernando de Noronha shared similar sources, they did not share identical source materials over the past  $\sim 30$  Ma. The reasons probably lie in compositional heterogeneities that existed in the Fernando de No-

ranho plume as well as in subcontinental lithosphere that may have underlain Fernando de Noronha, even though this province is oceanic. Specifically, some characteristics of Fernando de Noronha lavas may have been acquired from continental lithosphere underlying the islands owed to delamination from South America during plate movement (Gerlach et al., 1987). However, none of the Fernando lavas have isotopic or trace-element characteristics close to the northeastern Brazil lavas which we believe to carry the largest proportions of lithospheric component, namely, lavas from center 8.

The geographic distances between the Brazil basaltic centers should not discount the possibility that these two provinces shared a single source of upwelling asthenosphere over the past  $\sim 30$  Ma. This is true even for the relatively distant São Pedro center in Pernambuco state (Fig. 1) because all of the lava centers are within the diameters hypothesized for plumes (100s of km) causing hotspot magmatism (e.g., Griffiths and Campbell, 1990). This large 'diameter' of magmatism may have been demonstrated by penecontemporaneous magmatism at center 3 ( $\sim 13$  Ma) and at Fernando de Noronha ( $\sim 12$  Ma).

To summarize, overall compositions of the northeastern Brazil alkalic basalt lavas are consistent with the Fernando de Noronha hotspot having imparted magmatism in northeastern Brazil beginning  $\sim 30$  Ma. In detail, however, northeastern Brazil and Fernando de Noronha lavas have some compositional distinctions that can be attributed to local compositional characteristics within the asthenospheric (plume) source or to the compositions and amounts of subcontinental lithospheric melts that mixed with asthenospheric melts at each setting.

## 7. Conclusions

On the basis of trace-element and isotopic compositions, the Tertiary alkalic basalt lavas of Rio Grande do Norte and Pernambuco states in northeastern Brazil are consistent with magmas that represent mixtures of melts from both asthenospheric and lithospheric mantle sources. The asthenospheric mantle endmember represented in each lava is largely characterized by HIMU plus DM, and is attributed to the Fernando de Noronha plume. The subcontinental

lithospheric endmember represented in these lavas is isotopically closer to EM1. While the proportions of asthenospheric and lithospheric melt contributions vary among the samples studied—but probably always < 10% lithosphere—the asthenospheric melts represented correspond to smaller percent melts than those of the lithosphere.

In a general way, the northeastern Brazil lavas share similar isotopic and trace-element compositions with those of Fernando de Noronha lavas. While the Fernando de Noronha lavas are largely asthenospheric, they may also represent mixtures of melts from delaminated subcontinental lithosphere.

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