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Contributions to Mineralogy and Petrology

Petrology, isotope characteristics, and K-Ar ages of the Maranhão, northern Brazil, Mesozoic basalt province

R.V. Fodor[1], **A.N. Sial**[2], **S.B. Mukasa**[3], **and E.H. McKee**[4]

[1] Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, USA
[2] Departamento de Geologia, Universidade Federal de Pernambuco, Recife, PE, Brazil
[3] Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109, USA
[4] U.S. Geological Survey, Menlo Park, CA 94025, USA

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Abstract. Northern Brazil contains remnants of Mesozoic flood basalts and hypabyssal rocks that were apparently emplaced during tectonism related to opening of the Atlantic Ocean. Analyses and new K-Ar ages reveal that this $\sim 700 \times 250$ km Maranhão province (5°–8° S) has low-Ti basalts (~ 1.1 wt% TiO_2) in the western part that range about 160 to 190 Ma, and high-Ti basalts (3.4–4.4 wt% TiO_2) in the eastern part about 115–122 Ma. Low-Ti basalt compositions are less evolved and have a smaller range, Mg# 62–56, than the high-Ti basalts, Mg# 44–33. General characteristics of the least evolved members of low- and high-Ti groups include, respectively, Zr 100 and 250 ppm, Sr 225 and 475 ppm, Ba 200 and 500 ppm, Nb 10 and 26 ppm, Y 29 and 36 ppm, $La/Yb_{(n)}$ 4.2 and 8.8, where $La_{(n)}$ is 30 and 90. Overall compositions resemble the low- and high-Ti basaltic rocks of the Mesozoic Serra Geral (Paraná) province in southern Brazil. The Maranhão low-Ti basalts have more radiogenic Sr and Pb and higher $\delta^{18}O$ than the high-Ti basalts. Respectively, low- vs high-Ti: ε_{Sr} 26–54 vs 15–18; $^{206}Pb/^{204}Pb = 18.25–.78$ vs 18.22–.24; and $\delta^{18}O$ 8.9–12.6 vs 6.5–8.6. Nd isotopes overlap: ε_{Nd} -1.6 to -3.8 vs -2.1 to -3. Ages, compositions, and isotopes indicate that the low- and high-Ti groups had independent parentages from enriched subcontinental mantle. However, both groups can be modeled from one source composition if low-Ti basalt isotopes reflect crustal contamination, and if the parentages for each group were picritic liquids that represent either higher (for low-Ti) or lower (for high-Ti) percentages of melting of that single source. When comparing Pb isotopes of Maranhão and Serra Geral high-Ti basalts (uncontaminated) to evaluate the DUPAL anomaly, Maranhão has Pb $\Delta 7/4 = 4.6–11$, and Pb $\Delta 8/4 = 72–87$; Serra Geral has Pb $\Delta 7/4 = 10–13$, and Pb $\Delta 8/4 = 95–125$. The small difference is not enough to conform to DUPAL contours, and is inconsistent with large-scale isotopic heterogeneity of mantle beneath Brazil prior to rifting of South America from Africa. Maranhão low-Ti magmas probably relate to the opening of central North Atlantic, and high-Ti magmas to the opening of equatorial Atlantic. The proposed greater percentage of source melting for low-Ti basalts may reflect a Triassic-Jurassic hotspot, while lesser melting for high-Ti magmas may relate to Cretaceous decompressional (rifting) melting.

Introduction

Much of the magmatism in South America was basaltic and associated with the opening of the Atlantic Ocean during the Mesozoic (Amaral et al. 1966; May 1971; Sial 1976). Both northern and southern Brazil have basaltic representatives of the Mesozoic continental rifting events, but geologists have given most attention to those in the south, namely, the Paraná, or Serra Geral, continental flood-basalt province, 160 to 110 Ma (e.g., Bellieni et al. 1984; Fodor et al. 1985a, b; Mantovani et al. 1985; Petrini et al. 1987; Hawkesworth et al. 1986, 1988). The studies have led to relevant petrologic observations for the Serra Geral basalt province, such as coexisting high- and low-Ti basalt groups with corresponding isotopic signatures and specific geographic occurrences. These characteristics have spawned conjecture about the South Atlantic subcontinental mantle with respect to mantle-source homogeniety/heterogeniety, lithosphere remobilization, contamination of basaltic magmas by crust, incompatible-element enrichment in basalts, and the DUPAL isotopic anomaly (e.g., Bellieni et al. 1986; Hawkesworth et al. 1986, 1988; Fodor 1987).

Less attention has been given to Mesozoic basalts in northern Brazil (Fig. 1), probably because little field exposure remains. Initial work in the Maranhão basin of northern Brazil suggests that basalt and diabase emplacement occurred between 210 to 110 Ma (Sial 1976), which precedes and overlaps that of the Serra Geral

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Offprint requests to: R.V. Fodor

Fig. 1. Map showing locations in the northern Brazil states of Maranhão, Piaui, and Goias

(Paraná) in southern Brazil. Having two separate continental basalt provinces (Maranhão and Serra Geral) originating in essentially identical geologic times and under similar tectonic framework provides opportunities to compare petrogeneses of rift-related flood basalts, and to evaluate homogeniety/heterogeniety of subcontinental South Atlantic mantle, a region where anomalous isotopic characteristics are identified in the ocean basin (Hart 1984, 1988).

Our intention is to bring the petrologic understanding of the northern Brazil basaltic rocks of the Maranhão province to a level comparable with that of the Serra Geral and to evaluate Maranhão with respect to Serra Geral. This report therefore characterizes the Maranhão province in terms of major- and trace-element geochemistry, isotope compositions, and new K-Ar ages, and relies heavily on comparison to the same kind of data for the Serra Geral (Paraná) province. It contributes to evaluating Mesozoic subcontinental mantle of Brazil, and to the growing understanding of the composition of Atlantic mantle from Mesozoic to present, the melting processes within, and the role that continental crust had on basalt compositions.

Sample locations and descriptions

We examined 29 basaltic rocks from the states of Maranhão, Goias, and Piaui (Fig. 1). Outcrops are limited to scattered exposures along road, quarry, and stream cuts. The sampled area is about 700 km across, and is divided by 45° W longitude into western and eastern parts, which, as analyses show, correlate with basalt compositions. We refer to the entire region as the Maranhão province, after the regional structural name, Maranhão basin (e.g., Sial 1976; Asmus and Baisch 1983).

Basalts collected west of 45° W contain clinopyroxene (augite), plagioclase, and Fe-Ti oxides, and sometimes pigeonite or olivine (altered to smectite) in largely intergranular, aphyric (sometimes microporphyritic) basaltic textures. Grain sizes are generally less than 1 mm. Most eastern Maranhão samples have coarser (diabasic) textures of clinopyroxene, plagioclase, Fe-Ti oxides, and sometimes pigeonite, where grains are 1 to 3 mm. Some samples also have glass that is now partly devitrified and observed in thin sections as either isolated "clots" or in amounts large enough to comprise vitrophyric textures of glass charged with crystallites of Fe-Ti oxides.

Western samples, those from Maranhão and Goias states, probably represent flood basalts, while those from eastern Maranhão largely were hypabyssal as dikes (Sial 1976). Some samples from Piaui are exceptions; for example, 2 and 2A have basaltic textures.

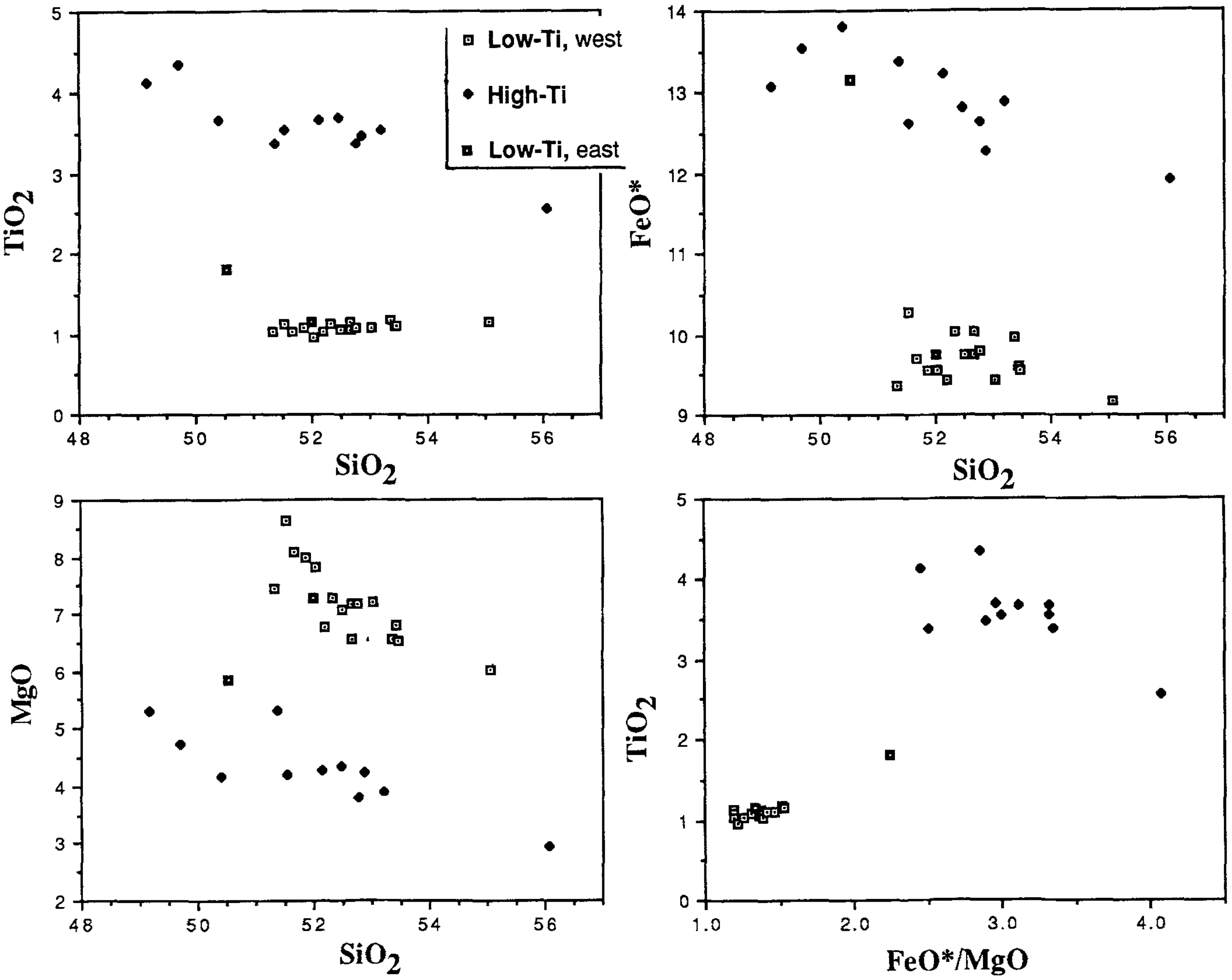


Fig. 2. Major-element variation diagrams showing distinctions between the low-Ti basalt group in western Maranhão province (see Fig. 1), low-Ti basalts in eastern Maranhão province, and the high-Ti basalt group in eastern Maranhão province, northern Brazil

Modal percentages of Fe-Ti oxides differ by a factor of two in these two basalt groups. Six diabasic samples have 8–15 vol% Fe-Ti oxides and an average of 10.7%. Sixteen basaltic samples have 2.2–11 vol% Fe-Ti oxides and an average of 5.2%. There is no petrographic indication of cumulate Fe-Ti oxides among these samples.

As a group, the Maranhão basaltic rocks have undergone some weathering and alteration. Evidence occurs in some samples as calcite, zeolites, smectite, and as albite- and orthoclase-rich zones in plagioclase, and is suggested in some by unusually high whole-rock Sr and Ba.

Analytical techniques

Major- and trace-element abundances were determined by X-ray fluorescence using glass disks and pressed powder pellets in conjugation with reference samples from the U.S., Canadian, and South African geological surveys. Accuracy for major elements is within 2% except for Al and Na, which are 5–10%. Trace elements by XRF are within 10%, but for abundances less than 10 ppm, accuracy approaches 25%. We acquired rare-earth element abundances by INAA; 8 samples were analyzed at North Carolina State University, using U.S. Geological Survey reference samples BHVO, W2, and AGV, and 6 samples at Oregon State University radiation center, using U.S.G.S. and in-house standards. Accuracy in each case is between 5 and 15%. Whole-rock FeO was determined by titration, and all Fe is expressed as FeO in whole-rock and mineral compositions, except where indicated to be recalculated as FeO and Fe_2O_3. Pb, Sr, and Nd isotopic compositions were determined on a triple collector VG Isomass 354 thermal ionization mass spectrometer at the University of Florida; Table 3 states measurement details. Plagioclase and pyroxene compositions were determined for four samples using an ARL-EMX electron microprobe at NCSU, and plagioclase, microcline, and clinopyroxene reference minerals.

Whole-rock and mineral compositions

Compositions listed in Table 1 and variation diagrams in Fig. 2 show that TiO_2, FeO, and MgO divide the Maranhão basalts into low-Ti (relatively low Fe and high Mg) basalts of western and eastern (2 samples) Maranhão province, and a group of high-Ti (high Fe, low Mg) basalts in eastern Maranhão. The high-Ti

Table 1. Composition of low-Ti and high-Ti basalts of the Maranhão basalt province, northern Brazil, listed in order of Mg#. Oxides

	Low-Ti basalts (west)[a]															
	4A	13	506	26	19	21	11	29	8	10	29A	17	502	28	25	9
SiO_2	51.52	51.86	51.68	52.04	52.49	53.03	52.67	52.77	52.50	52.33	52.20	53.43	53.47	53.37	52.43	52.68
TiO_2	1.14	1.08	1.03	0.96	1.05	1.09	1.07	1.09	1.07	1.13	1.03	1.10	1.11	1.18	1.17	1.16
Al_2O_3	13.90	15.25	14.72	14.90	14.84	15.13	14.97	14.45	14.90	15.03	14.43	15.00	14.89	14.06	14.31	15.10
FeO*	10.29	9.55	9.70	9.56	9.36	9.44	9.75	9.80	9.74	10.03	9.44	9.60	9.55	9.96	9.17	10.04
MnO	0.17	0.16	0.16	0.15	0.16	0.16	0.17	0.17	0.16	0.17	0.14	0.17	0.16	0.16	0.17	0.18
MgO	8.63	7.99	8.08	7.80	7.46	7.22	7.17	7.19	7.07	7.26	6.78	6.79	6.52	6.58	6.01	6.55
CaO	10.13	10.23	11.19	10.94	11.12	10.59	10.63	10.40	9.81	10.49	11.60	9.28	9.88	9.55	9.96	9.76
Na_2O	2.27	2.37	1.85	2.14	1.76	2.09	1.78	2.18	2.35	2.24	2.10	2.54	2.30	2.34	2.47	2.18
K_2O	0.83	1.12	0.69	0.57	0.93	0.83	1.07	1.09	1.45	0.93	1.26	1.54	0.99	0.91	1.23	1.53
P_2O_5	0.14	0.18	0.13	0.14	0.10	0.14	0.13	0.15	0.12	0.15	0.16	0.12	0.14	0.19	0.17	0.15
Sum	99.02	99.79	99.23	99.20	99.27	99.72	99.41	99.29	99.17	99.76	99.14	99.57	99.01	98.30	99.73	99.33
FeO	5.60	6.24	5.15	5.12	5.30	6.77	5.96	6.61	5.43	6.58	4.02	3.70	6.60	6.61	5.25	5.54
Fe_2O_3	5.16	3.67	5.05	4.93	4.51	2.93	4.21	3.54	4.31	3.83	6.02	6.55	3.27	3.72	4.35	5.00
H2O+	1.14	2.61	3.39	1.30	2.51	2.91	5.29	2.94	1.95	1.64	2.71	3.89	0.71	1.43	0.71	3.96
Mg#	62.4	62.4	62.3	61.8	61.2	60.2	59.3	59.2	59.0	58.9	58.7	58.4	57.5	56.7	56.5	56.4
Rb	24	37	5	21	6	4	20	47	30	28	42	47	40	36	40	43
Sr	189	245	193	191	260	393	404	217	246	193	219	366	181	177	216	705
Ba	189	203	187	176	203	189	285	193	930	252	230	387	224	238	260	1150
Zr	120	107	95	106	97	96	109	105	105	110	108	117	113	128	130	123
Nb	11	12	9	10	10	11	11	11	12	12	10	12	11	12	12	17
Y	28	29	27	31	28	25	30	33	38	31	41	30	33	33	35	71
V	295	272	283	253	272	275	255	242	297	292	281	310	275	290	275	303
Cr	645	410	395	270	360	360	210	250		180	305	205	185	260	175	
Ni	123	92	76	77	88	75	70	69	76	80	68	65	62	64	80	57
Zn	87	97	65	73	80	80	70	89	85	63	60	53	21	28	115	63
Zr/Nb	10.9	8.9	10.5	10.6	9.7	8.7	9.9	9.5	8.8	9.2	10.8	9.8	10.3	10.7	10.8	7.2
La	14.0	11.6			9.7				14.6	12.4			12.9	13.3	17.4	
Ce	28.4	27.6			21.9				28.3	24.4			27.2	27.4	31.8	
Nd	18.3	15.8			11.5				17.6	14.0			16.1	15.0	17.8	
Sm	3.13	3.03			2.71				3.54	3.55			3.2	3.83	3.76	
Eu	0.94	1.03			0.95				1.30	1.10			1.1	1.21	1.21	
Tb	0.53	0.56			0.54				0.66	0.88			0.64	0.57	0.72	
Yb	1.80	1.82			1.20				2.04	1.95			2.01	2.3	2.2	
Lu	0.27	0.26			0.17				0.27	0.33			0.29	0.32	0.27	
$La/Yb_{(n)}$	4.1	4.1			5.2				4.6	4.1			4.1	3.7	5.1	

[a] West refers to western part of Maranhão province (Fig. 1), [b] East refers to eastern part of Maranhão province

group has a relatively wide SiO_2 range, from 49 to 56 wt%, and displays decreasing Ti, Fe, and Mg with increasing SiO_2. There is also a comparatively large range in FeO*/MgO, with which TiO_2 inversely correlates. The low-Ti group has more restricted SiO_2, about 51 to 55 wt%, and also decreasing MgO with SiO_2; TiO_2 increases slightly with SiO_2, and FeO* has no trend. There is a notable difference in $Mg\#s = Mg/(Mg + Fe^{+2}) \times 100$) between these two groups (Table 1). High-Ti basalts have approximately Mg# 40, while the low-Ti basalts have about Mg# 59.

The high-Ti group has increasing incompatible-element abundances attending TiO_2 decreasing from 4.1 to 2.6 wt% (Fig. 3). Sr, however, does not correlate with Ti, and V increases with Ti. The low-Ti group shows slightly increasing Zr and P and high amounts of weathering-sensitive Sr and Ba in a few samples. Sample 9 has secondary mineralization that apparently accounts for its high Y and Nb.

Both basalt groups are light rare-earth element (LREE) enriched (Fig. 4). However, the high-Ti group has greater LREE abundances and higher $La/Yb_{(n)}$ than the low-Ti group.

Plagioclase, clinopyroxene, and pigeonite compositions were examined in four samples to determine differences between high- and low-Ti basalts, and the alteration of plagioclase. Low-Ti basalt (sample 4A) has plagioclase and pyroxene averages of $An_{70}Or_{1.3}$, $Fs_{15}Wo_{36}$ (cpx), and $Fs_{25}Wo_{8}$ (pg).

High-Ti basalt (sample 1) has averages of $An_{49}Or_{3.7}$, $Fs_{22}Wo_{36}$ (cpx), $Fs_{38}Wo_{9}$ (pg). Low-Ti basalts 2 and 2a, which co-exist with high-Ti basalts in the eastern part, have plagioclase partially altered (deuterically?) to albite-rich (An_{90}) and orthoclase-rich (Or_{50-85}) areas. Pyroxenes in high-Ti basalts are not unusually high in TiO_2, less than 1 wt%, but both clinopyroxene and pigeonite in high-Ti basalts have more TiO_2 than those phases in low-Ti basalts (Fig. 5).

in wt% and volatile-free (after 1000° C ignition); trace elements in ppm

Low-Ti (east[b])		High-Ti basalts										
2	2A	33A	3	31A	1A	2B	30A	32A	33	30B	1	32
52.01	50.52	49.18	51.37	49.70	52.88	52.48	51.55	52.14	50.41	53.19	52.79	56.08
1.15	1.80	4.14	3.38	4.34	3.48	3.70	3.56	3.68	3.68	3.56	3.38	2.55
13.72	14.55	13.80	12.81	13.30	13.60	13.73	13.40	13.38	13.10	13.50	13.70	13.64
9.75	13.15	13.09	13.37	13.55	12.29	12.81	12.63	13.23	13.80	12.90	12.65	11.93
0.17	0.21	0.17	0.20	0.18	0.18	0.19	0.18	0.19	0.21	0.19	0.20	0.20
7.28	5.85	5.33	5.33	4.75	4.24	4.33	4.21	4.25	4.16	3.88	3.78	2.93
10.00	7.40	9.10	8.17	8.46	5.42	7.80	7.57	7.48	8.03	6.65	6.48	5.24
4.07	3.80	2.54	2.56	2.52	4.00	2.65	2.87	3.05	2.59	3.50	3.55	3.37
1.47	1.57	1.33	1.69	1.48	2.54	1.82	1.93	1.71	1.72	2.18	2.35	2.67
0.14	0.16	0.46	0.64	0.55	0.63	0.71	0.70	0.68	1.00	0.77	0.76	0.97
99.76	99.01	99.14	99.52	99.83	99.26	100.22	98.60	99.79	98.70	100.32	99.64	99.58
6.71	10.44	8.57	8.58	7.93	7.82	8.54	7.56	8.90	8.30	6.86	8.36	7.47
3.37	3.01	5.02	5.37	6.24	4.96	4.74	5.63	4.81	6.11	6.70	4.76	4.95
0.92	2.24	1.29	1.32	1.65	1.18	2.10	0.78	1.62	2.07	0.99	1.20	2.17
59.7	46.8	44.6	44.1	41.0	40.6	40.1	39.8	38.9	37.4	37.3	37.2	32.7
45	38	30	33	33	49	41	33	42	34	47	56	54
276	205	513	455	471	400	456	471	490	486	450	460	456
394	354	425	558	483	680	558	630	577	544	654	765	847
128	135	220	275	328	352	316	314	296	267	333	339	436
8	9	23	29	25	39	31	35	30	32	37	37	44
30	38	35	39	34	46	41	44	41	45	45	45	58
505	447	447	337	424	275	305	331	341	362	293	239	135
455	215	115	100	10	40	120	25	40	55	110	15	60
64	53	54	40	46	28	28	27	28	15	28	8	10
85	78	103	150	125	180	124	135	138	150	135	165	185
16.0	15	9.6	9.5	9.5	9.0	10.2	9.0	9.9	8.3	9.0	9.2	9.9
12.2	13.8	31.8	41.0	29.6							35.5	55.6
25.4	29.5	71.0	84.5	63.1							72.2	131.0
10.0	16.0	54.4	59.2									78.0
3.23	4.72	7.89	10.07	7.82							10.89	14.9
1.08	1.57	2.80	3.38	2.55							3.82	4.65
0.63	0.91	1.22	1.75	1.47							2.08	2.20
1.92	2.4	2.30	3.06	3.17							3.58	3.88
0.23	0.49	0.26	0.34	0.33							0.38	0.65
4.1	3.7	8.9	8.7	6.0							6.4	9.3

K-Ar ages

New data on seven samples, listed in Table 2, fall into the Mesozoic age range noted by Sial (1976), and show that Maranhão ages correspond with sample locations and compositions. Four low-Ti samples from the western part have ages of about 154, 160, 165, and 189 Ma, and two high-Ti samples from the eastern part are about 115 and 122 Ma. Eastern low-Ti basalt 2 is about 144 Ma. However, it has Ab- and Or-rich alteration areas in plagioclase, which probably contribute to the rock yielding a lower than actual age. That is, eastern low-Ti basalt may represent the low-Ti Triassic-Jurassic magmatism of western Maranhão province. It appears, then, that on the basis of ages, compositions, and textures, basaltic magmatism occurred in the Maranhão basin of northern Brazil as mainly low-Ti Triassic-Jurassic flood basalts, and as high-Ti Cretaceous hypabyssal emplacement.

Isotope compositions

We analyzed nine whole-rock samples for Sr, Nd, Pb, and O isotopes. Samples 2 and 2A were included despite having plagioclase altered in part to Ab- and Or-rich zones because they are examples of low-Ti basalt intermixed with high-Ti basalt in eastern Maranhão province.

The Sr and Nd isotope compositions are enriched relative to bulk earth (Table 3; Fig. 6), where low- and high-Ti basalts have essentially the same Nd isotope compositions but the low-Ti basalts have more radiogenic Sr. Expressed as initial $^{87}Sr/^{86}Sr$, the low-Ti basalts are about 0.7064, and the high-Ti basalts are about 0.7057. Maranhão is similar to Serra Geral in terms of enriched isotope compositions and by the low-Ti basalts having higher Sr isotope ratios relative to associated high-Ti basalts. There is, however, only little overlap between Maranhão and Serra Geral samples.

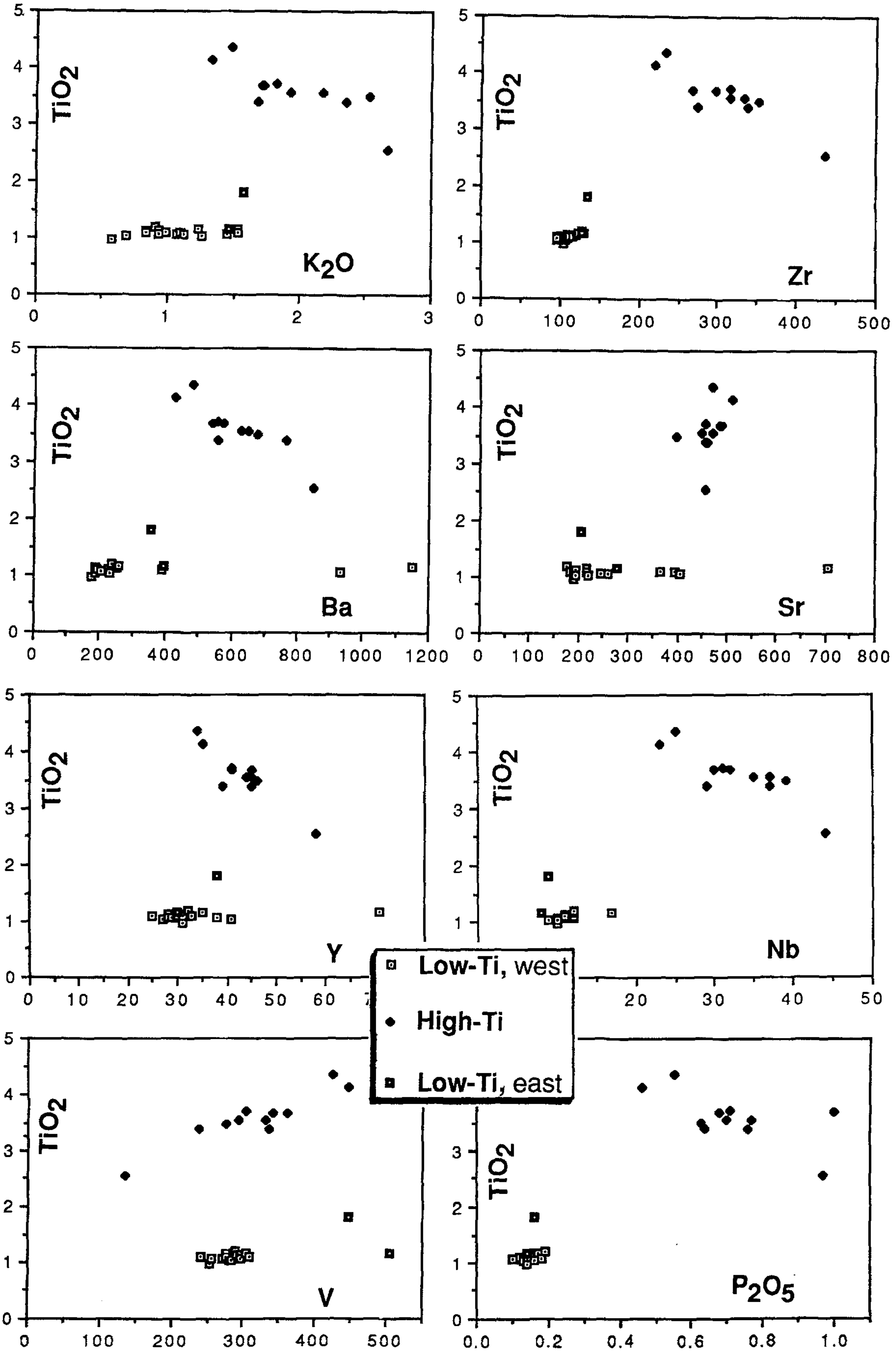


Fig. 3. Trace-element plotted against TiO_2 for the low-Ti and high-Ti Maranhão province basalts, northern Brazil. Low-Ti basalts occur in the western and eastern parts of the province (see Fig. 1)

The Pb isotope compositions are enriched relative to MORB and resemble those of Serra Geral and Walvis ridge (Fig. 6). One distinction, however, is that both types of Maranhão basalts are more radiogenic than Serra Geral high-Ti basalts, and both types fall in or close to the field for low-Ti Serra Geral basalts. Maranhão low-Ti basalts are more radiogenic than high-Ti basalts, the same relationship observed between low-Ti and

Table 2. Whole-rock K-Ar ages for low- and high-Ti basalt from the Maranhão province, northern Brazil

	K_2O^a	^{40}Ar rad (mol/g)	^{40}Ar rad (%)	Calculated age (in m.y. $\mp\sigma$)
Low-Ti basalts (west Maranhão)				
4A	0.67	1.91903×10^{-10}	79.5	189.3 ± 5.5
502	0.77	1.91389×10^{-10}	35.2	164.9 ± 5.6
28	1.06	2.54199×10^{-10}	51.2	160.0 ± 5.0
10	0.37	8.57372×10^{-11}	54.8	153.8 ± 5.4
Low-Ti basalt (east Maranhão)				
2	1.26	2.7272×10^{-10}	49.2	144.1 ± 4.7
High-Ti basalts				
32	3.17	5.75131×10^{-10}	88.7	121.8 ± 3.0
1	2.60	4.44908×10^{-10}	66.9	115.0 ± 3.7

Note – The samples were crushed, sieved (to 600–100 mesh size), washed, and treated for 30 min in 14% HNO_3 and 1 min in 5% HF solutions

The method used for gas extraction in the high-vacuum system is similar to that described by Dalrymple and Lanphere (1969). Argon analysis was performed by standard isotope-dilution procedures and by using a 60° sector, 15.2 cm-radius Neir-type mass spectrometer. Potassium analyses were performed by a lithium metaborate flux fusion-flame photometry technique. $\lambda_\varepsilon+\lambda'_\varepsilon=0.581\times10^{-10}\ yr^{-1}$. $\lambda_\beta=4.962\times10^{-10}\ y^{-1}$. $^{40}K/K_{total}=1.167\times10^{-4}$ mole/mole

[a] wt%, by flame photometry

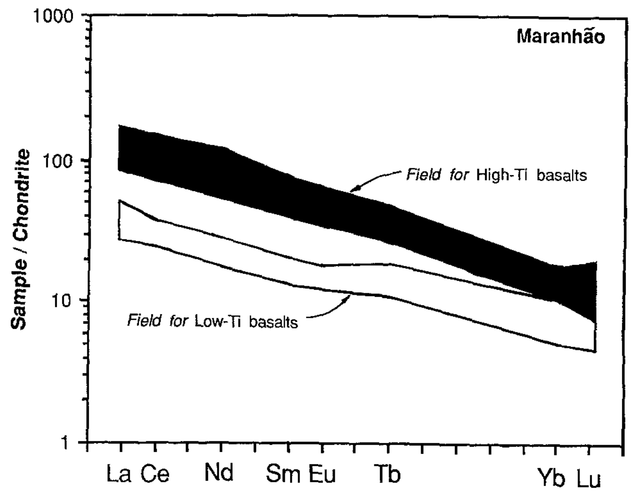


Fig. 4. Rare-earth element patterns for low-Ti and high-Ti basalts of the Maranhão province, northern Brazil

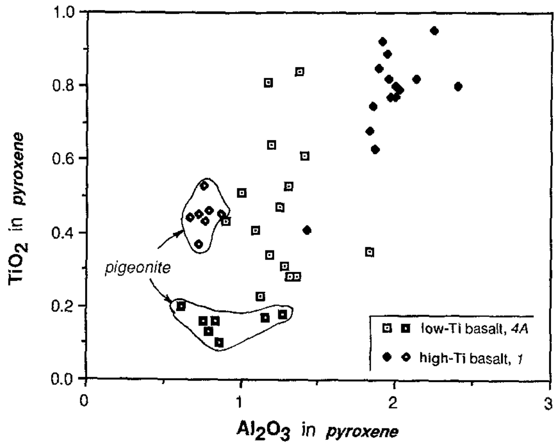


Fig. 5. An evaluation of TiO_2 in clinopyroxene (augite) and pigeonite in representative low-Ti and high-Ti Maranhão basalts. Each symbol represents one electron microprobe spot analysis

Table 3. Measured Sr, Nd, Pb, and oxygen isotope compositions for low- and high-Ti basalts, Maranhão province, northern Brazil

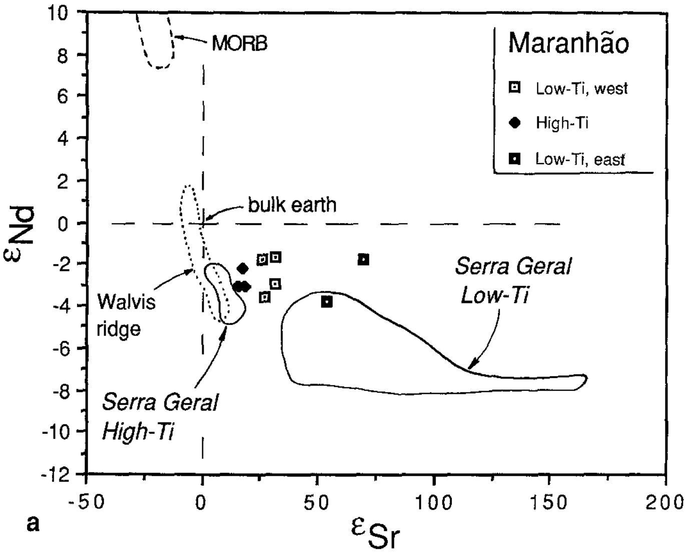
	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	Sm	Nd	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	ε_{Nd}	ε_{Sr}	$\delta^{18}O$
Low-Ti (west Maranhão)										
4A	0.70728 ± 1	0.512496 ± 05	3.831	15.44	18.522	15.611	38.727	−1.71	25.8	
502	0.70818 ± 1	0.512434 ± 05	3.383	13.75	18.625	15.640	38.712	−2.94	31.1	9.01
28	0.70801 ± 1	0.512507 ± 30	3.808	15.59	18.591	15.631	38.725	−1.6	31.1	10.02
10	0.70728 ± 1	0.512412 ± 20	3.477	14.11	18.622	15.617	38.665	−3.5	26.2	8.87
Low-Ti (east Maranhão)										
2	0.70929 ± 1	0.512394 ± 05	3.375	14.34	18.248	15.625	38.666	−3.8	53.9	12.64
2A	0.71052 ± 1	0.512516 ± 05	4.724	18.27	18.783	15.699	38.806	−1.7	69.4	11.66
High-Ti										
33A	0.70608 ± 1	0.512478 ± 30	8.768	40.03	18.243	15.579	38.557	−2.2	17.5	6.50
1	0.70620 ± 1	0.512438 ± 05	12.39		18.223	15.512	38.384	−3.0	15.1	7.53
32	0.70640 ± 1	0.512426 ± 05	15.88		18.231	15.536	38.471	−3.0	17.8	8.65

Sm and Nd by isotope dilution, in ppm

Errors for Sr and Nd isotopic compositions represent 2σ of the mean based on in-run statistics

Sr ratios normalized to $^{86}Sr/^{88}Sr=0.11940$. $^{87}Sr/^{86}Sr$ for NBS987 $=0.710226\pm9$. Nd ratios normalized to $^{146}Nd/^{144}Nd=0.7290$. $^{143}Nd/^{144}Nd$ on La Jolla standard $=0.511850\pm7$

Fractionation-related normalization factors based on replicate analyses of Pb standard NBS981: $^{204}Pb/^{206}Pb=0.08\%$. per a.m.u.: $^{207}Pb/^{206}Pb=0.05\%$ per a.m.u.: $^{208}Pb/^{206}Pb=0.09\%$ per a.m.u.



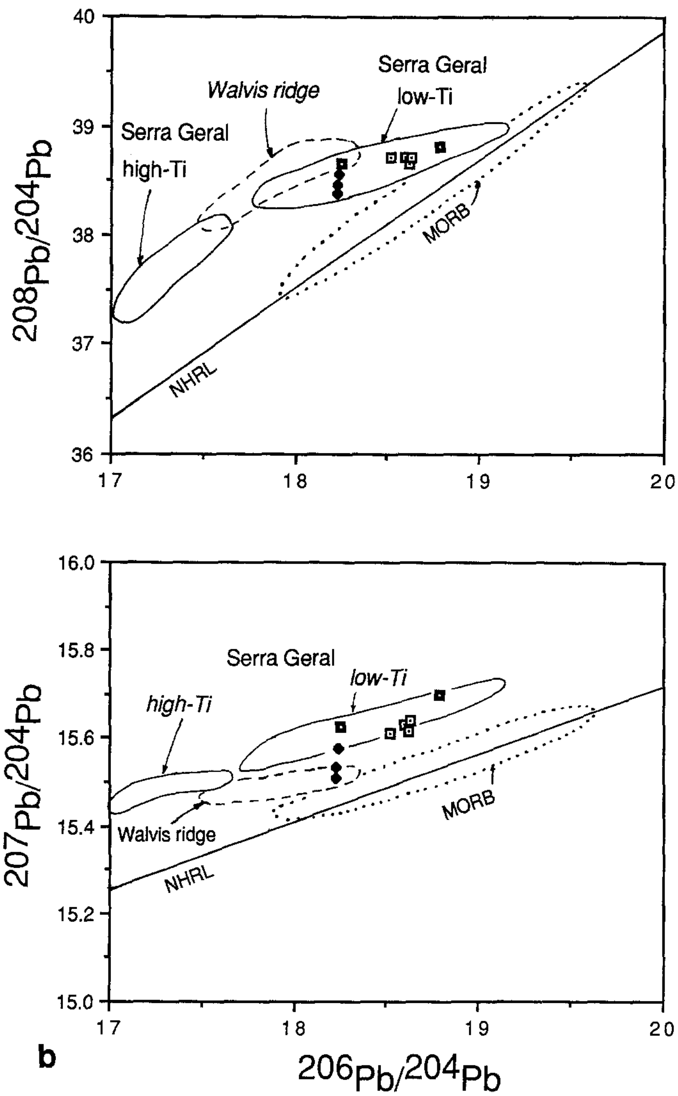


Fig. 6. a Sr and Nd isotope diagram for Maranhão province basalts compared to isotope compositions for the southern Brazil Serra Geral (Paraná) flood basalt province (Hawkesworth et al. 1986) and the Walvis ridge (Richardson et al. 1982). **b** Pb isotope diagram for Maranhão basalts and reference data (as above). The northern hemisphere reference line (NHRL) is from Hart (1984)

high-Ti Serra Geral basalts. In one case, however, a low-Ti basalt (east) has Pb isotope compositions similar to those of its associated high-Ti basalts.

The lowest $\delta^{18}O$ value is +6.5 for high-Ti basalt 33A, compatible with a mantle-source (Table 3; Fig. 7). This sample also has among the lowest initial $^{87}Sr/^{86}Sr$ values, 0.7058. The most evolved high-Ti basalt, sample 32, has a relatively high $\delta^{18}O$ of 8.65. The low-Ti basalts have higher $\delta^{18}O$ values of 9–10‰, which correspond to higher $^{87}Sr/^{86}Sr$ ratios. Low-Ti basalts 2 and 2A stand apart from the others by still higher $\delta^{18}O$ of 12, but their higher $\delta^{18}O$ probably reflects plagioclase alteration, as may their high radiogenic Sr.

Discussion

Mantle Sources – isotope compositions

Bulk compositions, Sr and Pb isotope ratios, sample locations, and ages indicate that the high- and low-Ti ba-

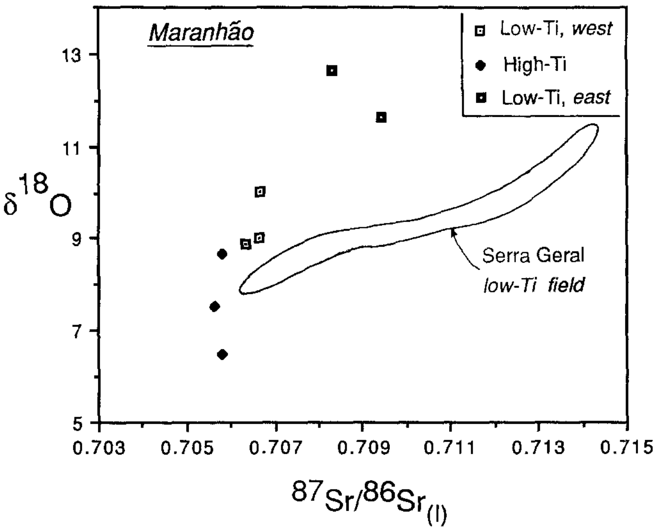


Fig. 7. Oxygen isotopes plotted against initial Sr-isotope ratios for Maranhão province basalts. The Serra Geral low-Ti basalt reference is from Fodor et al. (1985a)

salt groups of the Maranhão province had separate parentages. If the source for each group was enriched subcontinental lithosphere, material commonly promoted for flood basalts (e.g., Hawkesworth et al. 1983, 1986, 1988; Menzies et al. 1987), different zones of mantle at least 100 km apart (laterally) contributed to the western and eastern parts of the Maranhão province.

Relatively low Sr and O isotopic values indicate that minimal assimilation (and alteration) affected the high-Ti group, and the samples may therefore closely represent the isotope characteristics of their source. Similarly, high-Ti Serra Geral basalts are also interpreted to be nearly free of crustal contamination (Hawkesworth et al. 1986). The higher δ^{18}O of +8.65% for Maranhão sample 32 probably represents fractionation rather than assimilation because SiO_2 is evolved (56 wt%) and because its $^{87}Sr/^{86}Sr$ ratio is not correspondingly high (Fig. 7).

The source for Maranhão low-Ti basalts may, in light of discussions for Serra Geral low-Ti basalts (Hawkesworth et al. 1988), have ancient subduction zone components and be compositionally distinct from that for high-Ti basalts (e.g., higher $^{87}Sr/^{86}Sr$). On the other hand, the isotope compositions presented here are also consistent with low-Ti magmas (more radiogenic Sr and Pb and higher δ^{18}O relative to the high-Ti group) having had isotope compositions similar to those for high-Ti magmas but modified by assimilation of continental crust, and by the rocks having undergone weathering. The positive correlation between Sr and O isotopes of the low-Ti basalts suggests a history of assimilation-fractional crystallization processes, as it does for Serra Geral low-Ti rocks (Fig. 7) – although we cannot discount weathering as having influenced the oxygen isotope compositions.

Available isotope data, then, characterize two basalt groups in the Maranhão province as originating in different zones of subcontinental mantle, or, alternatively, in essentially the same source composition, followed by some modification of isotope compositions in low-Ti magmas by crustal contamination. While the first model easily explains neighboring but distinctive basalt groups, it requires special geologic processes to create regional heterogeneity in the mantle beneath northern Brazil. The alternative model does not complicate the nature of the subcontinental mantle, but requires different percentages of partial melting of a single source. Similar Pb isotope compositions for sample 2 (low-Ti, east) and its associated high-Ti basalts (Fig. 6b) supports the concept that one source composition can produce both low- and high-Ti basalts. We evaluate this situation in terms of major and trace elements.

A common source?

Evaluating one source for all Maranhão basalts requires modeling parentages in picritic liquids that represent either "low" or "high" percentages of melting of one mantle composition (as integrated over, for example, tens of kilometers). (Picritic parentage has been viewed favorably for flood basalts, e.g. Cox 1980; Cox and Hawkesworth 1985). As presented for the Mesozoic low-Ti and high-Ti Serra Geral basalts (Fodor 1987), high source melting, such as 25%, would produce liquids with incompatible-element abundances relatively lower than in liquids produced by half as much melting. Therefore, greater melting yields low-Ti (and low Sr) liquids susceptible to increases in $^{87}Sr/^{86}Sr$ from continental crust. Less melting accordingly yields basaltic liquids higher in TiO_2, or parentage more suitable for the high-Ti basalts.

The Mg#s of both Maranhão basalt types indicate that they are products of extensive fractionation. Table 4 shows calculations for fractionation of viable picritic parent liquids to produce representative Maranhão low- and high-Ti basalt compositions. The calculations use phase compositions that approximate equilibrium with liquids compositionally midway between parent and daughter (Appendix).

A parent with about 18 wt% MgO (from about 25% source melting) could yield low-Ti basalt by crystallization of nearly equal amounts of olivine, clinopyroxene, and plagioclase (gabbro crystallization of Cox 1980) for about 65% total. A parent with about 14 wt% MgO and slightly higher incompatible-element contents could yield high-Ti basalt by crystallizing a preponderance of plagioclase plus olivine and clinopyroxene for a total of nearly 80% crystallization. These postulated high-Ti magmas subsequently would have crystallized Fe-Ti oxides as indicated, for example, by decreasing Ti and V over the compositional range observed for the high-Ti group (Fig. 3).

These models (Table 4) are not specific about magma evolution leading to low- and high-Ti Maranhão basalts because it is difficult to predict exactly what phenocryst compositions best represent such extensive crystallization. Nor can we establish where this crystallization occurred, whether at the mantle-crust interface as envisioned by Cox (1980), or continually from the mantle up to reservoirs in middle and/or upper crust. The main thrust of the models is demonstration that straightforward crystallization histories can explain some compositionally different basalt types as having parentages in the same source composition (isotope composition now obscured by varying amounts of magma contamination). Isotopic "homogeneity" as such in the source is not necessarily inconsistent with heterogeneity as depicted by ultramafic nodules and alpine peridotite with internal ranges in isotope compositions (Hamelin and Allegre 1988; Erlank et al. 1987). This is because melting integrated over large regions, as needed for flood basalts, could produce liquids that smooth out variations to achieve net Sr, Nd, and Pb values that describe a large mantle region.

The compositional similarity and limited range (e.g., Mg# 62–56) of low-Ti basalts in both the Serra Geral and Maranhão provinces suggest that these rocks represent regularly replenished magma reservoirs. Such reservoirs, in turn, could have kept the crustal environment warm and relatively easy to digest (e.g., low-Ti basalts

Table 4. Calculations for fractional crystallization relationships between hypothetical picritic liquids[a] and low- and high-Ti basaltic rocks[b] of the Maranhão province, northern Brazil. Trace-element calculations[c] include 25% and 12% partial melting of mantle (ol:cpx:opx as 60:15:25; or, where noted, ol:cpx:opx:gar as 60:10:25:05) to produce picrite liquids 'lo' and 'hi', respectively

	Mantle	Picrite 'lo'	Low-Ti basalt		Picrite 'hi'	High-Ti basalt	
			obs.	(calc.)		obs.	(calc.)
SiO_2		48.5	51.52		48.4	49.18	
TiO_2		0.50	1.14		0.95	3.95	
Al_2O_3		11.8	13.90		14.1	13.80	
FeO		8.8	10.29		9.2	13.09	
MgO		18.1	8.63		14.6	5.33	
CaO		10.9	10.03		10.8	9.10	
Na_2O		1.25	2.27		1.65	2.54	
K_2O		0.20	0.60[e]		0.38	1.5	
Sr (ppm)	45	180	215	(289)	325	480	(441)
Ba	16	64	192	(180)	124	489	(524)
Zr	9.5	35	105	(102)	55	245	(256)
Nb	0.8	3.2	10	(9.6)	6.2	26	(30)
Y	4	12.25	29	(24)	13.9	36	(39)
Y (garnet in source)		12.6		(25)	13.1	36	(37)
La	1.05	4.2	11.8	(11.9)	7.9	34	(34)
Sm	0.29	1.15	3	(3.2)	1.97	8.6	(8.5)
Eu	0.11	0.44	1	(1.08)	0.73	2.9	(2.5)
Sm/Eu_n	0.99	0.99	1.13	(1.12)	1.02	1.12	(1.28)
P_2O_5%	0.014	0.055	0.14	(0.16)	0.11	0.55	(0.53)
TiO_2%	0.12	0.48	1.14	(1.35)	0.85	3.9	(3.8)
K_2O	0.045	0.17	0.60[e]	(0.50)	0.35	1.5	(1.5)
Crystallization[d] of picrite (based on major-element calculations)							
ol		25.8			24.5		
cpx		20.7			20.2		
pl		20.6			34.9		
residual		33.8			21.2		
$\sum r^2$		0.01			<0.01		

[a] Picrite major elements based on experimental melts (Jaques and Green 1980)

[b] Major elements represented by samples 4A for low-Ti, and 33A for high-Ti (Table 1), except Ti and K in high-Ti sample, which are treated as trace elements; trace elements represented by averages of least evolved samples (low-Ti: 4, 13, 506, 26, and 19; high-Ti: 33A, 3, and 31A

[c] Distribution coefficients used are in the Appendix. Melting proportions 1:8:1 for ol:cpx:opx, and 1:4:1:4 for ol:cpx:opx:gar

[d] Phase compositions listed in Appendix

[e] K_2O arbitrarily set to 0.6 from observed 0.8 wt% to adjust for likely enrichment due to alteration/weathering

have more radiogenic Sr and Pb). The proposed petrogenesis is consistent with reservoirs for high-Ti magmas having little or no magma replenishment, thereby cooling relatively rapidly (e.g., retaining lowest Sr, Pb, and O isotope values) and fractionating extensively.

Mantle Sources – trace elements

The trace-element concentrations calculated in the melting and fractionation models (Table 4) use an ol+cpx+opx source, except where 5% garnet was included for Y because garnet influences the partitioning of Y more than other trace elements (e.g., Green et al. 1989). Using reasonable trace element abundances (Table 4) for the mantle source yields values that compare well with trace element values in Maranhão low- and high-Ti basalts. Certain trace-element ratios also match well across the two groups, such as Zr/Nb and Ba/Nb (Fig. 8).

Hawkesworth et al. (1988) question reconciliation of high-Ti and low-Ti basalts through a common source because modeling certain elements cannot perfectly reproduce observed abundances in single (i.e., representative) rock compositions. Imprecise fits, however, can be attributed to any of several variables (selection of modeled compositions; alteration, e.g., Rb was intentionally not modeled; crustal contamination; distribution coefficients inappropriate over extensive crystallization in varying P-T and open/closed-system environments, e.g., Nielson 1988; Green et al. 1989; mode of source and melt proportions used in model) – and some latitude should therefore be afforded trace element models. Additionally, a Eu anomaly could appear in high-Ti liquids after more than 30% pl separation (see Sm/Eu in Table 4). On the other hand, highly oxidizing conditions, which may occur during the production of high-Ti(Fe) magmas (Juster et al. 1989), may reduce Eu plagioclase/liquid partitioning (Drake and Weill 1975) and concomitantly reduce the likelihood of a negative Eu anomaly forming during plagioclase crystallization. In any case, low Mg# and $Al_2O_3 \sim 14$ wt% assure that substantial crystallization, including pl, is part of the high-Ti basalt history.

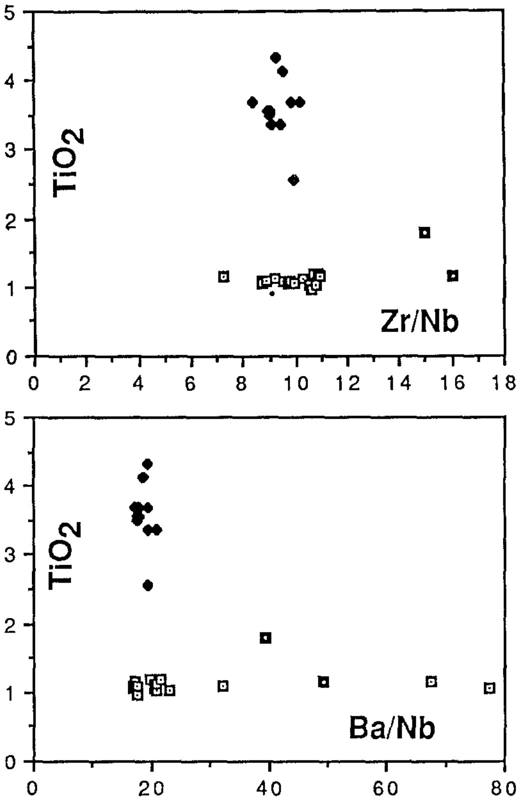


Fig. 8. Similarity of trace-element ratios for Maranhão high-Ti basalts and low-Ti basalts (western portion) (symbols as in Figs. 2, 3, 6 and 7); ratios in low-Ti basalts of eastern Maranhão are higher, although high Ba in part reflects weathering and/or alteration

In general, trace element abundances are compatible with essentially one source composition common to both low- and high-Ti basalt types. This is not, however, to discount some variations in modal mineralogy that are likely to exist in the source over the lateral distance represented by the Maranhão province. Higher V and Zr/Nb ratios in eastern low-Ti basalts than in western low-Ti basalts (Figs. 3 and 8) suggest such variations. But on the basis of the samples presented here, there is no indication from trace element concentrations in Maranhão basalts that notably different source materials were necessary to have produced the notably different basalt types.

Significance of K-Ar ages

According to the ages of basaltic dikes on Liberia (Dalrymple et al. 1975), the eastern North American diabase dike system, and offshore northern Brazil basaltic rocks (Fodor and McKee 1986), magmatism attended the rifting of North America from Africa about 200 million years ago to open the central North Atlantic Ocean (May 1971). The Maranhão low-Ti basalts of northern Brazil, having K-Ar ages that range from about 160 to 200 Ma, fit into this tectonic event. The ages of the Maranhão high-Ti basaltic rocks instead correspond to the opening of the equatorial Atlantic, which is estimated at about 120 Ma (Pindell et al. 1988).

Speculation on melting

In a qualitative way, the bi-modal ages of Maranhão basalts and the corresponding tectonic events can be used to speculate why varying percentages of melting occurred (as proposed above). The older basalts (Triassic-Jurassic) may have had origins above a hotspot regime, as suggested by continental reconstruction that places Maranhão near the St. Helena hotspot at 180 Ma (Morgan 1983). Melting from a heat source plus decompression due to rifting may have enabled high percentages of partial melting. On the other hand, the 150–120 Ma continent reconstruction (Morgan 1983) does not have a hotspot associated with Maranhão. Possibly, then, only decompression accounted for melting, caused by equatorial rifting occurring about 120 Ma (Pindell et al. 1988), and melting was therefore comparatively lower in percentage.

Flood basalt isotopes and the DUPAL anomaly

The Maranhão samples examined here have more radiogenic Sr and Pb (and some Nd) isotope compositions than the high-Ti basalts of the Serra Geral province in southern Brazil, but overlap isotopically with some low-Ti Serra Geral and Walvis ridge basalts (Fig. 6). Any similarity in Pb-isotope values between Maranhão and Serra Geral is significant in terms of the DUPAL anomaly (as described by Hart 1984, 1988). DUPAL contours show that oceanic mantle compositions change over the distance from equatorial to middle latitudes in the South Atlantic, or a latitudinal distance equivalent to that between Maranhão and Serra Geral provinces. Extrapolation of Hart's (1984) Pb-isotope contours onto Brazil from the ocean suggests a corresponding difference in continental mantle beneath northern and southern Brazil.

Comparing Maranhão and Serra Geral Pb-isotope compositions, however, shows otherwise. Figure 9 expresses isotope compositions for high- and low-Ti basaltic rocks from both Maranhão and Serra Geral and for the Walvis ridge as $\Delta 7/4$ and $\Delta 8/4$. Assuming that Pb data for high-Ti basalts do not reflect much, if any, continental component, there are only small differences among Maranhão, Serra Geral, and Walvis ridge. That is, both northern and southern Brazil subcontinental mantle deviate from the North Atlantic reference line by nearly the same amount. This point is further made by the Tertiary Abrolhos Islands offshore Brazil at 18° S; they are located between northern and southern Brazil and do conform to the DUPAL contours (Fig. 9). All of these features are inconsistent with large-scale heterogeniety of mantle beneath Brazil prior to rifting of South America from Africa. They are more in line with a large-scale subcontinental homogeniety when compared to the varying isotopic compositions observed for South Atlantic mantle represented by oceanic basalts.

If subcontinental mantle of Brazil does not conform to DUPAL contours, and if DUPAL characteristics existed deep in the mantle before the opening of the Atlantic (Hart 1988), manifestation of the anomaly may have

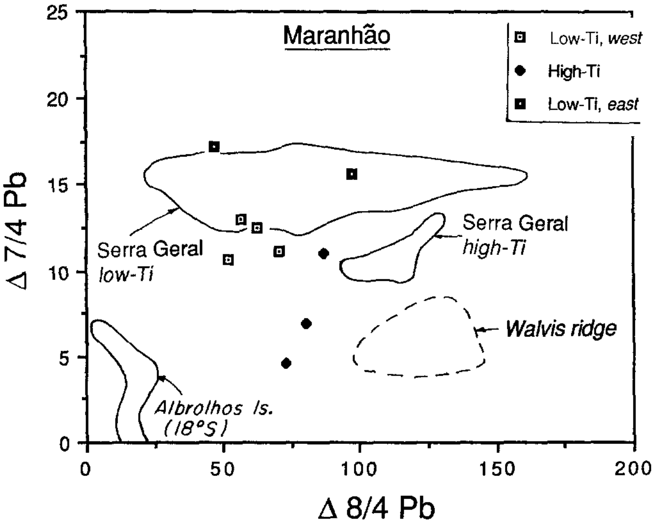


Fig. 9. Pb isotopes in Maranhão and Serra Geral basalts plotted as delta 207/204 Pb and delta 208/204 Pb, or deviations from the northern hemisphere reference line (see Hart 1984, for explanation), to evaluate these provinces with respect to the DUPAL anomaly. There is little difference between two Mesozoic continental provinces about 1500 km apart, yet the Walvis ridge and Abrolhos Islands (Fodor et al. 1989) are oceanic provinces that conform to DUPAL

been suppressed by continental lithosphere. Rifting, however, removed this "barrier" to enable DUPAL to participate in oceanic magmatism. If DUPAL is inherent in upper, depleted mantle (i.e., MORB source), it is manifested through various mixing proportions between depleted mantle and enriched underlying mantle (DMM and EMII of Hart 1988). This can occur after continental rifting permits low pressure (upper) mantle melting (e.g., Fodor and Vetter 1984) to contribute to oceanic magmatism.

Appendix

Mineral compositions used in Table 4

	Picrite 'lo'			Picrite 'hi'		
	pl	ol	cpx	pl	ol	cpx
SiO_2	47.9	39.9	53.1	50.5	39.2	53.0
TiO_2			0.55			0.70
Al_2O_3	33.0		1.5	30.9		2.0
FeO*	0.55	14.9	6.4	0.65	18.1	8.8
MnO		0.19	0.17		0.24	0.23
MgO		44.8	17.6		41.6	16.2
CaO	16.5	0.22	19.5	14.5	0.27	18.7
Na_2O	2.2		0.22	3.0		0.26
K_2O	0.06			0.18		
An	80			72		
Fo		84			80	
Fs			10			14
Wo			40			39

Distribution coefficients used in Table 4

	ol	cpx	opx	pl	gar
Sr	0.01	0.06	0.04	1.8	
Ba	0.01	0.01	0.01	0.2	
Zr	0.01	0.1	0.18	0.01	
Nb	0.01	0.01	0.01	0.01	
Y	0.13	0.9	0.18	0.18	9.1
La	0.01	0.06	0.015	0.13	
Sm	0.01	0.19	0.045	0.07	
Eu	0.01	0.2	0.06	0.4	
P	0.01	0.01	0.01	0.01	
Ti	0.01	0.20	0.02	0.01	
K	0.01	0.01	0.01	0.18	

Data sources: Schilling et al. (1978), set 1; Le Roex et al. (1981)
Green et al. (1989)

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