GEOCHEMISTRY OF BASIC DIKES FROM WESTERN BAHIA, BRAZIL

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RESUMO Foram investigadas a petrologia e a geoquímica de catorze amostras de diques relativamente modernos do oeste da Bahia, Brasil. Muitos dos diques são toleítos continentais embora, em algumas características geoquímicas, pareçam tender a tipos oceânicos.

Poucos diques, pertencentes provavelmente a uma geração muito mais moderna, têm tendências alcalinas, e uma amostra rica em titânio e ferro é provavelmente o resultado de um estágio tardio de segregação.

Os toleítos mostram variações de composições como resultado de uma provável cristalização, fracionada durante a ascensão do magma. Esse fracionamento ocorreu no sentido de uma típica tendência de diferenciação com enriquecimento em ferro.

Alguns elementos-traços peculiares (conteúdo em Rb e Sr, e relação K/Rb) indicam que os diques da Bahia mostram certas afinidades com alguns doleritos do Karroo e provavelmente com os basaltos brasileiros da Serra Geral.

ABSTRACT Petrology and geochemistry of 14 samples of relatively young dikes from the Western Bahia, Brazil, have been investigated. Most of the dikes are continental tholeiites although in some geochemical characteristics they appear to be swifited towards oceanic types. A few dikes, belonging probably to a much younger generation, have alkalic tendencies and one titania-iron-rich sample is probably the result of a late stage segregation. The tholeiites show compositional variations as a result of probable fractional crystallization during the ascension of the magma. This fractionation occurred in the sense of a typical iron-rich differentiation trend. Some trace element peculiarities (Rb, Sr contents and K/Rb ratio) indicate that the Bahia dikes show certain affinities with some Karroo dolerites and probably with the Brazilian Serra Geral basalts.

INTRODUCTION The basement area in the Ibitiara-Ibiajara district (Western Bahia State, Brazil), the geology and petrology of which has been roughly described (Schobbenhaus, 1967; Nagell *et al.*, 1967), is intersected in all its component units by post-orogenic basic dikes. Basic dikes are diffused in all continental masses and a considerable number of published data exist dealing with their petrology and chemistry. For the Brazilian shield, on the contrary, very scanty data are available on basic dikes, the few papers published concern mainly their mineralogy and petrology (see for example Marini *et al.*, 1967; Betten-court and Ruegg, 1972; Oliveira *et al.*, 1972). Recently Gomes and Berenholc (1973) studied chemical variations within a dike of Southern Brazil. The present paper would contribute to the knowledge of the petrology and chemistry of basic dikes from northern regions of the Brazilian shield. In more general terms, results of this research may be used for comparative studies between various groups of basaltic rocks.

SHORT DESCRIPTION OF THE GEOLOGY OF THE AREA AND FIELD OBSERVATIONS The area from which samples were collected is situated in Western Bahia State and extends more than 60 km towards NS and 10 km WE, extending essentially between Ibitiara and Ibiajara. In this area several different structural units are recogni-

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zable. The oldest basement rocks, attributable to the lower Precambrian (gneiss, migmatites), crop out mainly in the extreme northern and southern parts of the area and are crossed by two principal granite intrusions (Ibitiara and Ibiajara granites) characterized by coarse grained texture and subvolcanic characteristics. A metasedimentary sequence (arenites, phyllites, slates), slightly metamorphosed to the greenschist facies, covers the ancient basement rocks over a large part of the area. It strikes towards NW-SE, together with other structural units. Metavolcanic rocks of rhyolitic and rhyodacitic composition (Froes *et al.*, 1972) form a belt extending NW-SE, concordant therefore with the general tectonics of the area. Relationships between the various units are hard to define because of lack of control of contacts and age data. The metasedimentary formation is normally considered to be upper Precambrian, this concordant with the sole age determination giving about one billion years (Tavora *et al.*, 1967). The same authors dated one sample of the granite of Ibitiara (500 m.y.) and one sample of the metavolcanic rocks (390 m.y.). Basic rocks present in the area are constituted by banded amphibolites in migmatitic terrains, epidote-rich rocks, and diabasic dikes cutting ancient basement rocks as well granites and metasediments. Most of the dikes suffered strong deuteric or metamorphic alteration into epidote-saussurite-calcite products. The present paper considers samples coming from 13 unaltered or slightly altered basic dikes crossing granite intrusions and from one dike cutting the metasedimentary sequence. The main field features presented by the rocks studied are now summarized.

Dike thickness varies from a minimum of few cm to a maximum of 50 m. Their general strike is NW concordant with the main tectonics of the area, except for a few dikes that strike NE, almost orthogonally with the others. Age determination on diabases of the area are completely lacking, but if we accept for all the granitic rocks of the area an age in the range of 500 m.y., we must deduced that a great part of the dikes must be younger than this value. Furthermore, the NE striking dikes, even if mutual intersections with other dikes are not visible, on the basis of petrologic and chemical features, can be consider younger or very much younger (mesozoic?) than other diabases. Different generations of dikes extending over large intervals of time are very common in archaic complexes (see for example Rivalenti and Sighinolfi, 1970).

Age estimates through extrapolations from data on neighbouring areas are not possible, since the sole age data available on dikes from Western Bahia concerns older (partially metamorphosed) dikes cutting the metasedimentary complex. Ages of these dikes vary from 1 150 to 530 m.y. (Tavora *et al.*, 1967).

All the dikes show chilled contacts. From rims to the center of the dikes the grain size normally increases, particularly in the case of larger dikes for which the texture passes from aphanitic to doleritic near the center.

PETROLOGY All the samples are characterized by an ophitic intergrown of plagioclase and clinopyroxene. Plagioclase is often zoned and varies from An_{81} from the center of some crystals to An_{39} . Pyroxene is usually of augitic type, but pigeonite and enstatite may also appear near the contacts of the dikes. Olivine is usually limited to minor amounts in some samples and has a composition ranging from Fa_{80} to Fa_{50} . Olivine, pigeonite, and enstatite, when they occur, are partially re-absorbed and show augitic rims.

Biotite is normally a reddish-brown type and is often strictly associated with magnetite and ilmenite. Brown and green hornblende may be also present. Alteration (deuteric or metamorphic) of the preceeding minerals gives biotite, epidote, uranalite, quartz and particularly calcite in some samples. No strong metamorphic features can be seen to have affected the dikes except a probable neoformation of a part of the biotite and hornblende

(and quartz in the sample 23-01). The samples striking NE-SW (samples 23-122, 23-M-98 and Liyr) belong probably to a later generation and differ slightly from the other dikes in some structural and mineralogical features. The texture is a little more coarse grained, the plagioclase is fairly acid (up to 30% An) and there are major amounts of biotite, hornblende and olivine phenocrystals.

CHEMICAL DATA The analytical results for major and trace elements as well as Niggli numbers and some element ratios are reported in Table I. The CIPW norms are given in Table II. Calculation of norms were made considering the P_2O_5 to be O; this would not alter the calculated values too much. Water content and FeO/Fe_2O_3 ratio (together with petrographic observations) give an idea of the rate of deuteric alteration which the samples have undergone. Examination of the norms reveals most of the rocks to be tholeiites (or olivine tholeiites when normative olivine and hypersthene appear) following Yoder and Tilley (1962). In addition most of the samples can be classified as tholeiites according to the definition of Miyashiro *et al.* (1969) (when olivine microphenocrysts are present, the crystallization sequence olivine-plagioclase-clinopyroxene can be discerned). Slight compositional variations within the various dikes can be explained in terms of some differentiation phenomena which the tholeiitic magma suffered during its ascent, except for a few dikes (all probably much younger) showing an alkalic tendency. If the samples are plotted on an AFM diagram (see for example Green and Poldervaart, 1958; Mac Donald and Katsura, 1964) most of the samples follow a tholeiitic trend, although clearly shifted towards an iron-rich trend as sometimes occurs when a tholeiite magma is differentiated (Kuno, 1968), and only a few samples approximate an alkali trend. The same indications can be drawn plotting the samples on the $MgO-FeO+Fe_2O_3$ diagram (Fig. 1).

One sample of alkalic character gives results very similar to the "high-titania" alkali basalts described by Robinson (1969) and to some late cenozoic dikes from Western Greenland (Rivalenti and Sighinolfi, 1970). Furthermore, similar rocks have been recently found in Hawaii and were interpreted as late stage segregation products (Bunch and Keil, 1971).

DISCUSSION OF SOME GEOCHEMICAL TRENDS The important role of trace element distribution in understanding relationships between various basaltic groups has been outlined by several authors (see for example Gast, 1968). The deductions from the study of these elements concern some important problems such as that of the initial composition of magma and rate of fractional crystallization that may have occurred within the magma during its ascent to the surface. Therefore, geochemical trends followed by trace elements will be discussed here in light of possible fractionations in respect to the original magma. Relationships between elements were not tested statistically because of the small number of samples; nevertheless, some conclusions can be drawn.

Ferromagnesian elements Despite the possible variations existing in the source material, some "igneous" relationships according to the normal fractionation patterns of tholeiitic magma (see for example Greenland and Lovering, 1966) are recognizable.

This is the case with correlations between the couples *mg-Ni*, *mg-Co*, *MnO-total Fe*, *Zn-total Fe*, *Zn-MnO* (positive) and *mg-Zn* (negative). Some of these relationships can be seen in Fig. 2.

The positive correlations between Mn, Zn and iron are well explainable because all these elements have a tendency to enter the ferromagnesian minerals, following the geo-

Table I – Analytical results (total Fe as Fe_2O_3 ; trace elements except Tl: ppm)

	23-01	23-101	23-122	23-137	23-200	23-209	23-M-32	23-M-62	23-M-98	M-17	M-19	DIA-1	Liyr	F. Soc.	Average
SiO_2	48.86	48.23	49.78	48.11	49.11	49.98	47.30	47.47	48.90	47.20	45.90	46.21	45.98	49.11	48.01
TiO_2	1.36	1.74	2.01	1.35	1.16	1.77	1.14	1.69	1.79	1.10	1.25	1.06	3.23	1.84	1.61
Al_2O_3	14.94	14.34	12.88	16.22	17.19	15.65	16.83	14.74	13.22	15.86	17.05	16.52	13.62	14.65	15.26
Fe_2O_3	4.70	4.58	3.06	4.70	1.67	3.11	2.30	4.81	7.49	2.71	2.96	1.85	5.03	4.20	3.80
FeO	6.60	8.79	12.73	8.33	8.98	9.86	9.35	8.59	9.84	9.20	8.92	9.50	11.37	8.29	9.31
MnO	0.174	0.191	0.291	0.184	0.161	0.201	0.181	0.192	0.325	0.177	0.177	0.168	0.227	0.193	0.199
MgO	7.28	7.52	5.06	7.16	8.04	5.67	9.22	7.14	5.03	8.78	8.22	9.59	6.83	6.46	7.29
CaO	9.48	9.77	7.77	8.00	8.59	8.34	8.49	9.79	7.73	8.51	9.59	8.32	6.96	8.79	8.58
Na_2O	1.55	1.71	2.73	1.75	2.46	2.37	2.06	1.93	1.74	2.12	1.94	1.73	2.71	2.63	2.10
K_2O	0.25	0.65	0.94	0.34	0.29	0.59	0.37	0.50	0.86	0.18	0.41	0.62	0.74	0.52	0.52
H_2O^+	3.64	2.64	1.80	3.33	1.83	1.60	2.47	2.25	2.66	2.92	2.96	2.85	2.66	2.28	2.56
Total	98.83	100.16	99.05	99.47	99.48	99.14	99.71	99.10	99.58	98.76	99.38	98.42	99.36	98.91	
Total Fe	12.03	14.34	17.19	13.94	11.64	14.05	12.68	14.34	18.41	12.92	12.86	12.39	17.65	13.40	13.27
Li	17	13.6	22	15	2.1	3.3	13.6	14.4	21.2	12.6	13	7	53	9.7	15.5
Cr	200	337	312	175	176	380	337	287	105	127	113	160	122	207	217
Co	61	70	61	68	73	61	65	66	61	74	70	71	63	56	66
Ni	149	174	82	121	150	75	136	121	81	152	147	190	106	86	126
Cu	167	241	207	69	69	88	152	142	204	62	82	65	37	125	122
Zn	125	135	231	141	120	139	125	144	225	152	147	186	190	195	161
Rb	5	25	32	10	5	11	6.5	18	19	4	10	8.5	58	9	15.8
Sr	314	430	215	265	265	254	286	245	274	245	138	190	415	340	277
Tl ppb	60	300	240	110	60	90	60	110	160	30	70	40	370	160	133
Pb	9.4	13	27	9.4	6	14.5	10	14.5	33.5	4.5	13	3.5	9.4	10.7	12.7
K/Rb	420	216	244	280	480	415	476	228	389	375	340	600	105	478	360
Rb/Sr	0.016	0.058	0.149	0.038	0.019	0.043	0.023	0.073	0.069	0.016	0.072	0.045	0.140	0.026	0.056
Rb/Tl	83	83	133	91	83	122	108	164	119	133	142	212	157	56	120
k	0.10	0.20	0.18	0.11	0.07	0.14	0.11	0.15	0.25	0.05	0.12	0.19	0.15	0.12	0.14
mg	0.54	0.51	0.36	0.50	0.57	0.44	0.59	0.54	0.35	0.57	0.55	0.60	0.51	0.48	0.51

Table II — CIPW norms for the diabasic rocks (unknown phosphor content considered to be zero)

	23-01	23-101	23-122	23-137	23-200	23-209	23-M-32
Q	7.88	3.28	1.88	5.42	—	4.11	—
or	1.48	3.84	5.55	2.01	1.71	3.49	2.19
ab	13.11	14.46	23.09	14.80	20.81	20.04	17.42
an	33.07	29.53	20.12	35.40	35.01	30.32	35.58
wo	5.82	7.90	7.69	1.79	3.17	4.61	2.72
en	3.98	4.88	3.18	1.10	1.81	2.34	1.62
fs	1.38	2.56	4.56	0.59	1.22	2.16	0.97
en	14.14	13.84	9.42	16.73	15.60	11.77	14.79
fs	4.92	7.27	13.51	8.93	10.51	10.83	8.84
fo	—	—	—	—	1.82	—	4.59
fa	—	—	—	—	1.35	—	3.02
mt	6.81	6.64	4.44	6.81	2.42	4.51	3.33
il	2.58	3.30	3.82	2.56	2.20	3.36	2.16
	23-M-62	23-M-98	M-17	M-19	DIA-1	Liyf	F. Soc.
Q	2.46	9.83	—	—	—	—	2.96
or	2.95	5.08	1.06	2.42	3.66	4.37	3.07
ab	16.32	14.72	17.93	16.41	14.63	22.92	22.24
an	30.08	25.72	33.23	36.60	35.48	22.82	26.64
wo	7.71	5.27	3.75	4.58	2.41	4.89	7.08
en	4.76	2.88	2.22	2.72	1.43	2.76	4.30
fs	2.51	2.19	1.34	1.62	0.87	1.92	2.40
en	13.02	9.64	16.94	11.02	14.05	13.06	11.79
fs	6.85	7.33	10.21	6.57	8.52	9.08	6.58
fo	—	—	1.89	4.71	5.88	0.83	—
fa	—	—	1.26	3.09	3.93	0.63	—
mt	6.97	10.86	3.93	4.29	2.68	7.29	6.09
il	3.21	3.40	2.09	2.37	2.01	6.13	3.49

Figure 1 — MgO against $\text{FeO} + \text{Fe}_2\text{O}_3$ (from Joplin, 1968). Solid circles: Bahia diabases. CA: calc-alkaline association; AB: alkali basalt association; T: tholeiitic association

Figure 2 — Some ferromagnesian elements against *mg* parameter

chemical behaviour of iron (see for example Wager and Mitchell, 1951). Because the diabases of Bahia show iron enrichment the relatively high average content of Mn and Zn in comparison with other basaltic groups (see Condie *et al.*, 1969) will be also explained. If we consider the *mg* parameter as an indicator of the degree of fractionation as Shido *et al.* (1971) do, we can argue that all the dikes (except perhaps the samples showing alkalic character) form a slightly differentiated suite. Thompson *et al.* (1971), considering oceanic tholeiites, discovered two different fractionation trends of distinct chemical character depending on whether olivine (OL-tholeiites) or plagioclase (PL-tholeiites) crystallize first in the early stages of crystallization. Early crystallization of olivine would cause a major accumulation of Ni, Cr, Pb, Ga, etc. and a depletion of Sr. By comparing the average values of these elements in the Bahia dikes with averages for other basalt groups we can deduce that the Bahia diabases probably followed an OL-tholeiitic trend, but, while nickel conforms well with an accumulation through precipitation of olivine (positive correlation Ni-*mg*), chromium does not (although its average value is notably higher than other figures for continental tholeiites). A possible explanation of the lack of any correlation between Cr and *mg* can be given admitting, as very likely, that chromium separates partially in a oxide phase, locally concentrated as cumulate independently from olivine.

Strontium and lithium The average value for strontium (212 ppm) is fairly low in comparison with common values for continental tholeiites and intermediate between the values for continental and oceanic tholeiites. Following Condie *et al.* (1969), in basalts two fractionation trends (normal-Sr trend and Sr-depletion trend), can be distinguished on the basis of the rate with which Sr is depleted relative to K and Rb and enriched relative to Ca. The Bahia dikes do not fit any of these two trends, since they present both Sr and Rb contents lower than normal contents.

Lithium figures agree with the normal values for basaltic rocks (see Heier and Billings, 1970), except for the samples showing alkaline character characterized by a strong Li enrichment.

Rubidium, lead, thallium and potassium There are obvious positive correlations between Rb-K, Rb-Tl and Tl-K, (Fig. 3) both for tholeiites and samples with alkalic character, in spite of a certain spread in K/Rb ratio values. A wide range in variation of the K/Rb

Figure 3 — Rubidium, thallium and lead against potassium

ratio seems to be peculiar of diabasic rocks from everywhere (see for example data of Condie *et al.*, 1969) and is normally related to K-Rb fractionations during the upward emplacement of magma or local contaminations from country rocks. Lead also shows a fairly good correlation with potassium, according with its well known behaviour in magmatic minerals where its highest values usually occur in early crystallizing feldspars. Most of the samples present Pb contents markedly higher (more than 10 ppm) than averages normally found in basaltic rocks (see Wedepohl, 1970). The average value of rubidium (9 ppm) is clearly lower than the figures for continental tholeiites and approximates that of some oceanic basalts retained to be very "primitive" (Clarke, 1970). Some abnormally low Rb contents, account for K/Rb ratios higher than the upper limit (300) of values in common

Figure 4 — K vs. K/Rb diagram. The areas outlined for the major rock types are redrawn from Condie *et al.* (1969). AB: alkali basalts; CT: continental tholeiites; AT: antarctic and Tasmanian tholeiites; ST: submarine tholeiites; UB: ultramafic rocks

terrestrial rocks (see Heier, 1970). Fig. 4 gives the plot of the samples on a K/Rb vs. K diagram in which various fields for basaltic groups were delimited following Condie *et al.* (1969). For both Rb contents and K/Rb values the Bahia dikes results are very similar to some Karroo dolerites (McDougall, 1963) and to some island tholeiites (see Condie *et al.*, 1969). Observations of some geochemical features (K/Rb values, Sr isotopic composition etc.) lead Compston *et al.* (1968) to suggest that two large and distinct magmatic provinces characterize tholeiites, one including the Brazilian Mesozoic Serra Geral basalts and African Karroo dolerites, and the other a number of tholeiites such as Antarctic and Tasmanian tholeiites. Although nothing definitive can be confirmed because of the scarcity of comparative chemical data and lack of Sr isotopic data, the similarity in the K/Rb values, Sr contents etc. suggest that the Bahia dikes probably can be placed in the first group.

The thallium average (133 ppb) agrees well with normal contents for basaltic rocks (see Albuquerque *et al.*, 1972; Albuquerque and Shaw, 1972) and the K/Tl values generally fall into the field of the Mid-Atlantic basalts.

CONCLUSIONS The preceeding petrologic and chemical observations have shown that:

- 1) Most of the Bahia basic dikes present typical features of continental tholeiites slightly differentiated from an "original" magma through an early separation of olivine (OL-tholeiites) and shifted towards an iron-rich differentiation trend.
- 2) A probably much younger generation of dikes with an alkalic tendency cuts with distinct strike the various types of substrate rocks. The last stage of differentiation probably is represented by titania-iron-rich rocks.
- 3) Slight compositional variations in major and trace elements probably reflect some fractional crystallization effects suffered during the emplacement and ascent of the basaltic magma. If contaminations from the surrounding crustal rocks have occurred, it would only regard (only sporadically) the exchange in both the direction of minor amounts of trace elements such as Rb, Li, and Pb.
- 4) Some trace element peculiarities distinguishing the Bahia dikes from other basaltic rocks are: a) slight enrichment of Ni and Cr relative to common continental tholeiites; b) contemporaneous depletion trends for both K-elements and strontium.

5) Some geochemical features seem to indicate that the Bahia dikes occupy a transitional position between typical continental and oceanic tholeiites and that they probably belong to the same magmatic province as some Karroo dolerites and as the Mesozoic Serra Geral basalts.

ANALYTICAL METHODS Both major and trace element determinations were made by atomic absorption spectroscopy using a 303 Mod. Perkin Elmer spectrophotometer unit and 165 chart recorder. Procedures for the various element determinations are so summarized:

Major elements were analyzed (analyst Sighinolfi) using the decomposition procedure suggested by Bernas (1968) and modified in some details.

Cr, Co, Ni, Zn and Cu (analyst Linhares) were determined following the method described by Linhares (1973).

All other trace elements except thallium were determined following Sighinolfi (1969).

Thallium (analyst Sighinolfi) was determined by flameless A.A. spectrometry using the HGA-70 graphite analyzer following Sighinolfi (1973).

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