MAFIC DIKE SWARMS OF THE GOIÁS MASSIF. CENTRAL BRAZIL.

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RESUMO OS ENXAMES DE DIQUES MÁFICOS DO MACIÇO DE GOIÁS, BRASIL CENTRAL. Relações de campo e litogeoquímica permitiram indivualizar três enxames de diques máficos no Maciço de Goiás. O enxame mais antigo compreende diques que secionam terrenos *granhóide-gi-eenstone,* são recobertos por rochas mctassedimentares proterozóicas e foram metamorfisados nas fácies xisto verde ou anfibolito. Esses diques mostram concentrações de TiO_2 inferiores a 2% e apresentam similaridade química com basaltos do tipo N-MORB. Diques não metamorfisados, mas localmente cisalhados, secionam rochas arqueanas e proterozóicas do Maciço de Goiás e foram posicionados, provavelmente, nos estágios finais de deformação do Ciclo Brasiliano (~600 Ma). Esses diques apresentam concentrações de TiO_2 entre 2 e 3% e são quimicamente semelhantes aos basaltos continentais da província do Deccan. O enxame de idade mais recente compreende diques sem deformação ou metamorfismo, mais ricos em TiO_2 (>3%) e com composição química também semelhante aos basaltos do Deccan. O posicionamento destes diques ocorreu, provavelmente, no Mesozóico, durante a fragmentação do *Gondwana.*

Palavras-chave: Diques máficos, geoquímica, Maciço de Goiás, Brasil.

ABSTRACT Three mafic dike swarms occur in lhe Goiás Massif. The earliest dikes cut Archaean granitoid-greenstone terranes partially overlain by Proterozoic metasedimentary units, underwent metamorphism of the greenschist to amphibolite fácies and consist of low-titanium (<2% TiO_2) basaltic rocks chemically similar to N-MORB. Unmetamorphosed but locally sheared dikes cut archaean and proterozoic rocks, have 2 to 3% TiO_2 and are more like Deccan continental flood basalts. They were probably emplaced during the late stage of the Brasiliano cycle. Younger mafic dikes of the Goiás Massif are unmetamorphosed and undeformed, enriched in TiO_2 (>3%0) and chemically similar to Deccan continental flood basalts. The emplacement of these dikes was probably related to the fragmentation of Gondwana during Mesozoic. The geochemical similarities between the Neoproterozoic and Mesozoic dikes of the Goiás Massif support the inference that the geochemical features of the Mesozoic mantle were inherited frorrï processes that occurred during the Proterozoic.

Keywordsi mafic dikes, geochemistry, Goiás Massif, Brazil.

INTRODUCTION Although mafic dikes of at least two generations are acommon feature of the Precambrian crust of the Goiás Massif terrane, central Brazil, where they form swarms with a high dike densily (Figure 1) they have receivcd only cursory attention (Sial et al. 1984, Fuck et al. 1985). In recent years there hás been increasing interest in the distribution, classification, geochemistry, and petrology of the Proterozoic dike swarms of the Goiás Massif (Kuyumjian 1991, Girardietal. 1992, Valente & Kuyumjian 1993andTomazzoli & Nilson 1994).

The oldest regional rocks are chiefly represented by Archaean high-grade granitoid-gneisses and low-grade granite-greenstone terranes cut by **metamorphosed mafic** subvertical dikes striking NE-SW, NW-SE and less frequently E-W. These dikes are deformed, faulted, and recrystallized. Their widths range from a few centimeters to about 80 meters. Individual dikes can be traced along strike up to 20 km and frequently show displacements due to local faulting. These dikes intersect granitoid nuclei of the Archaean granite-greenstone terrane and adjacent granitoid gneisses„and are partially overlain by Proterozoic metasedimentary-ujíits, suggesting that they were probably intruded during íhe late Archaean and/or early Proterozoic. Some of these dikes terminate abruptly within the greenstone belts, after cutting the contact with the neighboring granitoids.

Unmetamorphosed and undeformed, but locally sheared E-W, NE-SW and less frequently N-S striking dikes range from a few centimeters to tens of meters in width and are several tens of meters to about 80 km long. These dikes deform and displace previous dikes, crossciU the Archaean terrane, the middle to Neoproterozoic Grupo Paranoá metasedimentary rocks, the Middle-Upper Proterozoic Araxá Group metasediments in the Pirenópolis region and the Neoproterozoic Mara Rosa volcano-sedimentary sequence. In shear zones, original textures are destroyed, and the rock is reduced to intensely foliated, fine-grained schist. According to Araújo Filho (1992), these shear zones are related to the regional compressive episode at the end of the Neoproterozoic Brasiliano event.

These data indicate that the intrusion of the dikes probably dates back to the early Braziliano Orogeny (-800 Ma).

The **younger** mafic dikes from Goiás are the best preserved. They postdate ali the Precambrian rocks and have not bcen affected by any deformations. Individual dikes typically exceed 30 m in width and some can be traced for distances of upto 100 km.

To charactcrize the chemistry of the Massif of Goiás mafic dike swarms, 70 samples were collected from forty outcrops.

PETROGRAPHY AND CLASSIFICATION The metamorphosed mafic rocks are fine to médium amphibolites composed predominantly of an assemblage of amphibole, plagioclase, and magnetite/ilmenite. Nearly ali dikes commonly contain up to 5 % quartz. Their mineral assemblages indicate greenschist (actinolite, albite-oligoclase, quartz, garnet and magnetite/ilmenite) and amphibolite (hornblende, andesine, quartz, epidote and magnetite/ilmenite) fácies. Less metamorphosed dikes, locally contain actinolite around relics of clinopyroxene crystals. Sphene, apatite, biotite, and zircon are accessory minerais. Coarse-grained dikes locally contain quartz-alkali feldspar intergrowths. Holocrystalline textures prevail over slightly porphyritic textures.

The unmetamorphosed dikes consist of diabase, have subophitic texture and they are composed of plagioclase (andesina-labradorita), augite and minor opaque mineral. When sheared, the primary mineral assemblage is variably transformed to hornblende, oligoclase-andesine, quartz, biotite, epidote, sphene and opaque minerais.

Typical younger mafic dikes of the Goiás Massif are fine-grained, have subophitic to ophitic texture, and are olivine- to quartz-diabase composed mainly of andesine-labradorite, diopside, hyperstene and rare augite, with ilmenite, pyrite, apatite and rare olivine as accessories.

On a CIPW normative basis, the distribution of the metamorphosed dikes in the R l -R2 diagram of De La Roche et al. (1980) are andesi-basalt and tholeiite, while the unmetamorphosed and younger dikes are andesi-basalt, andesite and olivine-tholeiite.

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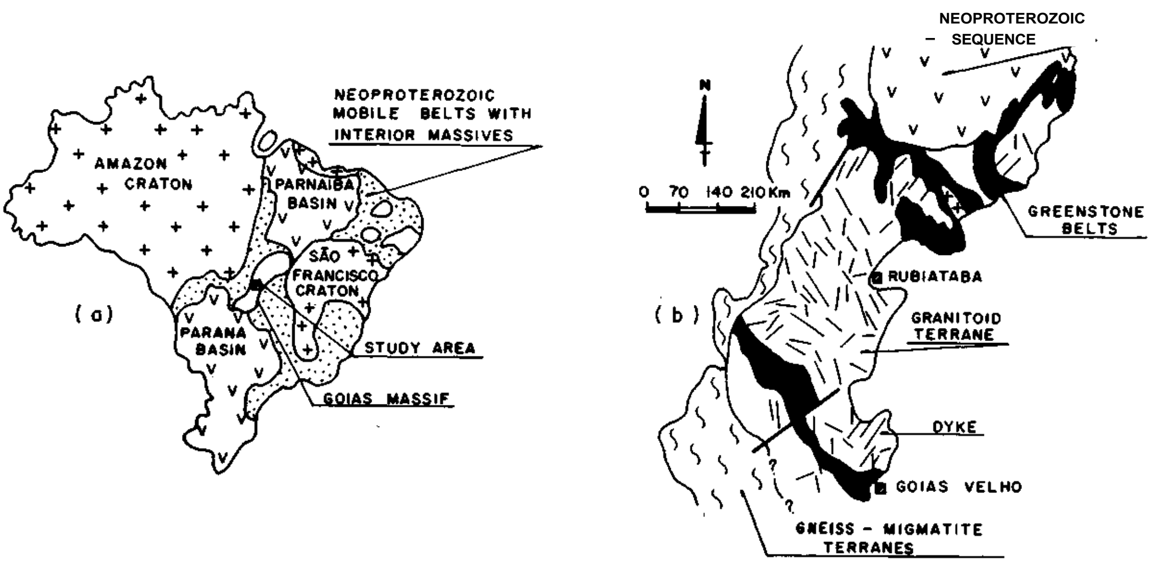

Figure 1 - Simplified geologic map of the Goiás Massifshowing distribution of major dike swarms. (J) gneiss-migmatitic terranes; (2) granitoid terranes and mafic dikes; (3) greenstone belts; (4) Neoproterozoic inagmatic are; (5) Brasília mobile belt and (6) Paraguai-Araguaia mobile belt.

Figura l - Esboço geológico do Maciço de Goiás mostrando a distribuição dos principais enxames de diques. (1) terrenos gnáissico-migmatíticos; (2) terrenos granitóides e diques máficos; (3) *greentone belts;* (4) arco magmático neoproterozóico; (5) Faixa Brasília e (6) Faixa Paraguai-Araguaia.

Table 1 - Representative chemical data of the Goiás Massifmafic dikes. Major and minor elements in % and trace elements in ppm.

Tabela l - Dados químicos de diques do Maciço de Goiás. Elementos maiores e menores expressos em %. Elementos traço em ppm.

	RD3-9	RD1-9	RD1-4	RD1-6	RD3-3	RD3-12	RD3-10	RD2-1	RD2-9	RD2-3	RD3-11	RD3-14	RMP-1	RD3-18
SiO_2	50,85	53,31	50,15	52,11	49,35	49,98	49,82	47,03	50,83	48,51	49,61	49,52	43,41	52,2
Al_2O_3	12,81	14,01	15,42	14,22	13,01	14,91	11,21	13,72	11,26	9,06	10,71	9,42	12,31	10,8
Fe_2O_3	1,9	1,11	0,19	0,22	10,23	0,96	1,99	12,04	3,56	7,06	5,19	5,85	6,99	6,78
FeO	9,33	9,54	10,76	10,43	5,51	9,96	10,33	6,71	12,88	14,18	10,26	11,43	9,89	7,11
CaO	10,39	10,75	11,35	10,64	10,01	10,93	8,81	8,24	8,85	8,15	9,04	8,48	12,31	7,29
MgO	8,9	7,16	6,87	7,36	6,85	5,84	10,91	5,31	4,63	5,29	5,71	5,44	8,14	4,62
Na_2O	2,32	2,09	1,92	2,09	1,91	2,72	1,89	2,41	2,32	1,91	2,54	2,69	1,79	2,79
K_2O	0,12	0,37	0,09	0,01	0,29	0,21	0,26	0,83	0,73	0,64	0,41	0,51	0,32	1,74
MnO	0,15	0,19	0,18	0,19	0,15	0,15	0,16	0,17	0,22	0,22	0,19	0,21	0,14	0,18
P_2O_5	0,06	0,22	0,11	0,24	0,02	0,09	0,11	0,47	0,25	0,25	0,53	0,32	0,25	0,5
TiO_2	1,01	1,12	1,17	1,25	1,35	1,41	1,47	2,22	2,27	2,42	3,32	3,48	3,51	3,89
PF	1,39	0,62	1,22	1,11	1,68	1,93	2,29	0,91	1,66	2,6	2,04	1,99	1,11	2,59
TOTAL	99,25	100,22	99,43	99,87	100,36	99,31	99,25	100,06	99,45	100,31	99,55	99,34	100,17	100,49
Ni	154	168	145	147	85	90	216	120	118	59	58	62	113	54
Cr	350	218	190	200	158	104	660	157	90	91	66	59	152	22
V	336	342	344	366		316	330	313	404	430	890	680	472	767
Zr	37	7	17	25	21	21	28	74	158	148	193	204	188	260
Y	18	22	23	24		20	20	40	41	63	45	46	17	34
Nb	4		3,5		14	5,5	6	9	14	8,5	20	22	19	24
Sr	101	106	101	101	105	117	86	269	130	95	198	195	296	700
Ba	31	34	29	30	20	33	47	568	142	82	141	131	58	600
La	3,16	3,59	3,64	3,53	3,39	1,98	3,99	19,02	11,81	9,83	11,55	13,95	48,61	30,51
Ce	9,75	11,88	11,5	11,85	10,9	7,16	11,54	45,4	26,44	20,21	31,45	38,59	104,51	75,98
Pr														
Nd	6,4	7,96	7,97	8,01	7,04	3,74	7,66	24,25	13,77	13,06	18,73	26,99	53,32	35,54
Sm	1,86	2,24	2,19	2,28	1,99	1,07	2,17	5,21	4,11	4,09	5,06	7,01	9,24	7,4
Eu	0,65	0,74	0,76	0,73	0,63	0,37	0,69	1,53	1,09	1,28	1,41	2,08	3,45	2,11
Gd	2,06	2,43	2,44	2,38	2,13	1,11	2,35	4,72	4,61	4,96	4,97	7,03	6,24	5,64
Dy	2,74	3,04	2,88	2,97	2,87	1,33	2,95	5,56	5,46	5,43	4,99	7,63	4,43	4,11
Ho	0,56	0,62	0,57	0,61	0,61	0,28	0,6	1,13	1,15	1,01	1,01	1,47	0,85	0,77
Er	1,53	1,74	1,48	1,63	1,66	0,85	1,49	3,17	3,42	2,61	2,77	3,66	2,04	1,65
Tm														
Yb	1,31	1,63	1,24	1,42	1,51	0,76	1,23	2,83	2,92	2,39	2,31	2,72	1,43	1,09
Lu	0,15	0,16	0,15	0,17	0,16	0,11	0,14	0,33	0,39	0,31	0,31	0,31	0,18	0,15

Minor ultramafic dikes composed of different proportions of serpentine, tale, actinolite, chlorite, magnetite/ilmenite, and relics of igneous olivine and clinopyroxene also occur, but are subordinated.

WHOLE-ROCK GEOCHEMISTRY Major and trace elements were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES) at the Laboratório de Geoquímica of the Instituto de Geociências, Universidade de Brasília. Selected samples were analyzed by ICP-MS for rare earth elements, Hf, Ta, Th, and Nb at BRGM-Orléans, France. The majority of samples are low in volatiles (LOI), ranging from 0.62 to 2.93 % (average = 1 .83 %). Representative analyses ofthe mafic dikes are presented in Table l.

The SiO_2 vs Na_2O+K_2O (Lê Bass et al. 1986), Ti vs V (Shervais 1982) and Zr/P vs Nb/Y (Floyd and Winchester 1975) diagrams show that studied dikes are mostly tholeiitic basalts, with SiÜ2 ranging from 47.03 to 53.31 % and MgO from 3.72 to 8.90 %. As primary mantle-derived tholeiitic melts normally have mg # [MgO/(MgO+FeOt)] greater than 0.68 and Ni between 300 and 500 ppm, the mg # and Ni contents (0.31-0.62 and 43-210 ppm, respectively) suggest that the mafic dikes from Goiás represent differentiated basaltic magmas.

Major and mainly trace element data indicate the existence of three groups of basalts with almost similar MgO contents, that differ in the TiO_2 content (<2%=lower titanium-LTi; 2-3%=medium titanium-MTi and >3%=high titanium-HTi)

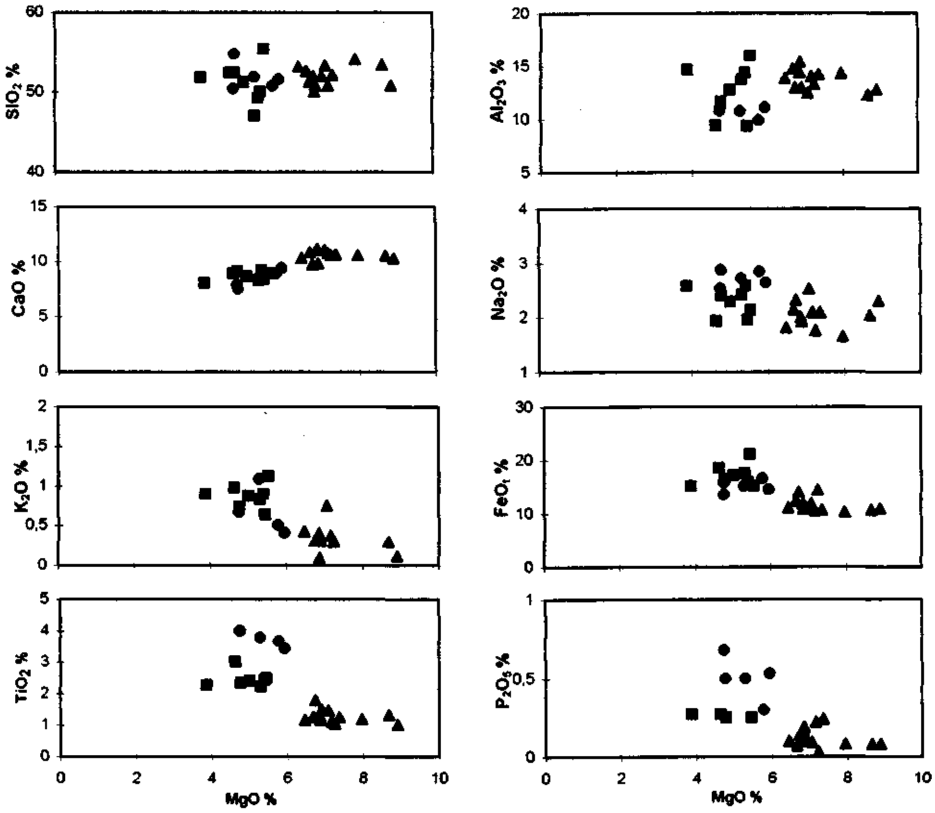

Figure 2 - Major and minor elements of the Goiás Massifmafic dikes plotted against MgO. ● HTi-dikes, ■MTi-dikes and ▲. LTi- dikes

Figura 2 - Diagrama de elementos maiores e menores versus MgO para os diques máficos do Maciço de Goiás, ●diques de alto TiOi, ■diques de TiCh intermediário e ▲ diques de baixo TiO_2.

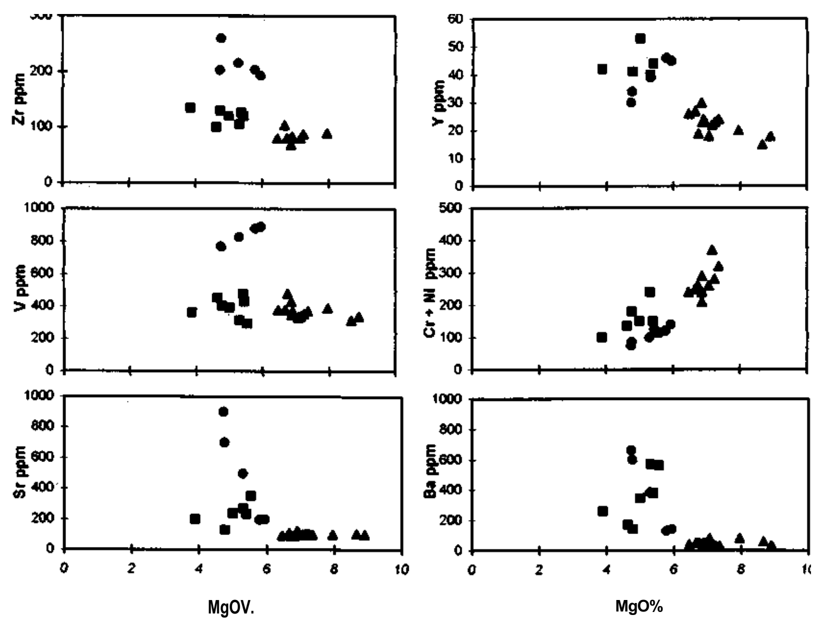

Figure 3 - Trace elements ofthe Goiás Massifmafic dikes plotted against MgO. For legend see Figure 2.

Figura 3 - Diagrama de elementos traço versus MgO para os diques máficos do Maciço de Goiás. Vide legenda da Figura 2.

and incompatible elements contents (Zr, Y, V, Cr, Ni, Sr and Ba). Figures 2 and 3 show that, HTi-dikes generally have higher concentrations of P_2O_5, TiO_2, V, Zr and Sr, and lower contents of AhOs, Ni and Cr than the LTi-dikes. The decrease of Al_2O_3 with decreasing MgO contents, and the positive correlation between CaO and MgO, suggest plagioclase and calcic pyroxene fractionation.

Although a genetic relationship between LTi-, MTi-, and HTi-dikes may be suggested, the variation trends of TiO_2, P_2O_5, Zr, and V show compositional gaps between the three groups of mafic dikes.

The TiO_2, P_2O_5, Ni, Cr, V, Y, Sr and Ba variations are shown in figure 4, and Zr was chosen as a common abscissa for ali plots because it is considered to be good index of

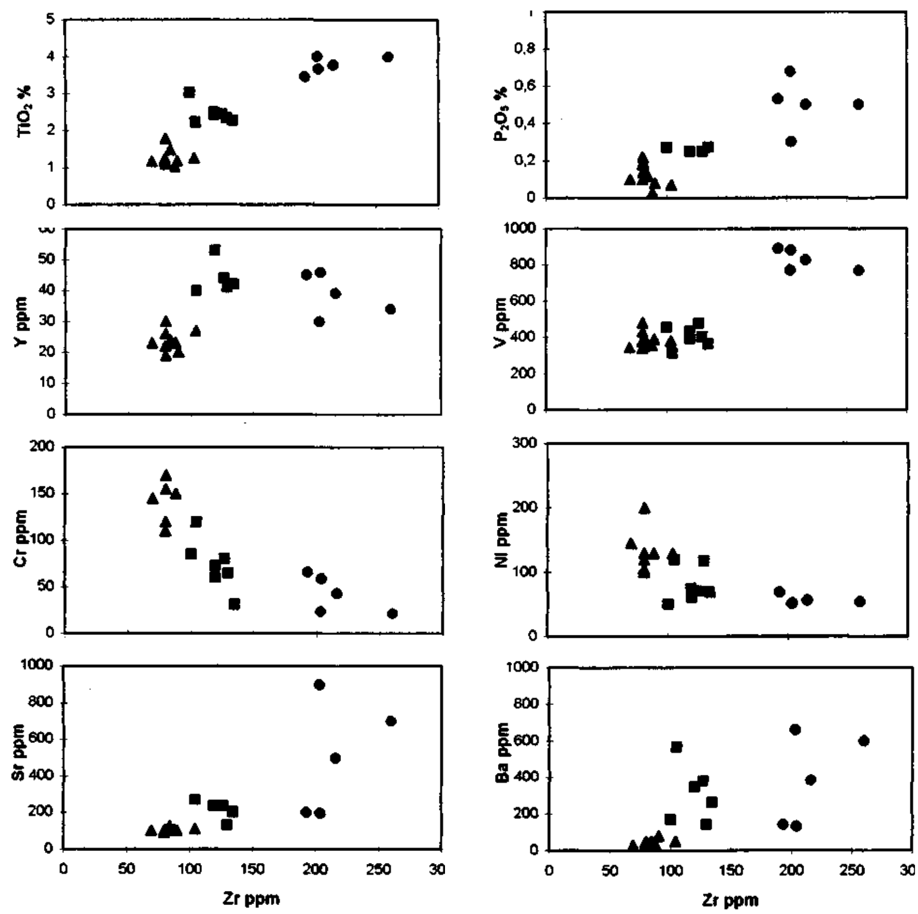

Figure 4 – Selected minor and trace elements ofihe Goiás Massifmafic dikes plotted against Zr. For legend see Figure 2.
Figura 4 - Diagrama de elementos menores e traço específicos versus Zr para os diques máficos do Maciço de Goiás. Vide legenda da Figura 2.

differentiation. Generally, there is a positive correlation bc-tween Zr and Ti, V, Y, Sr and Ba, and a negative correlation between Zr and Ni and Cr between the swarms. Although sharing the characteristics of the other dikes for most elements, the HTi-dikes (>3.0 % TiO_2), are richer in TiO_2, P_2O_5, Zr, and V. The higher contents of Ti, P, Zr and V can not be explained by different melting degrees of a source of constant composition, fractionation or by cumulus effects, which were not observed in the studied samples, and requires a complementary enrichment in their parent melts. The LTi- and HTi-dikes have distinct Zr/Ti, Zr/V and Zr/Y ratios.

The LTi- dikes have Zr/Ti (average=0.008), Zr/V (avcr-age=0.17) and Zr/Y (average=2.47) ratios which are usually lower than those of MTi dikes (Zr/Ti=0.011, Zr/V=0.35 and Zr/Y=3.86) and HTi-dikes (Zr/Ti=0.009, Zr/V=0.26 and Zr/Y=5.78).

Continental crust is characterized by lower Ti/Zr and P/Zr ratios (<54 and <4 , respectively) than MORB (59 and 4, respectively). In mantle normalized plots, crustal contaminated basic rocks would develop pronounced negative anomalies of P and Ti (Weaver & Tarney 1984). Mafic dikes of the Goiás Massif have Ti/Zr>55 and P/Zr>5, and in the mantle normalized multi-element diagram they show absence or small negative anomalies of Nb, P and Ti (Figure 6), suggesting small or absence of crustal contamination.

Rare earth element patterns of selected samples are shown in figure 5. The nearly flat REE patterns of the LTi-dikes (LaN/YbN=1.5 to 2.16) are similar to the depleted Archaean tholeiitic basalts and to mid-ocean ridge basalts (MORB), particularly to some tholeiitic basalts from the FAMOUS área (Langmuir et al. 1977), the Mid-Atlantic Ridge (Schilling 1975) and from the Southwest Indian Ridge (LeRoex et al., 1983). The patterns of MTi- and HTi-dikes show modest fractionation (La_N/Yb_N 3.43-4.50) resembling continental floor basalts (Basaltic Volcanism Study Project 1981). Ali samples have a small negative Eu anomaly, normally indicative of plagioclase removal.

Figure 6 presents primordial mantle normalized multi-element plols of the studied mafic dike samples compared with avcragcd published data of ocean-island basalt, mid-ocean ridge basalts, and continental flood basalts, plotted for comparison. Paraná and Deccan flood basalts are included as rcpresentatives of continental magmatism, as being derived from lithospheric (Hawkesworth et al. 1988) and asthenospheric (Lightfoot & Hawkesworth 1988) mantle sources, respectively. The LTi-dikes have almost flat multi-element patterns, displaying enrichment of Zr with respect to P and Y, and small negative K anomalies closely resembling N-MORB. These suggest that the magmas probably derived from a depleted asthenospheric upper-mantle source. The absence of negative Nb anomalies limits the amount of crustal contamination. Although the HTi-dikes are most enriched in incompatible trace elements than the MTi- dikes, they display almost identical multi-element patterns, similar to the Deccan continental basalts, from which they differ only in the positive K anomalies in the MTi-dikes, negative Nb anomalies in the MTi-dikes and lack or very small negative Nb anomalies in the HTi-dikes. The incompatible element Zr/Y and Zr/Nb ratios of MTi- (3.65 and 7.0, respectively) and HTi-dikes (4.14 and 19.45, respectively) are comparable to the same ratios in the T-MORB (3.35 and 13.80, respectively) and Deccan basalts (4.06 and 12.69, respectively). The MTi-dikes multi-

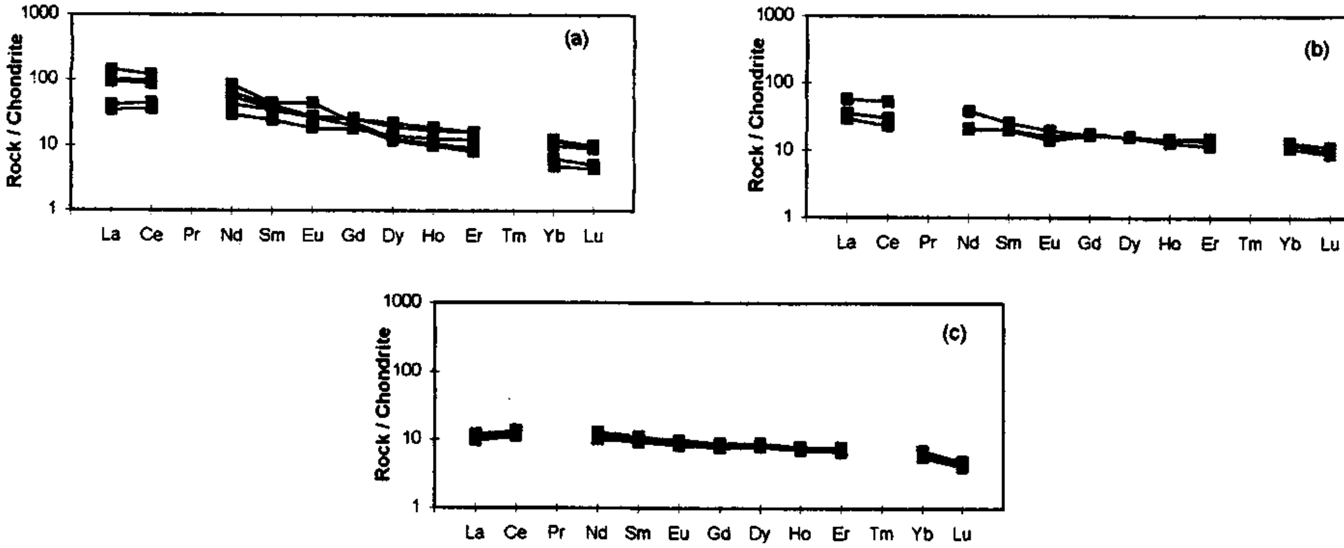

Figure 5 - Rare ecirth elementpatterns of representaiive Goiás Massifnwfic clikes. (a) >3% TiO_2 dikes; (b) 2-3% TiO_2 dikes and >2% TiO_2 dikes. Nonnalizing valites after Nakamura (1974).
Figura 5 - Padrões de elementos terras raras de amostras representativas dos diques máficos do Maciço de Goiás, (a) diques com >3% TiO_2; (b) diques com *2* a 3% TiO_2 e diques com >2% TiO_2. Fatores de normalização recomendados por Nakamura (1974).

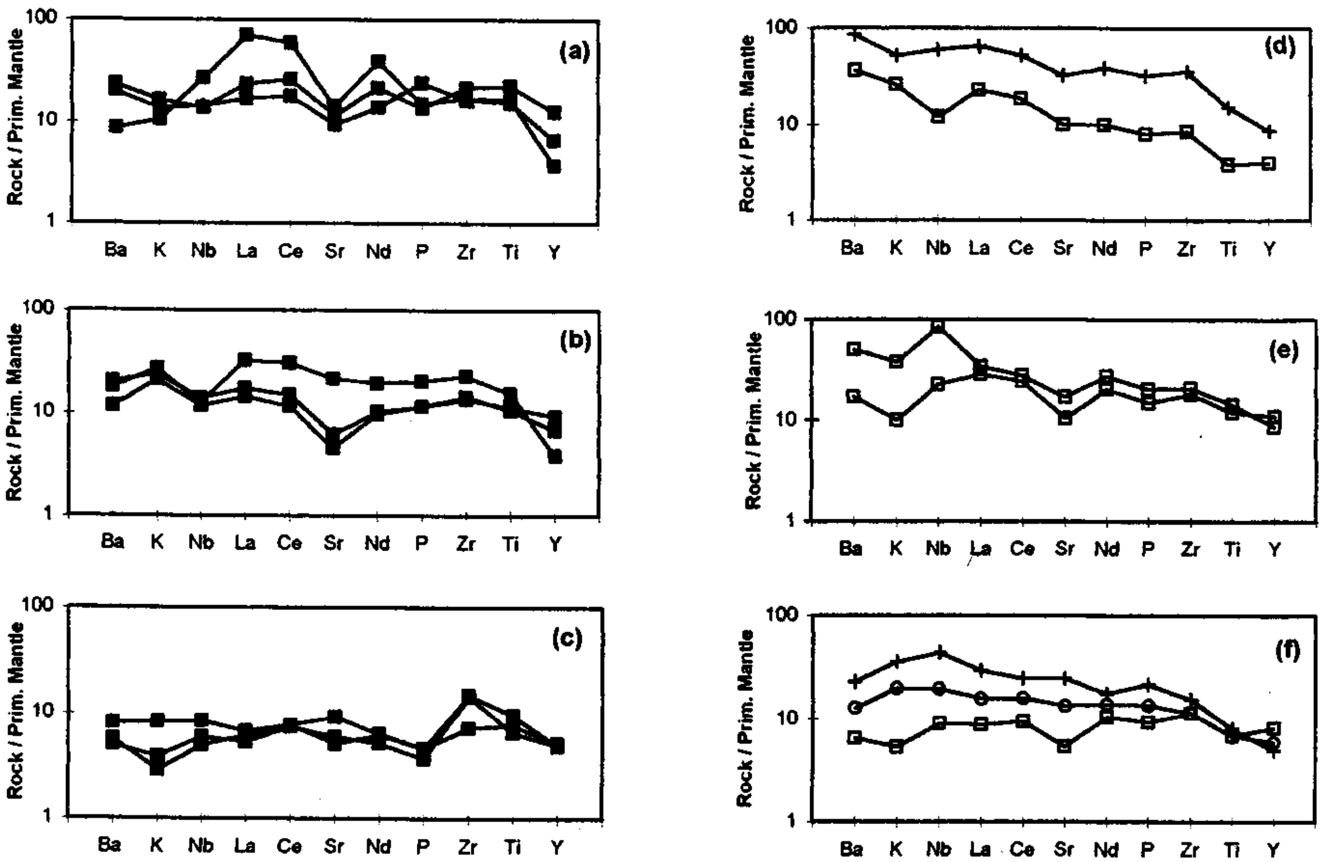

Figure 6 - Primitive mantle-normalized multi-element plofs of representative Goiás Massifmafic dikes. (a) 3% TiO_2; (b) 2-3% TiO_2 and (c) >2% TiO_2; (d) + High- and O Low-TiO_2 Paraná continental flood basalts (Bellieni et al 1986); (e) □ Deccan continental flood basalts (Lighfoot & Hawkesworth 1988); (f) □ N-MORB (Lê Roex et al. 1983), (O) T-MORB (Lighfoot & Hawkesworth 1988) and + P-MORB (Lê Roex et al. 1985). Normalizing valuesfrom Sun & McDonough (1989).
Figura 6 - Diagrama multi-elementar normalizado a manto primitivo para os diques máficos do Maciço de Goiás, (a) >3% TiCh; (b) 2-3% TiO_2 e (c) <2% TiO_2; (d) basaltos de derrames continentais com alto (+) e baixo (□) TiO_2 da Bacia do Paraná (Bellieni et al. !986); (e) □ basaltos de derrames continentais da Bacia do Deccan (Lighfoot & Hawkesworth 1988); □ N-MORB (Lê Roex et al. 1983), (o) T-MORB (Lighfoot & Hawkesworth 1988) e + P-MORB (Lê Roex et ai. 1985). Fatores de normalização indicados por Sun & McDonough (1989).

element patterns more closely resemble T-MORB. The negative Nb anomalies in the HTi- and mainly in the MTi-dikes indicate that the astenospheric melts interacted with the sub-continental lithosphere or were contaminated by continental crust. Therefore, the MTi- and the HTi-dikes may have had an evolutionary history similar to that suggested for the Deccan basalts, i.e. derivation from asthenospheric sources followed by the interaction with sub-continental lithospheric mantle and small crustal contamination.

CONCLUSIONS Geological and geochemical evidence indicate that at least two mafic dike swarms were emplaced in the Goiás Massif: the first, consisting of low-titanium basalts, hás a composition similar to depleted asthenospheric mantle derived N-MORB, and were probably emplaced during the Archaean and/or Lower Proterozoic as they are overlain unconformable by Middle Proterozoic metasediments. The second, consisting of higher-titanium basalts (>2% TiOz), hás geochemical characteristic similar to the continental flood basalts from the Deccan Basin.

Dikes with concentrations with TiO_2 varying from 2 to 3% crosscut the Goiás Massif precambrian terranes and have been affected by shearing during regional compression that took place at the end of the Brasiliano/Pan African Neoproterozoic cycle. The intrusion of these dikes probably occurred during late stages of lhe Brasiliano deformation (~ 600 Ma). None of the younger dikes (TiO_2>3%) seem to have been affected by deformation and it is suggested that they correlate with the Mesozoic Paraná Province magmatism, revealing significant chcmical diversity within individual provinces due to heterogeneity of the mantle sources and crustal contamination. If this is correct, the younger dikes are associated with the break-up of the Gondwanaland supercontinent during the Jurassic and Cretaceous, preceding the opening of the South Atlantic Ocean at the latitude of the Tristan da Cunha hot spot (cf. Hawkesworth et al. 1986 and Fodor 1987).

Il hás been suggested that lhe Mesozoic mantle inherited its geochemical and isolope features from processes that occurred during the Proterozoic (Mantovani et al. 1987, Hawkesworth et al. 1988, Oliveira and Tarney 1990 and Mazzucchelli el ai. 1995). The geochemical similarities be-Iween lhe Neoproterozoic MTi- and lhe Mesozoic (?) HTi-dikes from lhe Goiás Massif supporl lhal possibility.

Acknowledgements: Financial support for field visits and lab work was provided through Conselho Nacional de Desenvolvimento Científico e Tecnológico grant N° 500203/92-0.

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MANUSCRITO A-939
Recebido em 06 de outubro de 1997
Revisão dos autores em 10 de janeiro de 1998
Revisão aceita em 20 de janeiro de 1998