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MAFIC DIKE SWARMS OF QUADRILÁTERO FERRÍFERO AND SOUTHERN ESPINHAÇO, MINAS GERAIS, BRAZIL

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ABSTRACT Mafic dikes are abundant in the Quadrilátero Ferrífero and Southern Espinhaço regions, southeastern State of Minas Gerais. The dikes range from 1,7 Ga to 120 Ma and form at least three swarms that differ in trend, mineralogy, composition and age. The oldest swarnrhas a baddeleyite U/Pb age of 1,7 Ga (Ibirité Gabbro) and K- Ar age of about 1 ,7- 1 ,5 Ga (schists), trends north-south, the dikes vary in width from centimeters to meters, and are deformed and metamorphosed to cnlorite-sericke-quartz-plagioclase schist or are some meters wide and contain plagioclase, augite,- ilmenite, quartz and traces of baddeleyite. These dikes are enriched in LREE [(La/Sm)N =3,68 -6.39], and depleted to enriched in HREE [(Dy/Yb)N = 0,82 - 1,29]. These dikes (and sills also) are related to the opening of the Espinhaço Basin.

Nprthwest-and northeast-trending mafic dikes have a U/Pb age of about 906 Ma. They are commonly ten meters wide, and are of metagabbro with relict igneous textures and containing altered plagioclase (Ans-52), amphibole, epidote, ilmenite, quartz, and apatite. Samples of this dike swarm are slightly enriched in LREE and HREE with a (La/Sm)N = 1 .32 to 2.2 and (Dy/Yb)N = 1 .36 to 1 .88, respectively, and also show small negative europium anomaly. Sills, stocks, plugs, laccoliths and phaccoliths with compositions similar to dikes are present in the study area. The Sm-Nd data indicate negative ENU (T) (+ 1 .34 and - 3.20) and model ages (T_{DM}) of ca. 2.59 and 1 .35 Ga. These dikes may be related the first stages of the Panafrican/Brasiliano event.

North-south, east-west, northwest and northeast trending Phanerozoic dikes are of diabase composed of plagioclase (An«)), augite and magnetite. They show moderate LREE (La/Sm)N = 2,53, and slight HREE enrichments, (Dy/Yb)N = 1,47. These dikes have a K/Ar age of about 120 Ma and may be related to the fragmentation of Gondwanaland. The Quadrilátero Ferrífero and Southern Espinhaço dikes are tholeitic and exhibit prominent iron-enrichment. Some trace element distributions are similar to continental rift basalts. They represent significant amounts of mafic melts formed during the beginning of ample extensional tectonic regimes. There are significant variations in incompatible and partially compatible element abundances both within and between dike swarms, which is due not only to heterogeneous mantle sources, but also to crustal contamination.

RESUMO ENXAMES DE DIQUES MÁFICOS DO QUADRILÁTERO FERRÍFERO E ESPINHAÇO MERIDIONAL, MINAS GERAIS, BRASIL Enxames de diques máficos são abundantes no Quadrilátero Ferrífero Quadrilátero Ferrífero e Espinhaço Meridional, sudeste de Minas Gerais. Três eventos de magmatismo básico ocorrem nestas regiões, cada qual com feições estruturais, petrográficas, geoquímicas e geocronológicas próprias. O enxame mais antigo tem idade de 1,7-1,5 Ga (U/$P_{badeleita}$ -Ibirité Gabbro e K-Ar_{RT} -xistos) e ocorre como *sills* e diques de direção NS, deformados e metamorfisados, ou como diques não deformados com a textura ignea preservada. Os deformados são clorita-sericita-quartzo-plagioclásio xistos, enquanto os indeformados são gabros com plagioclásio (Anse), augita, ilmenita, quartzo e traços de badeleita. Esses diques mostram um enriquecimento em ETRL [(La/Sm)N = 3,68 -6,39] e um empobrecimento ou leve enriquecimento em ETRP [(Dy/Yb)N = 0,82 - 1,29]. Estes corpos são relacionados com a abertura da bacia Espinhaço. Diques NW e NE e idade U/Pb em torno de 906 Ma, possuem largura variável, estão deformados e possuem textura ignea parcialmente preservada, exceto em zonas de baixa deformação, onde apenas as bordas estão foliadas. São metagabros com plagioclásio (Ans2,5), augita, ilmenita e traços de apatita e quartzo, muitas vezes transformados em um agregado de tremolita-actinolita ou hornblenda e zoisita/clinozoisita. Amostras destes diques mostram um enriquecimento em ETRL e ETRP ((La/Sm)N = 1,34 a 2,2 e (Dy/Yb)N) = 1,36 a 138). Os dados Sm/Nd apontam valores de ENCJ = + l ,34 e -3,20 e idades modelos (T_{DM}) = 2,59 e l ,35 Ga. Estes corpos são relacionados aos primeiros estágios do evento Panafricano/Brasiliano.

Os diques mais jovens possuem idade aproximada de 120 Ma, possuem direções variáveis, estão indeformados e consistem de diabásios com plagioclásio (Anóo.os), augita e magnetita. Esters diques mostram enriquecimento em ETRL e pequeno em ETRP ((La/Sm)N = 2,53 e $(Dy/Yb)_N$ = 1,47)) e se relacionam à fragmentação do Supercontinente Gondwana.

Os diques máficos de ambas regiões possuem caráter toleitico, com proeminente enriquecimento em ferro, representam volumosas fusões mantélicas que marcam o inicio de amplos regimes distensivos. As suas características químicas sugerem uma afinidade com basaltos intraplaca continental. Variações significativas no comportamento de elementos traço incompatíveis e parcialmente compatíveis dentro e entre os enxames são interpretadas como uma combinação de processos magmáticos, evolução a partir de fonte mantélica heterogênea e contaminação crustal.

INTRODUCTION Mafic dike swarms occur in all continents and have been generated since the Archean (Halls 1982). They represent significant amounts of mafic melts that cross the crust marking the beginning of ample extension tectonic regimes.

The mineralogy and chemical composition of Precambrian dikes are very similar to Phanerozoic flood basalt (e.g Deccan, Karoo, Columbia River), and can represent the source of volcanic centers removed by erosion during periods of continental emergence (Halls 1982, Tarney & Weaver 1987, Friz-Topfer 1991).

A variety of geological methods have been applied in the study of dikes, mainly aiming their petrogenetic evolution. Dike swarms, mainly those of Precambrian age, are essential tools for the understanding of the geodynamic process, and certainly, are sensitive indicators of the geological processes that took place during the history of the earth.

This paper describes the mafic dike swarms of the Quadrilátero Ferrífero and Southern Espinhaço situated in the southern portion of the São Francisco Craton (Fig. 1). Our main aim is to characterizate the basic pulses that occur in

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these regions, by the investigation of their field relationships, petrography and geochemistry.

GEOLOGICAL SETTING The Quadrilátero Ferrífero and Southern Espinhaço are key areas to understand the tectonic evolution of the São Francisco Craton.

Quadrilatero Ferrífero The Quadrilatero Ferrífero and adjacent regions contain Archean to Paleoproterozoic granite-gneissic terranes and greenstone belts (Rio das Velhas Supergroup), and supracrustal rocks of Paleoproterozoic (Minas Supergroup), Paleoproterozoic-Mesoproterozoic (Espinhaço Supergroup) and Neoproterozoic (São Francisco Supergroup) ages (Fig. 1 and 2).

The supracrustal units of the Minas and .Rio das Velhas Supergroups surround and are surrounded by granite-gneiss domes. These domes are of polydeformed gneiss, metatonalite to metagranite, amphibole, metaultramafic rocks, as well as pegmatites, metamorphosed under amphibolite facies during Archean and Tranzamazonic times (Cordani *et al.* 1980, Machado *et al.* 1989a, Chemale *et al.* 1994).

The Rio das Velhas Supergroup is divided into the Nova Lima Group, consisting of a lower ultramafic unit, an intermediate felsic-mafic unit, and an upper chemical unit (Ladeira 1980, Schorscher 1978), and the Maquine Group, which consists of quartzites (Dorr 1969) (Fig. 2).

The overlying Paleoproterozoic Minas Supergroup consists of a lower clastic unit (Caraça Group), a middle clastic-chemical unit (BIF-bearing Itabira Group), and an upper chemical-clastic unit (Piracicaba Group).

The Paleoproterozoic-Mesoproterozoic Espinhaço Supergroup is exposed in the northern portion of the Quadrilátero Ferrífero, in the Cambotas mountains (Fig. 2) (Schorscher *et al.;* 1982;Marshak&Alkmim 1989, Chemale Jr. *etal.* 1994), and consists of metaconglomerates and quartzites.

Both the Archean and Paleoproterozoic units display a complex metamorphic and deformational history (Dorr 1969, Marshak & Alkmim 1989, Chemale *et al.* 1994). Several bodies of basic dikes occur in the Quadrilátero Ferrífero, and are intimately related with the different tectonic-metamorphic events of the region. The main basic dikes are shown in figure 2.

Southern Espinhaço The Southern Espinhaço is a part of the N-S elongated Aracuai belt (Uhlein *et al.* 1986, Chemale Jr. *etal.* 1993) (Figs. 1 and 3), and is represented by alluvial, coastal eolian, deltaic, and marine sediments of the Espinhaço Supergroup. Volcanic rocks (e.g. Conceição do Mato Dentro rhyolite) of 1,75 Ga (Brito Neves *et al.* 1979) occur as intercalation at the base of the Supergroup, and mafic rocks intruded the unit before the Brasiliano Cycle (Silva *et al.* 199la and b).

Exposures of Archaean granite-gneiss complexes and volcano-sedimentary rocks occur within this belt. The former consist of polydeformed gneisses, with minor migmatites and amphibolite. The later contains greenschists, talc-chlorite schist, sericite schist, banded iron formations, sericite quartzite, quartz schist, and quartzite.

The Southern Espinhaço region is rimmed by metasedimentary rocks of the Salinas Group, of Brasiliano age to the north, Archean to Paleoproterozoic granite-gneiss complexes and small remnants of rocks belonging to the Minas and Rio das Velhas Supergroups, strongly reworked during the Brasiliano Cycle, to the East, and deformed Neoproterozoic sedimentary covers of the Sao Francisco Supergroup (Macaúbas and Bambui Groups) to the West. The later overlies the Espinhaço Supergroup by angular and erosive unconformities (Pflug & Renger 1973).

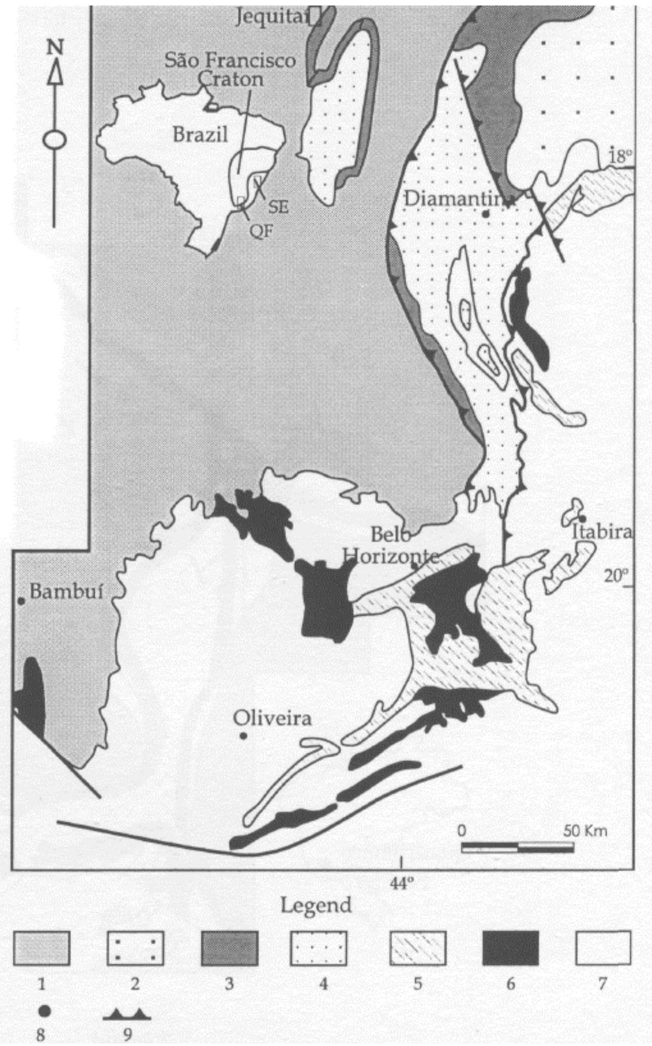

Figure 1 - Geological map of southern portions of the São Francisco Craton and southeastern of the Aracuai Belt, after Chemale et al. (1991). (1) Bambuí Group; (2) Salinas Group; (3) Macaúbas Group; (4) Espinhaço Supergroup; (5) Minas Supergroup; (6) Archaean Greenstone Belts; (7) Granite-gneis terrains; (8) Towns; (9) Thrust faults

DIKE SWARM GEOLOGY **Types of Intrusions** Considering their stratigraphic positions, compositions and ages, we divide the mafic swarm of the Quadrilátero Ferrífero and Southern Espinhaço into three types:

(1) N-S oriented, centimetric to metric wide dikes, sills, and stocks, either deformed, metamorphosed and lacking igneous features, or undeformed and with preserved igneous texture. In the Southern Espinhaço, these dikes are restricted to the sin-rift sequence of the Espinhaço basin; (2) Dikes, sills, stocks, laccoliths, lopoliths or plugs, with northeast, north-south, northwest, locally east-west directions. The width of the dikes and sills is decimetric to metric, and the hypoabyssal bodies vary from metric up to 5 km in diameter. Intrusions of this type cut through all rocks of the Minas and Espinhaço Supergroups;

(3) Decimeter to centimeter wide, north-south, east-west, northwest, and northeast oriented, undeformed and non metamorphosed dikes with fully preserved igneous texture. These dikes intruded into all Precambrian rocks of the region.

Contacts The contact relationships of the intrusions with the country rocks are not always clear, due to alteration and

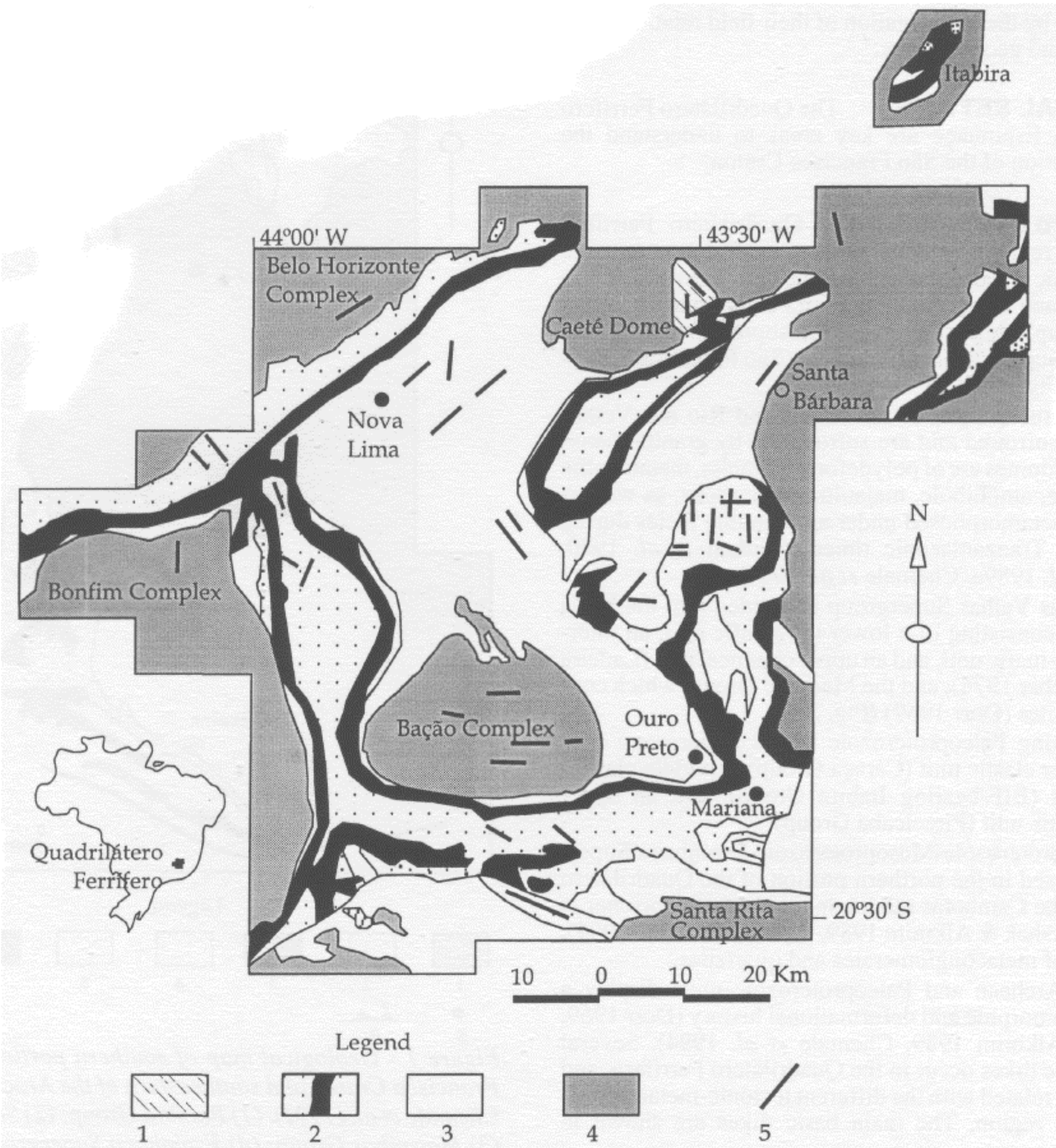

Figure 2 - Geologic map of the Quadrilátero Ferrífero. (1) Espinhaço Supergroup, (2) Minas Supergroup, (3) Archaean Greenstone Belts, (4) Granite-gnaiss terrains, (5) Mafic Dikes (modified after Dorr J969)

scarcity of outcrops. When preserved, the contacts are discordant in low strain zones or tectonic in high strain zones. In the Southern Espinhaço, the contacts of the larger mafic bodies are generally covered by sediments.

Tectonic contacts have a North-South orientation, similar to those of the regional structures. Recrystallization of both the intrusion and the host rocks at the contacts is generally conspicuous, as indicated by the silicification of the former, and the chloritization of quartzites. Transtension zones are commonly invaded by quartz veinlets.

Structural Features The structural features observed in the mafic intrusions include anastomosed mylonitic foliation, centimetric tension gashes, fractures (conjugated or not), thrust, normal and transcurrent faults, and mineral, stretching and crenulation lineations.

The dikes have a border foliation parallel to the regional foliation of the Minas and Espinhaço Supergroups. The mylonitic foliation in the hosts varies between N22°E/65°SE and N74°E/44°SE, while at the border of the mafic bodies it varies between N40°E/22°SE and N55°E/30°SE. The mineral and stretching lineations both in the dikes and host rocks are approximately east-west, while the crenulation lineation is north-south.

The inverse faults are N-S and define the contacts of the basic bodies with the hosts. In these cases, the borders of the bodies are either sheared or, under shallower crustal levels, brecciated. In low strain domains, the basic bodies are only incipiently affected by regional deformation, while the host rocks still preserve their primary features.

In the western border of the Southern Espinhaço, the mafic intrusions are related to transcurrent and normal faults. In the southern portions of the eastern border, the contacts are apparently tectonic and marked by inverse and thrust faults.

The kinematic indicators associated to tension gashes indicate that the main tectonic transport took place from east to west, as also previously deduced by Ulhein *etal.* (1986), and Chemaleeftf/. (1993).

Petrography GROUP I Rocks of this group are quartz-chlorite schist and chlorite-chloritoid-sericite schist, as well as locally undeformed, melanocratic, equigranular, coarse to medium-grained gabbro and microgabbro.

The quartz-chlorite schists are light green to greyish, fine grained, and contain chlorite (50-55%), quartz (30-35 %) with minor ilmenite (10%) and plagioclase (Ano5). Relicts of primary feldspar may occur. Accessories include apatite and zircon. Leucoxene is the most abundant secondary mineral and formed after ilmenite. Besides deformation and metamorphism, samples of this group also underwent metasomatism, as indicated by the presence of sericite.

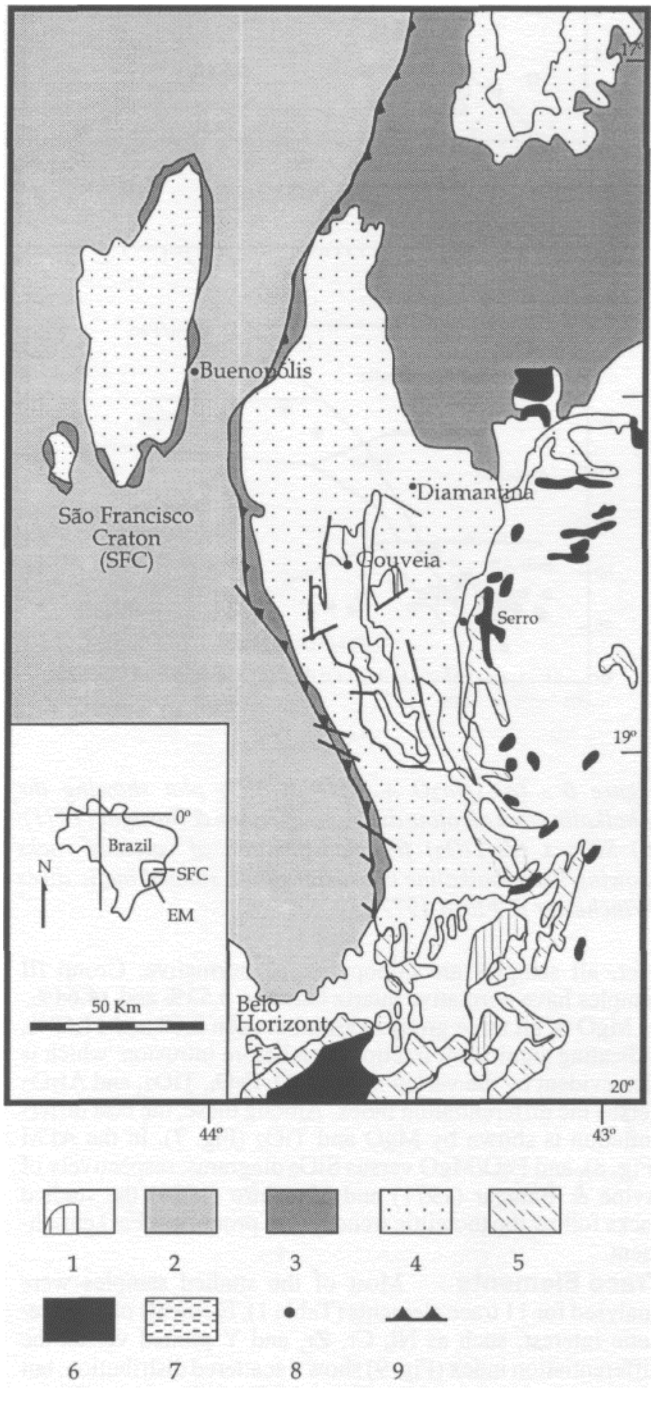

Figure 3 - Geologic map of Southern Espinhaço, (l) metabasics; (2) Mantiqueira Province with Brasiliano granites; (3) Bambui Group; (4) Macaúbas Group; (5) Espinhaço Super group; (6) Minas Supergroup; (7) Granite-gnaiss terrains; (8) Towns; (9) Thrusts (Modified from Dossin 1983)

The chlorite-chloritoid-sericite schists are greenish. Primary features such as millimetric to centimetric vesicles occur locally. These schists have granoblastic and lepidoblastic textures, are fine grained, and are formed by sericite (65%), chlorite (15%), magnetite (5%), tourmaline (2-5%), titanite (1%), and zircon (1%). When present, the proportions of chloritoid may be as high as 10%.

The gabbros and microgabbros have intergranular, locally also ophitic textures. They consist of labradorite (An56-60) laths, subhedral to anhedral augite, and up to 5% of subhedral to anhedral ilmenite. The plagioclase and augite crystals are slightly deformed. Trace amounts of potassium feldspar may occur and is myrmekitic at the contact with labradorite. Apatite, quartz, and locally also zircon and baddeleyite are accessories. Quartz, in particular, occurs either as anhedral isolated and interstitial crystals, or associated to potassium feldspar as myrmekitic and micrographic intergrowths.

Chemical data of pyroxene shows that its composition lies between intermediate pigeonite and subcalcic augite (Fig. 4). Plotted in the $CaMgSiO_3$-$CaFeSiO_3$-MgSiOs-$FeSiO_3$ system (Fig. 5), at several temperatures and 1 atm pressure (Linsdey 1983), the analytical data indicate that the pyroxene crystallized between 1100° and 1200°C, with an approximate average of 1150°C.

GROUP II Rocks belonging to Group II are the most abundant in the Quadrilátero Ferrífero and Southern Espinhaço. They consist of massive, melanocratic, medium grained metagabbros, locally with preserved ophitic and sub-ophitic primary textures. Thin bodies are commonly foliated.

The metagabbros consist of 50-55% of plagioclase laths (An60.05 to Anos), with interstitial subhedral to anhedral augite (35-40%) and subhedral to anhedral ilmenite (3-5%). The pyroxene is commonly uratilitized into actinolite-tremolite or hornblende, and plagioclase saussuritized to zoisite/clinozoisite. Quartz, apatite, potassium feldspar, biotite, and zircon are accessories.

GROUP III Rocks of this group are melanocratic, medium to fine grained, massive diabase dikes with intergranular texture characterized by lath-shaped labradorite (An60,50), with interstitial augite. The texture is locally ophitic. Magnetite, pyrite, ilmenite, olivine, apatite, titanite, and quartz are accessories. Leucoxene occurs as alteration of ilmenite.

Plagioclase (45-65%) is the most abundant mineral in these rocks. The mineral occurs as subhedral, clean, slightly sericitized, zoned and twinned crystals, commonly with fractures, undulate extinction and corrosion bays.

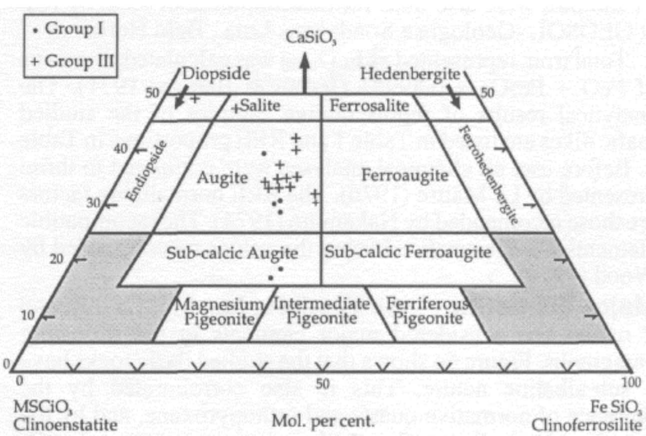

Figure 4 - Classification of pyroxenes of mafic dike swarms plotted in the system $CaMgSiO_3$ – $CaFeSiO_3$ – MgSiO3-$FeSiO_3$ (Poldervaart and Hess 1951).

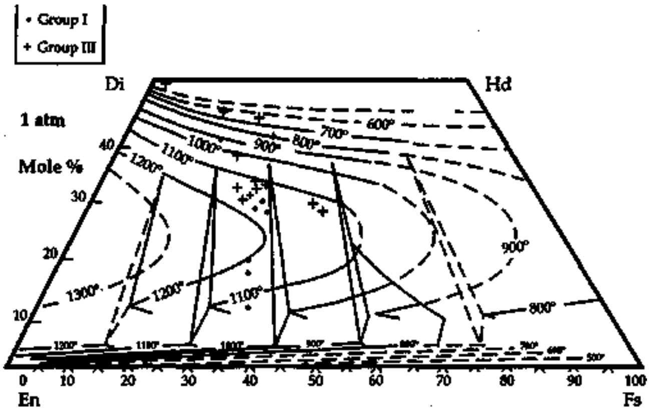

Figure 5 -Pyroxene compositions of the studied mafic dikes plotted in the system Di-Hd-Fs-En at latm (Linsdley 1983).

The clinopyroxene (15-45%) is subhedral to anhedral, locally euhedral, and presents lamellar twinning and undulating extintion. Chemical data of the pyroxene are compatible with the composition of augite (Fig. 4), and, as in figure 5, the mineral crystallized at approximately 1150°C.

Magnetite (6-10%) occurs either as skeletal and sutured crystals, bordered by titanite and leucoxene, or as lath-shaped crystals. Microprobe analysis of magnetite shows that it may contain up to 2.6% of vanadium. Pyrite (3-5%) occurs as cubic disseminated crystals. Olivines is generally altered to iddingsite, but relicts are rich in fayalite (Fa49-5g). Quartz is rare and occurs as interstitial anhedral crystals. Apatite is the main accessory and is-euhedral to needdle shaped.

Rocks of this group may locally be hyalocrystalline, with a matrix composed of plagioclase, lath-shaped and skeletal magnetite, and glass with the composition of subcalcic ferrous-augite. When hypocrystalline, they contain submillimetric vesicles filled with partially altered volcanic glass.

PETROCHEMISTRY About 20 mafic bodies were sampled for chemical analysis, totaling 76 samples. After cleaning, grinding and reduced to powder, the samples were analyzed for major, minor and trace element determinations in the Geochemical Laboratory of the University of Brasilia. FeO was determined by volumetry, K_2O and Na_2O by flame photometry, LOI by gravimetry, and the remaining major and minor element oxides, as well as selected trace elements by inductivelly coupled plasma emission (ICP). Among theses, 11 samples were also used for determination of REE by ICP at GEOSOL -Geologia e Sondagens Ltda., Belo Horizonte.

Total iron, represented as FeO_{total} was calculated by means of FeO + Fe_2O_3 x 0.89981 (Irvine & Baragar 1971). The analytical results of representative samples of the studied mafic dikes are listed in Table 1 and REE proportions in Table 2. Before use, all chemical analyses were compared to those presented by Le Maitre (1976). The REE normalizing factors are those recomended by Nakamura (1974). The incompatible elements were normalized using the values recommended by Wood (1979).

Major Elements Si, Ti, Al, Fe, Mn, Mg, Ca, Na, and P oxides are considered major elements in the following paragraphs. Figure 6a shows that the studied basic rocks have a sub-alkaline nature. This is also corroborated by the presence of normative quartz and orthopyroxene, and by the samples plot in figure 6b, which in its turn suggests that Zr and Ti had low mobility since intrusion.

Normative quartz of Group I samples is between 2.32% and 14.05%, while in Group II it averages 6.45%. When not quartz normative, they have 0.09 to 14.1% normative olivine. However, all samples are clinopyroxene normative. Group III samples have normative quartz between 5.53% and 14.64%.

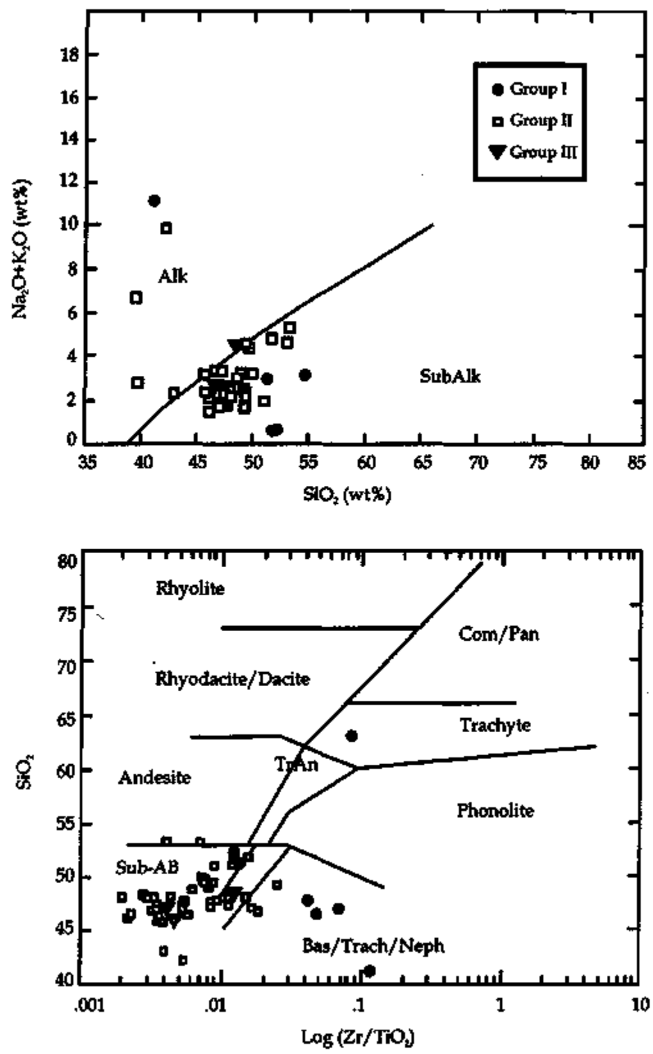

Figure 6 - (a) (Na_2O + K_2O) x SiO2 plot showing the subalkaline andalcaline divisions of Irvine & Baragar (1971). (b) SiO_2 x (Zr/TiO_2) for classification of volcanic rocks showing the subalkaline character of the studied mafic dikes (Winchester & Floyd 1977).

MgO of all three groups varies between 2.68 and 11.68%, indicating significant fractionation before intrusion, which is also evident by the variation of MgO, FeO_t, TiO_2, and Al_2O_3 versus the differentiation index. Among these, the best differentiation is shown by MgO and TÍÜ2 (Fig. 7). In the AFM (Fig. 8), and FeO/MgO versus SIO_2 diagrams, respectively of Irvine & Baragar (1971) and Myashiro (1974) the studied rocks follow the tholeiitic trend with a prominent FeO enrichment.

Trace Elements Most of the studied samples were analysed for 11 trace elements (Table 1). Elements of petrogenetic interest, such as Ni, Cr, Zr, and Y plotted versus the differentiation index (Fig. 9) show a scattered distribution, but with decreasing contents of Cr and Ni, and increasing Y and Zr.

Due to the low mobility of Ti and Zr during alteration and low grade metamorphism, as well as the small variation of their ratios during mantle partial melting and formation of basaltic liquids, their ratios closely reflect the composition of the sources (Condie 1985a). In both studied regions, Group I

*Table l - Chemical composition of mafic dikes of the Quadrilátero Ferrífero e Southern Espinhaço regions. *GroupI, Group II, **GroupIII*

	*RR48	*RR48/I	*IB104	*D01	*D02	*D03	DPK01	DPK02	PF01	PF02	DAT01	DAT03	GOU02	SB01	SB02
SiO_2	51,88	52,3	46,41	41,28	46,58	47,05	47,2	46,42	46,01	47,32	46,26	48,12	39,73	43,08	42,3
TiO_2	1,57	1,56	4,03	1,28	2,05	1,95	2,11	1,09	1,04	2,11	2,35	1,24	1,18	1,95	1,19
Al_2O_3	13,1	13,17	12,12	26,51	12,02	12,62	13,29	15,1	16,03	13,43	13,39	13,69	25,83	12,74	25,6
Fe_2O_3	2,63	2,53	4,61	5,88	13,65	12,8	4,43	6,04	2,59	11,53	5,33	3,36	3,4	2,45	0,2
FeO	14,61	14,58	12,5	3,64	1,71	1,6	10,04	4,58	8,26	3,05	8,17	7,88	10,84	11,99	10,06
MnO	0,22	0,21	0,24	0,1	0,13	0,1	0,2	0,19	0,2	0,19	0,17	0,17	0,2	0,17	0,21
MgO	8,02	7,91	4,76	5,25	6,74	6,08	7,16	8,41	9,1	7,14	7,35	9,13	7,65	6,75	4,83
CaO	0,22	0,28	9,77	0,1	9,64	9,37	11,55	11,63	12,02	10,74	10,53	11,44	1,05	9,35	2,22
Na_2O	0,39	0,37	2,11	0,6	2,39	2,26	1,98	1	1,8	2,13	2,13	1,37	0,63	1,81	0,59
K_2O	0,19	0,24	0,79	10,52	0,58	0,5	0,056	0,66	0,33	0,63	0,48	0,29	5,97	0,5	9,25
P_2O_5	0,14	0,15	0,31	0,09	1,53	1,48	0,24	0,22	0,14	0,14	0,14	0,16	0,3	0,24	0,22
PF	7,1	7,07	2,64	5,39	5,16	5,29	3,11	4,36	2,67	2,06	4,2	3,52	2,47	9,67	4,05
Total	100,07	100,37	97,96	100,64	102,12	101,1	101,87	100,5	100,37	100,47	100,5	100,37	99,25	100,7	100,72
Zn	220	218	210	77	130	76	109	120	101	95	90	85	120	335	135
Co	65	61	186	38	52	31	81	78	77	77	83	140	87	86	72
Ni	45	43	64	128	353	97	89	84	126	120	111	121	99	86	79
Cr	52	49	14	36	30	27	100	94	203	200	180	165	141	125	92
V	339	342	793												
Be	5	5	2	5	5	6	5	5	5	5	5	5	5	5	5
Cu	6	105	129	19	111	97	85	92	74	69	191	68	102	90	20
Zr	120	116	113	920	600	830	48	38	23	25	27	111	36	47	40
Y	29	22	40	32	39	46	25	23	12	12	15	16	28	46	38
Sr	5	5	193	63	76	41	241	235	364	366	309	358	247	42	283
Ba	80	105	295	1351	3200	1052	196	189	183	185	88	89	153	17	21
FeO*	16,98	16,86	16,65	8,93	14	13,12	14,03	10,02	10,59	13,43	12,97	10,9	13,9	14,2	10,24
F/F+M	0,68	0,68	0,78	0,63	0,68	0,68	0,67	0,55	0,54	0,66	0,64	0,55	0,65	0,68	0,68

	SB04	SB05	SB07	SB11	SJC01	CAP02	CAP04	CAM02	CAM04	PK03	SJC02	CQ02	CQ03	CQ04	CQ05
SiO_2	46,2	46,46	46,23	53,2	48,01	49,39	45,84	46,62	47,58	46,92	47,96	47,53	47,12	47,56	47,43
TiO_2	1,93	1,91	2,65	3,92	1,66	1,74	3,92	2,03	2,06	1,25	1,67	1,63	1,57	1,58	1,58
Al_2O_3	12,68	11,18	12,03	12,37	13,6	14,47	12,76	13,56	13,09	13,76	14,5	14,36	13,39	13,71	13,79
Fe_2O_3	0,91	0,91	2,97	7,27	2,7	2,65	4,23	5,3	4,21	2,45	2	2,2	2,85	2,64	2,62
FeO	12,59	11,73	11,09	8,66	8,16	11,34	11,65	9,47	9,43	8,87	7,85	7,87	7,78	8,1	8,1
MnO	0,18	0,21	0,19	0,09	0,16	0,21	0,21	0,2	0,2	0,19	0,16	0,18	0,17	0,17	0,18
MgO	6,65	5,49	5,86	3,65	9,13	7,19	5,34	7,15	7,25	9,82	8,56	8,76	8,8	8,91	8,92
CaO	7,37	10,05	9,38	7,89	12,06	7,9	9,04	10,7	10,27	9,91	11,49	11,99	12,28	12,45	12,33
Na_2O	2,05	1,63	1,41	2,59	2,22	2,05	2,48	2,02	2,02	1,57	2	1,9	1,9	1,32	1,38
K_2O	0,1	0,1	0,1	2,03	0,30	0,1	0,76	0,48	0,66	0,34	0,34	0,38	0,39	0,37	0,39
P_2O_5	0,28	0,16	0,2	0,12	0,19	0,41	0,46	0,24	0,26	0,13	0,21	0,21	0,21	0,18	0,18
PF	9,3	10,45	8,47	5,65	2,54	2,9	2,92	2,14	3,06	3,87	2,47	2,68	3,29	3,02	3,4
Total	100,24	100,28	100,58	107,44	100,75	100,35	99,61	99,91	100,09	99,08	99,21	99,69	99,35	99,53	100,25
	184	217													
Zn	88	58	3	177	87	142	149	111	110	94	103	110	97	108	117
Co	69	61	76	34	79	104	101	80	82	94	73	75	123	77	80
Ni	26	47	82	129	163	67	67	84	88	176	151	159	156	159	176
Cr			119	272	512	21	29	77	111	256	293	320	368	422	431
V	1	1								256	271	290	281	260	281
Be	58	27	1	5	1	2	2	1	5	25	25	1	1	5	5
Cu	60	27	34	27	117	89	77	99	90	109	128	110	112	103	102
Zr	52	23	36	169	20	86	93	25	99	89	159	108	53	216	40
Y	131	100	38	16	21	44	45	27	26	15	24	23	23	21	23
Sr	18	21	48	50	218	27	28	247	250	312	220	210	224	174	203
Ba			14	329	118	565	565	170	192	324	145	155	148	137	293
FeO*	13,41	12,35	13,76	15,2	10,59	13,73	15,46	13,29	13,22	11,08	9,65	9,85	10,35	10,35	10,46
F/F+M	0,67	0,7	0,7	0,81	0,54	0,66	0,75	0,65	0,65	0,53	0,53	0,53	0,54	0,54	0,54

Legenda: * Grupo I Group II ** Grupo III

*Table l - Chemical composition of mafic dikes of the Quadrilátero Ferrífero e Southern Espinhaço regions. *GroupI, Group II, **GroupIII (continuation...)*

	RR33	RR33/P	CAM07	TAM01	TAM02	TAM02A	TIM01	TIM02	TIM03	TIM04	TIM05	TIM061	GLAU01	MG1\E	MG03A
SiO2	51,1	53,3	47,69	51,89	48,36	39,93	49,03	50,01	46,43	49,43	51,1	49,72	49,3	49,36	48,21
TiO2	2,85	1,62	1,79	2,57	4,81	4,81	3,87	4,06	3,89	3,2	3,08	3,4	2,1	1,9	0,87
Al2O3	15,43	19,41	12,93	14,31	13,78	14,87	11,57	11,16	11,57	12,91	14,09	14,04	13,17	10,14	12,66
Fe2O3	3,48	3,39	2,62	3,07	7,85	11,47	3,47	11,6	2,47	2,32	2,31	2,25	2,51	2,2	2,63
FeO	8,8	4,76	9,72	9,47	7,1	5,44	14,5	7,18	14,32	11,87	12,08	12,23	12,23	8,38	7,39
MnO	0,16	0,04	0,21	0,14	0,24	0,23	0,18	0,19	0,06	0,21	2,79	0,26	0,25	0,17	0,19
MgO	2,86	1,68	7,55	3,66	4,2	6,39	5,02	4,46	4,95	3,6	6,34	3,07	6,6	11,98	10,01
CaO	6,41	6,24	10,39	6,39	3,95	8,6	5,09	5,1	5,14	5,76	2,73	6,06	9,76	12,26	13,04
Na2O	2,8	4,27	2,26	2,92	2,27	2,39	2,05	1,8	1,88	2,82	1,74	2,68	1,7	1,19	1,53
K2O	0,19	1	0,57	1,92	0,31	0,44	1,11	1,41	1,29	1,73	0,22	1,73	0,74	0,45	0,3
P2O5	0,8	0,06	0,19	1,07	0,59	0,56	0,57	0,64	0,65	0,65	0,88	1,07	0,22	0,11	0,1
PF	4,31	3,42	3,14	2,99	3,65	4	3,69	2,79	8,3	1,65	13,08	3,01	1,85	3,4	3,09
Total	99,19	99,19	99,06	100,42	99,11	99,13	100,15	100,4	100,95	96,15	100,44	99,82	100,43	100,73	100,04
Zn	2	23	137	120	142	143	200	205	195	168	170	160	149	83	82
Co	74	11	82	60	110	114	86	88	86	72	70	75	117	113	112
Ni	33	13	100	35	80	75	65	68	68	40	44	42	94	180	157
Cr	39	35	123	30	50	32	30	28	30	20	20	21	157	721	340
V	139	57	390	324	655	670	600	620	595	433	490	467	42	277	200
Be	5	5	3	1	1	1	3	3	3	3	3		2	1	1
Cu	31	15	79	10	52	52	360	340	345	158	179	182	54	42	42
Zr	96	241	84	82	84	82	187	182	185	169	168	164	53	164	23
Y	60	6	27	32	20	20	102	63	64	62	61	63	42	15	11
Sr	372	521	231	970	600	600	85	88	86	163	165	160	92	239	305
Ba	81	3081	200	930	115	116	230	250	260	373	376	380	113	102	73
FeO*	11,93	7,81	2,08	12,23	14,17	15,76	17,62	17,62	16,54	13,96	14,16	14,25	14,49	10,47	9,77
F/F+M	0,81	0,82	0,62	0,77	0,77	0,71	0,78	0,8	0,77	0,8	0,88	0,83	0,68	0,62	0,49

	MG06B	R824/IV	R824/III	R7390/VI	MG04/B	ITA01	R730/B	R730/B	PK06	PK05	PK04	NR21	NR92	**FL001	**1B001	**FL002
SiO_2	48,1	48,84	47,01	49,77	48,19	48,06	47,56	47,02	48,06	47,39	46,99	46,41	47,06	47,78	51,32	62,5
TiO_2	2,36	1,79	3,03	2,29	1,22	3,58	3,27	3,22	1,23	1,31	1,18	4,03	4,14	1,31	3,44	0,72
Al_2O_3	12,77	12,71	12,09	14,01	13,22	12,46	11,13	11,87	14,54	14,36	14,89	12,12	12,26	15,91	12,81	15,08
Fe_2O_3	2,84	3,05	3,21	3,41	2,37	2,58	2,16	3,74	3,03	2,54	2,66	4,61	5,18	9,8	5,58	0,64
FeO	10,19	10,39	12,7	10,48	8,46	10,66	13,89	13,04	7,83	7,83	7,11	12,5	12,9	1,6	9,38	9,65
MnO	0,21	0,23	0,25	0,19	0,18	0,22	0,23	0,24	0,17	0,17	0,14	0,24	0,23	0,19	0,19	0,18
MgO	7,36	7,44	5,59	4,42	9,19	6,29	5,28	6,16	7,87	7,42	7,76	4,76	4,43	8,48	4,13	4,01
CaO	10,08	8,73	9,35	7,33	11,05	9,44	8,48	8,98	15,4	18,71	12,75	9,77	9,45	12,37	7,26	2,29
Na_2O	2,11	2,5	2,47	3,35	1,6	2,14	2,33	2,49	1,68	1,82	1,93	2,11	2,14	1,48	2,16	2,65
K_2O	0,58	0,49	0,79	1,11	0,56	0,54	1,02	0,91	0,56	0,92	0,52	0,79	0,81	0,36	0,77	1,05
P_2O_5	0,26	0,2	0,39	0,35	0,14	0,72	0,31	0,33	0,12	0,14	0,2	0,31	0,3	0,72	0,8	0,68
PF	3,13	3,57	3,5	3,19	3,48	3,28	4,35	1,2	3,01	3,5	3,48	2,34	2,28	1,1	2,67	1,99
Total	99,98	99,94	108,38	99,9	99,66	99,97	99,2	99,2	103,5	105,7 1	99,71	97,96	100,58	100,5	100,51	101,44
Zn	123	121	154	145	91	182	149	155	96	92	84	210	202	156	182	154
Co	118	111	118	133	117	125	143	120	80	67	68	186	176	139	137	86
Ni	101	109	78	85	144	118	62	80	113	94	112	64	59	51	60	46
Cr	168	278	75	35	256	149	40	73	130	121	116	14	14	5	42	5
V	356	371	494	183	236	390	327	558	251	211	185	793	776		169	
Be	2	1	2	2	1	2	2	2	1	1	1	2	1,92	5	2	2
Cu	63	65	94	95	77	89	113	101	71	38	36	129	128	244	49	247
Zr	47	68	99	104	81	66	110	72	81	71	131	113	108	340	270	306
Y	32	36	44	39	16	33	44	38	16	16	15	40	39	46	50	45
Sr	231	334	303	303	314	467	179	188	335	396	427	193	195	454	250	453
Ba	195	146	242	435	1326	167	233	316	123	234	130	295	275	652	796	644
FeO*	12,75	13,14	15,59	13,55	10,59	12,98		16,41	10,56	10,12	9,5	16,65	16,96	10,42	14,36	10,23
F/F+M	0,64	0,64	0,74	0,76	0,54	0,68	-	0,73	0,56	0,58	0,55	0,78	0,8	0,56	0,78	0,72

Legenda: * Grupo I GroupII ** Grupo III

Table 2 - REE data of Mafic Dikes of the Quadrilátero Ferrífero and Southern Espinhaço

Sample	La	Ce	Nd	Sm	Eu	Gd	Dy	Ho	Er	Yb	Lu
CAM2	11,52	29,07	15,87	3,65	1,123	3,281	3,807	0,746	1,946	1,635	0,179
DAT1	9,104	23,29	12,56	2,601	0,628	2,148	2,147	0,415	1,05	0,876	0,099
DAM1	43,44	99,95	41,67	7,723	1,196	4,439	3,458	0,742	2,252	2,689	0,376
SB3	9,677	26,56	16,27	4,45	1,241	4,366	4,85	0,98	2,692	2,282	0,27,
PK4	9,466	24,05	12,46	2,674	0,861	2,187	2,121	0,43	1,192	0,913	0,115
ITA18	20,9	53,91	31,5	6,84	2,414	5,516	4,548	0,877	2,208	1,664	0,2
RB24-I II	13,42	36,26	22,58	5,932	1,804	5,682	5,918	1,141	2,882	2,188	0,258
TAM01	55,87	131,7	65,34	12,16	3,582	8,611	6,706	1,25	2,928	2,065	0,25
TIM05	40,32	99,23	50,04	10,6	2,349	9,412	10,29	2,05	5,54	4,751	0,568
IBI04#	93,35	157,6	52,26	9,012	1,966	7,193	7,01	1,41	3,877	3,499	0,455

samples have Ti/Zr ratios between 80 and 225, while in Group II the rations vary from 110 to 1227, and in Group III from 35 to 212. This indicates different degrees of mantle partial melting, but they may also be explained by mantle enriched or crustal contamination. The issue of enriched mantle *versus* crustal contamination has been widely discussed and, in most cases, its explanation has only been possible through isotope studies. The low ratios suggest enriched mantle sources, similar to those that originated the continental basalt flood, while the higher ratios may suggest a more depleted mantle.

In the MgO x FeO_t x Al_2O_3 plot (Fig. 10), the samples fit to the field of continental rift-type basalts and therefore of continental intraplate regimes.

Rare Earth Elements (REE) Rare earth elements (REE) are important petrochemical discriminators for basic rocks. Even having similar chemical behaviour, the REE may be fracionated during melting and fractional crystallization (Henderson 1984), but may be a clue to source compositions. The mafic dike swarms of the Quadrilátero Ferrífero and Southeastern Espinhaço present three types of REE patterns, as shown in figure 11.

Rocks of Group I are represented by two samples (Fig. 11). Sample DOI (quartz-chlorite schist), show LREE fractionation [(La/Sm)N = 3,47] and HREE depletion [(Dy/Yb)N = 0,82]. Sample IBI04 (gabbro), has a strong LREE fractionation [(La/Sm)N = 6,39], but an almost flat HREE distribution [(Dy/Yb)N = 1,28]. The samples of Group II show a moderate LREE fractionation [(La/Sm)N = 1,34-2,83] and a light to moderate HREE fractionation [(La/Sm)N = 1,34 to 2,08]. Group III has a LREE frationation [(La/Sm)N = 2,53] and a less significant HREE fractionation (Dy/Yb)N = 1,47].

Spidergrams To construct the spidergrams we normalized the elements to primordial mantle values (Wood 1979). The elements are arranged, from left to right in decreasing order of incompatibility, thus providing information about the nature of the mantle source, crustal contamination and assimilation processes.

The classification of the mafic dikes into three distinct petrographic groups is also evidenced by their REE patterns. Both features corroborate the conclusions of Weaver & Tarney (1981b) and Tarney & Weaver (1987) that different magmatic pulses have different patterns. The different REE patterns in the same magmatic pulse may reflect an heterogeneous source (Condie *et al.* 1987).

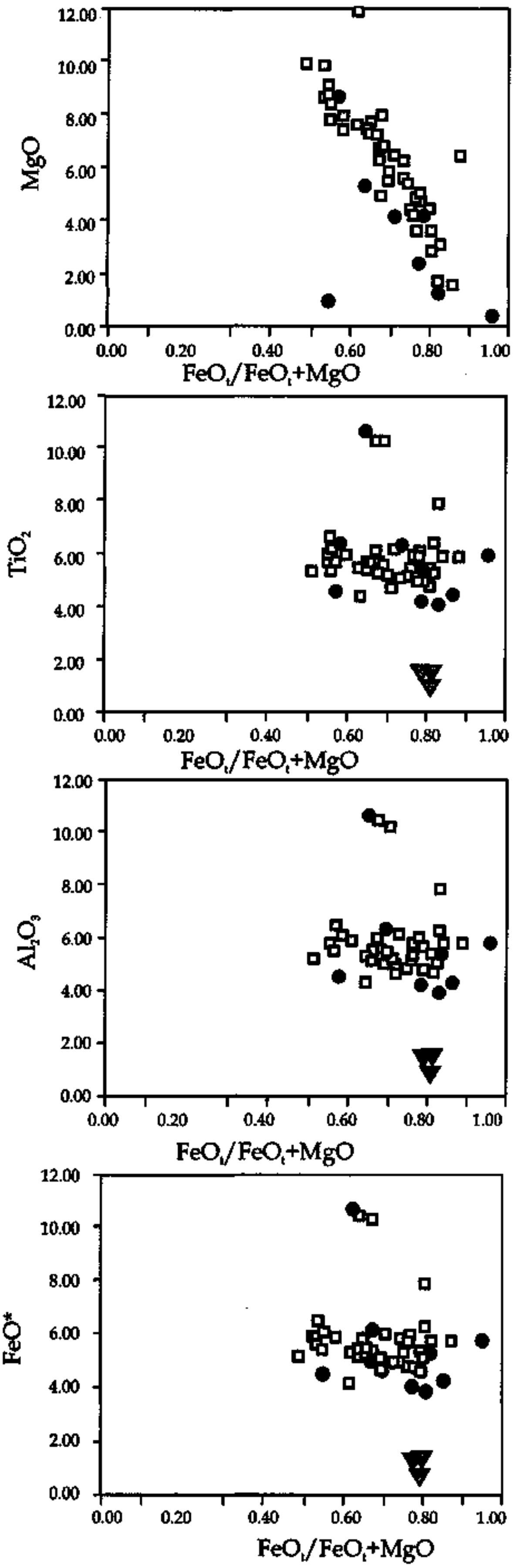

Figure 7 - Marker plots for MgO, Al_2O_3, *TiO_2 and Feo versus the differentiation rate of the studied mafic rocks.*

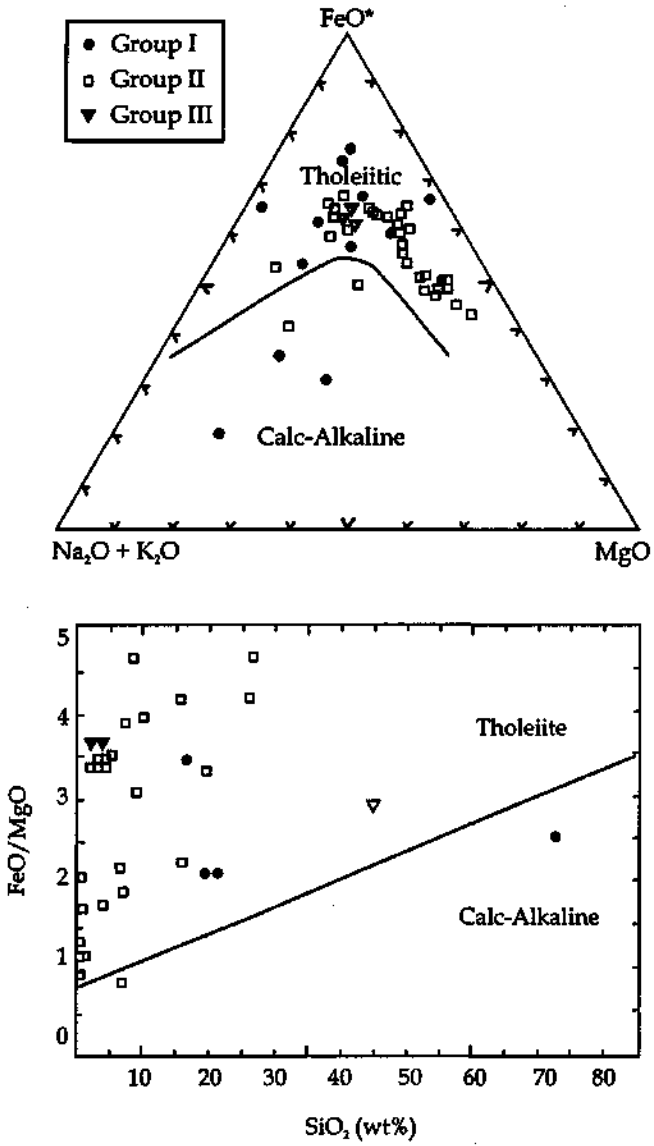

Figure 8 -AFM and SiO_2 x FeO/MgO diagrams, respectively of Irvine & Baragar (1971) and Miyashiro (1974) of the studied basic rocks..

Figure 12 contain the spidergrams of the studied mafic rocks, grouping the samples with similar behaviors. The different patterns corroborate a previous indication that the studied mafic dike swarms resulted from different magmatic pulses.

When normalized to primordial mantle, sample IBI04 of Group I has negative K and Sr anomalies, more accentuated in Zr, as well as positive La, Ce, and Nd anomalies, and a slight positive Sm anomaly (Fig. 12a). The negative K and Zr anomalies are, possibly, due to crustal contamination/assimilation. Sample D01 has negative Sr, P, and Ti anomalies and positive K, Nd and Zr anomalies. The negative P and Ti anomalies can be explained either by a source poor in these elements, or by retention in the mantle during partial melting. The positive K and Zr anomalies are, possibly, due to metamorphism. The positive Zr anomaly may also be explained by contamination with rocks of the upper crust, as proposed by Taylor & McLennan (1985).

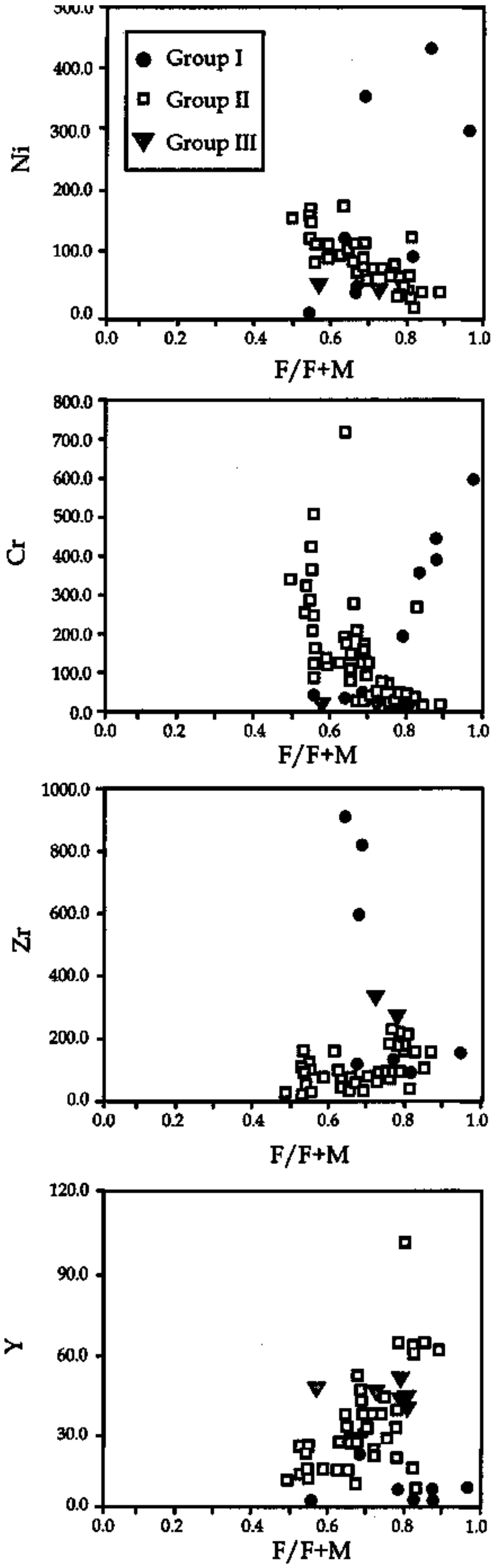

Figure 9 - Ni, Cr, Zr, and Y versus differentiation index of the studied basic rocks

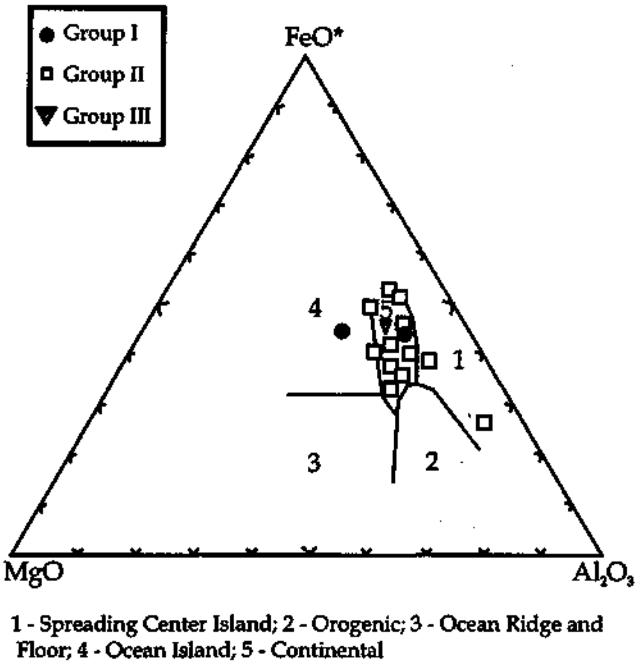

Figure 10 - MgO x FeO_t x Al_2O_3 *tectonic setting diagram of Pearce et al. (1977)*

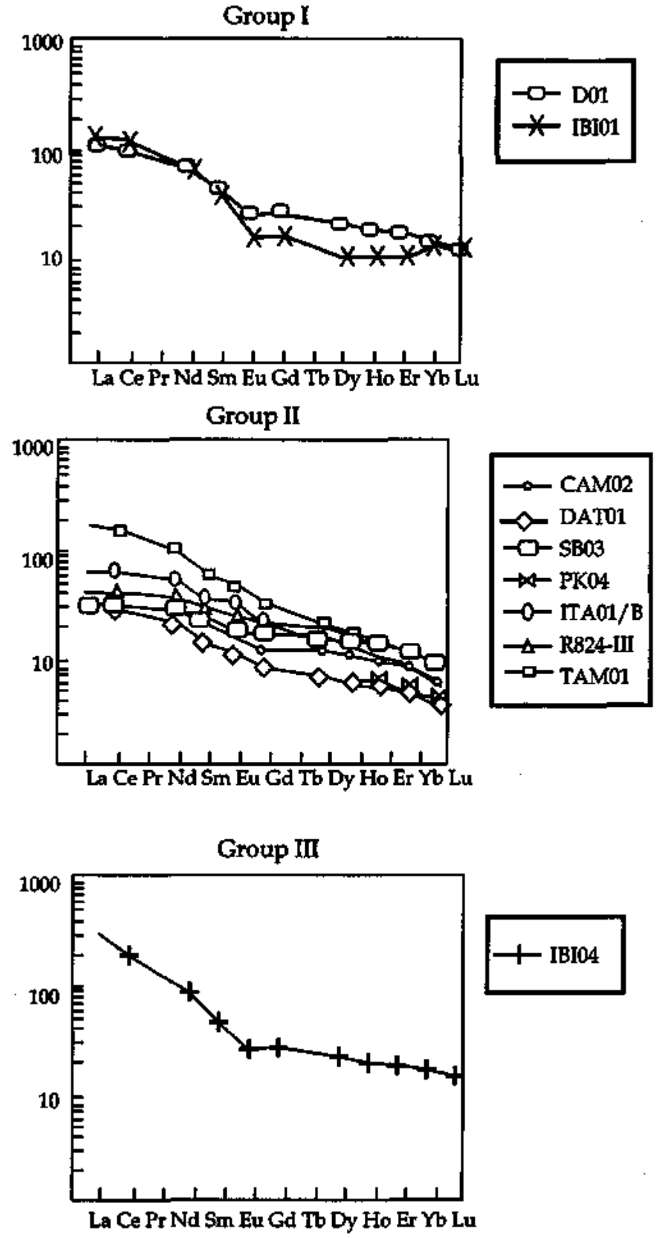

Figure 11 - REE patterns of the three mafic dike swarms of the Quadrilátero Ferrífero and Southern Espinhaço

Samples of Group II (Fig. 12b) shows small negative Sr, Zr, and occasionally also Ba anomalies, and positive Sm, eventually also Ti anomalies. Sample TIM05 has negative K, Sr, Zr and positive Ti anomalies. Sample SB03 has small negative Ba and K, negative Sr and Zr, and positive Sm anomalies. Despite of these differences, these patterns may be grouped into one single envelope. Sample PK04 differs from others of the same group by its positive Sr and Zr anomalies, and sample SJC02 (Fig. 12c) by its slight negative B a and Sr, and a strong positive P and less strong Sm anomalies.

Some samples of Group II have patterns that are similar to tholeiitic island arc basalts, while others are more compatible with continental rift basalts. The negative Zr anomalies may be due to retention in the mantle residual melt.

Group III has negative K, Sr and Zr, and positive La, Ce and Nd anomalies (Fig. 12d). The La and Ce enrichment can be explained either by their mobility during metamorphism and/or hydrothermal alteration, or by a larger fractionation of these elements in the source, or even by crustal contamination. The positive P anomaly may be due to crustal contamination.

The negative Sr anomalies of these groups probably reflect its mobility during metamorphism and /or the hydrothermal alteration. However, part of these anomalies may also be due to pyroxene rather than plagioclase fractionation.

Radiometric Data Previous radiometric datings of the studied mafic dikes have been published by Teixeira (1995), Machado *et al.* (1989b), and Machado & Carneiro (1992). More recently we obtained complementary data.

By means of K/Ar ages, Teixeira (1995) attempts to estabilish the main extension period of the southern portion of the São Francisco Craton. The authors suggests that the more important crustal fracturing events took place by 2,1 -1,85 Ga (K/Ar in amphibole), and 1,7-1,5 Ga (K/Ar in total rock, amphibole and plagioclase), and, therefore, that the most important mafic dike intrusions in the craton ocurred during the Paleo-Mesoproterozoic times.

The most important mafic dike swarm of Group II cut the basement rocks of the Southeastern Espinhaço region, these dikes have zircon and baddeleyite with an U/Pb age of 906 +/ -2 Ma (Machado *et al.* 1989b). A similar K/Ar age of 1,0 Ga was also found by Machado & Carneiro (1992) in green hornblende of rocks belonging to Group II of the Quadrilátero Ferrífero.

For this paper we dated baddelyite of the Ibirité gabbro (IBI04) at the Royal Ontario Museum. The extraction of U and Pb used a procedure described elsewhere (e.g. Heaman & Machado 1992). The isotopic composition of these elements was determined on a VG354 mass spectrometer in single collector mode. The U and Pb blanks are estimated to be 0.5 and 2.0 pg, respectively. These values must be accurate, considering that total common Pb in fraction *#2* is of 3.1 pg. The used U decay constants are those of Jaffey *et al.* (1971). The discórdia calculation used the program of Davis (1982).

Sample IBI-04 contained a small number of tinny (< μ) baddeleyite crystals. The baddeleyite yield was insufficient to

Table 3 - U-Pb results for baddeleyite of sample IBI-04.

Fraction	#1	#2
Weight (micrograms)	1	8
U (ppm)	891	503
Pb (ppm)	260	50
Th (ppm)	46	92
Total Common Pb (pg)	8.7	3.1
$^{206}Pb/^{204}Pb$ (measured)	2,488	24,273
$^{206}Pb/^{238}U$	0.29580+78	0.10212+18
$^{207}Pb/^{235}U$	4.2547+115	0.8638+15
$^{207}Pb/^{206}$	0.10432+9	0.06135+7
$^{206}Pb/^{238}U$ Age (Ma)	1671	627
$^{207}Pb/^{235}U$ Age (Ma)	1685	632
$^{207}Pb/^{206}Pb$ Age (Ma)	1702	652

analyse more than two fractions. The grains were then subivided into a smaller fraction of best transparent fragments (#1 in Table 3) and a larger fraction of fractured grains. Many grains were frosted, probably due to incipient formation of zircon by metamorphism. The two fractions have contrasting $^{207}pb/^{206}pb$ ages of 1702 and 652 Ma, atypical for pristine baddeleyite. The best quality baddeleyite grains (#1) have the oldest age, interpreted to closely approximate the time of the gabbro emplacement. The poor quality baddeleyite grains contain some metamorphic zircon and may more closely reflect the time of the gabbro metamorphism.

A discórdia line (Fig. 13) of the two analyses yield an upper intercept age of 1714 ± 5 Ma, interpreted as the best estimated for the time of gabbro emplacement while the lower intercept age of 618 ± 3 Ma is interpreted as the time of gabbro metamorphism. The lower uranium content (503 ppm) of the poorer quality fraction (#2) is consistent with metamorphic zircon which, in other examples of coronitic gabbros (Davidson & Van Breemen 1988, Heaman & Le Cheminant 1993) tends to relatively low U contents (<150 ppm). If this interpretation is correct, then the amount of discordance along the discórdia line for fraction #2 cannot be explained only by the

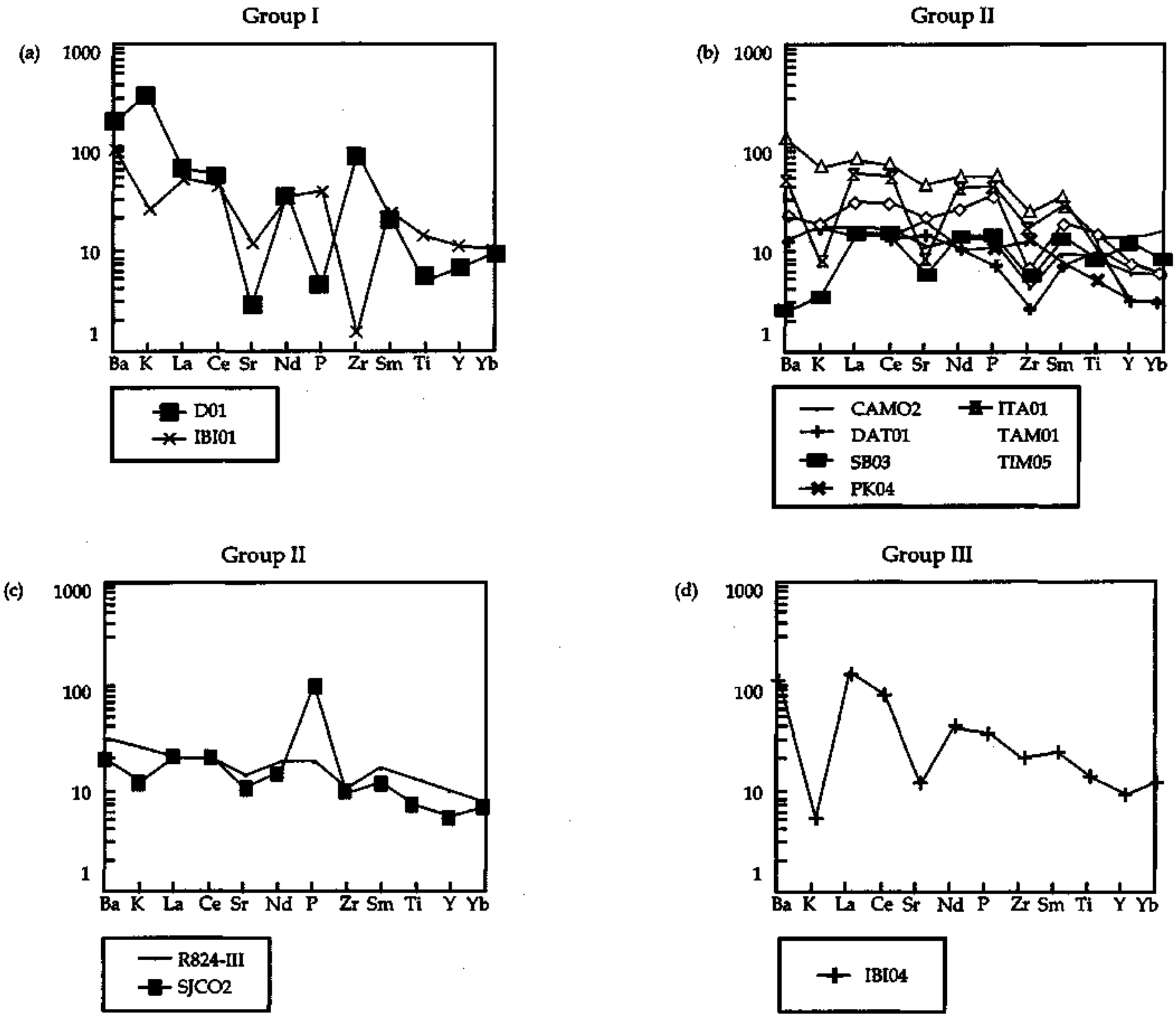

Figure 12 - Spidergram of the three mafic dikes swarms of the Quadrilátero Ferrífero and Southeastern Espinhaço

presence of some metamorphic zircon and U mass balance considerations. The baddeleyite in this analysis must also have experienced significant Pb-loss, as documented in in few rare examples (e.g. Heaman & Grotzinger 1992).

Of Group III, only the sample C088, a diabase of the Quadrilátero Ferrífero, was dated, yielding a K/Ar whole rock age of 120 Ma, thus correlated to the early stages of Gondwanaland breakup (Chemale *et al.* 1991, Silva *et al.* 1991 a and b). This age is compatible with the K/Ar whole-rock 170 to 220 Ma interval previously obtained by Dossin *et al.* (1995) in rocks of the same group.

Two samples were processed for Sm-Nd dating (SB03 e DAT01) at the Instituto de Geociências of the University of São Paulo. The experimental procedure includes the technique of acid digestion, separation of Sm/Nd by using a small column of ion exchange, and isotope ratio measurements in a thermal ionization mass spectrometer with multiple and single

Table 4 - Sm-Nd results for Mafic Dikes of the quadrilátero Ferrífero and Southeastern Espinhaço

	Sm	Nd	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd	T_{DM} (Ga)
SB03 (Gr. II)	5.157 +/- 0.004	18.38 +/- 0.007	0.1707 +/- 0.00015	0.512321 +/- 0.000027	+1,34	2.59
DAT01 (Gr. III)	3.15	14.33	0.1338 +/- 0.00009	0.512335 +/- 0.000024	-3.20	1.35

collector systems (Sato *et al.* unpublished).

The Sm-Nd data indicate end (T) (+1,34 and -3.20) and model ages (T_{DM}) of ca. 2.59 and 1.35 Ga. The results are presented in Table 4.

The analytical data indicate a Nd isotopic composition depleted in ^{143}Nd. The negative epsilon values indicate that the basic rocks derived from sources with lower Sm/Nd ratio than the condritic reservoir. This means that such rocks derived from, or assimilated old crustal sources lowered in the Sm/Nd ratio when their magmas separated from CHUR.

The isotopic data, the high LIL content, and the quartz-normative nature of these dikes suggest crustal contamination during intrusion. Nd isotopic characteristics of the both studied areas suggest long crustal residence of the dikes precursor magmas.

GEOTECTONIC CONTEXT OF THE MAFIC DIKE SWARMS From the above described data, it is possible to infer the geotectonic context of the mafic dike swarms of the southern portion of the São Francisco craton and deduce their stratigraphic relationship with the supracrustals rocks. The data indicate that the Minas and Espinhaço supracrustals were intruded by at least three basic dike swarm events.

The first event, with a north-south direction, cuts sin-rift sections of the Espinhaço Supergroup and has been correlated to the opening of the Espinhaço sedimentary basin (Silva *et al.* 1991a and b). Metarhyolites associated to the early stages of sedimentation yield a zircon U/Pb age of 1,7 Ga (Brito Neves 1979), thus having the same age of the basic dikes.

These data show that the basic dikes may correspond to the first magmatic pulse that cuts through the Paleoproterozoic supracrustals of the studied regions. They also indicate that these rocks formed during the extensional event responsible for the Espinhaço basin. On the other hand, the occurrence of felsic rocks of the same age as that of the basic rocks points

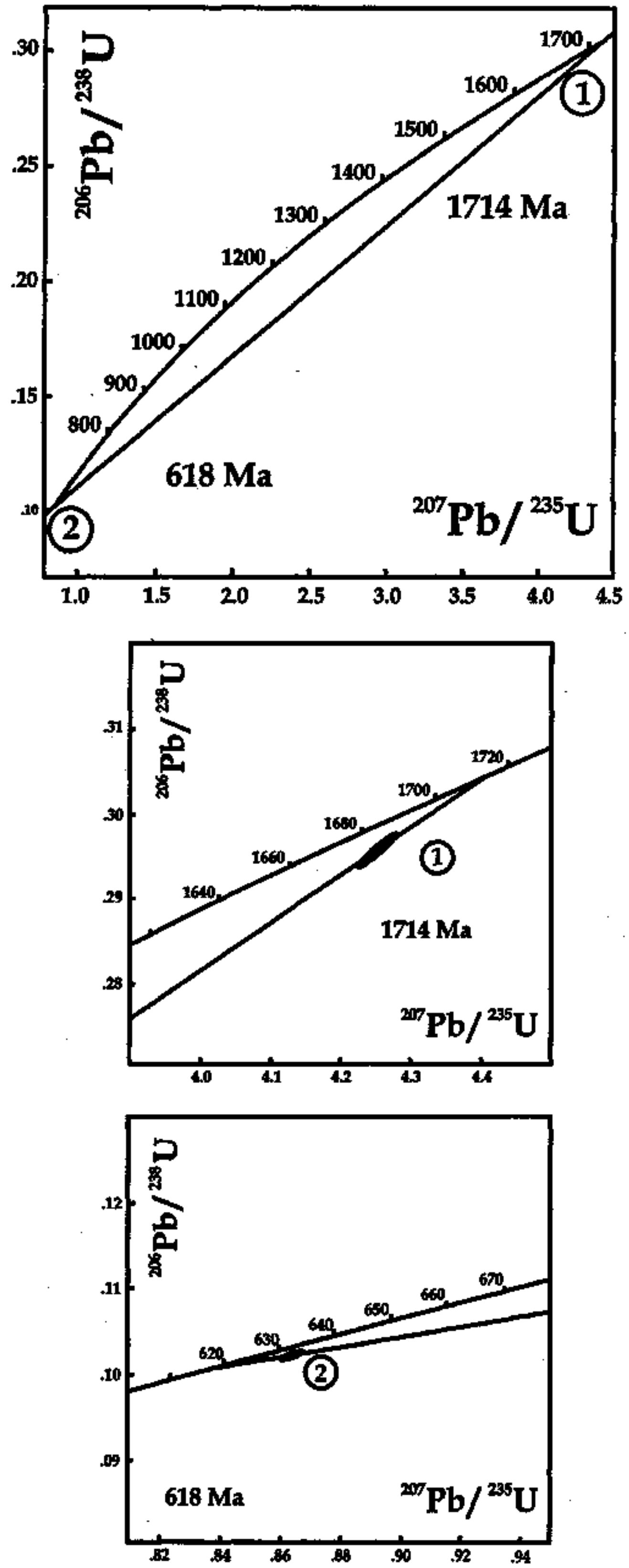

Figure 13 - Baddelyite U/Pb discórdia line of sample IBI04

to a bimodal magmatism (Silva *et al.* 1995), respectivelly from lower crustal and mantelic sources.

Dike rocks of the second pulse (906 ± 2 Ma - Machado *et al.* 1989b) are deformed and metamorphosed under green-schist facies, but with preserved igneous features, and cut through all units of the Minas and Espinhaço Supergroups. According to Machado *et al.* (1989b) this pulse of mafic dikes preceedes the beginning of the sedimentation of the São Francisco Supergroup. Recently, the Espinhaço Project (1994) evidenced that they also intruded rocks of the Macaubas Group.

The second pulse marks an important period of crustal extension of the Brasiliano-Panafrican cycle early stages. Mafic rocks of this event also been reported ensewhere in Brazil and in the Kalahari craton (D' Agrella-Filho *et al.* 1990, Renne *et al* 199, Heaman 1991).

Sm/Nd data of the metagabbros of this group have a ENd (T) (+1,34 and - 3.20) and model ages (T_{DM}) of ca. 2.59 and 1.35 Ga. They also have a high content in LIL and normative quartz; This may suggest crustal contamination, and indicate that magmas of this group resulted from partial melting of an enriched sub-continental lithosphere, further modified by their interaction with the continental crust.

Group III is the youngest in the studied regions and consists of undeformed and unmetamorphosed diabase dikes that cut through all Precambrian structures. Their K/Ar age is of ca. 120 Ma (Chemale Jr. *et al.* 1991, Silva *et al.* 1991a and b), thus correctable with the extensive flood basalts of the Paraná Basin, in southern Brazil. The few geochemical data suggest that the Neoproterozoic gabbros and Mesozoic dikes are similar, as previously reported by Oliveira & Tarney (1990). These similiralities indicate that the mantle composition did not change significantly from Proterozoic to the Mesofanerozoic, as also suggested by Mazzucchelli *et al.* (1995) for the mafic dikes in Uruguay.

CONCLUSIONS Despite of still being fragmentai, the geological knowledge of mafic dikes of the southeastern Minas Gerais improved in the last few years. The available data indicate that the supracrustal rocks of Minas and Espinhaço Supergroups were intruded by at least three basic magmatic events, each with its own structural, petrographical, geochemical, and radiometric characteristics.

The first magmatic pulse is related to the opening of the Espinhaço sedimentary basin, at about 1.7-1.5 Ga. The second is associated with the Panafrican-Brasiliano event and has an age of 906+/-2 Ma. The third has an age of approximately 120 Ma and took place during the fragmentation of Gondwana. This leds to the conclusion that the São Francisco Craton underwent successive periods of crustal extension, the most voluminous and widespread taking place during the Neoproterozoic Panafrican-Brasiliano orogeny.

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REFERENCES

BRITO NEVES, B.B; KAWASHITA, K. & DELHAL, J. 1979. A evolução geocronológica da Cordilheira do Espinhaço: Novos Dados e integração. *Rev. Bras. Geoc.*, 9(l):71-85.

CHEMALE JR., R; ROSIÈRE, C.A. & ENDO, I. 1991. Evolução tectônica do Quadrilátero Ferrífero, Minas Gerais -Um modelo (Tectonic Evolution of the Qua- drilátero Ferrífero, Minas Gerais. A Model). *Pesquisas,* 18: 104-127.

CHEMALE JR., F.; ROSIÈRE, C.A. & ENDO, I. 1994. Tectonic Evolution of the Quadrilátero Ferrífero, MG, Brazil. *Precam. Res.,* 65:25-54.

CONDIE, K.C. 1985a. Secular Variation in the Composition of Basalts: an index to mantle evolution. *Jour. Petrology,* 26:545-563.

CONDIE, K.C.; BOBROW, D.J. & CARD, K.D. 1987. Geochemistry of Precambrian Mafic Dike from Southern Superior Province. In: Halls, H.C. and Fahrig, W.F. (eds.) *Mafic Dike Swarms.* Geol. Assoc. of Canada Special Paper, 34:95-108.

CONDIE, K.C. & HUNTER, D.R. 1976. Trace element geochemistry of archean granitic rocks from the Barbeton region, South Africa. *Earth Plan. Sci. Lett.* 29:389-400.

CORDANI.U.G.; KAWASHITA.K.; MUELLER.G.; QUADE.H.; REIMER.V. & ROESER.H.P. 1980. Interpretação tectônica e petrológica de dados geocronológicos do embasamento do bordo sudeste do Quadrilátero Ferrífero, Minas Gerais. Acad. Brás. Cienc., *Anais...Rio* de Janeiro, 52:785-799.

CORDANI,U.G.; TEIXEIRA.W. & SIGA JR.,O. 1989. Geocronologia do Quadrilátero Ferrífero. In: XXI Semana de Estudos de Ouro Preto, SICEG, Ouro Preto, Boi. 21:27-44.

D'AGRELLA-FILHO, M.S.; PACCA, I.G.; RENNE, P.R.; ONSTOTT, T.C. & TEIXEIRA, W. 1990. Paleomagnetism of Middle Proterozoic (1,01 to 1,08 Ga) mafic dikes in southeastern Bahia State - São Francisco Craton, Brazil. *Earth Plan. Sci. Lett.,* 101:332- 348.

DAVIS, D.W. 1982. Optimum linear regression and error estimation applied to U/Pb data. *Can. J. Earth Sci.* 19: 2141-2149.

DAVISON, A. & VAN BREEMEN, O. 1988. Baddeleyite-zircon relationships in coronotic metagabbros, Greenville Province, Ontario: implications for geochronology. *Contrib. Mineral. Petrol.,* 100:291-299.

DORR, J.N. 1969. Physiografic, stratigraphic, and structural development of the Quadrilátero Ferrífero, Minas Gerais. *U.S. Geol. Surv. Pap.,* 641A-.110S; Washington.

DOSSIN,T.M.;DOSSIN, I. A.; CHAR VET, J. & BONHOMME, M.G. 1995. K-Ar chronology of a Mesozoic dike swarm from southern Espinhaço Region (SE Brazil). *Jour, of South Am. Ear. Sci.,* 8:47-53.

FRIZ-TOPPER, A. 1991. Geochemical characterization of Pan-African dike swarms in Southern Sinai: from continental margin to intraplate magmatism. *Precam. Res.,* 49:281-300.

HALLS, H. 1982 . The Importance and Potencial of Mafic Dikes Swarms in Studies of Geodynamic *Process. Geoscience Canada,* 9:145-154.

HEAMAN, L.M.1991. U-Pb dating of giant radiating dike swarms: potential for global correlation of mafic magmatic events. In:Teixeira,W., Ernesto, M. and Oliveira, E.P.eds. Ill INTERN. *Symposium on Mafic Dikes.* Extends Abstracts, p.7-8. São Paulo.

HEAMAN, L.M. & GROTZINGER, J.P. 1992. 1.08 G.a. diabase sills in the Pahrump Group, California. Implications for development of the Cordilleran miogeocline. *Geology,* 20:637-640.

HEAMAN, L.M & MACHADO, N. 1992. Timing and origin of midcontinent rift alkaline magmatism, North America: evidence from Coldwell Complex. *Contrib. Mineral. Petrol.,* 110:289-303.

HEAMAN, L.M & LECHEMINANT, A.N. 1993. Paragenesis and U-Pb systematics of baddeleyite (ZrOa). *Chemical Geology* (Including Isotope Geoscience), 110:95-126.

HENDERSON, P. 1984. *Rare Earth Element Geochemistry Developments in Geochemistry, 2.* Elsevier, New York, 51 Op.

IRVINE, I.N. & BARAGAR, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. *Can. Jour. Earth Sci.,* 8: 523 - 548.

JAFFEY, A.H., FLYNN, K.F., GLENDENIN, L.E., BENTLEY, W.C. & ESSLING, A.M. 1971. Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U. *Phys. Rev.,* 4:1889-1906.

LADEIRA, E. A. 1980. *Metallogenesis of Gold at the Morro Velho Mine, and in Nova Lima District, Quadrilátero Ferrífero, Minas Gerais, Brazil.* Unpubl. PhD thesis, University of Western Ontario, London, 272pp.

LE MAITRE, R.W. 1976. A proposal by the IUGS Subcomission on the Systematics of Igneous Rocks for a Chemical classification of volcanic rocks based on the total alkali silica (TAS) diagram. *Australian Jour. Earth Sci.,* 31: 243-255.

LINDSLEY.D.H.1983. Pyroxene thermometry. *Am. Mineral.,* 68:477-493.

MACHADO, N.; NOCE, C.M.; BELO DE OLIVEIRA, O.A. & LADEIRA, E.A. 1989a. Evolução geológica do Quadrilátero Ferrífero Arqueano e Proterozóico Inferior, com base em geocronologia U/Pb. In: 5° SIMP. GEOL. NÚCLEO MG - 1° SIMP. GEOL. Núcleo Brasília, SBG - NÚCLEO MG, *Anais...Belo* Horizonte, BOL. 10:1-5.

MACHADO, N.; SCHRANK, A.; ABREU, F.R.DE; KNAUER, L.G. & ALMEIDA-ABREU, P.A. 1989b. Resultados o preliminares da geocronologia U/Pb na Serra do Espinhaço Meridional.In: 5° SIMP. GEOL., Núcleo de MG - 1° SIMP. GEOL. Núcleo Brasília, SBG - Núcleo MG, *Anais.* ..Belo Horizonte, BOL. 10: 171 -174.

MACHADO, N. & CARNEIRO, M.A. 1992. U-Pb evidence of late Archaean tectono- thermal activity in the southern São Francisco shield, Brazil. *Can. J. Earth Sci.,* 29(11):2341- 2346.

MARSHAK, S. & ALKMIM, F.F. 1989. Proterozoic extension/contraction tectonics of the São Francisco Craton of the São Francisco Craton and adjacent regions, Minas Gerais, Brazil: a kinematic model relating Quadrilátero Ferrífero, São Francisco Basin and Cordilheira do *Espmhaco.Tectonics,* 8 (3):555-571.

MAZZUCCHELLI, M.; RIVALENTI, G.; PICCIRILLO.E.M.; GIRARDI,V.A.V.; CIVETTA, L. & PETRINI.R. 1995. Petrology of the Proterozoic mafic dike swarm of Uruguay and constraints on their mantle source composition. *Precam. Res.,* 74:177-194.

MIYASHIRO, A. 1974. Volcanic rock series in island arcs and active continental margins. *Am. J. Sci.* 274:321-355.

NAKAMURA, N. 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochem. Cosmoche. Acta.* 38: 757-775.

OLIVEIRA, E.P. & TARNEY, J. 1990. Petrogenesis of the Canindé de São Francisco Complex: a major Late Proterozoic gabbroic body in the Sergipe Foldbelt, northeastern *Brazil. Jour. South Am. Earth Sci.,* 3:125-140.

PEARCE, J.A.; GORMAN, B.E. & BISKETT, T.C. 1977. The relationship between major elements chemistry and tectonic environment of basic and intermediate volcanic rocks. *Earth Planet. Sci. Lett.,* 36:121-132.

PFLUG, R. & RENGER, F. 1973. Estratigrafia e evolução geológica da margem sudeste do cráton Sanfranscicano. In: XXVII CONGR. BRÁS. GEOL., Anaw...Aracaju, 2:5-19.

POLDER V AART, A. & HESS.H.H. 1951. Nomenclature of clinopyroxenes in the system $CaMgSÍ_2O_6$-$CaFeSÍ_2O6$-$Mg_2SÍ_2O_6$-FeS i_2O_6. *Journ. Geol.,* 59:472.

RENNE, P.R.; ONSTOTT, T.C.; D'AGRELLA-FILHO, M.S.; PACCA, I.G. & TEIXEIRA, W. 1990.^{40}Arr^{39}Ar dating of 1,0-1,1 Ga magnetizations from the São Francisco and Kalahari cratons: tectonic implications for Pan-African and Brasiliano mobile belts. *Earth Plan. Sci. Lett.,* 101:349-366.

SATO, K., TASSINARI, C.C.G., KAWASHITA.K & PETRONILHO, L. Método geocronológico Sm/Nd no IG-USP e suas aplicações (unpublished).

SCHORSCHER, H.D. 1978. Komatiitos na estrutura greenstone belt Série Rio das Velhas. Quadrilátero Ferrífero, Minas Gerais, Brasil. XXX Congr. Bras. Geol., *Anais...Recife,* Bol. Esp. 1:292-293.

SCHORSCHER, H.D., CARBONARI, F.C., POLÔNIA, J.C. & MOREIRA, J.M.P. 1982. Quadrilátero Ferrífero - Minas Gerais State: Rio das Velhas greenstone belt and Proterozoic rocks. *Intern. Symp. Early Arch. Prot.,* Salvador, Excur. Annex., 46 pp.

SILVA, A.M.; KUYUMJIAN, R.M. & CHEMALE JR., F. 1991a. Mafic dikes swarms in the southern São Francisco Craton, Southeastern Brazil. In:Teixeira,W., Ernesto.M. and Oliveira,E.P.eds. Ill Intern. Symposium on Mafic Dikes. *Extend. Abstracts,* p.90- 93. São Paulo.

SILVA, A.M.; KUYUMJIAN, R.M. & CHEMALE JR., F 1991b. Rochas básicas do Quadrilátero Ferrífero e Espinhaço Meridional: Estudos preliminares. *REM - Revista da Escola de Minas,* Ouro Preto, 45(1 e 2): 60-62.

SILVA, A. M.; CHEMALE JR., F. & HEAMAN.L. 1995. The Ibirité Gabbro and The Borrachudo Granite: the rift-related magmatism of Mesoproterozoic age in the Quadrilátero Ferrífero, MG. *Anais* ... 8° Simpósio de Geologia de Minas Gerais, Diamantina, MG: 89-90.

TAYLOR, S.R. & MCLENNAM, S.M. 1985. The Continental Crust:its Composition and Evolution. Blackwell, Oxford, 312pp.

TARNEY, J. & WEAVER, B.L. 1987. Geochemistry and Petrogenesis of Early Proterozoic Dike Swarms. In: Hall, H.C. and Fahrig, W.H. (eds.) *Mafic Dike Swarms.* Geol. Assoc. of Canada Special Paper 34, p. 81-94.

TEIXEIRA, W. 1985. *A evolução geotectônica da porção meridional do cráton São Francisco, com base em interpretações geocronológicas.* PhD Thesis, Unpubl., IG-USP, São Paulo.

THOMPSON, R.N.; MORRISON, M.A.; HENRY, G.L. & PARRY, S.J. 1984. An assessment of the relative roles of crust and mantle in magma genesis: An elemental approach. *Philos. Trans. Royal Soc.* London A310:549-590.

ULHEIN, A.; TROMPETTE, R.R. & EGYDIO DA SILVA, M. 1986a. Estruturação tectônica do Supergrupo Espinhaço na região de Diamantina (MG). *Rev. Bras. Geoc.,* 16(2):212-216.

WEAVER, B.L. & TARNEY, J. 1981b. The Scourie Dike Suite: petrogenesis and geochemical nature of the Proterozoic subcontinental mantle. *Contributions to Mineral, and Petrol.* 78:175-188.

WOOD, D.A. 1979. A variable veined suboceanic upper mantle -genetic significance for mid-ocean ridge basalts from geochemical evidence. *Geology, 7:* 499-503

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