The Mantiqueira Metamorphic Complex, Eastern Minas Gerais State: Preliminary Geochronological and Geochemical Results

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ABSTRACT

The Mantiqueira Metamorphic Complex, in eastern Minas Gerais State, Southeastern Brazil, forms part of a large arcuate belt of Paleoproterozoic age, composed essentially of tonalitic-granodioritic biotite-hornblende gneisses and migmatites, with subordinate mafic rocks and metasediments, as well as granitoid intrusions.

Preliminary geochronological studies, mainly based on whole rock Rb-Sr work, indicate that the main metamorphism and deformation took place between 2.300 and 2.000 Ma, the Sr isotopic data suggesting a partial reworking of the Archean crust.

Major and trace element whole-rock geochemistry indicates the presence of two distinct calc-alkaline suites. Due to the regional scope of the present study, however, this inference needs to be further tested. The suites characterized up to now in the Mantiqueira Complex range from basic to acid terms: one corresponds to a low-K calc-alkaline sequence, while the other represents a LILE-enriched high-K calc-alkaline sequence, relatively enriched in K, Ti, Fe, P, Rb, Zr, Nb and Y. Thus, the preliminary results suggest a mature magmatic arc environment for these suites.

Calc-alkaline sequences very similar with the Mantiqueira rocks have been recently described in the adjacent Juiz de Fora Metamorphic Complex that was similarly reworked during the Paleoproterozoic. This similarity, if demonstrated by additional U-Pb geochronology, together with Sr and Nd isotopic analyses and geochemistry, raises the possibility that the Juiz de Fora Complex, which is thrust over the Mantiqueira Complex, could be a charnockitized lower portion of the latter unit. Both complexes were finally welded with the Paraíba do Sul and Costeiro metamorphic complexes during the Neoproterozoic/eo-Cambrian times.

Key words: gneisses, migmatites, calc-alkaline sequences.

INTRODUCTION

The Mantiqueira Metamorphic Complex (MMC), that occupies the region of the homonymous hill range in Minas Gerais State, was defined as Série Mantiqueira (Barbosa, 1954), composed of banded gneisses with subhorizontal foliation. Ebert (1958) denominated such rocks as Piedade Gneiss in the locality of Piedade do Rio Grande, Minas Gerais State, and this name has been used regionally in some works (e.g., Machado Filho *et al.*, 1983). In this work we adopted the name Man-

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tiqueira Complex not only due to priority but also taking into account the fact that Ebert (*op. cit.*) defined the Piedade Gneiss as gneissic metasediments and, according to our studies, it in fact originated from extensive plutonic sequences.

MMC comprises several lithotypes of biotite and hornblende gneisses and migmatites, granitic, granodioritic and tonalitic in composition, and includes mafic rocks as schollen, boudins, layers, dikes and enclaves. This complex, more than 10,000 km^2 in area, occurs as an arcuate belt (Mineiro belt; Teixeira, 1985) in the transition zone between the southeastern boundary of the São Francisco Craton and the Ribeira belt (Fig. 1). The Mineiro belt consists mainly of medium grade gneissic-migmatitic-granitoid terrains of Paleoproterozoic age, but also contains vestigial Archean material in its interior (e.g.; Teixeira, 1982; Teixeira *et al.*, 1987a; Teixeira & Figueiredo, 1991). Its tectonomagmatic episodes originated NS to NNE-SSW trending structures in the transition zone of the Craton, as well as the reworking of the eastern part of a large Archean terrain, part of which includes lithologies of the Barbacena Metamorphic Complex.

Several large intrusive granites, monzonites and sienites, mostly undeformed, have their emplacement roughly concordant with the regional trend of the Mineiro belt (Fig. 1), and are interpreted to be syn- to late tectonic plutons in relation to the Paleoproterozoic evolution of this belt (e.g., Heilbron *et al.*, 1989; Viana, 1991; Brandalise & Viana, 1993; Quéméneur *et al.*, 1994; Noce, 1995). On of these plutons, – the Ressaquinha Complex – occurring in (1:100.000 scale) Barbacena sheet, has Rb-Sr ages ranging from 2.00 to 1.81 Ga (Padilha *et al.*, 1991). The Matola Massif that occurs as a NS body near the locality of São João del Rei (not shown in Fig. 1) is probably tectonically associated with these Paleoproterozoic intrusives because of its alkaline to shoshonitic affinity and intrusive field relations (e.g., Ebert, 1958; Alves *et al.*, 1962; Coutinho, 1968).

In the northern sector of the Mineiro belt, adjacent to the northern limit of the area investigated, the Acaiaca Granulitic Complex occurs, metamorphosed under conditions of medium to high pressure and 700-900°C (Jordt Evangelista, 1984). It yields concordant Rb-Sr and Pb-Pb ages of about 2.0 Ga and shows Sr, Pb and Nd isotopic parameters indicating reworking of Archean crust (Teixeira *et al.*, 1987b; K. Sato pers. comm., 1966).

An Archean history for the Barbacena Complex was first demonstrated by Cordani *et al.* (1973) on the basis of a whole Rb-Sr reference isochron of 2.70 Ga obtained for migmatitic gneisses occurring around the locality of Barbacena. More recently, whole rock Rb-Sr isochrons in this complex (Padilha *et al.*, 1991) indicated both Archean (2.70-2.55 Ga) and Paleoproterozoic (2.27-2.00 Ga) results. The younger results, interpreted to be associated with the Transamazonian cycle evolution (2.20-1.90 Ga), reinforces a relationship with the deformation and regional metamorphism on the Mineiro belt, as suggested by Teixeira (1985). The high $^{87}Sr/^{86}Sr$ initial ratios (IR's), from 0.7085 to 0.71570, reported for the younger results point to crustal reworking in agreement with the Archean results cited above.

Söllner *et al.* (1991) dated by the U-Pb method two different zircon populations present in an outcrop of the Barbacena Complex: 1) euhedral prismatic, pink, transparent zircons from a dark layer of a banded gneiss yielded an age of about 3.40 Ga, and according to the interpretation of the authors these magmatic zircons were re-sedimented together with volcanic material; 2) white and metamictic xenomorphic zircons (*from a volcanic detritus* – sic) yielded an upper concordia intercept $^{207}Pb/^{206}Pb$ age of about 3.10 Ga. On the other hand, the lower intercept with the concordia indicated that episodic Pb loss took place during the Neoproterozoic, estimated at 620 Ma.

Because the polycyclic crustal evolution of the Barbacena and Mantiqueira complexes it is difficult to establish a clear geologic boundary between them. However it appears that an extensive tectonic front associated with a major shear zone could be the limit between these two complexes (Fig. 1). This structure controlled the occurrences of the Dom Silvério supracrustal relicts and tectonic slices of the Mantiqueira rocks, both lithostratigraphic units being thrust over the Barbacena complex, westward.

The Andrelândia and São João Del Rei metasediments (quartzites, phyllites, schists, marbles, gneisses and calc silicatic rocks) occur southwestward of the MMC, overlaying crystalline basement rocks, mainly amphibolite facies gneisses, intruded by granodioritic plutonism. The gneisses and granitoids have Rb-Sr radiometric ages between 2.20 and 1.90 Ga (e.g., Cordani & Teixeira, 1979; Machado Filho *et al.*, 1983), also considered to be related to the Mineiro belt evolution (Teixeira & Figueiredo, 1991). Several outcrops of the Andrelândia and São João Del Rei supracrustals yielded younger Rb-Sr ages in the range 800-600 Ma and 1330-900 Ma, and were interpreted as indicative of the existence of two metamorphic episodes in the area (e.g., Heilbron *et al.*, 1989), however this interpretation is still debatable.

The MMC is overthrust by the Juiz de Fora Complex in the East (e.g., Machado Filho *et al.*, 1983). This complex comprises (Campos Neto & Figueiredo, 1990) reworked terrains predominantly composed of two calc-alkaline plutonic sequences, one "normal", the other enriched in large ion lithophile elements (LILE), both charnockitized and with lenses of preserved orthogneiss protoliths. Migmatites are very common, and locally contain xenoliths of the charnockitic rocks. Moreover, both the Juiz de Fora charnockitic rocks and the preserved lenses of orthogneisses may contain calc-silicatic xenoliths and basic enclaves. S-type granites occur also in the region.

Söllner *et al.* (1991) consider the Juiz de Fora Complex as dominantly metasedimentary, while other authors (e.g., Figueiredo & Campos Neto, 1989; Campos Neto & Figueiredo, 1990) consider its protoliths as predominantly plutonic based on field evidence, such as the presence of basic enclaves and calc-silicatic xenoliths and cross-cutting relations, as well as geochemical evidence (e.g., the presence of two different calc-alkaline basic to acid sequences; see further discussion).

In the Caparaó range (northward of the area investigated), U-Pb zircon dates on the Juiz de Fora charnockites yielded an upper intercept age with the concordia of about 2.20 Ga, while the lower intercept yields an age of 590 Ma (Söllner *et al.*, 1991). These results confirm geochronological reconnaissance studies carried out by Cordani *et al.* (1973). The Rb-Sr isochrons in several outcrops yielded ages of about 2.05 Ga and 585 Ma, whilst the K-Ar ages range from 455 to 430 Ma. In particular, the younger dates demonstrate the existence of an amphibolite facies metamorphism associated to the Rio Doce Orogeny, in agreement with the model proposed by Campos Neto (1991).

Our work presents an integrated interpretation for geochronological and whole-rock chemical results carried out in selected outcrops of the MMC, in eastern Minas Gerais State, approximately bounded by the localities of Santos Dumont, Barbacena, Ubá and Viçosa (Fig. 1). The geochemical and Rb-Sr and K-Ar radiometric studies allow to a qualitative evaluation of the MMC tectonic evolution, and envisage a comparison with the neighboring Juiz de Fora Complex. The preliminary geochronological and geochemical results are compared with published data of the MMC rocks and metamorphic complexes occurring within both the Southern and Northern São Francisco Craton leading to discussion of the nature and significance of the Paleoproterozoic episodes.

SAMPLING STRATEGY AND PETROGRAPHY

The samples of the MMC selected for both the geochemical studies and geochronology were mostly collected in quarries and main roadcuts to obtain the freshest material for the analyses (see Fig. 1). The whole rock Rb-Sr determinations were carried out in a total of four outcrops (14, 22, 25 and 27; Tab. I) to evaluate the period of the main metamorphic event in the area, while 7 outcrops were investigated by K-Ar mineral geochronology (11, 14, 22, 23, 26, 30 and 32; Tab. II). Three of these (14, 23, 26) have been analysed for both biotite and hornblende to allow interpretation of the thermochronology of the MMC accross an EW regional section. Twenty-five chemical analyses were performed on samples from 10 outcrops, most of which providing more than one sample (see Tabs. IV to VIII). These analyses were in-

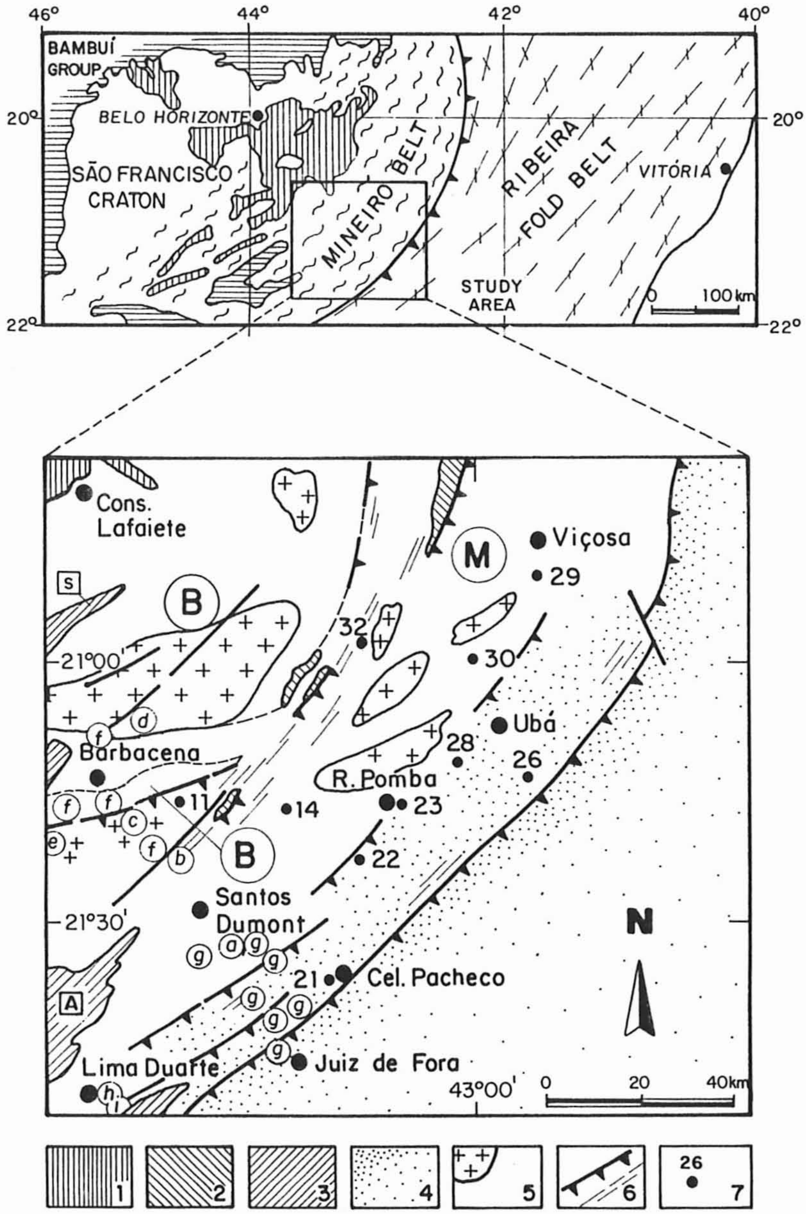

Fig. 1 — Geological sketch map of the investigated area showing the location of the selected samples for geochronology and geochemistry (adapted from Machado Filho *et al.*, 1983; Santos, 1991; Bradalise & Viana, 1993). Inset shows the study area in the geological framework at the southern part of the São Francisco, adjacent to the Neoproterozoic Ribeira belt. Symbols: 1 – Rio das Velhas and Minas Supergroups; 2 – Dom Silvério Group; 3 – Andrelândia (A) and São João del Rei (S) Groups; 4 – Juiz de Fora Complex; 5 – Barbacena (B) and Mantiqueira (M) complexes (γ = granitoid intrusions); 6 – Major faults and shear zones. The coarse dashed line represents the limit between the Barbacena and Mantiqueira complexes, as proposed by Machado Filho *et al.* (*op. cit.*). Published radiometric data are plotted in italic (see Tab. III).

TABLE I
Rb-Sr whole rock analytical data of the Mantiqueira Complex.

Lab. no.	Sample	Rock	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$
11183	26-IX	migmatite	86.0	336.0	0.73602 (5)	0.743 (21)
11184	26-XI	migmatite	62.0	337.0	0.72955 (20)	0.534 (15)
11185	27-I	gneiss	127.0	270.0	0.74429 (9)	1.366 (38)
11186	27A-III	gneiss	65.0	579.0	0.71513 (12)	0.325 (9)
11187	27-IV	gneiss	185.0	244.0	0.77449 (8)	2.209 (62)
11188	27-VIII	gneiss	51.0	744.0	0.70849 (9)	0.198 (6)
11189	27-XXII	gneiss	89.0	321.0	0.72638 (6)	0.804 (23)
11173	14-MI	banded gneiss	89.0	200.0	0.74712 (12)	1.162 (33)
11174	14-PI	banded gneiss	152.0	315.0	0.75610 (5)	1.403 (39)
11175	14-IX	banded gneiss	60.0	304.0	0.74263 (11)	0.573 (16)
11176	14-XII	banded gneiss	95.0	318.0	0.73919 (8)	0.867 (24)
11177	22-II	migm. gneiss	69.0	614.0	0.71570 (6)	0.325 (9)
11178	22-III	migm. gneiss	102.0	397.0	0.72830 (6)	0.745 (21)
11179	22-X	migm. gneiss	75.0	432.0	0.72078 (9)	0.503 (14)
11180	22-XI	migm. gneiss	42.0	653.0	0.71076 (6)	0.186 (5)
11181	26-I	migmatite	48.0	250.0	0.73226 (7)	0.398 (11)
11182	26-VI	migmatite	109.0	462.0	0.73211 (5)	0.684 (19)
11183	26-IX	migmatite	86.0	336.0	0.73602 (5)	0.743 (21)
11184	26-XI	migmatite	62.0	337.0	0.72955 (2)	0.534 (15)

TABLE II
K-Ar analytical data of the Mantiqueira complex, in the area investigated.

Lab. no.	Sample	Lithology	Mineral	%K	Ar^{40}rad (*10-6)	Ar^{40}atm	Age (Ma)
6779	11-I	gneiss	biotite	6.164	163.59	15.29	580 ± 12
6813	14-A	amphibolite	hornblende	0.999	24.17	18.41	535 ± 13
6816	14-A	amphibolite	biotite	6.869	162.08	4.36	524 ± 19
6814	22-III	migm. gneiss	biot. + chlor.	5.058	175.78	8.58	733 ± 68
6781	22-III	migm. gneiss	biotite	7.644	171.61	6.32	502 ± 19
6810	23-XIII	gneiss	hornblende	0.523	40.97	20.54	1354 ± 29
6807	23-XIII	gneiss	biotite	6.209	185.28	7.11	641 ± 29
6808	26-XIIa	amphibolite	hornblende	0.498	51.62	15.35	1637 ± 29
6812	26-XIIa	amphibolite	biotite	7.260	175.34	6.82	534 ± 6
6809	30-II	amphibolite	biotite	7.428	165.58	6.37	498 ± 9
6778	32-I	gneiss	biotite	7.124	163.07	3.55	510 ± 7

TABLE III
Summary of radiometric data available for the Mantiqueira Complex and adjacent tectonic units.

Tectonic unit/lithology	Age (Ma)	Method	Ref.**
Mantiqueira/gneiss 14	2144±175 (IR*=0.71213±272)	Rb-Sr	1
Mantiqueira/migm. gneiss 22	2212±68 (IR=0.70492±30)	Rb-Sr	1
Mantiqueira/migmatite 26	2120±256 (IR=0.71262±237)	Rb-Sr	1
Mantiqueira/migmatite 27	2233±47 (IR=0.70274±26)	Rb-Sr	1
Mantiqueira/gneiss	~2200 (IR~0.702) 680 (0.707)	Rb-Sr	3 (*a*)
Mantiqueira/granulite	2684±110 (IR=0.7139±19	Rb-Sr	2 (*b*)
Ressaquinha/gneiss	1815±72 (IR=0.7122±15)	Rb-Sr	2 (*c*)
Ressaquinha/gneiss	1975±51 (IR=0.7085±51)	Rb-Sr	2 (*d*)
Ressaquinha/gneiss	1998±95 (IR=0.7157±18)	Rb-Sr	2 (*e*)
Barbacena/gneisses and granulites	2880±166 (IR=0.7060±12)	Rb-Sr	3 (*f*)
Juiz de Fora/granulites	2230 (IR=0.71) 2880 (0.708)	Rb-Sr	3 (*g*)
Juiz de Fora/migm. gneiss	1483±25 (IR=0.70261±11)	Rb-Sr	2 (*h*)
Juiz de Fora/enderbite	643±13 (IR=0.70934±8)	Rb-Sr	2 (*i*)
Rio Casca/gneisses	2160±213 (IR=0.7157±22)	Rb-Sr	4
Lavras/gneiss	1982±108 (IR=0.7041±13)	Rb-Sr	5
Seritinga granodiorite	2065±73 (IR=0.7071)	Rb-Sr	5
Mantiqueira/gneisses	2353±52 (IR=0.70201)	Rb-Sr	5
East of Mariana/gneisses	2009±219 (IR=0.7103±28) ~2850 (2 data)	Rb-Sr	6
Acaiaca/granulites	1991±42 (IR=0.7061±4)	Rb-Sr	7
Acaiaca/granulites	1996+425/–600 (μ1=8.6±0.1)	Rb-Sr	8

*IR = $^{87}Sr/^{86}Sr$ initial ratio; **1 = this work (data in Tab. I); 2 = Padilha *et al.* (1991); 3 = recalculated from Delhal *et al.* (1969) and Cordani *et al.* (1973); 4 = Machado Filho *et al.* (1983); 5 = Heilbron *et al.* (1989); 6 = Cordani *et al.* (1980); 7 = Teixeira *et al.* (1987b). Italic letters (*a* to *i*) listed in the right hand column correspond to the outcrops plotted in Fig. 1. Reference numbers 4 to 8 are from outcrops located outside the area investigated. Obs.: published Rb-Sr results were calculated according to the constants reported in Steiger & Jäger (1977).

tended to establish the regional geochemical features of the MMC.

Most of the outcrops comprise gneisses with sub-horizontal banding (e.g., 11, 14, 21, 23, 30, 32) metamorphosed under regional amphibolite facies, but granulitic facies lithologies were observed in outcrops 25, 26 and 29. In particular, outcrop 23 contains undeformed granitic material within the melanossomatic facies while mafic bodies concordant with the metamorphic banding were observed in outcrops 11, 30 and 28. Gneisses 22 and 29 were partly subjected to migmatization, and in the latter

TABLE IV
Mantiqueira Complex low-K calc-alkaline sequence (CA).

	30a	14m II	28 VII	21 XII	28 XI	23 IV	29 XII	21 IX
SiO_2%	47.9	50.7	53.2	57.8	60.9	66.2	67.0	67.5
TiO_2	2.2	1.6	0.82	0.56	0.52	0.36	0.58	0.37
Al_2O_3	13.7	12.9	15.5	15.2	16.8	16.9	16.2	16.5
Fe_2O_3	4.9	3.1	2.1	3.6	2.5	0.97	0.41	0.59
FeO	8.2	9.5	6.7	5.1	3.7	2.1	2.6	1.9
MnO	0.18	0.18	0.18	0.17	0.08	0.05	0.03	0.03
MgO	6.6	6.3	5.7	4.1	0.90	1.4	0.59	0.59
CaO	11.2	10.7	7.8	6.0	5.6	4.8	3.6	3.7
Na_2O	2.6	2.7	4.1	4.4	3.9	5.1	3.8	5.4
K_2O	0.56	1.0	2.1	1.4	3.8	1.3	3.9	2.1
P_2O_5	0.23	0.16	0.18	0.10	0.30	0.12	0.15	0.11
H_2O^+	0.50	0.65	0.59	0.64	0.23	0.29	0.47	0.47
H_2O^-	0.11	0.03	0.06	0.06	0.13	0.07	0.06	0.06
CO_2	1.1	0.35	0.60	0.70	0.30	0.30	0.25	0.50
S	0.11	0.06	0.05	0.06	0.08	0.05	0.05	0.02
F	0.04	0.08	0.18	0.10	0.05	0.04	0.05	0.04
Total	100.02	99.98	99.80	99.93	99.66	99.98	99.68	99.82
Cl ppm	46	530	860	260	90	220	320	130
Cr	179	184	129	343	14	7	28	14
Ni	198	108	74	41	119	16	23	7
Ba	153	83	1644	525	2973	414	2844	1455
Rb	3	nd	43	29	40	37	111	61
Sr	208	73	1140	515	573	553	867	758
Nb	44	nd	32	nd	22	28	26	nd
Zr	91	142	66	44	80	70	363	121
Y	34	33	27	29	26	10	10	10

outcrop subvertical banding was observed. Outcrops 26 and 27 were strongly migmatitized, the latter being intruded by an amphibolite dike discordant to the metamorphic foliation.

Petrographically, the gneissic rocks have commonly granoblastic textures. The common mineral constituents of the gneisses are quartz, microcline, plagioclase, hornblende and biotite. The main accessories are opaque minerals, zircon, titanite and apatite. Chlorite, sericite, carbonate and epidote are rare. A few number gneisses (e.g., 27) are kinzigites with quartz, K-feldspar, garnet (up to 20%), biotite, sillimanite, cordierite, and sericite, titanite and zircon as accessory phases. The granulites are composed of quartz, plagioclase, biotite, orthopyroxene, hornblende and apatite, and as accessory phases, garnet, zircon, opaque minerals and epidote.

The mafic rocks (amphibolites) exhibit granoblastic to nematoblastic textures. They are composed of hornblende, plagioclase, feldspar, quartz, biotite, epidote and opaque minerals. Two types of

TABLE V
Mantiqueira Complex LILE-enriched high-K calc-alkaline sequence (K-CA).

	11 A	23 XIII	26 XII	22 III	30 III	22	11	32	26	14
SiO_2%	43.9	46.6	51.4	60.7	64.7	65.2	65.6	66.2	70.0	70.9
TiO_2	3.3	3.5	2.5	1.4	0.83	0.82	0.68	0.67	0.31	0.29
Al_2O_3	14.1	13.5	14.1	14.4	15.1	14.7	15.4	15.0	14.8	14.1
Fe_2O_3	3.2	2.0	2.7	2.3	1.0	1.8	1.4	0.82	0.40	0.60
FeO	12.3	11.1	8.5	5.4	4.1	3.3	2.7	2.5	1.8	1.8
MnO	0.22	0.18	0.14	0.07	0.07	0.07	0.05	0.03	0.02	0.02
MgO	6.6	6.2	5.4	3.0	1.2	1.4	1.5	1.7	0.66	0.69
CaO	10.1	10.5	6.6	4.5	4.5	3.6	3.3	1.9	2.5	2.6
Na_2O	2.4	2.5	3.7	3.0	3.9	3.3	4.6	4.0	4.0	4.1
K_2O	2.3	2.0	3.0	2.9	2.9	4.3	3.1	5.4	4.5	3.8
P_2O_5	0.45	0.50	0.44	0.61	0.40	0.31	0.33	0.41	0.16	0.12
H_2O^+	0.76	0.87	0.63	0.69	0.67	0.43	0.70	0.42	0.33	0.28
H_2O^-	0.15	0.02	0.06	0.12	0.07	0.18	0.12	0.10	0.08	0.09
CO_2	0.30	0.25	0.60	0.35	0.35	0.30	0.30	0.30	0.30	0.30
S	0.02	0.20	0.16	0.08	0.03	0.05	0.01	0.09	0.02	0.01
F	0.07	0.01	0.14	0.21	0.11	0.11	0.10	0.12	0.04	0.02
Total	100.01	99.91	100.01	99.61	99.86	99.69	99.77	99.56	99.84	99.93
Cl ppm	56	990	170	1460	700	1060	nd	76	nd	39
Cr	130	92	99	57	35	14	28	7	7	7
Ni	118	108	105	43	28	24	24	16	8	8
Ba	608	491	1066	1406	2380	2985	1267	4347	1353	846
Rb	46	28	121	111	89	73	85	120	79	53
Sr	364	240	221	405	716	595	470	1451	380	204
Nb	52	44	38	nd	22	38	38	nd	28	20
Zr	182	421	402	566	343	393	202	273	107	131
Y	43	49	51	49	28	52	25	21	20	10

amphibolites appear to be present in the area because one type presents garnet as an index mineral, whilst the other titanite. The common trace minerals in the mafic rocks are chlorite, sericite, and carbonate. In particular, sample 28 is a porphyritic meta-gabbro with granular texture in a lepidoblastic to nematoblastic matrix. Its main mineral constituents are feldspar, hornblende, pyroxene, garnet, biotite and opaque minerals. The accessories are epidote, quartz and carbonate.

METHODOLOGY

The Rb-Sr (Tab. I) and K-Ar (Tab. II) analyses were performed at the Centro de Pesquisas Geocronológicas (CPGeo) of the Instituto de Geociências, Universidade de São Paulo. Both the Rb-Sr and K-Ar results were calculated according to the constants of Steiger & Jäger (1977). The whole-rock Rb-Sr isochron age calculation (outcrops 14, 22, 26 and 27; Fig. 2a,b,c,d) followed the procedures of Williamson (1968). These results,

TABLE VI
Mantiqueira Complex amphibolitic dikes (28 AI, 14 A, 30, 29) and samples with distinct chemical characteristics.

	28 A I	14 A	30	29	32 A	23 A II	32 I
SiO_2%	46.4	48.6	52.6	52.9	46.8	47.6	55.2
TiO_2	4.2	2.0	0.96	1.0	0.86	1.0	1.8
Al_2O_3	12.0	12.4	15.3	19.2	12.8	13.1	17.2
Fe_2O_3	7.4	4.2	3.1	2.0	3.3	2.9	0.78
FeO	9.0	11.4	7.6	6.4	8.4	11.1	5.6
MnO	0.26	0.21	0.15	0.11	0.15	0.22	0.06
MgO	4.1	5.8	4.4	3.4	11.2	8.1	2.9
CaO	9.4	10.2	7.2	7.2	11.1	10.0	4.7
Na_2O	3.2	2.6	3.6	4.8	2.2	2.7	5.5
K_2O	1.1	1.5	2.5	1.4	1.9	1.7	3.3
P_2O_5	1.2	0.21	1.2	0.44	0.13	0.12	1.6
H_2O^+	0.55	0.26	0.51	0.32	0.56	0.44	0.61
H_2O^-	0.23	0.07	0.14	0.12	0.09	0.11	0.05
CO_2	0.80	0.30	0.30	0.50	0.30	0.70	0.25
S	0.24	0.17	0.13	0.20	0.13	0.10	0.17
F	0.12	0.03	0.22	0.08	0.13	0.13	0.06
Total	99.97	99.88	99.77	99.95	99.96	99.91	99.75
Cl ppm	180	410	700	180	230	1140	280
Cr	7	34	68	28	576	137	85
Ni	80	102	86	63	520	220	121
Ba	506	187	1440	660	350	297	1740
Rb	63	19	95	6	74	37	160
Sr	535	123	760	777	244	557	1700
Nb	84	38	42	38	29	24	26
Zr	250	114	320	230	26	28	800
Y	68	33	68	29	20	27	41

were interpreted together with published Rb-Sr and Pb-Pb data (Tab. III), as well as K-Ar dates available for the Mantiqueira, Barbacena and Juiz de Fora complexes (e.g., Machado Filho *et al.*, 1983).

The whole-rock chemical analyses (major and trace elements) presented here were performed at GEOLAB-GEOSOL in September 1989. X-ray fluorescence (XRF) analyses (Rigaku-Denki "Geigerflex") on fused samples with lithium tetraborate and lanthanum oxide have the following detection limits: 0.10% for SiO_2, Al_2O_3, Fe_2O_3 and MgO; 0.05% for CaO, TiO_2 and P_2O_5. Na_2O (0.01%), K_2O (0.01%) and MnO (0.01%) were done by Atomic Absorption Spectrometry (AAS); CO_2 (0.01%) by wet chemistry; FeO (0.05%) by volumetry; H_2O^- (0.01%) by weight loss at 110°C and H_2O^+ (0.01%) by the Penfield method; F (0.003%) by the specific ion eletrode technique; and Ba, Sr, Rb, Zr, Y (with detection limits of 10 ppm) and Nb (20 ppm) by XRF (Philips PW 1480) in pressed pellets.

Four samples of charnockites from the Juiz de Fora Complex, in the region of Itaperuna, Rio de Janeiro State, had been previously analyzed by AAS (by Gert Andrews) for major and minor elements and by XRF for trace elements in the laboratory of the Department of Earth Sciences of the Memorial University of Newfoundland, Canada. Comparing the results obtained in Canada (MUN) with the those obtained from GEOSOL (GS), it is clear that in general the data are compatible with the following major exceptions: GEOSOL data show lower SiO_2 than the MUN analyses (49.6 vs. 50.4; 63.3 vs. 64.0; and 68.5 vs. 70.2 and 69.2 vs. 70.2); higher Zr (80 vs. 36; 620 vs. 541; 261 vs. 380 and 85 vs. 100) and Nb (e.g., 25 vs. 03; 34 vs. 32; 23 vs. 09) and, particularly, Na_2O values (e.g., 3.8 vs. 2.79; 3.0 vs. 2.65; 3.9 vs. 3.10). The MgO are available among the duplicate analyses, higher for values lower than about 3%. The GEOSOL data may also have high Na_2O and low SiO_2, shown by the presence of normative nepheline in NF 09 GS, as suggested by the petrographic studies.

RESULTS AND DISCUSSION

GEOCHRONOLOGY

The new Rb-Sr isochron ages (Fig. 2 a,b,c,d) are concentrated between 2230 and 2110 Ma, and the IR's vary into two groups: 0.705-0.703 and 0.713-0.712. This variation indicates different crustal materials participated in the Paleoproterozoic evolution. An age histogram (Fig. 3) that includes also the available whole Rb-Sr, Pb-Pb and U-Pb zircon data (see Tab. III), within the eastern

TABLE VII
Typical compositions of Mantiqueira Complex gneissic low-K calc-alkaline (1 to 4) and high-K calc-alkaline (5 to 8) sequences (this work).

	1	2	3	4	5	6	7	8
SiO_2	48.51	53.45	59.15	67.38	51.70	61.37	66.34	70.19
TiO_2	2.16	0.90	0.54	0.45	2.51	1.42	0.68	0.30
Al_2O_3	13.26	15.57	15.77	16.32	14.20	14.59	15.28	14.44
Fe_2O_3	15.06	10.65	6.56	3.00	12.20	8.40	4.02	3.48
MnO	0.20	0.16	0.08	0.03	0.14	0.07	0.04	0.02
MgO	6.23	5.12	4.08	0.59	5.43	3.03	1.61	0.68
CaO	10.75	7.58	5.72	3.60	6.64	4.55	3.32	2.49
Na_2O	2.61	4.02	4.14	4.60	3.72	3.03	4.02	3.98
K_2O	1.00	2.36	3.77	3.90	3.02	2.93	4.32	4.28
P_2O_5	0.22	0.18	0.20	0.13	0.44	0.62	0.37	0.14
Total	100.00	99.99	100.01	100.00	100.00	100.01	100.00	100.00
Cr	180	130	14	20	99	57	28	7
Ni	110	74	119	15	105	43	20	8
Rb	3	43	40	61	121	111	85	79
Ba	153	1640	525	1455	1066	1405	2985	1353
Sr	208	760	515	758	221	405	595	380
Nb	40	32	22	26	38	30	38	24
Zr	115	66	80	121	402	566	273	120
Y	34	27	26	10	51	49	23	15

TABLE VIII
Typical compositions of Juiz de Fora Complex charnockitic low-K calc-alkaline (1 to 4) and high-K calc-alkaline (5 to 8) sequences (M.C.H. Figueiredo, unpublished data).

	1	2	3	4	5	6	7	8
SiO_2	50.50	62.54	66.43	72.41	49.62	59.20	62.44	70.90
TiO_2	0.90	0.71	0.38	0.30	2.03	0.77	0.90	0.80
Al_2O_3	15.00	15.74	14.58	14.28	14.38	17.02	15.58	14.26
Fe_2O_3	11.00	6.56	4.99	2.90	15.19	7.74	6.54	2.91
MnO	0.17	0.12	0.08	0.05	0.21	0.12	0.14	0.04
MgO	8.80	3.53	2.90	0.90	5.87	3.67	3.22	1.00
CaO	10.00	5.14	3.60	2.50	8.10	5.40	4.62	2.51
Na_2O	2.80	3.83	3.99	3.60	3.14	3.67	3.52	3.11
K_2O	0.70	1.61	3.00	3.00	1.01	2.04	2.71	4.32
P_2O_5	0.11	0.22	0.07	0.08	0.46	0.37	0.32	0.14
Total	99.98	100.00	100.00	100.02	100.01	100.00	99.99	99.99
Cr	210	45	50		87	51	75	
Ni	80	14	28	4	71	25	22	4
V	210	96	60	25	284	112	75	41
Pb	10	13	20	20	19	22	15	20
Zn	125	93	88	65	142	122	101	68
Rb	3	61	65	70	14	71	56	88
Ba	140	807	999	679	405	673	1046	1476
Sr	310	585	350	370	197	571	462	311
Ga	17	20	22	27	26	24	21	13
Nb	6	6	4	3	14	10	11	9
Zr	65	136	107	180	203	107	282	261
Y	14	22	10	10	59	17	23	5
La	13.40	21.38	19.47	22.37	35.64	38.21	26.95	12.25
Ce	38.00	54.47	51.93	64.92	94.17	90.69	68.87	28.52
Pr	5.80	6.76	6.99	6.49	12.25	11.72	7.84	2.75
Nd	25.00	27.74	24.97	26.37	48.81	41.27	37.40	14.76
Sm	4.80	5.04	4.19	4.29	11.14	7.64	7.24	2.93
Eu	1.50	1.41	0.90	0.90	1.49	0.84	1.71	0.93
Gd	4.70	4.44	2.80	2.80	11.64	5.40	6.03	2.42
Dy	3.60	4.03	1.70	1.60	12.05	4.18	4.83	1.30
Er	2.00	1.82	0.90	0.80	6.48	1.63	2.41	0.83
Yb	1.30	1.61	0.90	0.70	5.16	1.43	1.71	0.72

border of the São Francisco Craton in Minas Gerais, indicates a concentration of the results in the time interval 2.1-1.9 Ga, interpreted to be the peak of the medium to high- grade regional metamorphism. During this period syn- to late tectonic plutonism took place in the area, as well (e.g., Padilha *et al.*, 1991). The other ages indicate an Archean heritage for part of the protoliths of the MMC.

The evolution of the MMC and the adjacent tectonic units can be also illustrated in a diagram of the IR's of the isochrons plotted against time (Fig. 4). The high IR's of a group of samples (0.707 to 0.716), well above the mantle reference

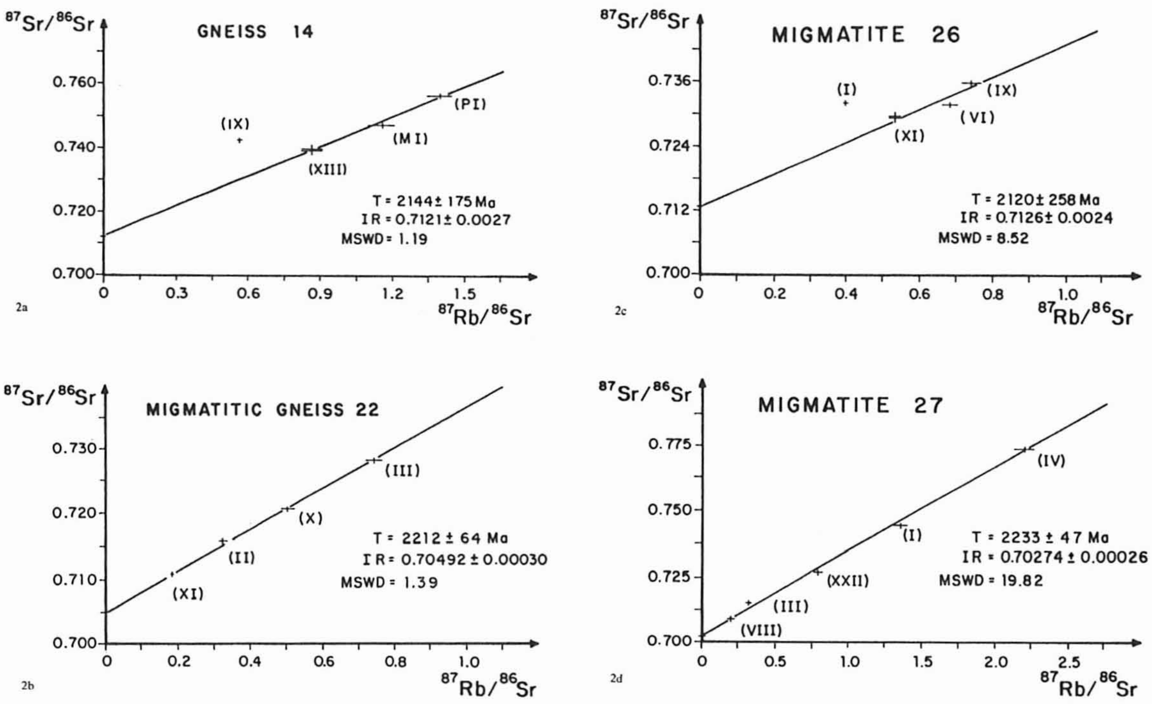

Fig. 2 — Rb-Sr whole rock isochron diagrams for selected outcrops of the Mantiqueira Complex.

line for the Paleoproterozoic time, demonstrate crustal reworking with complete isotopic rehomogenization of the materials did exist in the area, like was the interpretation proposed for the Acaiaca granulites on the basis of Pb-Pb whole rock isotope work (see previous section and Tab. III). On the other hand, the possible existence of subordinate mantle derived rocks during the Paleoproterozoic is suggested by the few analytical data with relatively low IR's (0.705 to 0.702) that plot close to the mantle reference line.

The resulting Sr isotopic signature suggests there are two regional isotopic rock systems within the MMC (Fig. 4): system A with medium Rb/Sr ratios and low IR's at 2200-2000 Ma which may allow the formation of Paleoproterozoic or-

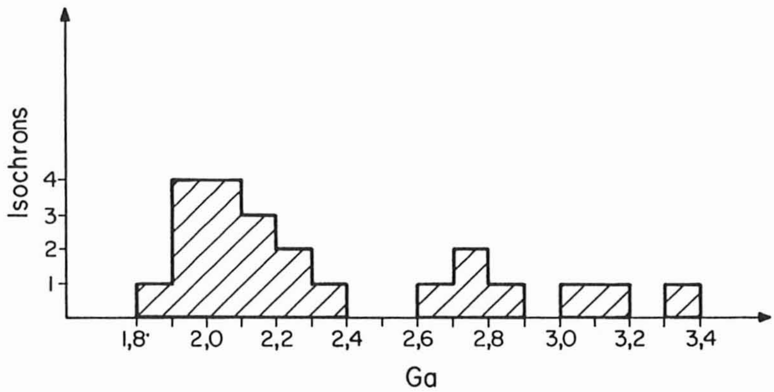

Fig. 3 — Age histogram for various rocks of the studied area. Data from Delhal *et al.* (1989); Cordani *et al.* (1973); Cordani *et al.* (1980); Teixeira *et al.* (1987a,b); Machado Filho *et al.* (1983) and Heilbron *et al.* (1989). See Table III and the text for details.

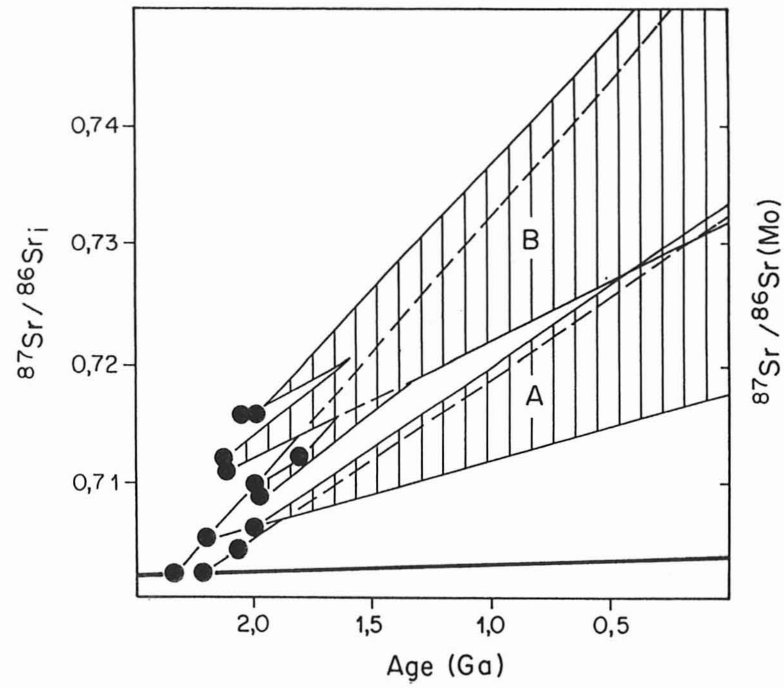

Fig. 4 — Sr isotopic evolution diagram for selected rock of the Mantiqueira Complex. There are two systems (A and B) with relatively distinct evolutions. System A exhibits Rb/Sr ratios lower than that of system B, and includes rocks formed probably in the Paleoproterozoic. Data are from this work, Teixeira *et al.* (1987b), Machado Filho *et al.* (1983), and Padilha *et al.* (1991).

thoderived materials, in contrast with system B with high IR's, re-equilibrated during the Paleoproterozoic (2230-2110 Ma), comprising materials with very high Rb/Sr ratios, as already cited. System B probably resulted from reworking of upper crustal materials, perhaps during a possible collision event of Transamazonian age (Teixeira & Figueiredo, 1991).

The new K-Ar apparent ages of the MMC (Tab. II) are compatible with both the complexity of the regional structures in the border of the São Francisco Craton, and tectonic history as proposed by Marshak & Alkmin (1989). The biotites dates (550-500 Ma) indicate complete rejuvenation of the country rocks after the end of the Brasiliano Cycle, and more properly, have a relationship with the Cambrian Rio Doce Orogeny (Campos Neto, 1991). At least one of the K-Ar hornblende analyses yielded an apparent age of 535 Ma therefore indicating temperatures above 450° for the last regional metamorphic episode. On the other hand, the apparent age of about 730 Ma (lab. no. 6814) is probably meaningless because of the low K content of the biotite. The 640 Ma age obtained for biotite 23-XIII is considered reliable, and suggests that a metamorphic episode prior to the Rio Doce Orogeny may have took place in the area.

The K-Ar biotite and hornblende ages for outcrops 14, 23 and 26 (Tab. II) indicate that the MMC was subjected to a heterogeneous thermal history during the Proterozoic. In the West (outcrop 14) the similar ages obtained for both minerals (~530 Ma) reveal the metamorphic conditions during the eo-Cambrian reached amphibolite facies, which was followed by fast uplift. It is noteworthy that this ~530 Ma age pattern was probably influenced by the development of a major shear zone (see Fig. 1) that appears to be the tectonic front between the Mantiqueira and the Barbacena complexes. A few kilometers westward from this zone, outcrop 11 shows a slighly older K-Ar age in biotite of about 580 Ma.

To the East the different ages obtained for hornblende and biotite pairs (outcrops 23 and 26) indicate that gradual uplift was limited to shallow levels of the crust, in agreement with greenschist metamorphic conditions. This situation maintained the lower portions of the crust below the argon blocking temperature of the hornblende (~450°C), producing the apparent ages between 1640 and 1350 Ma (Tab. II). Nevertheless, these hornblende dates do not have geological significance, and probably resulted of partial argon loss from older rock systems subjected to the Neoproterozoic overprints.

As a whole, the heterogeneous K-Ar cooling pattern is diagnostic of a polycyclic evolution of the Mantiqueira crust during the Proterozoic, finally influenced by the Rio Doce crustal shortening processes, in the Eo-Cambrian. The scenario is also consistent with the K-Ar ages (725-490 Ma) reported for gneissic rocks occurring between Santos Dumont and Juiz de Fora, reported in Cordani *et al.* (1973), Machado Filho *et al.* (1983) and Teixeira *et al.* (1987a,b), as well as with the cooling history of the Andrelândia and São João Del Rei metasediments (Heilbron *et al.*, 1989).

The Mantiqueira and Juiz de Fora complexes exhibit comparable polyphase tectonic evolution. The Archean and Paleoproterozoic U-Pb zircon ages are consistent with the high IR's (0.708-0.710) of Rb-Sr isochron ages, indicative of crustal reworking of the Juiz de Fora Complex during the Transamazonian cycle (e.g., Delhal *et al.*, 1969; Delhal & Dermaiffe, 1985; Machado *et al.*, 1989; Teixeira & Figueiredo, 1991).

Recent zircon U-Pb analyses in the Juiz de Fora rocks carried out by Söllner *et al.* (1991), together with a reinterpretation of previous U-Pb data (Delhal *et al.*, 1969; Cordani *et al.*, 1973), support the idea that a granulite facies metamorphism took place at about 2.20 Ga ago, as recorded in two different zircon populations (pink, euhedral prismatic, transparent and a globular, colourless, transparent), whilst an age component, older than 2.50 Ga, was found in a pink zircon population. The 2.20 Ga age obtained for such a metamorphic episode coincides within error with the Rb-Sr whole rock isochron age of 2.23 Ga for hypersthene gneisses occurring in the area (recalculated; Cordani *et al.*, 1973), and is also comparable with the age of the main metamorphism in the MMC, as already presented.

Finally, two additional younger Rb-Sr isochron results are available for the Juiz de Fora Complex, in the region of Lima Duarte: a migmatitic gneiss yielded 1480 Ma and an enderbite 640 Ma (Padilha *et al.*, 1991). The great difference of these ages has not still a clear relationship with the current structural and metamorphic framework available in the region, however it points to a polyphase character for the crustal evolution, and are in agreement with the K-Ar ages among 590 and 480 Ma reported for several gneissic rocks (e.g., Delhal *et al.*, 1969; Cordani *et al.*, 1973; Cordani & Teixeira, 1979; Machado Filho *et al.*, 1983).

GEOCHEMISTRY

Twenty five chemical analyses in the MMC (11,14, 21, 22, 23, 26, 28, 29, 30, 32; Fig. 1) allow the separation of three groups of samples (Figs. 5 and 6): a) a low-K calc-alkaline sequence (CA) relatively enriched in Mg, Ca, Na, Al and Cr (Tab. IV); b) a high-K calc-alkaline sequence (K-CA) enriched in large ion lithophile elements, richer in K, Ti, Fe, P, Rb, Zr, Nb and Y (Tab. V); c) four samples of amphibolitized dikes and three samples with quite distinct compositions compared with the others (Tab. VI). Of these three samples, 32-I shows low Fe, Mg and Ca and high Al and, particularly, Na, P, Rb, Sr and Zr, and may correspond to a sodic alkaline rock; 32 A presents high Mg, Cr and Ni and may have suffered cumulate processes; and 23 A-II has low Ti, P, Nb, Y and Zr and somewhat high Mg and Ni.

Major element data for the same region studied here (Viana *et al.*, 1991), also allow the separation of two different sequences, one enriched in Mg and Ca (e.g., samples 404, 195A, 96, 362B, 362C, 362D and 498A) and the other richer in Ti, Fe and P (e.g., samples 05, 592, 594, 49A, 362A, 75D, 497 and 498B), which appear to be correlated to the CA and K-CA sequences described above. Besides, some samples (e.g., 635, 635A and 362E)

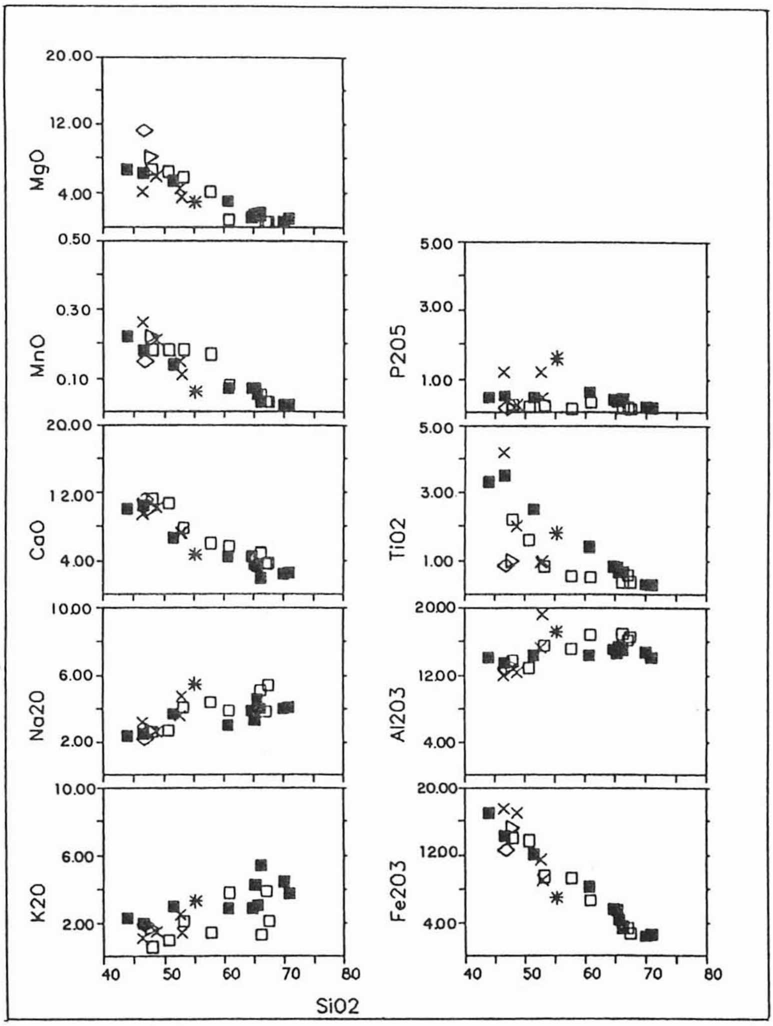

Fig. 5 — Harker diagrams for Mantiqueira Complex lithologies. Simbology: high-K calc-alkaline sequence (solid squares); low-K calc-alkaline sequence (open squares); amphibolitic dikes (x); sample 32 A (diamond); sample 23 AII (triangle); sample 32 I (asterisk).

appear to correspond to the CA sequence but have very distinct values of Ca and Al, while others (e.g., 593A and 593B), both very rich in K and P and 582 which corresponds to a serpentinite) have very different compositions.

Before attempting a discussion about the classification and tectonic discrimination of the rocks under investigation it must be stressed that the analytical problems already discussed, in particular the apparent high sodium and low silica values, will cause a dislocation of the rocks of both sequences towards a slightly more alkalic nature. For instance, the Peacock (1931) index for the CA sequence is about 58 while that for the K-CA is around 52 characterizing it as alkali-calcic. However, if we "correct" the analyses based on the MUN data both sequences would correspond to calc-alkaline series, the latter being slightly more mature.

On the Debon & Le Fort (1983) diagram both sequences range from gabbro to granodiorite-granite (Fig. 7) and the CA and K-CA suites can be classified as tonalitic calc-alkaline and granodioritic calc-alkaline, respectively.

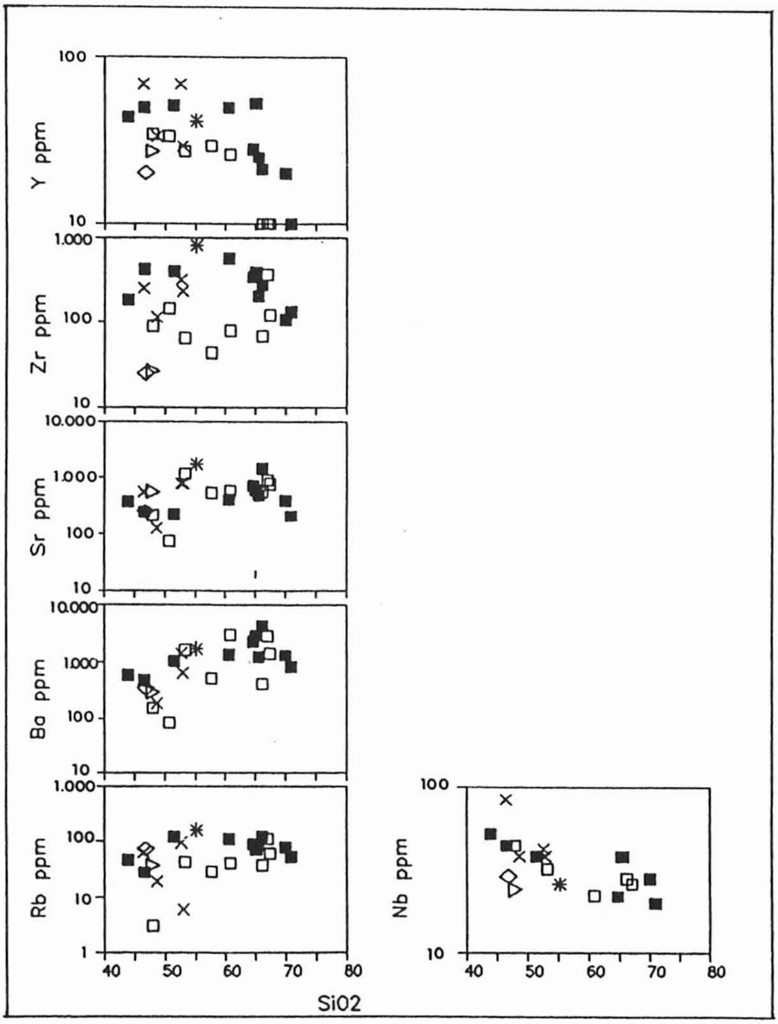

Fig. 6 — SiO_2 versus trace elements diagrams for Mantiqueira Complex lithologies. Same symbols as in Fig. 5.

Using Batchelor & Bowden (1985) tectonic discrimination of granitoids on the R1-R2 diagram (La Roche *et al.*, 1980), it can be seen (Fig. 8) that the samples plot predominantly in the subduction-related pre-collisional field and in the post-collisional uplift field, again with the K-CA sequence showing higher maturity. This diagram must be particularly sensible to the probable Na exaggeration (since the sodium values are multiplied by a factor of 11) and both sequences may, in fact, be located slightly towards the upper-right corner of the diagram.

Both sequences plot nearby in the AFM diagram (Irvine & Baragar, 1971) with the least differentiated rocks plotting in the tholeiitic field (Fig. 9) and with a general trend similar to those of recent magmatic arc granitoids, such as the Peruvian and Baja California batholiths and New Britain (in Brown, 1982).

Regarding the Rb and Sr distribution (Fig. 10) there is also a good distinction between the CA and K-CA series, with Rb/Sr ratios generally lower than 0.1 and higher than 0.1, respectively. The lower Rb/Sr ratios of the former sequence appear to be typical of lithotypes formed in magmatic arcs

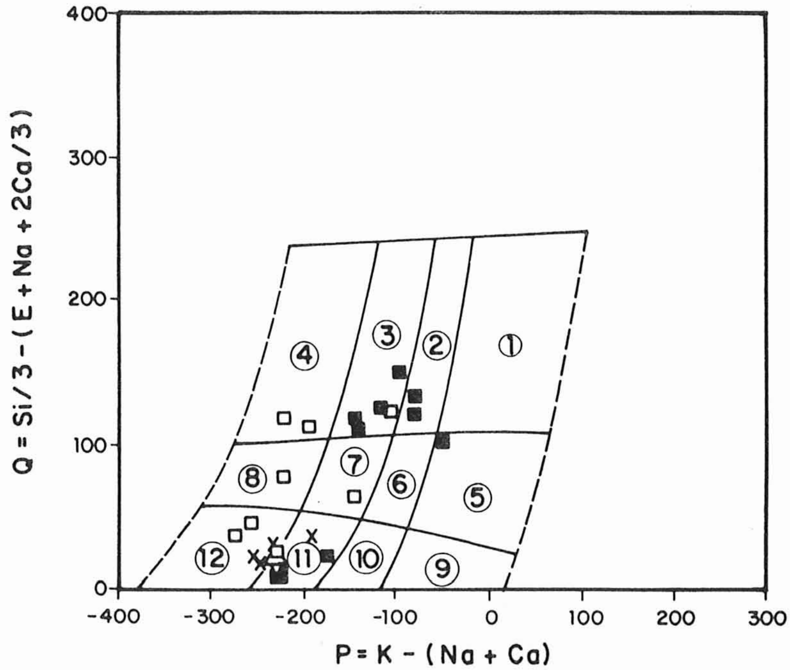

Fig. 7 — P-Q (Debon & Le Fort, 1983) classificatory diagram for Mantiqueira Complex lithologies. Fields: 1 – granite; 2 – adamellite; 3 – granodiorite; 4 – tonalite (trondhjemite); 5 – quartz syenite; 6 – quartz monzonite; 7 – quartz monzodiorite; 8 – quartz diorite; 9 – syenite; 10 – monzonite; 11 – monzogabbro; 12 – gabbro. Symbols as in Fig. 5.

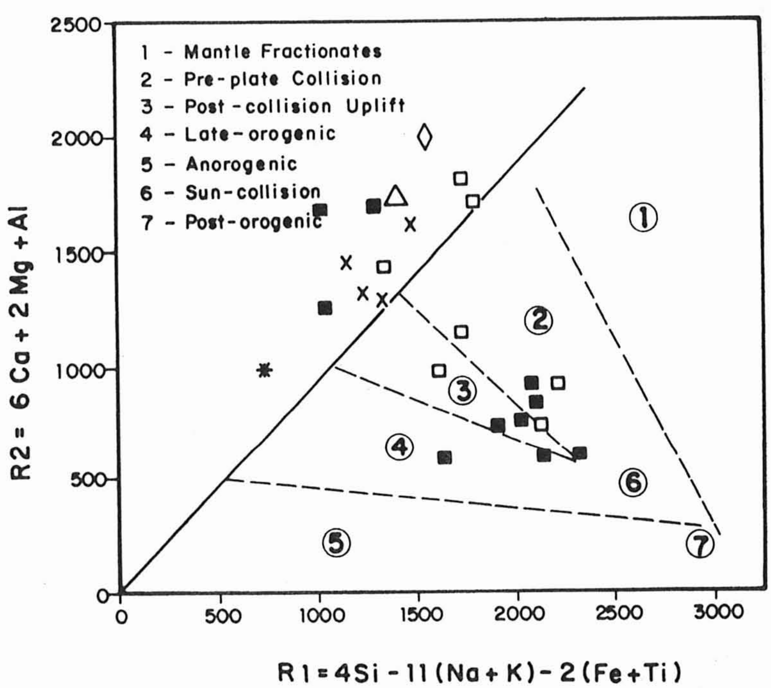

Fig. 8 — R_1-R_2 (La Roche *et al.*, 1980) diagram with the tectonic discriminant fields for granitoids (Batchelor & Bowden, 1985) for Mantiqueira Complex lithologies. Symbols as in Fig. 5.

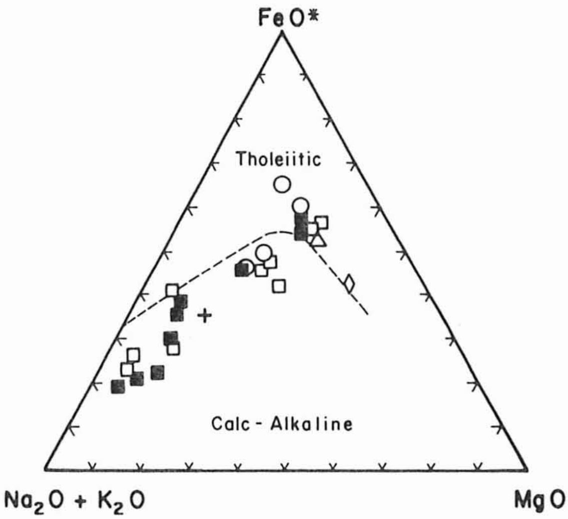

Fig. 9 — AFM diagram with the curve separating tholeiitic and calc-alkaline fields (Irvine & Baragar, 1971) for Mantiqueira Complex lithologies. Symbols as in Fig. 5.

such as the Uasilau-Yau-Yau plutonics from the recent New Britain island arc in Papua-New Guinea (Whalen, 1985), the gabbro-diorite-tonalite-trondhjemite sequence of Proterozoic age from southwestern Finland (Arth *et al.*, 1978) or the tonalitic-trondhjemitic precursors of the Archean Southern India charnockitoids (Condie & Allen, 1984).

The K/Rb ratios (Fig. 11) are somewhat variable, as expected for high-grade gneiss terrains, but

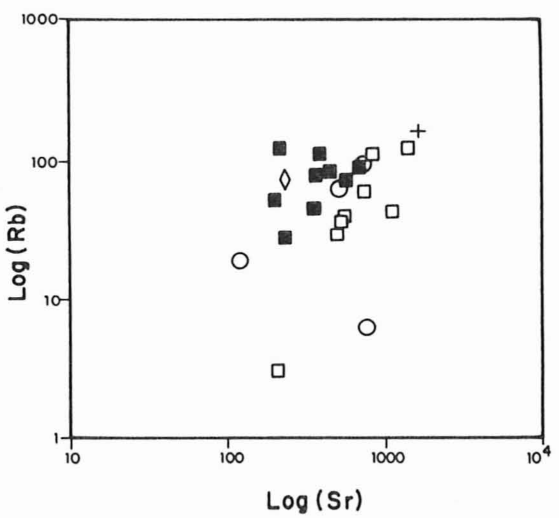

Fig. 10 — Sr-Rb distribution diagram for Mantiqueira Complex lithologies. Symbols as in Fig. 5.

the CA sequence has ratios near 250, comparable with average continental crust, while the K-CA has higher ratios, but not as high as many depleted high-grade gneiss terrains specially Archean ones (e.g., Lambert & Heier, 1968; Tarney & Windley, 1977) which have K/Rb ratios higher than 1000.

In the Zr versus the Zr/Y ratio (Fig. 12) the CA sequence generally show lower values of Zr and Zr/Y and a growing Zr/Y ratio with increasing Zr values, but the K-CA exhibits higher Zr and Zr/Y but this ratio varies little (around 10) suggesting an important fractional crystallization component in its differentiation (e.g., Pearce & Norry, 1979), or else this growing Zr/Y ratio could be attributed to fractionation of Zr- and Y-bearing phases. The basic compositions of each sequence already show significant differences in the amount of Zr and Zr/Y and the LILE enrichment of the K-CA sequence may indicate that it was derived by differentiation of basic magmas produced by partial melting of an enriched mantle source or assimilation/contamination in a thickened crust.

There is a reasonably good lithological, mineralogical and lithochemical correspondence between the MMC and subduction-related magmatic arc granitoids. There is also a good correlation between the MMC and the adjacent Juiz de Fora Complex (Figueiredo & Campos Neto, 1989; Campos Neto & Figueiredo, 1990) where two different calc-alkaline sequences, with the same characteristics of those described here as CA and K-CA, have been identified (see Tabs. VII and VIII). Additionally, the two sequences from the Juiz de Fora Complex show marked distinctions between their rare earth element (REE) distribution patterns, with the K-CA sequence obviously presenting higher REE contents.

In spite of the small number of whole-rock chemical analyses available for the Acaiaca granulites (Jordt Evangelista, 1984), located northward of the study area, these could also correspond to the same Mantiqueira-Juiz de Fora lithological association. Some of these granulites appear to correspond to the CA sequence (e.g., 210, 210q, 215, 210n and 218) while a few others (e.g., 210o and 210a) correspond to the K-CA sequence.

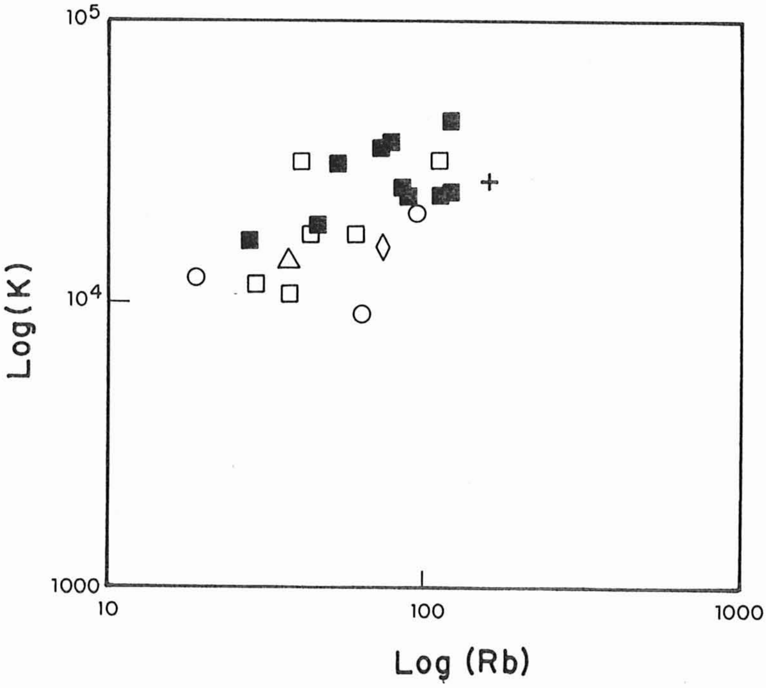

Fig. 11 — K-Rb distribution diagram for Mantiqueira Complex lithologies. Symbols as in Fig. 5.

FINAL REMARKS

The MMC biotite-hornblende gneisses and migmatites are characterized by the presence of two distinct calc-alkaline sequences ranging from basic to acid terms, both sequences indicating similar geochronological history in the Paleoproterozoic. One of the sequences can be considered as a normal or low-K calc-alkaline suite (CA) while the other corresponds to a LILE-enriched high-K calc-alkaline suite (K-CA). Although there is a good geochemical comparison with subduction-related lithotypes in general, a striking chemical similarity appears to occur between the two calc-alkaline sequences of the MMC with the adjacent charnockitic Juiz de Fora Complex.

The Juiz de Fora Complex corresponds to reworked terrains composed predominantly of two intimately associated calc-alkaline plutonic series, a normal and a LILE-enriched suite (Figueiredo & Campos Neto, 1989; Campos Neto & Figueiredo, 1990). Field evidence suggests not only the plutonic nature of these rocks but also a late, regional charnockitization of biotite-hornblende gneisses and migmatites, locally preserved as lenses and patches, by a CO_2 front. These authors also suggested that the Juiz de Fora Complex represents a large crustal flake thrust over the border of the southern portion of the São Francisco Craton, reworked in the Paleoproterozoic, and that this crustal slice is, in turn, overthrust by an hypothetical

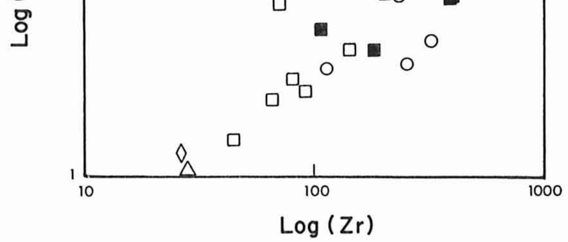

Fig. 12 — Zr versus Zr/Y diagram for Mantiqueira Complex lithologies. Symbols as in Fig. 5.

terrane containing the Paraíba do Sul and Costeiro complexes. The welding of these terrains would have occurred during the eo-Cambrian and such a collisional event may be registered in the S-type granites and migmatites (so-called kinzigitic gneisses) which are abundant in the Costeiro Complex.

A very similar geochemical picture with the Mantiqueira and the Juiz de Fora complexes comes from the granulitic plutonic sequence of the Jequié Complex and the adjacent Itabuna belt within the Northern São Francisco Craton (e.g., Figueiredo, 1989; Barbosa, 1990; Figueiredo & Barbosa, 1992). This belt consists essentially of tholeiitic, calc-alkaline and shoshonitic sequences formed in a subduction-related magmatic arc followed by collision at 2.00 Ga.

The Jequié Complex includes a granulitic plutonic area, composed of a dominant high-K calc-alkaline sequence with a subordinate low-K calc-alkaline sequence, bordered by mostly migmatitic plutonic and supracrustal rocks. The plutonic sequence can be separated into a high-K calc-alkaline sequence, enriched in K, Fe, Ti, P, Rb, Nb, Zr, Y, Nd and Sm and a subordinated low-K calc-alkaline sequence has been dated between 3.15 and 2.90 Ga by Rb-Sr and Sm-Nd (T_{DM}) methods (Wilson, 1987; Marinho *et al.*, 1994), while SHRIMP U-Pb zircon data in the intrusive Laje-Mutuípe plutonic unit yielded 2.8-2.7 Ga (Alibert & Barbosa, 1992). High-grade metamorphism in the Jequié granulites and migmatites took place between 2.7-2.6 Ga according to Rb-Sr geochronology (e.g., Cordani & Iyer, 1979).

The Archean plutonics were further affected to high-grade metamorphism and partial melting at about 2.00 Ga ago, and during these episodes migmatites were formed (e.g., Wilson, 1987; Marinho *et al.*, 1994). The anatexis of the calc-alkaline granulites, producing high-K granites, appears to be related to a 2.00 Ga collision of the Jequié and Congo proto-cratons (e.g., Figueiredo, 1989; Teixeira & Figueiredo, 1991). According to Figueiredo & Barbosa (1992) the protoliths of the Jequié plutonic calc-alkaline sequences were formed in a mid Archean mature island arc or an active continental margin due to the conspicuous presence of the LILE-enriched high-K calc-alkaline sequence.

In summary, from the typical compositions of the Mantiqueira and Juiz de Fora rocks, as well as the plutonic sequence of the Jequié rocks (Tabs. VII, VIII and IX), two calc-alkaline suites can be distinguished in each of these complexes. Moreover, there is a very good geochemical correlation among these complexes, particularly when one considers that the geochemical data comes from three different laboratories. In particular, within both the Mantiqueira and Juiz de Fora complexes the two calc-alkaline sequences occur mixed (by multi-intrusive and tectonic processes) from the regional to the outcrop scale being, so far, impossible to separate them in the field. In turn, within the Jequié Complex the low-K calc-alkaline sequence is subordinated (Wilson, 1987).

Further U-Pb zircon and Sm-Nd work coupled with paleomagnetic studies in the Mantiqueira, Juiz de Fora and Jequié complexes are needed to test the model. If correct such a tectonic relationship, the MMC would correspond to the southern extension of the Jequié Complex, while the Juiz de Fora Complex would represent the CO_2-fluxed charnockitic lower portions of the MMC, eventually thrust over it.

If the Mantiqueira and Juiz de Fora complexes correspond to an extension of the Jequié Complex it may be speculated that a mostly plutonic, very large, mature magmatic arc was formed during the Transamazonic cycle. The identification of a low-K sequence and a LILE-enriched high-K calc-alkaline sequence indicate an active continental margin tectonic setting for such an arc, probably reworking the border of an Archean continent, as supported by the radioisotopic data. Subordinate supracrustal rocks, now represented mainly by S-type granites and migmatites and calc-silicatic and quartzite lenses and xenoliths, also occur within the domains and may even correspond to arc-related basins.

Finally, crustal shortening processes took place in the Mantiqueira and Juiz de Fora complexes by the end of the Neoproterozoic and eo-Paleozoic, as suggested by the K-Ar dates.

TABLE IX
Typical compositions of Jequié Complex granulitic low-K calc-alkaline (1 to 3) and high-K calc-alkaline (4 to 7) sequences (data from Wilson, 1987).

	1	2	3	4	5	6	7
SiO_2	61.35	71.03	72.25	65.05	68.79	72.92	74.67
TiO_2	0.68	0.25	0.23	1.25	0.95	0.54	0.19
Al_2O_3	17.60	15.48	15.19	13.52	13.45	12.09	13.58
Fe_2O_3	5.85	2.21	1.74	7.76	5.93	4.48	1.72
MnO	0.09	0.03	0.03	0.10	0.10	0.07	0.03
MgO	2.59	0.93	0.75	1.30	1.00	0.32	0.19
CaO	5.52	3.06	2.24	4.04	3.28	1.31	1.25
Na_2O	4.55	4.94	4.89	3.06	3.38	2.72	3.57
K_2O	1.43	1.99	2.61	3.52	2.83	5.48	4.76
P_2O_5	0.33	0.08	0.06	0.39	0.30	0.08	0.04
Total	99.99	100.00	99.99	99.99	100.01	100.01	100.00
Cr	26	20	25	16	10	6	6
Ni	17	8	10	9	5	6	3
Co	38	38	32	37	40	49	53
V	77	30	27	83	60	14	12
Cu	15	3	4	9	8	5	1
Pb	15	20	26	25	24	38	47
Zn	80	47	41	95	89	101	47
Rb	29	33	80	85	71	190	259
Ba	705	801	605	1354	960	791	557
Sr	823	681	380	243	293	53	77
Nb	4.8	2.6	4.6	20.2	20.3	20.2	10.1
Zr	133	85	92	422	379	510	143
Y	12	8	5	56	32	77	29
Nd		10.5	10.5	65.9	60.7		36.0
Sm		1.9	1.8	12.1	9.0		6.7

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