Petrography and mineral chemistry of carbonatites and mica-rich rocks from the Araxá complex (Alto Paranaíba Province, Brazil)

GIANBOSCO TRAVERSA[1], CELSO B. GOMES[2], PIERO BROTZU[3],
NICOLETTA BURAGLINI[4], LUCIO MORBIDELLI[1], MARIA SPERANZA PRINCIPATO[5],
SARA RONCA[1] and EXCELSO RUBERTI[2]

[1]Dipartimento di Scienze della Terra, Università di Roma "La Sapienza", Piazzale Aldo Moro, I-00185 Roma, Italy
[2]Instituto de Geociências, Universidade de São Paulo, Rua do Lago 562, 05508-900 São Paulo, Brazil
[3]Dipartimento di Scienze della Terra, Università di Napoli, Largo S. Marcellino 10, I-80134 Napoli, Italy
[4]Dipartimento Scienze della Terra, Università di Catania, Corso d'Italia 55, I-95129, Catania, Italy
[5]Dipartimento Scienze della Terra, Università di Milano, Via Mangiagalli 34, I-20133 Milano, Italy

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contributed by CELSO DE BARROS GOMES*

ABSTRACT

The Araxá complex (16 km^2) comprises carbonatites forming a central core and a complex network of concentric and radial dykes as well as small veins; additionally, it includes mica-rich rocks, phoscorites and lamprophyres. Fenites also occur and are represented by Proterozoic quartzites and schists of the Araxá Group.

The petrographic study of 130 borehole samples indicates that the complex is basically made up by two rock-types, carbonatites and mica-rich rocks, and subordinately by a third unit of hybrid composition.

Carbonatites range chemically in composition, the most abundant type being magnesiocarbonatites. Dolomite and calcite correspond to the chief constituents, but other carbonate phases, including the Ce-group RE minerals, are also recognized. Phosphates and oxides are widespread accessories whereas silicate minerals consist of olivine, clinopyroxene, mica and amphibole.

Mica-rich rocks are represented by abundant glimmeritic rocks and scarce cumulitic phlogopite-, olivine- and diopside-bearing pyroxenites. Hybrid rocks mainly contain phlogopite and tetraferriphlogopite as cumulus and intercumulus phases, respectively; carbonate minerals may also be found.

Chemical data indicate that the carbonatites are strongly enriched in REE and have lower contents of Nb, Zr, V, Cr, Ni and Rb compared to the mica-rich rocks. The higher K, Nb and Zr contents of the latter rocks are believed to be related to metasomatic processes (glimmeritization) of the pyroxenites.

Similar REE patterns for carbonatites and mica-rich rocks seem to suggest that they are related to a single parental magma, possibly of ijolitic composition. Steep LREE/HREE fractionation and high ΣREE content of some carbonatite samples would be explained by hydrothermal and supergenic processes.

Key words: alkaline rocks, carbonatites, geochemistry.

INTRODUCTION

Alkaline rocks are found in southern Brazil in association with the Ordovician-Cretaceous sedimen-

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*Member of Academia Brasileira de Ciências
Correspondence to: Celso de Barros Gomes
E-mail: cgomes@usp.br

tary Paraná Basin and mainly distributed along its margins. They vary considerably in age (about 130 to 50 Ma, cf. Ulbrich & Gomes 1981) and composition, and have been assembled into distinct geographic provinces, such as the Alto Paranaíba Igneous Province (APIP), representing one of their most important ones, particularly due to the presence of economical deposits bearing niobium, phosphate, titanium and rare earth elements.

The Alto Paranaíba Province, which includes the renowned carbonatite intrusion of Araxá covering approximately 16 km^2, is in general related to a NW-trending linear structure bordering the São Francisco cratonic area (Fig. 1), which is thought to be in evidence since late Precambrian times. It comprises a large number of occurrences showing a wide variety of igneous forms and magma types. The emplacement of these numerous Mesozoic intrusions fits a narrow Proterozoic mobile belt of the Brasiliano Cycle (700-450 Ma, cf. Almeida et al. 1973), extending some 1500 km in central Brazil and also referred to as the Brasília folded belt. As pointed by geological and geophysical evidence (Hasui et al. 1975, Almeida et al. 1980, Pires 1986), the whole area corresponds to a well-defined regional high, the Alto Paranaíba arch, about 100 km wide and 300 km long.

This paper aims to discuss the petrography and geochemistry of the Araxá carbonatites and mica-rich rocks on the basis of data taken from drill-core samples. Considering the poor geology of the area, with the extensive and deep weathering forming lateritic soil mantles averaging 80 m thick and reaching 230 m in many places, the now available data represent a very important source of information that will certainly contribute to the better knowledge of these rocks.

THE ARAXÁ COMPLEX

Previously reported in literature as Barreiro, it consists of a circular intrusion, 4.5 km in diameter, with the central part mainly formed by a carbonatite predominantly beforsitic in composition (Fig. 2). A complex network of carbonatite as concentric and radial dykes quite variable in dimension and also small veins ranging from few milimeters to several centimeters in thickness are present intruding either alkaline or country-rocks. Additional lithologies include mica-rich rocks, phoscorites and lamprophyres. The complex has been emplaced into Proterozoic quartzites and schists of the Araxá Group and developed concentric and radial fractures and a very conspicuous dome structure within the country rocks. Also associated to these rocks (specially the quartzites) is the presence of up to 2.5 km wide contact aureole exhibiting clear textural, mineralogical and chemical evidence of fenitization processes (Issa Filho et al. 1984).

Radiometric ages on Araxá alkaline rocks were compiled for the first time by Ulbrich and Gomes (1981) and later on by Sonoki and Garda (1988), Gomes et al. (1990) and Morbidelli et al. (1995), with the whole data indicating an age span of 77-98 Ma. Also recently, Gibson et al. (1995) have discussed the age of magmatism in the Alto Paranaíba Province using values (old and new ones) obtained by different methods (K/Ar, Ar/Ar, U/Pb) on rocks and mineral separates from several occurrences, here included the Araxá complex. They concluded that the alkaline magmatic activity in the area had occurred over a narrow time interval between 80 and 90 Ma, the preferred age being 85 Ma. On the basis of a K/Ar determination on biotite, Hasui and Cordani (1968) recommended an age of 89 Ma for the Araxá complex.

SAMPLING AND ANALYTICAL PROCEDURES

The investigated samples came mainly from drill-cores, which were taken as part of a geochemical exploration program conducted by the Arafértil S/A mining company; its location is indicated in the simplified geological map of Fig. 2 (after Grossi-Sad & Torres 1976, in Issa Filho et al. 1984). Surface samples (BAR 1-9) were collected at the northern part of the intrusion. In spite of covering a small area of the whole complex, the available samples are believed to be representative by showing carbonatites and mica-rich rocks, the most significant

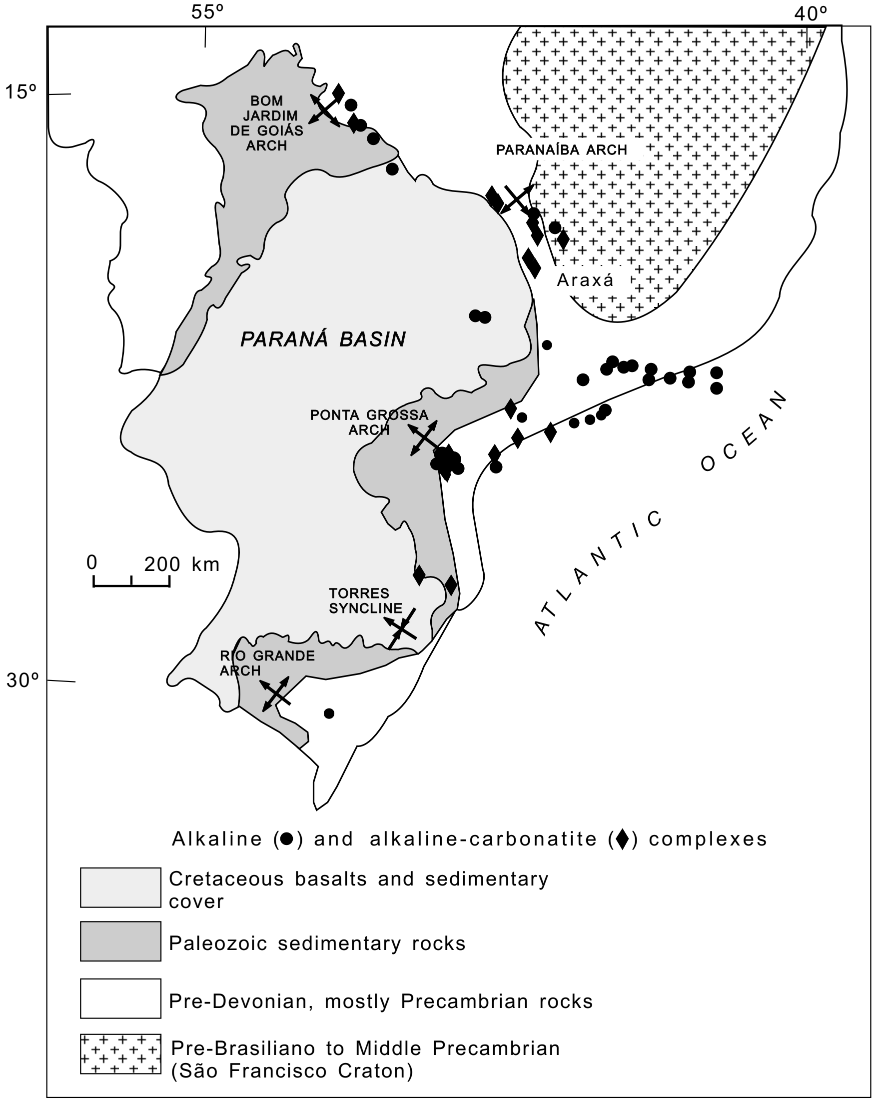

Fig. 1 – Alkaline and alkaline-carbonatite occurrences of southern Brazil (after Ulbrich & Gomes 1981 simplified). The Araxá complex is also indicated.

Araxá lithological types.

More than 130 samples from 28 different boreholes have been investigated in detail. The analytical program comprised X-ray diffractometric studies and X-ray fluorescence (XRF) analyses for major and trace elements. A representative number of samples was selected for REE determinations using the inductive coupled plasma technique (ICP-MS) at Activation Laboratories LTD Ancaster, Ontario, Canada. Additional analytical procedures included the determination of MgO by atomic absorption, FeO by titration, L.O.I. by gravimetry and CO_2 by gaschromatography. Precision and accuracy for trace elements were better than 10%.

Mineral analyses have been carried out using a Philips 515 scanning electron microscopy fitted with an energy dispersion system (EDAX PV 9000). Information on topographic features were provided

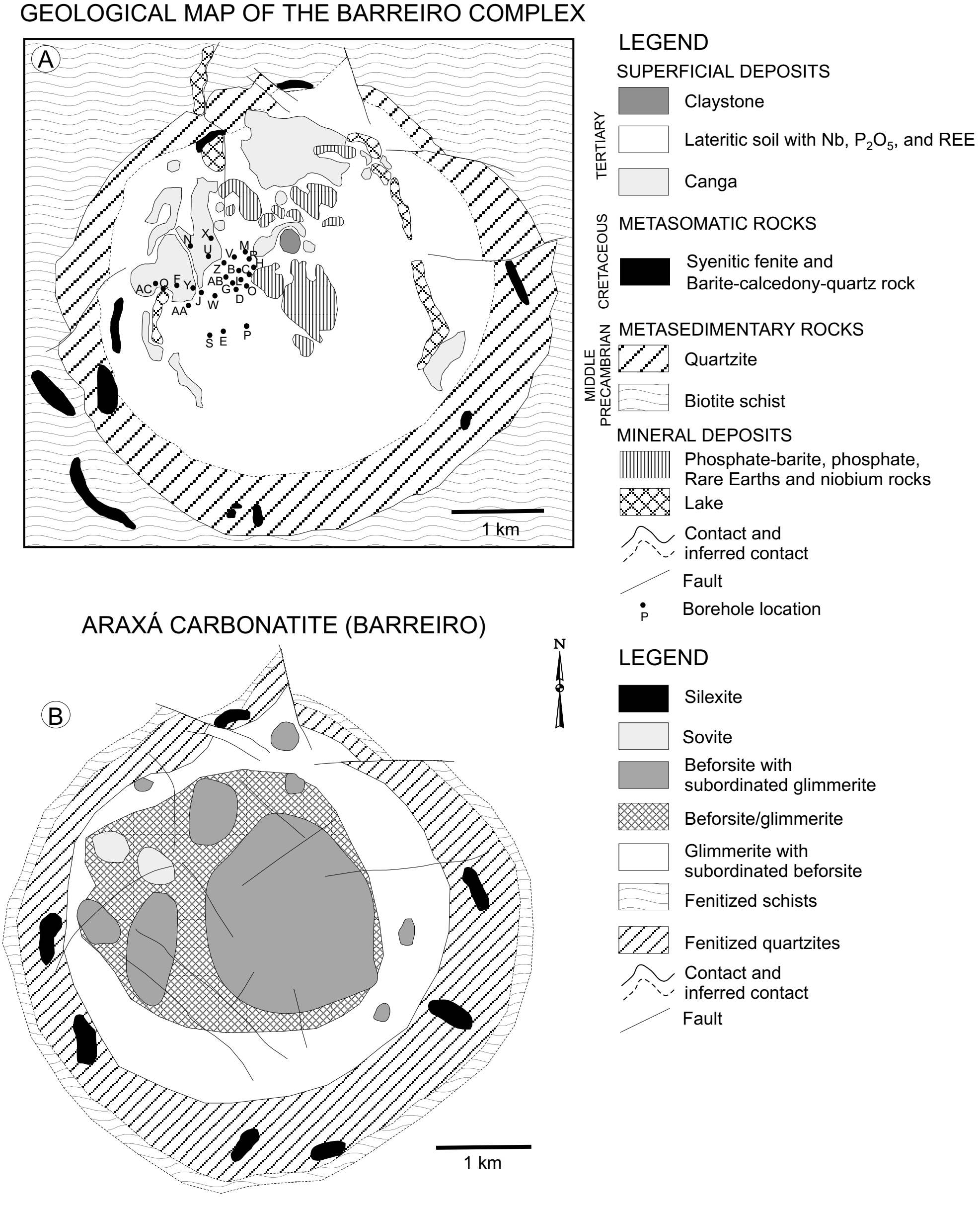

Fig. 2 – Schematic interpretation of the Araxá carbonatite geology (after Issa Filho et al. 1984) (A) and surface geological map (after Grossi-Sad & Torres 1976 simplified) (B). Also shown is the bore-holes area.

by backscattered and secondary electron images. Quantitative data have been corrected for ZAF factors (EDAX PV SUPQ).

Chemical data for carbonates have been recalculated using CO_2 mean values from literature (Deer et al. 1964, for calcite, dolomite, ankerite, siderite and magnesite; Speer & Hensley-Dunn 1976, for strontianite; Platt & Woolley 1990, for burbankite; Kasputin 1980, for ancylite and breunnerite). For additional minerals (Tables III to V), analyses were recalculated to 100%.

PETROGRAPHY

The Araxá complex is mainly represented by carbonatites and mica-rich rocks; a hybrid rock-type (MC), basically consisting of silicate and carbonate material, is also recognized. On the basis of the Woolley (1982) chemical classification, the carbonatites can be placed into three groups: calciocarbonatites (CaC), magnesiocarbonatites (MgC) and ferrocarbonatites (FeC).

Calciocarbonatites are texturally equigranular, hypidiomorphic to allotriomorphic and have grain size averaging 1-5 mm. Calcite and dolomite, present in variable amounts, make up the principal carbonate minerals, whereas ankerite, siderite, burbankite and ancylite are less frequent; strontianite and carbocernaite occur rarely. Other constituents are phlogopite, apatite, magnetite and arfvedsonite. Monazite, ilmenite, spinel, pyrochlore, rutile, zircon and ore minerals (pyrite and chalcopyrite) are found as accessories; barite, quartz and celadonite constitute the principal secondary phases.

Magnesiocarbonatites, the most abundant carbonatite type, are equigranular, fine-grained and chiefly allotriomorphic in texture. Carbonate phases consist mainly of dolomite with calcite being recognized in a few samples. Additional carbonates only scarcely identified are strontianite, ankerite, burbankite, ancylite, siderite and magnesite. Phlogopite, sometimes reaching large quantities, apatite and magnetite are also present. As accessories are found pyrochlore, rutile, monazite, baritocalcite, huanghoite, tainiolite and norsethite. Secondary phases include barite, quartz and celadonite.

Ferrocarbonatites are clearly subordinate to the previous types. They show similarities in texture, except for the presence in a few samples of large magnetite grains and celadonite-phlogopite aggregates pseudomorphically formed after olivine and pyroxene crystals thereby giving the rocks a porphyritic character. Dolomite is the major carbonate phase, while strontianite, siderite, burbankite and ankerite occur in minor amounts. Phlogopite is almost absent, whereas apatite is commonly found. Accessory minerals consist of monazite, ilmenite, pyrite, chalcopyrite, sphalerite, galena and cobaltite (?).

The Araxá carbonatitic rocks, which are brecciated, fine to coarse-grained, dark-colored, and strongly enriched in phlogopite and/or apatite and well developed magnetite crystals have been referred to as phoscorites by Issa Filho et al. (1984).

In many Brazilian complexes, carbonatites are closely associated with an ultramafic plutonic assemblage, having pyroxenites (sometimes jacupirangites), dunites, peridotites and glimmerites as important rock-types. There, glimmerites have been interpreted as the result of the phlogopitization of ultrabasic rocks due to the action of carbonatitic liquids (Morbidelli et al. 1986, Gomes et al. 1990).

Mineralogical studies on the Araxá mica-rich rocks allow to distinguish the presence of two mica-generations. The first phase has primary origin and is represented by large (average 1-5 mm in size), brown, idiomorphic zoned crystals, showing compositional variation from the core (phlogopite) to the rims (tetraferriphlogopite). The second phase is made up of minute brown crystals as small aggregates. They present homogeneous composition (tetraferriphlogopite) and are formed after the replacement of former clinopyroxene and olivine crystals. Mineral relicts are still present, indicating a clear secondary origin for the mica.

In an attempt to better describe the mica-rich rocks, they are here subdivided into two groups, mica-bearing rocks with olivine-clinopyroxene pseudomorphs (G) and mica-olivine pyroxenites (MOP).

The first group is basically constituted by glimmeritic rocks. As a result of late metasomatic processes, they are quite variable in texture and composition. Texture changes from granular to porphyritic, owing to either the presence of large phlogopite grains or aggregates of tetraferriphlogopite (glomerocrysts) originated after the substitution of olivine and clinopyroxene crystals. It can also be cumulitic, as mainly indicated by the concentration of aggregates frequently exhibiting layering structures. Cumulus minerals have mica (phlogopite and tetraferriphlogopite at the periphery of grains) as the most abundant phase, olivine and clinopyroxene being only found as relict crystals in association with micaceous material, which includes celadonite, carbonates and amphibole (antophyllite, arvfedsonite); subordinately, apatite and magnetite are also present. Primary intercumulus minerals are poorly defined considering the phlogopitization processes and the pronounced secondary carbonatization of aggregates. In addition to the many types of carbonates (dolomite, ankerite, magnesite, strontianite, breunnerite, ancylite and siderite as minute granular aggregates), these rocks contain opaques (ilmenite, chromite, pyrite, chalcopyrite, sphalerite and millerite), monazite, pyrochlore, zirconolite and calzirtite as accessory phases.

The second group is made up by pyroxenitic rocks showing no evidence of phlogopitization. Texture is characteristically cumulitic with clinopyroxene crystals, peripherically altered to an amphibole of arvfedsonitic composition as the principal cumulus phase; phlogopite and olivine are less abundant. Perovskite, magnetite, apatite and titaniferous garnet in minor amounts are also recognized. Layering can be present as promptly evidenced by monomineralic concentrations of apatite. Grain size of cumulus minerals is quite variable leading to textural changes from equi- to inequigranular (porphyritic), as suggested by large crystals of phlogopite surrounded by tetraferriphlogopite at its margins. The intercumulus assemblage consists mainly of small grains of clinopyroxene and tetraferriphlogopite. Carbonates (calcite, dolomite, ankerite, siderite and burbankite) are widespread and anthophyllite (sometimes talc) and celadonite represent typical alteration products of olivine and clinopyroxene, respectively. As accessories are found ilmenite, rutile, chalcopyrite, calzirtite and zirconolite.

The hybrid rocks show a "biotititic nature" and are characteristically orthocumulitic, with the texture grading from equi- to inequigranular as a result of the size increasing of phlogopite crystals. Cumulus phases comprise basically phlogopite; olivine and clinopyroxene, commonly transformed into minute aggregates of tetraferriphlogopite and celadonite, are rare. Large crystals of phlogopite display clear evidence of reabsorption with replenishment by intercumulus material (tetraferriphlogopite). Newly formed grains are perfectly idiomorphic and also poikilitic in texture with inclusions of apatite, perovskite and magnetite. The intercumulus minerals are composed by small crystals of phlogopite and carbonates (calcite and dolomite). However, the main carbonatic phase in these rocks is indicated by the presence of a network of minute veins filled in with carbonates (dolomite, ankerite and rare siderite) and also by many of the accessory minerals previously described in the carbonatites.

MINERAL CHEMISTRY

CARBONATES

Representative analyses of carbonate minerals from the two principal Araxá lithological groups (carbonatites and mica-rich rocks) are listed in Table I and all data plotted in Fig. 3. Graphs point to the similarity in composition for both groups, where the main differences dealing with the higher dispersion presented by the dolomite ($Mg/Fe > 4$) and ankerite ($Mg/Fe < 4$) analyses. The greater Mg-Fe compositional variation is also put in evidence by the presence of magnesite and breunnerite, in addition to siderite in mica-bearing rocks. On the other hand, only iron-enriched ($FeO/MgO > 50\%$) phases were noticed in carbonatites.

Calcites show homogeneous and limited composition and are, in general, low in MgO and FeO. The SrO content is higher than 1%, whereas MnO is practically absent. Dolomites display a wider compositional field, ranging from pure end-members to more iron-enriched compositions, the latter grading to ankerite types. The MnO and SrO proportions are consistently low. Ankerites also show regular contents for those minor elements. As illustrated in Fig. 3B, the MgO/FeO ratio in siderites is variable, the higher values are found in calciocarbonatites.

TABLE I

Representative carbonate analyses of Araxá rocks. Abbreviations for mineral names: Cc, calcite; Do,dolomite; Ak, ankerite; Sd, siderite; Ms, magnesite; Sr, strontianite; Br, breunnerite. For rock names: CaC, calciocarbonatites; MgC, magnesiocarbonatites; FeC, ferrocarbonatites; G, glimmerites; MOP, mica-olivine pyroxenites; MC, hybrid rocks.

	CcCaC	CcFeC	CcG	CcMOP	DoCaC	DoMgC	DoFeC	DoG	DoMOP	DoMC
FeO			0.7		1.8	3	2.5	2	0.6	2.1
MnO					0.3	0.5	0.4	0.5	0.8	0.6
MgO	0.3	0.2	1.2		19.5	19	18.8	18.5	19.9	16.9
CaO	55.2	54.6	53.5	55.1	31.3	29.7	31.3	31.7	31.6	32.7
SrO	1	1.7	1.1	1.3	0.6	1.3	0.5	0.8	0.6	1.2
CO_2	43.5	43.5	43.5	43.5	46.5	46.5	46.5	46.5	46.5	46.5

	AkCaC	AkMgC	AkFeC	AkG	AkMOP	SdCaC	SdMgC	SdFeC	SdG	
FeO	11.9	7.7	11	10.6	7.6	49.8	30.6	40.3	41.3	
MnO	0.9	1.3	1.5	1.1	1.8	0.9	3.1	1.9	2	
MgO	13.5	16.7	12.6	11.5	13.4	10.8	27.3	19.3	17.4	
CaO	29.3	29.5	30.3	32.1	32.2	0.2	0.4	0.2	1	
SrO	0.1	0.5	0.3	0.4	0.7		0.3			
CO_2	44.3	44.3	44.3	44.3	44.3	38.3	38.3	38.3	38.3	

	SdMOP	SdMC	MsG	SrCaC	SrMgC	SrFeC	SrG	SrMC	BrG	
FeO	37.5	35.3	4	0.2					24.3	
MnO	0.6	3.3	0.9						0.3	
MgO	22.6	22.6	42.3						34.2	
CaO	1	0.6	1.4	6.5	3.5	5.6	2	2.1	0.5	
BaO				1	6.4	1.5	4.8	9.3		
SrO				61.3	59.1	61.9	62.4	57.6		
CO_2	38.3	38.3	51.4	31	31	31	31	31	40.6	

Excluded strontianites (concentrations going up to 11.9% and 9.3% in samples from mica carbonatite and ferrocarbonatite groups, respectively), the BaO content is low or even unexistent.

REE CARBONATES

Here are included primary and secondary minerals in origin, that occur either as isolated grains or small aggregates consisting mainly of minute, needle-shape crystals. Chemical data reported in Table II make possible the characterization of several phases.

Burbankite, a primary mineral frequently found as minor inclusions in calcites and dolomites, shows significant compositional variations. It is REE-poor in calcio- and ferrocarbonatites and strongly enriched of these elements in magnesiocarbonatites and mica-olivine pyroxenites. In the first case, the REE-group is only represented by Ce, whereas in the second one La and Nd are also present. An inverse correlation is evidenced by SrO, whose concentration reaches higher values (27-31%) in the first rock-types. Additional differences are shown by BaO and Na_2O. BaO tends to be more concentrated (9.5-12.7%) in samples belonging to the second group. On the other hand, in spite of its irregular behaviour, the Na_2O content increases in calcio and ferrocarbonatites. The mineral may be found altered into small aggregates of minute crystals of *carbocernaite*. Chemical analysis of this

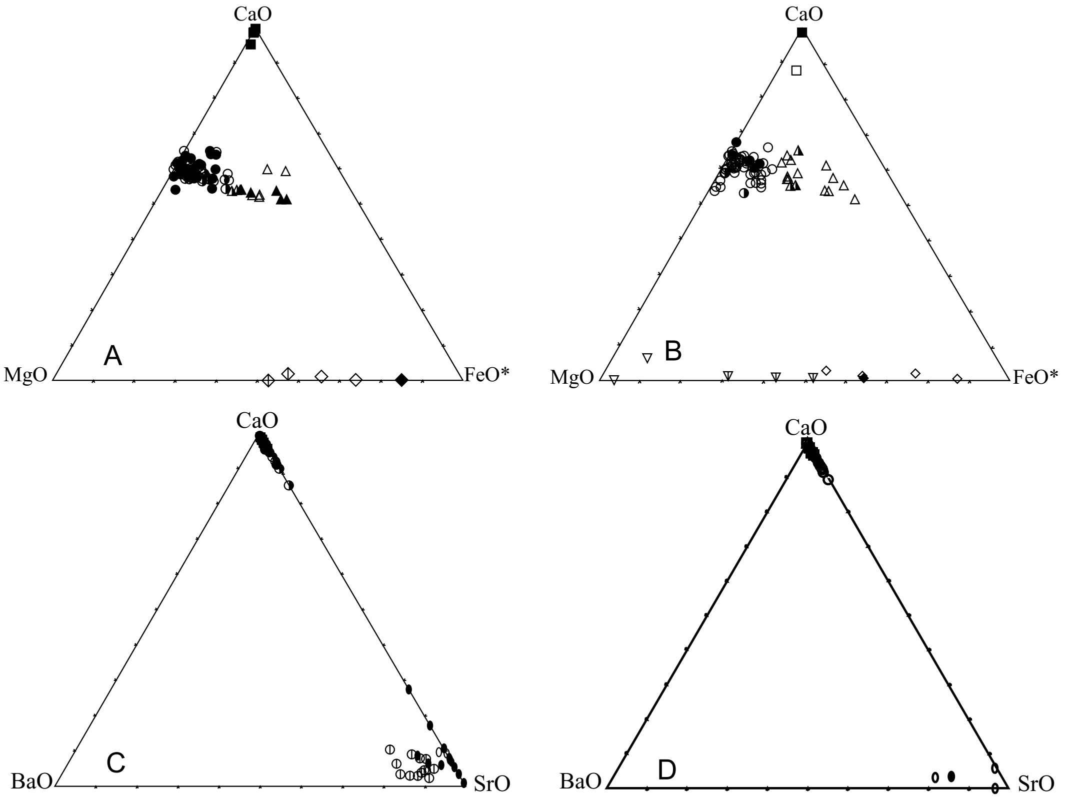

Fig. 3 – A) - CaO-MgO-FeO* (FeO* = FeO+MnO) diagram (wt%) of carbonates from Araxá carbonatites. Symbols: full square, CcCaC; empty square, CcFeC; full circle, DoCaC; half full circle, DoMgC; empty circle, DoFeC; full triangle, AkCaC; half full triangle, AkMgC; empty triangle, AkFeC; full diamond, SdCaC; barred empty diamond, SdMgC; empty diamond, SdFeC. For rock and mineral abbreviations see Table I. B) - CaO-MgO-FeO* (FeO* = FeO+MnO) diagram (wt%) of carbonates from Araxá mica-rich rocks. Symbols: empty square, CcG; full square, CcMOP; empty circle, DoG; half full circle, DoMOP; full circle, DoMC; empty triangle, AkG; half full triangle, AkMOP; empty diamond, SdG; half full diamond, SdMOP; full diamond, SdMC; inverse empty triangle, MgG; barred inverse empty triangle, BrG. C) - CaO-BaO-SrO diagram (wt%) of carbonates from Araxá carbonatites. Symbols: as in A except for full ovoid, SrCaC; barred empty circle, SrMgC; empty ovoid, SrFeC. D) - CaO-BaO-SrO diagram (wt%) of carbonates from Araxá mica-rich rocks. Symbols: as in B except for empty ovoid, SrG; full ovoid, SrMC.

phase (Table II) shows similarities relative to the data presented by the burbankite associated to calcio- and ferrocarbonatites. The main difference is the higher carbocernaite content of REE, which is compensated by its sodium deficiency.

Burbankite analyses reported in literature (Khomyakov 1995) differ, in general, in respect to the Araxá minerals, by their higher Na_2O, Ce_2O_3 and La_2O_3 and lower CaO and SrO contents, respectively.

Ancylite as minute crystals is commonly found in association with strontianite. Chemical data (Table II) point to a higher REE concentration for the mineral of magnesiocarbonatites and glimmeritic rocks in comparison to calciocarbonatites. Differences regard mainly the La_2O_3 and Nd_2O_3 distribution. The Sr content is high in both cases.

Huanghoite, *baritocalcite* and *norsethite* are

TABLE II

Representative REE carbonate analyses (burbankite, 1-8; ancylite, 9-15; carbocernaite, 16; huanghoite, 17; baritocalcite, 18-19; norsethite, 20) of Araxá rocks. For rock abbreviations see Table I.

	1	2	3	4	5	6	7	8	9	10
	CaC	CaC	CaC	CaC	MgC	MgC	FeC	MOP	CaC	CaC
	BY7A	BY7B	BU2A	BU2B	BB2A	BB2B	BAR9D	BAC1	BC7A	BC7B
La_2O_3					7.8	8.3		3.8	11	14.5
Ce_2O_3	5.3		3	3	11.5	11.4	1.4	10.4	31.4	32.8
Nd_2O_3					0.9	2		2.4	9.9	9.6
TiO_2	2.5									
FeO									2.9	
CaO	16.7	16.4	22.4	19.3	11.1	11.7	21	8.1	1	0.8
SrO	29.4	31.1	27.2	31	17	17.6	26.8	22.3	22.8	21.4
BaO		6.2	7	6.8	9.5	9.9	7.3	12.7		
Na_2O	10.5	10.8	4.9	4.3	7.1	4.1	8	4.4		
K_2O	0.1				0.5	0.5		0.5		
CO_2	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	21	21
	11	12	13	14	15	16	17	18	19	20
	MgC	MgC	MgC	G	MC	CaC	MgC	MgC	MgC	MgC
	BO2BA	BO2BB	BR1	BR3	BL9	BU1	BR4	BR1A	BR1B	BR4
La_2O_3	25.4	17.3	23.9	20	24	2.4				
Ce_2O_3	31.5	32.7	33.4	33.1	32.8	8.4	15.7			
Nd_2O_3	1.8	6.6	4.2	3.7	2.6		10.6			
FeO				2.7						2.2
MgO										15.2
CaO	0.4	0.4	0.9	1.1		23.2	2.9	15.2	13	
SrO	20	22.1	16.6	18.4	19.6	25.4	7.7	9.3	14.4	
BaO						6.6	43.1	45	42.1	52.7
Na_2O										
K_2O										
CO_2	21	21	21	21	21	34	20	30.5	30.5	30

Ba-rich (> 40%) phases (Table II) of secondary origin, rare occurrence and only identified in magnesiocarbonatites. The first mineral contains a significant amount of REE, whereas the second one consists of a Ca-Ba carbonate, also Sr-bearing. Data from literature (Kasputin 1980) show SrO values normally lower than 2%. Norsethite is essentially an Mg-Ba carbonate with low FeO content.

PHOSPHATES

Apatite is by far the most common and important phosphate mineral in Araxá rocks. In general, it makes up idiomorphic and prismatic crystals that occur either isolatedly or forming unimineralic concentrations. As cumulus phase, the mineral is mainly found associated with carbonatites, but also with mica-rich rocks. Chemical composition is regular, with large amounts of P_2O_5 and CaO. As a rule, the SrO content remains in the range of 3-5%, but can go up to 10% in some cases forming Sr-enriched apatites. Secondary phosphates are widespread and chiefly represented by Al-bearing phases.

Monazite is the principal REE-phosphate present in the investigated rocks. Selected analyses indicate Ce_2O_3 as the most abundant RE element, with the concentration going up to 37% in glimmerites; that particular sample shows higher SrO and BaO values and also contains 4.8% ThO_2. Despite the non-uniform composition of monazite, no systematic variation is indicated for the two lithological groups.

SILICATES

Except for nenadkevichite, chemical data on silicate minerals are not listed in tables and only the micas plotted on the available graphs.

1. Olivines, clinopyroxenes and amphiboles

Fresh olivines are essentially restricted to the mica-olivine pyroxenites. Composition is homogeneous lying within a narrow interval, $Fo_{86\text{-}92}$. CaO stands normally below 1%. The mineral can be found either altered into anthophyllite in pyroxenitic rocks or phlogopite-celadonite aggregates in glimmeritic rocks.

Clinopyroxenes also have uniform composition, with the data plotting on the diopside field. The FeO content is low and FeO/Fe_2O_3 partitioning follows to Papike et al. (1974). Other analyzed elements, such as TiO_2 and Al_2O_3, show values lower than 1.3% and 1.8%, respectively.

The amphiboles are secondary minerals mainly represented by two distinctive and characteristic types, *magnesioarfvedsonite* and *antophyllite* (Leake et al. 1997). The first phase is a common mineral to carbonatites and glimmeritic rocks, being acicular in shape and clearly derived from clinopyroxene crystals. Chemical composition indicates a large variation in FeO (1.1-17.3%), MgO (14.4-25.9%) and Na_2O (3.4-6.2%) contents. The mineral also bears high CaO and K_2O amounts. On the other hand, anthophyllite is basically a ferromagnesian phase with small contributions of CaO ($< 1.8\%$) and K_2O ($< 1.9\%$). It should be noted that the amphiboles in Araxá rocks are Al-poor phases. Thus, during crystallization processes the available Al would be principally destinated to the mica formation.

2. Micas

Micas are a very important mineral constituent, being represented by *phlogopite* and *tetraferriphlogopite*, the latter an intercumulus primary phase, but mainly found as small aggregates of secondary origin, and *celadonite* as the most common alteration product. Chemical analyses are plotted on the conventional Al-Mg-Fe^{2+} diagram (Figs. 4A, B). In general, early phlogopite, a high Al_2O_3 and low FeO phase, can be found grading progressively into tetraferriphlogopite as a result of Al-deficiency during the magmatic crystallization, which is in turn compensated by the Fe^{3+} entry occupying tetrahedral sites in the mineral structure. Figs. 4C, D, relating Si against Al^{IV}, put in evidence such deficiency. This particular feature has also been observed in other Brazilian alkaline-carbonatite occurrences, as emphasized by Morbidelli et al. (1995, 1997). Those chemical variations are followed by optical changes in the mineral as indicated by the inverse pleochroism normally exhibited by tetraferriphlogopite. Chemical data also draw the attention to the transformation of phlogopite into tetraferriphlogopite, the latter phase mainly occupying the periphery of grains and/or being concentrated along the cleavage planes. No significant differences in mica composition have been detected for the two lithological groups.

In Araxá rocks celadonite, commonly forming minute grains, is found associated to tetraferriphlogopite and ankerite as an alteration product of primary mafic minerals or even filling late veins, particularly those of ferrocarbonatites. The mineral presents variable FeO/MgO ratio and is highly potassic in respect to the data given in literature. Apparently, two types can be distinguished on the basis of SiO_2 and MgO contents, but the available data are still insufficient to draw conclusions.

A rare Li-bearing phase has been identified as

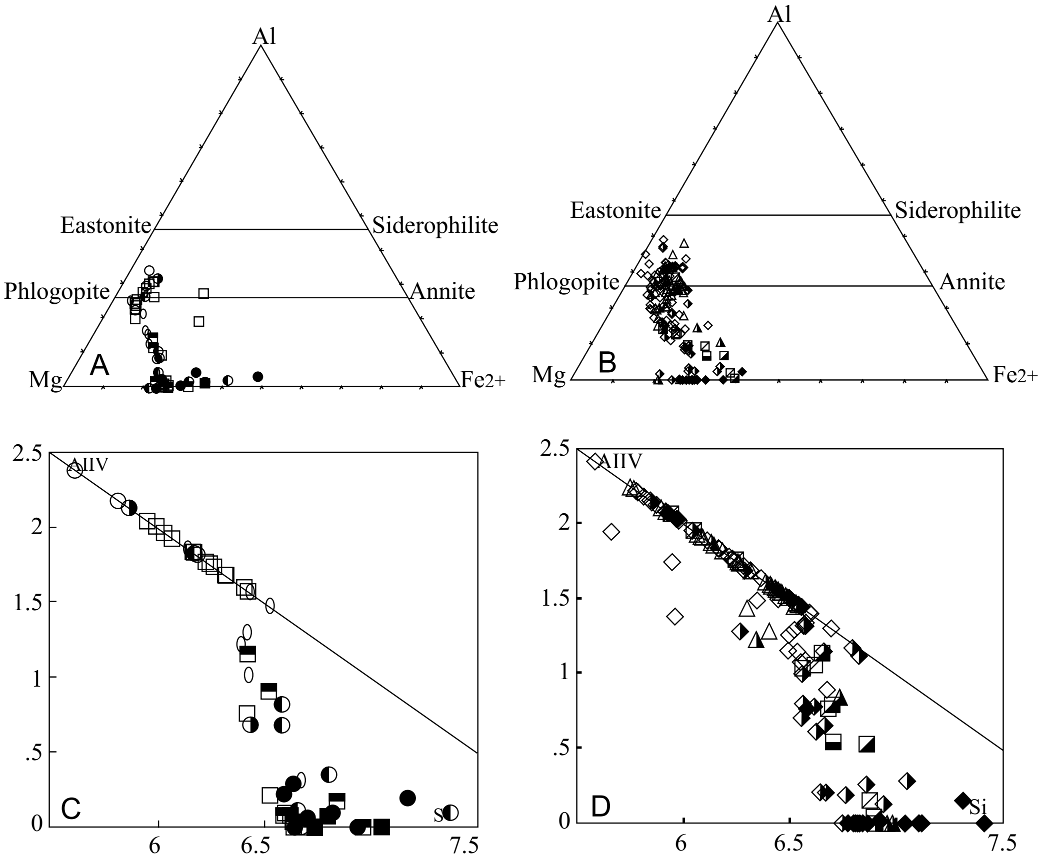

Fig. 4 – A) - Composition of phlogopites and tetraferriphlogopites from Araxá carbonatites plotted on the conventional Al-Mg-Fe^{2+} diagram. Symbols: empty square, CaC, core; half full square, CaC, rim; full square, CaC, ps; empty circle, MgC, core; left, half full circle, MgC, rim; empty ovoid, FeC, core; right, half full circle, FeC, rim; full circle, FeC, ps. Ps, pseudomorphs. B) - Composition of phlogopites and tetraferriphlogopites from Araxá mica-rich rocks plotted on the conventional Al-Mg-Fe^{2+} diagram. Symbols: empty diamond, G, core; half full diamond, G, rim; full diamond, G, ps; empty triangle, MOP, core; half full triangle, MOP, rim; barred empty square, MC, core; transverse half full square, MC, rim; half full square, MC, ps. C) - Composition of phlogopites and tetraferriphlogopites from Araxá carbonatites plotted on the Al^{IV}-Si diagram. Symbols as in A. D) - Composition of phlogopites and tetraferriphlogopites from Araxá mica-rich rocks plotted on the Al^{IV}-Si diagram. Symbols as in B.

accessory forming aggregates of acicular crystals in only two samples of magnesiocarbonatites. It is thought to belong to the lepidolite group as indicated by preliminary studies (Table III). A chemically similar mineral is referred to as *tainiolite* in literature and was described for the first time in 1938 in the alkaline district of Magnet Cove, USA, by Miser and Stevens (Foster 1960, Erd et al. 1983).

3. *Garnet*

This mineral has been described as an accessory phase in some mica-olivine pyroxenites, where it occurs associated to perovskite and opaque grains. It is basically a Ti-bearing andradite, with TiO_2 almost constant (10-11%), and referred to as melanite. A second Ti-andradite phase, but containing a large amount of ZrO_2 (11.3%), is also present. Acccord-

TABLE III

Representative tainiolite (1-2) and nenadkevikite (4-5) analyses of Araxá rocks. For rock abbreviations see Table I. For comparison, mineral analyses from Magnet Cove and Lovozero rocks, respectively.

	1	2	3	4	5	6
	MgC	MgC	Magnet	CaC	CaC	Lovozero
	BR5A	BR5B	Cove	BAR1A	BY6	Massif
Nb_2O_5				34.7	37.6	24.05
SiO_2	60.8	59.1	58.82	39.3	37.9	37.72
TiO_2			0.11	1.6	0.3	9.69
Al_2O_3		0.7	1.29			0.62
Fe_2O_3			0.4			
FeO	0.8	1.1	0.24			
MnO						1.08
MgO	19.6	20.3	19.18			0.45
CaO						4.3
Na_2O			0.64			3.34
K_2O	11.8	11.8	10.44	14.4	14.2	2.68
Li_2O	3	3	3.1			
H_2O	4	4		10	10	11.34
BaO						2.75
REE						0.25
Total	100	100	94.22	100	100	99.67

ing to the literature (Milton et al. 1961), the mineral can be more properly named ferric-kimzeyite.

4. Nenadkevichite

As an accessory phase, certainly of secondary origin, the mineral is found as minute inclusions in late apatite aggregates from calciocarbonatites. Table III lists the obtained chemical data and also an analysis of Kouzmenko from the Lovozero massif, Russia (Karup-Møller 1986). The Araxá mineral is strongly potassic and more Nb-enriched in comparison to the Russian material and also additionally contains very low TiO_2 and no CaO and Na_2O whatsoever.

Oxides

1. Pyrochlore

It makes up the principal accessory of Araxá rocks and is mainly found in glimmeritic rocks and carbonatites, particularly the Mg-rich types. The mineral is widespread as minute isolated grains, but also occurs in association with carbonates. Chemical composition is strongly variable and based on its considerable high Nb_2O_5 and low TiO_2 contents, the mineral is placed into the Nb+Ta>2Ti, Nb>Ta group (Hogarth 1977). Ta concentration is very low and normally below the detectable limit.

Site A in the mineral structure is in general occupied by Ca, Sr, Ba and Ce, but these elements vary considerably in concentration and may not necessarily be present in the same crystal. Owing to these strong variations in composition, some types could be more properly named bariopyrochlore, ceriopyrochore or even strontiopyrochlore. High Ba concentration in pyrochlore is believed to be an indicative evidence of its secondary origin (Heinrich 1980, Mariano 1989). In fact, bariopyrochlore is the most important mineral of the pyrochlore group at the Araxá mine (Hogarth 1977) and it is interpreted by Heinrich (1980) as a product of hydrothermal activities. In some glimmeritic rocks and also in one sample of magnesiocarbonatite, the BaO content lies over 10 wt%, occasionally reaching 23 wt%. The chemical data also point to the presence of Na_2O and ThO_2, the maximum values obtained being 7.4 wt% and 3.3 wt% in glimmeritic rocks and magnesiocarbonatites, respectively.

2. *Perovskite*

It is an accessory phase found in mica-olivine pyroxenites in association with titaniferous garnet and opaques. The mineral has a very uniform composition with TiO_2 and CaO as major components. Sporadically, FeO and SrO are present in minor amounts.

3. *Rutile*

The mineral is widespread in Araxá rocks, where it occurs as an accessory phase commonly forming isolated grains. In general, it contains TiO_2 content over to 90 wt% and FeO as the second major component. Nb_2O_5 is invariably present, the concentration going up to 9 wt%. On the other hand, Ta_2O_5 is rare and only detected in a few samples of calciocarbonatites. CaO is lower than 1 wt%.

4. *Magnetite, ilmenite and chromite*

Magnetite and ilmenite are very common phases, whereas chromite is scarce and only identified in glimmeritic rocks. Magnetite forms large grains in ferrocarbonatites. The FeO/TiO_2 ratio is almost constant in magnetite (ulvöspinel molecule ranging between 5-30% in carbonatites, 0-31% in glimmerites and 0-44% in pyroxenitic rocks) but quite variable in ilmenite, placing the composition between the members $FeO.TiO_2$ and $FeO.2TiO_2$. In magnetite, MnO and MgO are present in minor amounts, the concentration, however, goes up in ilmenite to 6.4 wt% and 12 wt%, respectively. The Cr_2O_3 content of magnetite is normally lower than 2 wt%; in a few samples of pyroxenitic and glimmeritic rocks it is higher, in the range of 5-9 wt%.

5. *Calzirtite and zirconolite*

They form accessory minerals in glimmeritic and mica-olivine pyroxenitic rocks; more rarely, they occur in calciocarbonatites. The calzirtite grains do not show much variation in chemical composition, which basically consists of TiO_2, CaO and ZrO_2 (Table IV). Keller and Schleicher (1990) reported an analysis of Brettel, Germany, bearing 67% ZrO_2, high Nb_2O_5 and small amounts of TiO_2 and CaO.

TABLE IV

Representative calzirtite (1-4) and zirconolite (5-10) analyses of Araxá rocks. For rock abbreviations see Table I.

	1	2	3	4	5
	G	G	MOP	MOP	MOP
	B16A	B16B	BS2	BM5	BM5
TiO_2	16.3	16.4	14.9	18.4	42.3
FeO	1.3	1.5		0.8	4.8
CaO	13.8	14.4	12.2	13.6	16.6
ZrO_2	68.6	67.8	72.9	67.3	36.3

	6	7	8	9	10
	G	G	G	G	G
	BO4	BQ1	BQ3	B16A	B16B
SiO_2	5.1				
TiO_2	37.5	19.7	26.8	25.8	24.2
FeO	4.1	7.9	7.6	8.3	7
CaO	14	13	13.3	13.2	12.3
ZrO_2	38.8	32.6	29.5	30.4	36.6
Nb_2O_5		22.2	20.2	18.3	14.6
Nd_2O_3				2.4	2.1
Ce_2O_3	0.7				
ThO_2		2.1	2.6	1.5	3.1

The Araxá zirconolite, on its turn, is characterized by higher TiO_2 and lower ZrO_2 contents regarding the calzirtite (Table IV). Zirconolite also contains Nb_2O_5 (15-22%), FeO and ThO_2 (1.5-3.1%). The phase described in Eichholz and Brettel rocks (Keller & Schleicher 1990) contains variable Nb_2O_5

(16-22%) and, additionally, ThO_2 (4-5%) and UO_2 (1.2-1.8%).

SULPHIDES

Except for mica-olivine pyroxenites having *chalcopyrite* as the main sulphide phase, *pyrite* is widespread in Araxá rocks. Chalcopyrite is also found in carbonatites and glimmeritic rocks. Both minerals show a simple and monotonous composition.

Additional sulphide minerals include *sphalerite* and *galena* in carbonatites and glimmerites and, more rarely, *cobaltite (?)*, also bearing a large amount of As, and *millerite* in ferrocarbonatites and glimmeritic rocks, respectively.

PETROCHEMISTRY

Representative chemical analyses for major and trace elements of carbonatites and mica-rich rocks are given in Tables V and VI. Data on carbonatites are plotted on the Woolley and Kempe's (1989) classificatory diagram (Fig. 5). In general, the carbonatites lie over the 50% CaO reference line, whereas the mica-rich rocks, except for a few samples, are placed below that value.

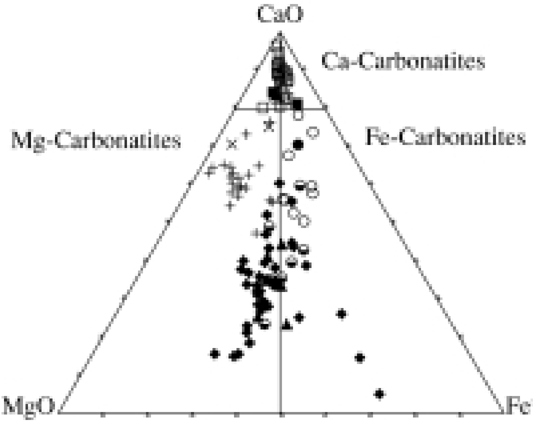

Fig. 5 – Composition of carbonatites and mica-rich rocks from Araxá plotted on the Woolley and Kempe's (1989) CaO-MgO-Fe* (Fe* = FeO+Fe_2O_3+MnO) diagram (wt%). Symbols: empty square, CaC; full square, CaC, Ph; vertical cross, MgC; inclined cross, MgC, Ph; empty circle, FeC; full circle, FeC, Ph; full diamond, G; half full circle, MOP; full triangle, MC. Ph, phoscorites.

Average compositions (major and trace elements by XRF) for the main Araxá rock-types are shown in Fig. 6. Carbonatites and mica-rich rocks, here included the hybrid lithotypes, are promptly distinguished on the basis of elemental distribution. It should be emphasized that the mica-rich rocks are quite homogeneous in composition and contain high contents of Cr and Ni; notably they are also enriched in Zr, Nb, La and Ce. The carbonatites, on the other hand, are strongly concentrated in La and Ce.

A negative correlation CaO-MgO (Fig. 7), which can be referred to as mineral ratios (e.g. calcite/dolomite in carbonatites and carbonate/phlogopite in mica-rich rocks), characterizes all the lithotypes. The second mineral relationship is also confirmed by the negative (CaO-SiO_2) and positive (K_2O-MgO and K_2O-SiO_2) correlations (Fig. 7). In addition, a CaO-MgO-K_2O diagram (not shown) draws the attention to the small phlogopite participation in carbonatites in respect to the mica-rich rocks.

Diagrams normalized according to the Woolley and Kempe's (1989) average compositions for CaC, MgC and FeC (Fig. 8) indicate that the Araxá rocks are less rich in V, Zn, Rb and Pb. In contrast, they contain larger amounts of Cu, the enrichment factors being from at least 2 up to 6.3 in FeC. Zr enrichment is also present in FeC.

P_2O_5 values for the Araxá carbonatites are close to the data reported by Woolley and Kempe (1989). Phoscoritic rocks associated to CaC show the highest P_2O_5 contents (16.97-17.40%). On the other hand, phoscorites related to MgC and FeC contain minor amounts of the element, in general, not over 12%.

Al_2O_3 and K_2O contents are low, as suggested by the dominant nature of the mica (tetraferriphlogopite) present in the carbonatites.

Nb mineralization is the most important feature regarding the Araxá carbonatites. Brazil is the first Nb exporter in the world, with the Araxá ore representing about 90% of the whole production. Contrasting to such situation, the analyzed samples have significantly lower Nb contents in relation to the

TABLE V

Representative bulk-chemical analyses of Araxá carbonatites (1, CaCPh; 2-6, CaC; 7-12, MgC; 13, FeC; 14, FeCPh; 15-17, FeC). For rock abbreviations see Table I; Ph, phoscorites. Major and trace elements in wt% and ppm, respectively.

	1	2	3	4	5	6	7	8	9
	BB3	BC6	BF3	BM1	BO3b	BY8	BA2	BC1	B14
SiO_2	1.29	1.75	3.74	1.08	0.33	0.45	1.88	0.67	0.09
TiO_2	0.20	0.17	0.44	0.12	0.02	0.31	0.05	0.15	0.02
Al_2O_3	0.20	0.07	0.04	0.06	0.04	0.05	0.04	0.08	0.02
Fe_2O_3	5.06	3.35	3.47	2.20	2.40	2.51	2.23	3.59	0.67
FeO	2.05	0.77	0.62	0.86	0.50	1.67	1.26	3.02	0.48
MnO	0.43	0.20	0.15	0.16	0.35	0.19	0.43	0.36	0.19
MgO	3.32	2.79	5.21	2.46	7.48	4.18	14.38	12.26	17.90
CaO	46.33	47.27	44.23	48.26	43.02	47.61	30.77	35.17	32.60
Na_2O	0.54	0.27	0.07	0.14	0.42	0.02	0.09	0.02	0.03
K_2O	0.04	0.16	0.09	0.27	0.03	0.06	0.04	0.07	0.01
SrO	1.72	1.52	0.90	1.63	1.66	0.45	1.64	1.46	0.75
BaO	1.02	0.27	0.20	0.25	0.85	0.53	4.67	0.54	0.30
P_2O_5	17.40	2.25	3.44	0.25	6.45	2.33	0.46	4.16	2.26
LOI-CO_2	1.64	0.07	1.82	0.36	1.03	0.12	1.71	0.67	3.21
CO_2	18.38	38.75	35.41	41.71	34.72	39.19	40.01	37.25	41.31
Total	99.62	99.66	99.83	99.81	99.30	99.66	99.66	99.48	99.84
V	101	48	42	22	19	68	13	44	12
Cr	20	23	< 20	< 20	< 20	22	< 20	22	< 20
Co	16	25	7	26	8	31	6	34	2
Ni	31	33	24	29	21	53	16	35	15
Cu	32	142	25	39	24	32	11	29	15
Zn	178	110	51	76	< 30	151	61	96	< 30
Rb	2	2	2	9	< 2	< 2	< 2	< 2	< 2
Y	853	130	148	60.7	132	128	57.9	148	180
Zr	662	169	142	18	104	250	34	343	136
Nb	85.9	41.6	31.9	30.2	138	170	43.7	83.3	23.5
La	432	585	348	548	2110	375	1036	1307	385
Ce	1194	1303	781	1038	3017	886	1816	2581	776
Pr	192	157	93.4	108	268	109	201	289	88.2
Nd	987	580	334	345	778	416	709	1023	313
Sm	333	103	54.7	44.8	106	84.2	122	151	58.6
Eu	129	31	18.6	13.4	33	28.5	36.1	43.2	21.9
Gd	299	71.6	49.2	35.5	89.8	67.1	82.6	109	57.1
Tb	46.1	7.1	6.07	3.14	9.02	7.57	6.41	9.67	7.8
Dy	209	29.1	30.1	13.3	35.4	30.9	19.9	38.3	39
Ho	34.6	4.84	5.5	2.18	5.3	4.8	2.28	5.71	6.98
Er	50.9	7.87	9.35	3.72	7.27	7.14	2.69	8.46	10.5
Tm	4.37	0.701	1.07	0.365	0.47	0.527	< 0.1	0.54	0.975
Yb	20.9	3.89	5.24	1.86	1.46	2.89	< 1	2.54	4.12
Lu	2.77	0.553	0.499	0.274	0.204	0.444	0.111	0.399	0.55
Hf	21.6	2.1	2.9	0.6	2.2	3.9	1.4	5.3	2.9
Th	744	102	77.7	33.1	129	148	163	109	40.2
U	28.7	4.05	3.42	5.09	4.69	78.6	1.93	18.5	3.15
ΣREE	3935	2885	1737	2158	6461	2020	4034	5569	1770
$(La/Lu)_n$	16	110	72	208	1074	88	969	340	73

TABLE V (cont.)

	10	11	12	13	14	15	16	17
	BL5	BO1a	BR1	BB4	BF2	BH3	BM3	BN2
SiO_2	2.50	0.43	2.30	0.86	2.07	1.74	0.62	2.85
TiO_2	0.09	0.03	0.06	0.03	0.67	0.07	0.12	0.99
Al_2O_3	0.09	0.07	0.06	0.10	0.05	0.11	0.09	0.15
Fe_2O_3	3.44	1.83	3.87	4.54	10.55	6.30	5.99	9.46
FeO	2.04	0.56	0.86	8.40	0.32	4.99	5.33	6.06
MnO	0.65	0.50	0.40	1.46	0.26	1.02	0.75	0.41
MgO	13.62	10.46	7.48	11.32	6.41	11.57	11.01	7.73
CaO	28.46	36.21	40.42	28.29	41.90	30.58	29.19	34.73
Na_2O	0.12	0.22	0.11			0.11	0.05	0.23
K_2O	0.14	0.04	0.26	0.05	0.23	0.26	0.06	0.33
SrO	2.96	3.62	1.84	1.08	0.71	1.56	1.85	0.85
BaO	3.66	2.27	2.37	0.96	0.18	1.42	2.69	1.34
P_2O_5	0.62	3.42	2.32	0.46	11.48	2.77	0.17	3.33
LOI-CO_2	1.97	0.94	1.91	1.56	2.58	1.06	2.32	0.01
CO_2	38.18	37.78	34.84	39.95	22.33	35.56	38.94	31.26
Total	98.54	99.38	99.10	99.06	99.74	99.12	99.18	99.73
V	36	21	40	29	122	45	49	153
Cr	22	< 20	< 20	40	457	58	88	33
Co	15	3	30	6	19	31	19	62
Ni	29	< 15	24	18	2070	38	224	72
Cu	15	16	49	12	34	21	13	360
Zn	225	48	691	60	79	103	646	268
Rb	6	< 2	6	< 2	10	10	2	11
Y	28	95.2	69.4	13.6	259	38.3	53.1	186
Zr	28	114	94	11	245	36	19	134
Nb	379	55.1	118	40.9	104	22.5	259	84
La	4619	6454	2814	2302	475	2001	2456	409
Ce	5848	8007	3978	5104	1071	4536	4175	919
Pr	440	627	324	570	139	479	409	118
Nd	1072	1526	881	1707	525	1652	1335	474
Sm	68.9	115	83	150	84.3	155	218	99.9
Eu	15.1	28.3	21.7	29.7	27.1	33	66.3	32.5
Gd	62.3	104	63.7	93.7	70	85.5	146	74.5
Tb	3.36	7.97	4.8	3.37	9.81	4.27	11.3	9.99
Dy	7.95	26.5	16.3	5.44	52.6	12.3	27.2	48
Ho	1.02	3.86	2.47	0.23	10.2	1.3	2.22	7.71
Er	1.59	5.77	3.77	0.11	20.6	1.47	2.03	11.2
Tm	0.074	0.357	0.244	< 0.1	3.24	< 0.2	< 0.1	0.905
Yb	< 2	< 2	< 2	< 1	19.2	< 1	< 1	4.27
Lu	0.336	0.269	0.084	0.003	2.265	0.047	0.083	0.576
Hf	1	2.6	2	0.6	5.6	0.9	1.3	2.2
Th	76.4	129	58.6	111	164	45.5	594	153
U	1.15	11.2	36.5	12.6	9.19	1.67	6.83	5.58
ΣREE	12140	16906	8193	9966	2509	8961	8848	2210
$(La/Lu)_n$	1428	2492	3480	79704	22	4422	3074	74

numbers listed in literature (cf. Woolley & Kempe 1989): 127 vs. 1204 ppm for CaC, 334 vs. 569 ppm for MgC and 194 vs. 1292 ppm for FeC.

Sr is variably enriched in Araxá carbonatites, the larger amounts being found in the MgC group, as also suggested by the occurrence of strontianite. Ba

TABLE VI

Representative bulk-chemical analyses of Araxá mica-rich rocks (1-12, G; 13-20, MOP; 21-24, MC). For rock abbreviations see Table I. Major and trace elements in wt% and ppm, respectively.

	1	2	3	4	5	6	7	8
	BD1	BG3	BI6	BN4	BO4b	BQ3	BT1	BT3
SiO_2	24.03	25.69	16.79	19.68	21.31	35.50	23.13	20.81
TiO_2	3.36	2.74	2.45	1.87	2.73	1.82	2.30	4.07
Al_2O_3	1.68	1.12	1.90	1.43	2.07	6.52	3.38	0.09
Fe_2O_3	10.69	6.28	20.12	6.88	10.17	7.27	11.49	26.57
FeO	3.95	3.30	9.15	2.94	3.09	2.66	5.31	12.14
MnO	0.33	0.37	0.41	0.28	0.29	0.17	0.35	0.81
MgO	17.71	15.77	13.63	18.09	17.80	21.26	11.75	14.52
CaO	12.76	14.93	15.29	18.70	14.76	5.78	18.27	2.88
Na_2O		0.13		0.14			0.61	0.13
K_2O	5.20	2.84	2.94	3.48	4.42	6.99	4.34	3.24
SrO	0.39	0.54	0.24	0.44	0.75	0.46	0.62	0.06
BaO	0.27	0.38	0.12	0.35	0.58	0.18	0.48	0.24
P_2O_5	1.03	0.28	2.41	1.09	1.52	0.13	7.71	0.10
LOI-CO_2	2.42	2.56	4.58	3.03	2.31	4.25	2.22	1.54
CO_2	15.56	22.67	9.42	21.00	17.69	6.08	7.46	12.70
Total	99.38	99.60	99.45	99.40	99.49	99.07	99.42	99.90
V	88	152	929	176	111	127	211	1071
Cr	576	178	< 20	816	369	174	< 20	26
Co	53	39	59	54	51	27	51	65
Ni	393	106	76	526	147	69	42	< 15
Cu	31	15	68	50	57	21	201	< 10
Zn	222	122	327	84	132	81	230	579
Rb	145	91	106	104	164	273	135	78
Y	35.5	41.1	64.1	59.4	31.6	51	205	14.8
Zr	1019	280	421	666	958	2909	2900	176
Nb	286	497	152	161	861	1792	539	183
La	1070	703	184	724	377	158	573	44.5
Ce	1822	1509	492	1189	817	475	1290	92.1
Pr	168	166	63.25	114	87	59.8	146	10
Nd	503	577	255	365	292	244	532	35.8
Sm	50.2	76.8	47.9	47.9	37.1	47.2	95.4	5.8
Eu	12.2	19.7	14.7	13.4	9.92	14.5	31.6	1.71
Gd	31.9	43.6	32.1	32.2	23.6	29.7	77.7	4.17
Tb	2.43	3.19	3.89	3.31	2.19	3.8	10.5	0.57
Dy	9.34	11.4	18.6	15	9.48	17.8	49.6	3.05
Ho	1.37	1.53	3.15	2.46	1.48	2.86	8.23	0.6
Er	2.03	2.7	5.3	3.8	2.18	4.65	12.7	1.13
Tm	0.168	0.29	0.576	0.334	0.159	0.482	1.23	0.158
Yb	0.42	1.37	3.04	1.47	0.71	2.46	5.89	0.82
Lu	0.045	0.188	0.345	0.189	0.095	0.237	0.564	0.086
Hf	28	7.3	9.2	12	21.4	65	48.3	3.5
Th	42.3	75.5	192	68.8	142	481	117	24.8
U	4.09	12.3	80.9	9.16	21.3	440	15.2	4.38
ΣREE	3673	3116	1124	2512	1660	1060	2834	200
$(La/Lu)_n$	2470	388.4	55.4	397.9	412.2	69.25	105.5	53.75

TABLE VI (cont.)

	9 BT6	10 BU4	11 BY5	12 BAC2	13 BM5	14 BS2	15 BS3	16 BZ1
SiO_2	23.87	17.56	32.12	14.31	31.56	30.41	24.41	25.67
TiO_2	2.84	2.42	3.41	1.14	3.53	2.14	3.02	4.59
Al_2O_3	2.51	2.36	2.33	1.70	2.15	2.83	3.03	3.23
Fe_2O_3	9.02	7.38	8.35	8.26	9.83	1.76	8.55	10.43
FeO	5.11	3.04	3.34	4.37	4.28	8.17	6.09	4.29
MnO	0.49	0.27	0.20	0.27	0.35	0.30	0.44	0.25
MgO	20.84	13.76	13.05	10.25	17.51	12.59	12.85	14.90
CaO	8.12	21.47	13.25	28.87	9.79	21.81	18.31	16.42
Na_2O	0.14	0.20	0.12		0.66	0.76	0.26	0.19
K_2O	4.27	3.27	3.34	2.85	4.82	3.08	3.10	3.81
SrO	0.16	0.52	0.16	0.73	0.15	0.41	0.41	0.27
BaO	0.38	0.32	0.31	0.26	0.16	0.22	0.61	0.24
P_2O_5	0.29	2.82	0.94	8.67	2.72	8.89	5.81	3.27
LOI-CO_2	2.04	1.99	2.08	2.36	2.31	2.31	1.70	1.93
CO_2	19.66	22.18	16.68	15.20	9.69	3.46	10.82	9.92
Total	99.74	99.56	99.68	99.24	99.51	99.14	99.41	99.41
V	175	148	255	131	196	236	196	141
Cr	590	315	916	153	819	67	160	490
Co	39	38	116	40	62	29	36	78
Ni	169	181	445	127	571	135	181	212
Cu	< 10	61	18	58	126	225	689	102
Zn	305	125	102	114	136	105	119	91
Rb	158	126	105	105	142	84	110	121
Y	13.2	47.6	38.9	210	47.4	160	85.6	83.7
Zr	386	426	148	1421	182	112	391	711
Nb	421	419	138	312	339	78.4	206	254
La	80	540	219	458	314	426	825	511
Ce	184	1265	425	1085	653	823	1653	1078
Pr	19.8	144	45.7	134	71.1	93.2	179	118
Nd	65.4	508	163	527	248	337	593	419
Sm	8.17	68	27.1	104	38.1	59.9	71.9	65.3
Eu	2.21	17.1	8.7	32.5	11.2	20.1	19.6	19.4
Gd	5.73	40.9	21.2	76.5	26.2	51.8	50.3	45.7
Tb	0.62	3.27	2.33	10.9	3.06	7.17	4.77	5
Dy	2.84	12.4	9.71	54.4	13.1	36.3	21	21.9
Ho	0.48	1.79	1.53	9.04	2.07	6.52	3.38	3.54
Er	0.88	2.57	2.51	13	3.04	10.7	5.58	5.48
Tm	0.114	0.138	0.222	1.06	0.253	1.16	0.499	0.485
Yb	0.66	0.67	1.34	4.5	1.29	5.42	1.94	2.19
Lu	0.066	0.084	0.122	0.523	0.181	0.553	0.257	0.265
Hf	8.2	5.7	3.9	37.2	3.7	2.6	7.8	16.3
Th	23.3	50.9	67.3	166	56.1	76.6	69.7	61.1
U	12.7	6.06	2.45	82.2	9.08	13.1	15.2	12.1
ΣREE	371	2604	927	2510	1385	1879	3429	2295
$(La/Lu)_n$	125.9	667.74	186.5	90.96	180.2	80.02	333.4	200.3

shows similar contents relative to the Woolley and Kempe (1989) numbers for CaC and FeC groups and is strongly enriched in MgC. These rocks also bear the highest values in L.O.I-CO_2 (Table V), probably associated to the presence of SO_3. In most of the alkaline-carbonatite complexes (cf. Woolley &

TABLE VI (cont.)

	17 BZ2	18 BAB2	19 BAC1	20 BAR8	21 BG1	22 BL2	23 BL8	24 BL9
SiO_2	27.82	18.47	19.13	32.85	25.02	18.55	24.18	18.70
TiO_2	3.81	2.36	3.62	5.05	4.93	2.57	3.44	2.19
Al_2O_3	2.58	2.01	1.82	3.52	5.76	1.84	2.70	1.99
Fe_2O_3	9.99	13.40	7.63	9.12	9.52	9.02	8.81	7.54
FeO	3.72	4.68	4.73	4.64	7.43	4.14	5.20	5.51
MnO	0.32	0.36	0.24	0.21	0.30	0.37	0.41	0.55
MgO	15.40	12.90	8.05	16.36	16.17	13.31	19.20	16.83
CaO	15.00	23.33	30.60	16.41	10.19	21.14	11.38	16.24
Na_2O	0.44	0.05	0.08	0.26	0.17	0.22	0.01	0.06
K_2O	4.18	3.79	2.60	3.95	5.24	3.88	5.13	3.95
SrO	0.49	0.42	0.48	0.17	0.42	0.82	0.84	1.03
BaO	0.38	0.21	0.15	0.25	0.85	0.53	0.28	0.38
P_2O_5	4.84	4.91	4.16	1.02	3.12	6.00	1.05	0.36
LOI-CO_2	2.22	1.79	1.31	1.76	3.05	2.03	2.23	1.96
CO_2	7.88	11.03	15.08	4.00	7.36	14.75	14.42	21.87
Total	99.07	99.71	99.68	99.57	99.53	99.17	99.28	99.16
V	173	182	273	198	152	132	82	36
Cr	533	34	156	745	260	234	486	374
Co	87	60	59	65	49	45	51	52
Ni	279	198	132	394	115	146	302	286
Cu	173	81	108	53	26	66	30	48
Zn	186	227	114	104	174	329	183	129
Rb	136	120	76	108	155	101	161	124
Y	133	125	65.5	48.2	84	158	31	10
Zr	283	345	183	631	385	302	699	446
Nb	127	236	162	286	486	558	774	254
La	476	555	447	469	1032	2150	1617	2102
Ce	1131	1202	923	960	1933	3631	2459	3040
Pr	136	139	98.7	101	202	329	218	255
Nd	497	511	333	346	681	963	627	684
Sm	80.9	80.4	45.9	48.8	93.2	91.5	59.3	50.8
Eu	24.7	23.9	13.5	13.9	26	23.2	14.2	10
Gd	57.7	57.9	34.7	32.8	62.4	66.1	38.2	27.1
Tb	6.62	6.38	3.88	3.33	5.84	6.63	2.61	1.28
Dy	30.7	28.3	17.2	14.2	23.3	33.2	8.7	3.07
Ho	5.19	4.76	2.67	2.19	3.36	6.13	1.17	0.33
Er	9	7.93	3.94	3.46	4.97	10.3	1.66	0.42
Tm	1	0.765	0.363	0.276	0.329	1.18	< 0.1	< 0.1
Yb	5.46	4.04	1.68	1.17	1.41	4.6	< 1	< 1
Lu	0.641	0.614	0.228	0.125	0.178	0.625	0.041	0.022
Hf	7.9	8.4	3.7	15.3	8.8	5	13.5	8.1
Th	82.7	76.7	55.2	41.3	73	89.4	41.4	18.7
U	17.2	14.3	26.3	16.5	10.9	16.3	16.1	2.13
ΣREE	2462	2622	1926	1996	4069	7316	5047	6174
$(La/Lu)_n$	77.13	93.89	203.6	389.7	602.2	357.3	4097	9924

Kempe 1989), Sr and Ba reach higher concentrations in FeC.

MgC rocks are also enriched in REE. For CaC, MgC and FeC, ΣREE vary within the intervals 1736-6460 ppm, 1769-16906 ppm and 2204-9965 ppm, respectively (Table V).

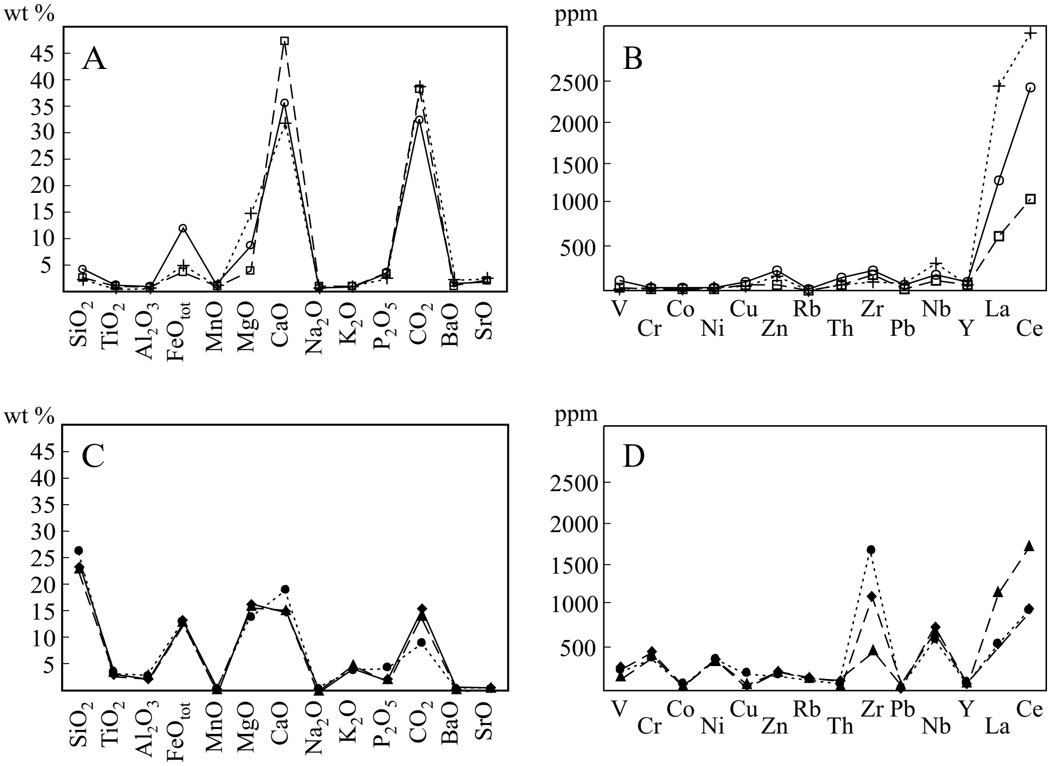

Fig. 6 – Average composition of carbonatites (A and B) and mica-rich rocks (C and D) from Araxá. Symbols: empty square, CaC; cross, MgC; empty circle, FeC; full diamond, G; full circle, MOP; full triangle, MC.

As previously mentioned, the mica-rich rocks, here included the hybrid lithotypes, are uniform in composition, independently of mica being either a primary or a secondary phase (Fig. 6). The most significant differences deal with the proportion of carbonate minerals, these mainly represented by dolomite, as indicated by the negative correlation CO_2-CaO. In MOP rocks, CaO is mostly associated to clinopyroxenes. CO_2 content varies within the three rock-types, the average values being 9%, 14% and 15.5% for MOP, MC and G, respectively.

Nb is strongly enriched in all three groups, with mean values (718 ppm, G; 668 ppm, MC; 571 ppm, MOP) considerably higher in relation to those of the carbonatites (MgC presents the highest average concentration, 334 ppm).

La/Ce ratios are almost constant for carbonatites, mica-rich rocks and hybrid lithotypes. G and MOP samples are particularly enriched in Zr and glimmeritic rocks contain high Nb contents.

Chondrite - normalized (cf. Boynton 1984) REE patterns for Araxá rocks are illustrated in Fig. 9. All the rock-types are strongly enriched in REE, the highest values found in some MgC samples. Steep LREE/HREE fractionation characterizes the three groups, as clearly pointed by the $(La/Lu)_n$ ratios listed in Tables V and VI, reaching up to 79704 in a MgC sample (BB4, an. 13, Table V).

The convex behaviour of the CaC sample BB3 (Fig. 9) with MREE values higher than those obtained for LREE, and also showing Y content of 853 ppm (average value for CaC=68 ppm), may be related to the presence of supergenic monazite.

MC and FeC rocks behave similarly to some samples presenting less enrichment in MREE and HREE; the reason is probably associated to

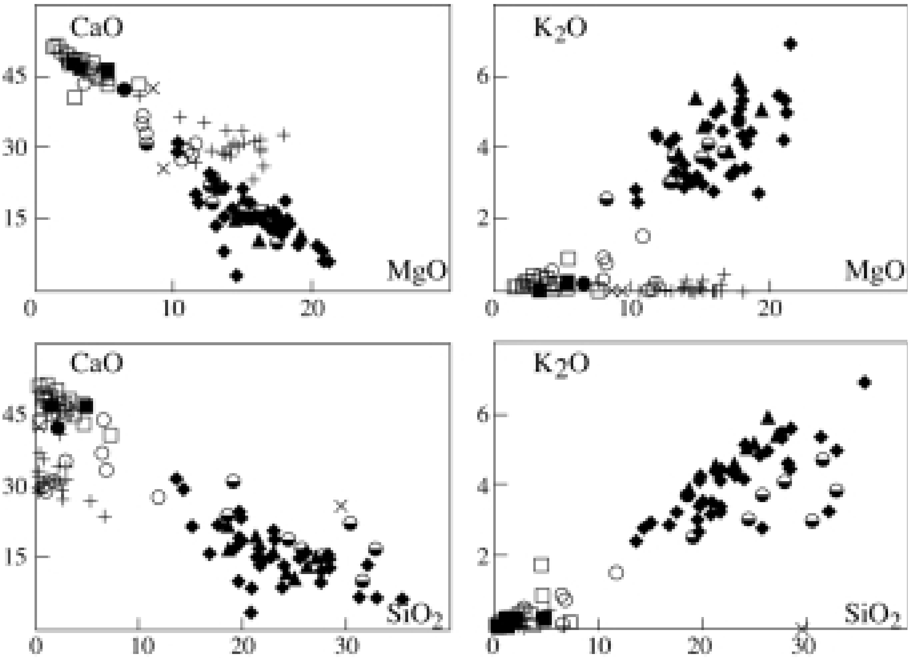

Fig. 7 – CaO and K_2O vs. MgO and CaO and K_2O vs. SiO_2 diagrams (wt%) for carbonatites and mica-rich rocks from Araxá. Symbols as in Fig. 5.

pyrochlore, which, according to Hornig-Kjarsgaard (1998), can be impoverished in HREE.

REE distribution in MOP rocks is very uniform and characterized by slight LREE/HREE fractionation, the maximum $(La/Lu)_n$ value being 389.7 (an. 20, Table VI). The regular behaviour of REE is indicative that garnet (melanitic or kimzeyitic in composition) has not played an important role in the fractionation process.

G rocks exhibit an irregular pattern with variable enrichment degree for LREE (La and Ce values ranging from 100 up to 3000 times chondrite) and also variable LREE/HREE fractionation.

CONCLUDING REMARKS

The investigated rocks cover a small area of the central-western portion of the Araxá complex. In addition to a few surface samples, they consist mainly of borehole material taken from 28 wells normally not deeper than 100 m. In spite of sampling limitation, the rocks are considered to be representative of the whole complex as they correspond to the principal lithologies present.

Two main lithotypes are recognized: carbonatites – ranging in composition from calcio-, magnesio- to ferro-types – and mica-rich rocks. Subordinately, a third petrographic variety of hybrid composition (silicate and carbonate material) is also found.

Magnesiocarbonatites (MgC) and calciocarbonatites (CaC) are widespread and represented by coarse- and fine-grained varieties, the latter forming dykes and small veins. Petrographically, they can be referred to as sovite-alvikite and beforsite-rauhaugite, respectively. In minor amounts, ferrocarbonatites (FeC) are also present, the iron enrichment as a result of the presence of Fe-carbonates and opaques as cumulus phases.

Carbonate minerals correspond to at least 80% of the whole composition of the rocks. In CaC rocks, calcite having low MgO and high SrO is the dominant carbonate phase, whereas dolomite makes up the main constituent in MgC and FeC types.

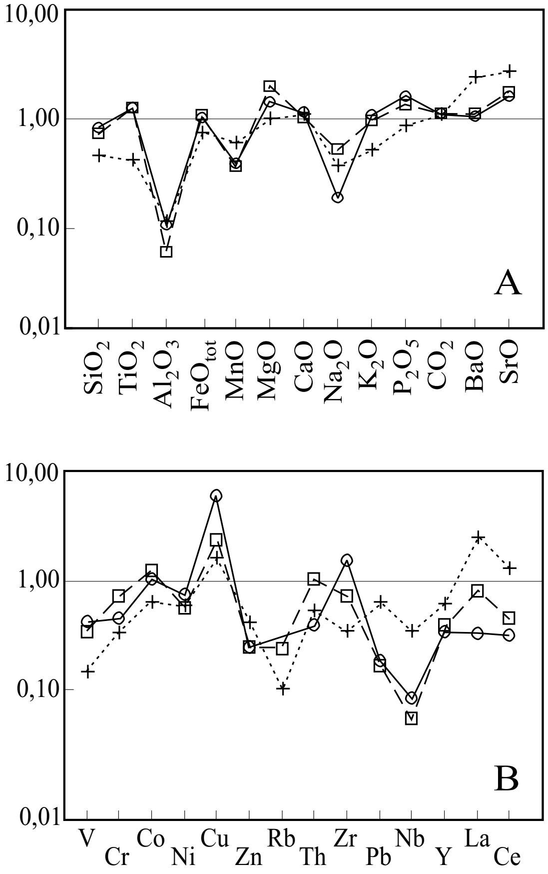

Fig. 8 – Average major (A) and trace element (B) compositions of calciocarbonatites, magnesiocarbonatites and ferrocarbonatites from Araxá normalized to the respective average values according to Woolley and Kempe (1989). Symbols as in Fig. 6.

Other carbonate phases are ankerite, siderite, strontianite and magnesite, the last two minerals only found in the MgC group. REE carbonates (Ce-group Rare Earth minerals: huanghoite; baritocalcite and norsethite) as primary or secondary phases are also present. Silicate minerals, well represented in MOP rocks showing no evidences of metasomatism, are magnesian olivine, diopside, phlogopite and tetraferriphlogopite. The accessory assemblage includes a variable number of minerals, the most diffuse ones being phosphates (apatite and monazite) and oxides (pyrochlore, rutile and magnetite). Magnesioarfvedsonite and antophyllite are secondary phases formed after the transformation of clinopyroxene and olivine crystals, respectively. Other common phases are celadonite, as alteration product of mafic minerals, quartz and baryte.

The carbonatitic rocks strongly enriched in apatite, phlogopite, magnetite and olivine pseudomorphs may be grouped into the phoscorites of Issa Filho et al. (1984).

The mica-rich rocks are represented by scarce, not completely transformed cumulitic pyroxenites (MOP) having phlogopite, olivine and diopside as principal cumulus phases. The most abundant lithotype of the group consists of glimmeritic rocks (G) where secondary micaceous aggregates were formed as a result of the pyroxenite modification. The original cumulitic nature of the pyroxenitic rocks is still preserved in some samples. The hybrid rocks (MC), occurring subordinately to the previous ones, are mainly composed of phlogopite cumulus having apatite, perovskite and magnetite grains as inclusions and of tetraferriphlogopite as intercumulus phase. Carbonate minerals (calcite and dolomite) are also found in association with the mica. These hybrid rocks are clearly intercepted by abundant minute veins of carbonatitic composition.

Average compositions for carbonatitic (63 analyses) and mica-rich rocks, here included the hybrid lithotypes (51 analyses), are shown in Fig. 10. Excluding phoscoritic and quartz - baryte - enriched rocks, the distribution of trace elements indicates that the carbonatites contain smaller amounts of V, Cr, Ni, Rb, Zr and Nb relative to the mica-rich rocks, but are highly enriched in La and Ce. No significant variations are presented by Co, Cu, Th, Pb and Y. Enrichment factors for the elements listed above are variable, the maximum values (16-18) dealing with Cr, Ni and Rb.

The global chemistry of both lithologic groups is indicative of interaction between two magma types, alkaline silicatic and carbonatitic, as suggested by the presence of cumulitic (pyroxenitic and biotitic in composition) rocks. Particularly the higher K, Zr and Nb contents of the mica-rich rocks, as compared to the carbonatites, could be related

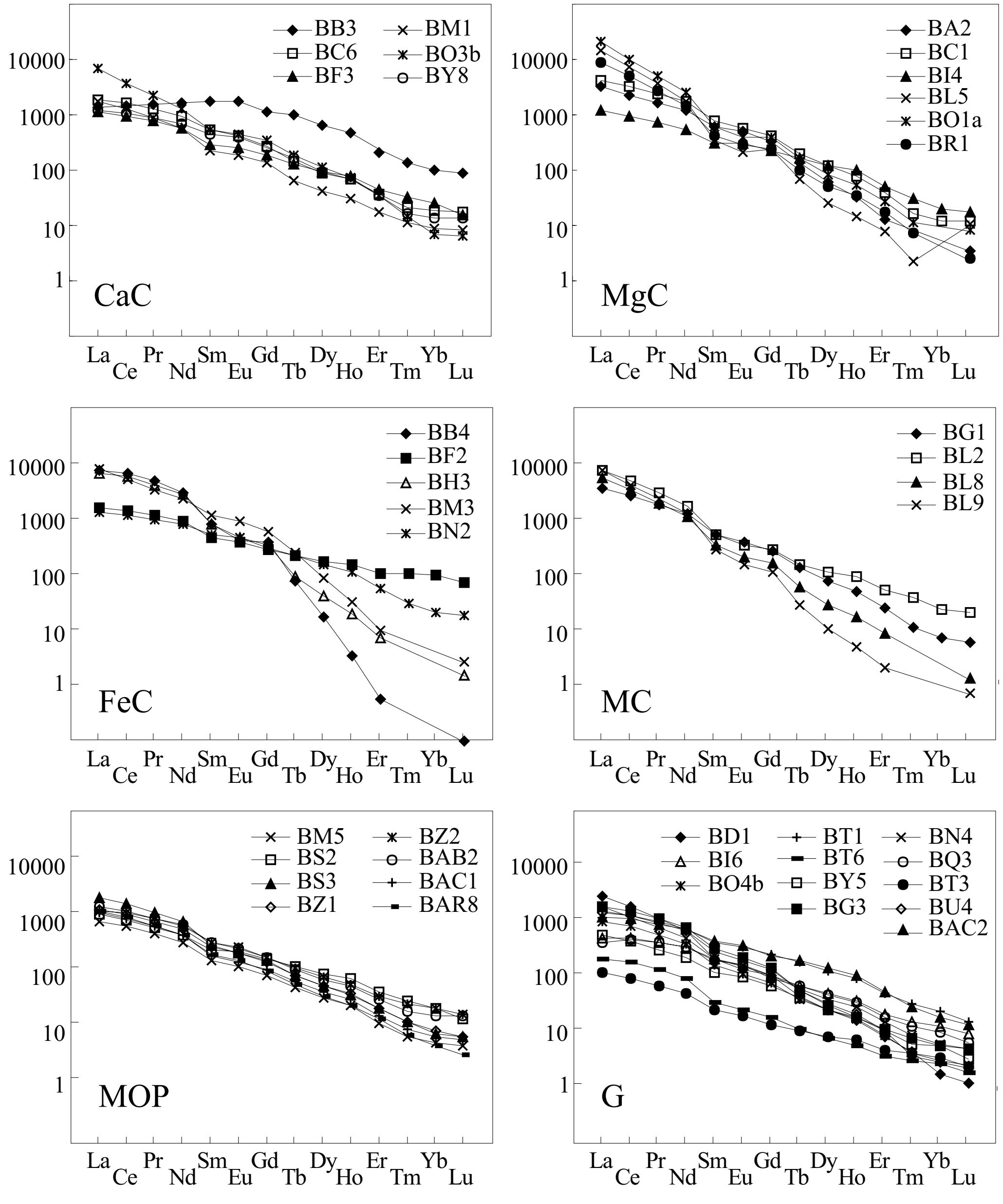

Fig. 9 – Chondrite normalized (Boynton 1984) REE patterns for carbonatites and mica-rich rocks from Araxá.

to metasomatic (glimmeritization) processes of the pyroxenites by fluids derived from the carbonatitic magma. Additionally, these fluids are also responsible for the fenitization of the country-rocks. Fig. 6 makes evident the Zr enrichment of MC and G rocks, these more affected by the potassic metasomatism, in comparison to the MOP ones. The relationship involving high Nb (Ta) and Zr concentrations and fenitization processes was also observed in xenoliths of fenitized granites occurring as inclusions in the Barra do Itapirapuã carbonatites (Ruberti 1998).

Chemical evidence (no significative relation

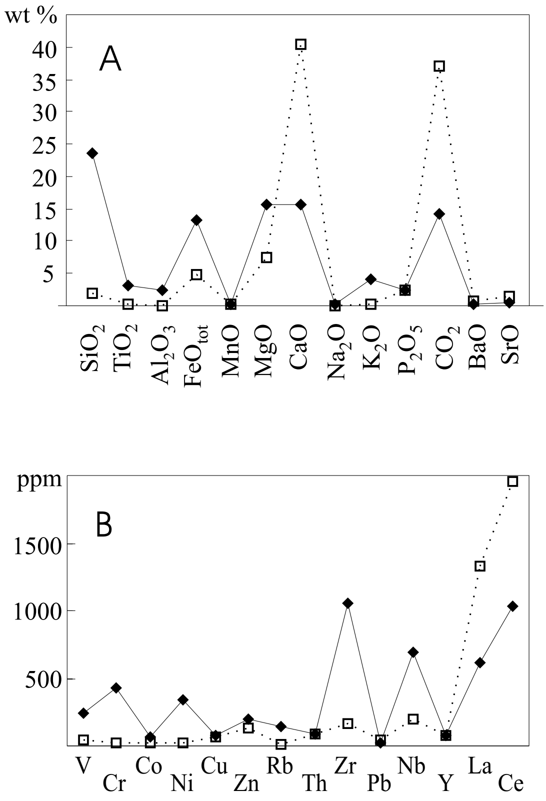

Fig. 10 – Average major (A) and trace element (B) compositions of carbonatites (CaC+MgC+FeC, square) and mica-rich rocks (G+MOP+MC, diamond) from Araxá.

between P_2O_5 and ΣREE contents in Tables V and VI and absence of negative Eu anomaly in Fig. 9, this a common feature of apatites of other alkaline complexes, cf. Eby 1975, Hogarth 1989) may indicate that in Araxá rocks the REE concentrations are mainly associated to carbonate minerals instead of apatites. Carbonates can usually contain anomalous concentrations of REE (cf. Mariano 1989). Yet, in Araxá, they represent an important mineral phase and can be present in large amounts.

The similar REE patterns (Fig. 9) displayed by some carbonatites and mica-rich rocks samples are indicative of their formation from the same parental magma, which is thought to be derived by low partial melting of a metasomatized lithospheric mantle, mainly characterized by the presence of LREE-enriched phases (sphene?). As suggested by Le Bas and Handley (1979) on the basis of chemical analyses of apatites from western Kenya rocks, the same REE behaviour could also explain the carbonatites as formed by fractional crystallization of an ijolite magma and an evolution as a pair of immiscible, coniugate liquids (Le Bas 1989).

The high ΣREE concentrations and the pronounced difference in LREE/HREE fractionation of some carbonatite samples could be related to direct or indirect enrichment processes regarding volatile transfer. It is well known from literature the different degree of mobility for the two REE groups, when associated to H_2O and P-enriched fluids at mantle or crustal pressure, respectively. Also, it should be noted (cf. Hogarth 1989) that some minerals such as pyrochlore can be enriched in La, Ta, Th, Zr and U and impoverished in HREE, Ca, F and Na during weathering processes. Horning-Kjarsgaard (1998), studying the relationship between concentrations and REE patterns for bulk rock and minerals, emphasize the paralelism present in apatite, carbonate, unaltered pyrochore and bulk rock patterns. The authors also interpret some deviations as due to the presence of pyrochlore, a phase carrying a high REE content and exhibiting anomalous REE distribution.

It is also important to keep in mind the effects of solubilization and reprecipitation processes on the Araxá apatites. Analytical data point to presence of secondary apatite bearing low Sr and REE. The REE contents of the Araxá rocks are probably affected by hydrotermal and supergenic processes, as evidenced by the lack of correlation between rock compositions and ΣREE values. An increase in (La+Ce) concentration through the evolutionary series calciocarbonatite - magnesio - carbonatite - ferrocarbonatite is postulated by Woolley and Kempe (1989) for carbonatite occurrences. However, as seen in Fig. 11, no relationship is shown by the investigated rocks. Pyroxenitic (MOP) and their metasomatic derived rocks (G) are clearly less enriched in REE.

It is suggested that vapor phase has influenced the texture formation of the different types of car-

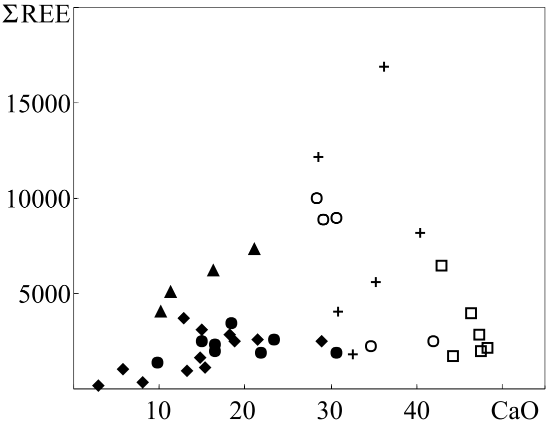

Fig. 11 – Composition of carbonatites and mica-rich rocks from Araxá plotted on the diagram ΣREE vs. CaO. Symbols as in Fig. 6.

bonatites and is also responsible for the dominantly dolomitic mineralogy of these rocks, usually containing low FeO contents. The high fO_2 is believed to favour the crystallization of oxides, such as magnetite, instead of iron-enriched carbonates (e.g. Fe-dolomite, ankerite). Thus, the fact that magnetite is widespread in all the rock-types and specially abundant in phoscorites, as well as the scarcity of ankerite, can be explained by the high fO_2 conditions which have contributed to keep the system always impoverished in iron owing to the oxides precipitation.

The Araxá silicate rocks are basically represented by piroxenites exhibiting evidence of being metasomatized by potassic fluids of carbonatitic origin. Rocks corresponding to silicatic primitive liquids were not found. On the basis of cumulitic rocks an ijolitic composition could be admitted as parental magma.

As seen from the different boreholes, horizontal and vertical distribution of rock-types indicates that the glimmeritization processes have acted irregularly and variably in intensity. Data are suggesting the presence of horizons of cumulitic rocks mainly pyroxenitic in composition penetrated by small carbonatitic veins of different nature.

Petrological considerations on the Araxá carbonatites are constrained by the presently available data (the isotopic work is still in progress). For the Juquiá complex, Brazil, for instance, a carbonatitic origin related to liquid immiscibility from a parental basanitic magma is postulated by Beccaluva et al. (1992). However, it is possible to assume for many Brazilian alkaline-carbonatite complexes a derivation from different parental magmas subjected to variable melting degrees of heterogeneous mantle sources, as indicated by the distinct contents and patterns of REE of carbonatitic and associated silicatic rocks (Morbidelli et al. 1986, 1999, Barbieri et al. 1987, Gomes et al. 1987, 1990, Brotzu et al. 1989, 1994, Macciotta et al. 1990, Beccaluva et al. 1992, Traversa et al. 1996, Horning-Kjarsgaard 1998).

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RESUMO

O complexo de Araxá (16 km^2) é constituído por carbonatitos na forma de um núcleo central e de complexa rede de diques concêntricos e radiais, além de pequenos veios; adicionalmente, ele contém rochas ricas em mica, foscoritos e lamprófiros. Fenitos também ocorrem e estão representados principalmente por quartzitos e xistos proterozóicos do Grupo Araxá.

O estudo petrográfico de 130 amostras de testemunhos de sondagem indica que o complexo reúne basicamente dois tipos litológicos, carbonatitos e rochas ricas em mica, e, subordinadamente, um terceiro de composição híbrida.

Carbonatitos apresentam composição química variável e têm magnésiocarbonatitos como o tipo mais abundante. Dolomita e calcita são os seus principais constituintes, mas outras fases carbonáticas, incluindo as pertencentes ao grupo dos carbonatos ricos em ETR, são também reconhecidas. Fosfatos e óxidos diversos caracterizam os acessórios mais comuns enquanto que os minerais silicáticos consistem de representantes dos grupos da olivina, clinopiroxênio, mica e anfibólio.

As rochas ricas em mica reúnem abundantes glimmeritos e escassos piroxenitos cumuláticos portadores de quantidades variáveis de flogopita, olivina e diopsídio. As rochas híbridas contêm principalmente flogopita e tetraferriflogopita, respectivamente, como fases cumulus e intercumulus; minerais carbonáticos podem também estar presentes.

Dados químicos indicam que os carbonatitos são fortemente enriquecidos em ETR e possuem teores mais baixos em Nb, Zr, V, Cr, Ni e Rb em relação às rochas mais ricas em mica. As concentrações mais altas em K, Nb e Zr dessas últimas poderiam ser atribuídas a processos metassomáticos (glimeritização) que teriam afetado os piroxenitos.

O comportamento similar dos ETR nos carbonatitos e nas rochas ricas em mica parece sugestivo de que essas litologias estão relacionadas a um mesmo magma parental, possivelmente de composição ijolítica. O pronunciado fracionamento ETRL/ETRP e os elevados teores em ETR de algumas amostras de carbonatitos poderiam estar ligados a processos de natureza hidrotermal ou mesmo supergênicos.

Palavras-chave: rochas alcalinas, carbonatitos, geoquímica.

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