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Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil

Brazilian Carbonatites: Studies of the Fazenda Varela (SC) and Catalão I (GO) Carbonatites and their Alteration Products

MILTON LUIZ LAQUINTINIE FORMOSO; EGYDIO MENEGOTTO & VITOR PAULO PEREIRA

Centro de Estudos em Petrologia e Geoquímica, Instituto de Geociências, Universidade Federal do Rio Grande do Sul,
Caixa Postal 15.001, CEP 91.500-000, Porto Alegre, RS, Brasil.

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Abstract - This paper presents some Brazilian carbonatites case studies: the Fazenda Varela (SC) and the Catalão I (Go) carbonatites. The mineralogical composition of the Fazenda Varela carbonatite is ankerite, Fe-dolomite, dolomite, synchysite and barite. Apatite and monazite are very rare accessories. The rock presents high amounts of REE, Ba, Ca, Sr, CO₂ and SO₃, significant Th and U, and small amounts of P, Nb and Ta. The weathering dissolves the carbonates, forms goethite and maintains barite in a saprolite facies. The laterite facies is probably related to the tertiary climate. The weathering promote Fe enrichment, followed by Mn, Th and U in the oxide phase. Ba, REE and P are fixed in the younger weathering (saprolite phase) and lost in the older weathering (laterite phase). In Catalão I Massif five hidrothermal events and the following magmatic events were identified: (1) Phoscorite and pyroxenite; (2) Banded carbonatite with alternated calcite and dolomite layers with apatite, magnetite and pyrite; (3) Magnesium carbonatite with pyrite, rare niobozirconolite and strontianite. Catalão I carbonatites are poor in Al, Mn, Na and K. Cr, Ni, Co, Cu, Li and Zr-rich samples do occur anomalously. Nb content in carbonatitic veins is very low and suggests that these rocks are not the source for the economic concentration of this element. In both calcite and dolomite, Ba content is smaller than Sr content. Sr, Fe and Mn are mostly associated with dolomite carbonatites. The banded carbonatite is relatively REE-poor, but the magnesium carbonatite bands are REE richer than the associated calcium carbonatite bands, which are extremely poor in all REE. The REE signatures of the distinct carbonatites didn't show anomalies.

Key words - carbonatite, carbonate, rare earths

INTRODUCTION

Carbonatite studies are important to further comprehension about alkaline rocks origin and associated processes, as metasomatism and fenitization, as well as to clarify problems related to the origin and distribution of some associated characteristic minerals. According to Sokolov (1994), Brogger's original definition and the International Terminological Commission recommendation, carbonatites are eruptive magmatic rocks essentially composed of carbonates. On the other hand, Heinrich (1966), Tuttle & Gittins (1966) and Wooley & Kempe (1989) define carbonatites as igneous rocks with more than 50% of carbonate content.

Carbonatites are usually rocks associated with economically important mineral deposits. Up to now, the Fazenda Varela Carbonatite (Santa Catarina, Brazil), in spite of its high rare earth elements content, has not presented economic potentiality due to its small area of occurrence and distribution as small dikes. Economic potentiality

studies in Catalão I (Goiás, Brazil) were developed in the 1970's and the following reserves were defined: apatitic phosphate (120 million tons, with more than 10% P₂O₅ content), niobium (35 million tons with 1,2% Nb₂O₅ content), titanium (200 million tons with more than 10% TiO₂ content), rare earth elements (79 million tons with more than 20% CeO₂ + La₂O₃ content) and vermiculite (6 million tons with 14% of vermiculite).

Sokolov (1983) points out some important aspects to be taken into account in the study of alkaline rocks and carbonatites: the source of the material; the processes involved in the carbonatite genesis as well as the evolution of the factors that command these processes; the physical chemistry of their formation; and the intrusion mechanisms.

The relationship between phoscorite (rock with calcite, magnetite, forsterite and apatite) and carbonatites is not well known yet, although some pieces of evidence point out to a cogenetic origin (Sokolov, 1983; Erikson, 1989). According to Sokolov (1983), geological evidence indicates that phoscorites are formed earlier than carbonatites, the

element distribution between cogenetic phases being influenced by a large temperature and pressure interval. However, Sokolov's own data on the partition coefficients of distinct minerals and carbonatites indicate similar values for these variables during rock formation. Anyway, the origin of carbonatitic magmas (lithosphere versus asthenosphere) as well as the genesis of these magmas (fractionation x immiscibility x metasomatized mantle fusion) are still controversial matters.

In terms of carbonatite weathering, Kasputin (1981) worked out a synthesis in which the author highlighted the highly soluble nature of these rocks by weathering processes and pointed out that the climatic conditions in Africa and Brazil have caused the development of lateritic crusts on carbonatites. Elianov *et al.* (1981) described the alteration mantle of URSS carbonatites. Slukin *et al.* (1989) presented a comparative study between the laterization of carbonatites in Siberia and Africa. Lottermoser (1988, 1990) discussed the rare earth elements mineralization of carbonatite in western Australia's Mt. Weld. Alcover Neto & Toledo (1993) studied the supergenic evolution of Juquiá Carbonatite (SP) which has resulted in the formation of an apatitic phosphate residual deposit presenting a P_2O_5 mean content of 16%. Pereira (1995), studying the alteration of Catalão I Carbonatite (GO), described in detail its mineralogical transformation and the genesis of the associated niobium deposit. Alcover Neto (1996) discussed geochemical aspects of both rocks and alteration products in Alkaline-Carbonatitic Cheriguelo Complex (eastern Paraguay) in his Doctorate Thesis at São Paulo University. Menegotto & Formoso (1996, 1997) presented the first results related to the alteration of Fazenda Varela Carbonatite.

This paper summarizes the results of recent research on carbonatites developed in the Earth Sciences Graduate Course at Rio Grande do Sul Federal University (UFRGS). These results are supported by Menegotto & Formoso (1996, 1997) and Pereira (1995) research works developed on Fazenda Varela (Santa Catarina) and Catalão I (Goiás) carbonatites (Fig. 1).

THE FAZENDA VARELA CARBONATITE

Geological setting

Fazenda Varela Carbonatite (Scheibe, 1978), located in Correia Pinto County, north of Lages,

Santa Catarina, is associated with alkaline rocks. It comprises an area of approximately 1550 x 900 meters that has a central point located at 27°39' S and 50°17' W. Previous studies in this area have been undertaken by Scheibe (1974, 1976, 1979, 1986), Scheibe & Formoso (1978, 1982) and Menegotto & Formoso (1996, 1997).

The carbonatitic rocks occur in the inner part of the Lages Dome where alkaline rocks, mostly phonolites, analcite trackytes, nepheline syenite, olivine melilitites and nephelinites, crop out as well as carbonatites, volcanic breccia and kimberlites (Scheibe, 1979). Their occurrence is restricted to two hills, named West Hill and North Hill. In these places, the carbonatitic rocks do not occur as an isolated body, but as a complex, anastomosed system of dikes within lithologies which, as a whole, are mostly composed of breccia. The scarcity of natural outcrops, as well as the veined pattern and the transitional nature of the boundaries between veins and country rocks do not allow the definition of the contacts.

In both hills, where carbonatites occur, there is a substantial number of trenches reclaimed by vegetation and filled up by debris, mostly at the top and slopes of North Hill. Several of these trenches, opened more than 3 decades ago, were cleared during the field works for the description of lithologies and alteration profiles as well as for sampling.

Even after the clearing of the trenches and their detailed examination, non-altered carbonatitic rocks were found only in two places: at a quarry in West Hill, which has been blasted by dynamite, and in a trench at the top of North Hill. In all other places, carbonatite is completely weathered into alterite and/or laterite.

The quarry in West Hill constitutes the main carbonatite occurrence. At this location a brown, fine-grained and highly porous carbonatite variety crops out. Scheibe (1979) described in the same area a body of approximately 20 meters of a white and relatively homogeneous carbonatite. According to Scheibe (1979) some drilling executed in the area has attested that this body is continuous at least 100 meters in depth. Nowadays, in this dynamited portion, few meters wide, almost pure but light brown carbonatite blocks occur. It seems that this light brown color represents the iron oxidation of an originally white carbonatite.

The major part of West Hill outcrops is characterized by a large number of veins that

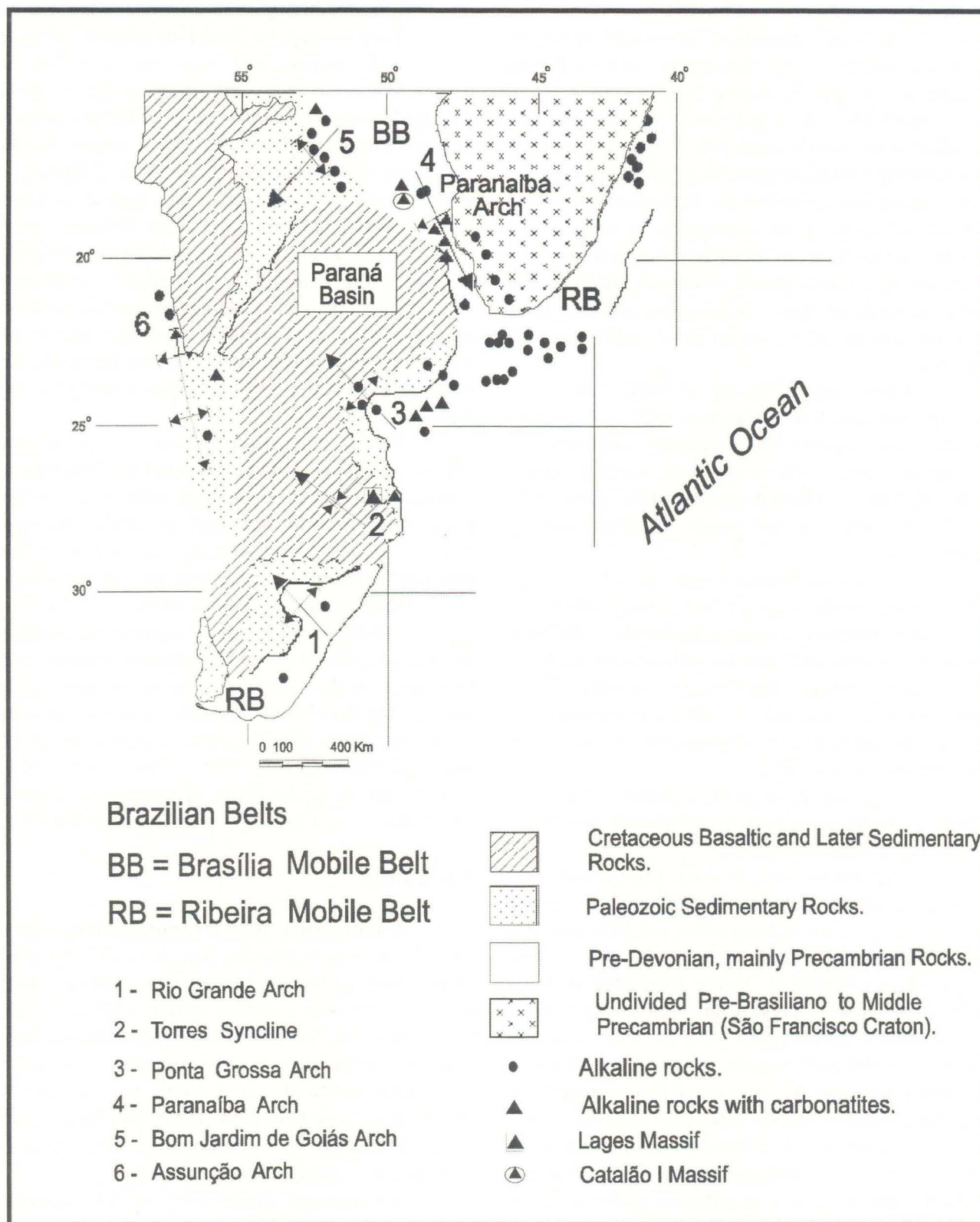


Figura 1 - Locality map of alkaline occurrences in the south of the Southern American Platform (After Ulbrich and Gomes, 1981; modified by Almeida, 1983).

crosscut each other within a feldspathic breccia. Vein thickness gradually changes from about half a meter to fractions of a millimeter.

The rock association, composed either by pure carbonatite or by carbonatite associated with feldspathic breccia, is intensively cross cut by small veins infilled by calcite and quartz, in a combined or isolated way, which represents a post-carbonatitic hydrothermal phenomenon. Field evidence suggests three successive episodes: the first episode consists of the intrusion of the carbonatite in sedimentary country rocks that were transformed into feldspathic breccia; the second episode comprises the formation of a network of thin calcite veins; and the third episode consists of the formation of a siliceous vein system.

Carbonatite at the top of North Hill occurs as sub vertical, few decimeters thick (20-50 cm) veins cross cutting the originally sedimentary, feldspathic breccia. It ranges from white to cream colored, fine- to medium-grained carbonatitic rocks enclosing oriented inclusions of greenish-gray materials.

The breccia composition includes a wide range of materials, among which a large amount of feldspathic material engulfing fragments of different sizes of alkaline and, mostly, sedimentary rocks of the country rocks. The breccia results of the fragmentation caused by alkaline/carbonatitic intrusions and further transformations by the action of temperature and fluids.

In the major part of the exposures, mostly in North Hill, the carbonatite is completely weathered into alterites and laterites.

The alterite has a dark brown color, is extremely porous and presents a high micro-porosity. In some places, where fresh rocks can be found, this material forms an aureole on the carbonatite surface exposed to weathering, hence indicating that the alteration is due to present-day weathering processes as these phenomena can be seen even in boulders originated around 10 years ago through dynamite blasting. In some other places, mainly in the occurrence of fresh rocks in North Hill, this lateritic alterite occurs as few decimeters thick veins in both sides of the fresh carbonatite veins. This fact indicates that there is a progressive alteration from both sides of the veins, causing their gradual reduction in thickness. This reduction can be complete and therefore would explain why it is so rare to find fresh rock veins on the surface, or even in

the trenches, where there is a total dominance of alteritic materials and breccia, as the latter are more resistant to weathering processes than carbonatites.

Laterite can be found in several areas of carbonatite occurrence and, on occasion, in peripheral areas over sedimentary rocks. In terms of laterite occurrence, two field evidences deserve further remark. In the North Hill trenches, laterite occurs as layers presenting variable thickness – seldom more than 50 cm – and spatial position. These layers can be horizontal, at different levels within the trenches, or sub vertical, probably following the completely weathered carbonatitic veins. Mid-slope in North Hill an extensive, horizontal laterite layer, of variable thickness, occurs all around the hill, approximately at the same altitude (around 950-1000 meters), creating a kind of collar around it.

Under macroscopic observation, laterite presents a spongy structure formed by filaments of a rigid, bright, metallic material (hematite) cross cut by a friable, earthy and dull material. The rigid portion presents high density and low porosity, whereas the friable ones are very porous and similar to the aforementioned lateritic alterite.

Taking into account its topographic position, laterite is supposed to indicate alteration under other than present-day climate, and is interpreted as representing the climatic event that generated bauxite on the peripheral alkaline rocks, probably during the upper Tertiary (Dani, 1998). The more friable portions represent the effect of present-day climate on laterite, which has been partially hydrated.

Mineralogy

Carbonatite petrographical description

– Carbonatites are granular, fine- to medium-grained rocks, usually with a high proportion of either empty (pores) or carbonate, seldom zeolites infilled cavities. Carbonates may be macroscopically individualized and, in some places, the presence of well-crystallized pyrite dispersed within the rock can be observed. In West Hill, carbonatite has a light brown color. Banding is a common feature and is determined by compositional variations.

Microscopic observation of thin sections attests to carbonatite's granular nature although a wide range of textural variations can be observed in a single thin section. Generally, the essential minerals are anhedral.

In the portions composed of pure carbonatite, even in the veins, it is possible to observe a clear predominance of rhombohedral carbonates (ankerite, Fe-dolomite, dolomite and rare calcite). Accessory minerals include barite, synchysite, apatite, rare monazite crystals and some opaque mineral.

Rhombohedral carbonates usually present a zonation originated by overgrowth. This zonation is reflected in the transparency of the carbonates, which are characterized by a foggy aspect in their central part and a clearer and purer nature towards their outer parts. This fact suggests a compositional variation characterized by a decrease in the iron content, whose exsolution and oxidation have determined the foggy aspect of the mineral. The exsolution produces an iron and manganese oxide banding that is well defined in the zonation as it follows the rhombohedral structure. In some crystals, the rhombohedron's central part becomes completely dark and clear and dark alternating bands occur towards the outer parts. Clean rhombohedral carbonates occur in the interstitial spaces, engulfing other minerals and infilling the empty space, hence indicating a late growing phase, even relative to the aforementioned foggy carbonate.

The presence of zoned, foggy rhombohedral carbonates, with release of Fe and Mn oxides, is more characteristic in the brown carbonatite of West Hill. In North Hill, where carbonatite is white, these features are not visible. The textural and structural characteristics show that the brown color of the West Hill carbonatite is a feature related to the white carbonatite alteration, probably an endogenous effect (hydrothermal ?).

Through X-rays diffraction, the zoned rhombohedral carbonate presents most of its peaks in the ankerite position, generally associated with distinct proportions of barite, for both white and brown carbonatites. Electron microprobe analyses have shown that only some carbonate strips yield an ankerite composition, being Fe-dolomite bands dominant. Fe-Dolomite X-rays diffraction peaks are almost coincidental with the ankerite ones. Calcite and dolomite were identified and generally associated with cavities and veins.

Barite occurs as clear and small (0,1 to 1 mm), commonly irregular to rounded crystals with irregular borders. Barite textural appearance indicates that it was crystallized later than carbonate, at least in terms of the first carbonatitic event. Barite clearly occurs in the interstitial spaces of

zoned and foggy carbonates and is enclosed by clearer carbonates, which occur in the peripheral areas and inside interstitial spaces, having been generated during a later event.

Apatite crystals, though occurring only in lesser proportion, are prismatic and smaller than 1 millimeter. Apatite can be found just inside the more primitive carbonates indicating that it was formed during the first carbonatitic magmatism event.

Synchysite, as described by Scheibe (1979), occurs as yellowish bunches, usually radiated, composed of fibrous aggregates. Their optical characteristics, though similar to all other carbonates, include a slightly lower birefringence and parallel extinction and negative elongation relative to the fibers. Synchysite occurs mainly either in the interstices left by the crystals of the first rhombohedral carbonates or close to the boundaries between carbonates and feldspar, in the peripheral areas of the veins, close to the breccia. This fact may indicate that synchysite is a hydrothermal product, as referred by Mariano (1989).

Monazite was identified in one thin section and has an anhedral morphology, very small size (from 0,1 to 0,3 mm) and is enclosed by carbonates. Similarly, only one pyrochlore crystal was found.

Pyrite occurs as millimetric cubic crystals disseminated in some samples, concentrated in some others, or even absent in others. Most of the smaller and irregular-shaped opaque minerals observed in the thin sections are iron oxides (magnetite, hematite and mainly goethite) which occasionally can form a boxwork structure that supports the rhombohedral carbonate morphology.

In thin sections made from samples taken from carbonates located at the boundary with the breccia, as in the vein carbonatites, variable proportions of quartz and feldspar were observed.

Alterite mineralogy – Alterite, which occurs directly in contact with carbonatite, either as a cortex or as a non-coherent material associated with the carbonatitic veins, was analyzed through X-ray diffraction. It has been noted that in a few millimeters all the carbonate is completely dissolved. Under present-day climatic conditions carbonatite alteration preserves barite. Through carbonate dissolution (iron dolomite and ankerite) iron is recrystallized as goethite. No other neoformed mineral was observed.

Thin-section studies, undertaken after resin impregnation, suggest a non-isovolumetric alteration, even taking high porosity into account.

Laterite mineralogy – X-ray diffraction has shown that laterite comprises a mixture of goethite and hematite, being one of them locally dominant. The more friable laterite samples represent either almost pure goethite or goethite associated with barite. This fact suggests the hypothesis of an earlier carbonatite alteration, during a laterization phase related to bauxite development in alkaline rocks.

Geochemical aspects

Fresh rock geochemical characterization – Tables 1 to 3 show the composition of fresh carbonatite samples in terms of major elements, trace elements and rare earth elements. Analyses of the major part of the elements were done by the association of X-ray fluorescence (XRF), inductively coupled plasma (ICP) and instrumental neutron activation analyses (INAA), being used LECO for the S and CO₂ determination, volumetry for FeO, gravimetry for H₂O⁺ and H₂O⁻. ICP, INAA and LECO analyses were undertaken by Activation Laboratories LTD (Canada). Volumetry, gravimetry and XRF analyses were developed in the Petrology and Geochemistry Study Center at UFRGS.

Table 1 shows that carbonatite has a high Fe content, associated with Ca, Mg and CO₂, which is coherent with the main carbonate composition (Ferdolomite an ankerite) and suggests that the difference in color observed between the white and brown carbonatites is related to the Fe oxidation state.

Barite high concentration is represented by the significant Ba and SO₃ content, stored as major elements. In the same way, the low amount of apatite is confirmed by the low P content. Sr and REE are so significant in carbonatites as to make them major elements; the former probably following Ca in the rhombohedral carbonates, whereas the latter as a component of the synchysite.

Among the analyzed trace elements (Tab. 2), Th (up to 360 ppm) and associated U (up to about 29 ppm) high contents must be highlighted, which is in agreement with the high radiometric values verified in this area (Scheibe, 1974). On the other hand, the very low Nb content, if compared with other carbonatites (Pereira, 1996), is connected to the very low proportion and random distribution of pyrochlore crystals.

REE analyses on samples from both pure carbonatites or those presenting some influence

Table 1. Chemical analyses (data in %) of major elements from samples of Fazenda Varela Carbonatite.

SAMPLE	VII.1.1.a	VII.1.2	II.2.1	II.4.2.a	I.2.3.	II.2.2	III.4.2	JM.1	JM.5
Rock type	1	1	2	2	3	3	3	3	3
SiO ₂	1.20	1.19	2.72	2.85	10.86	6.01	5.49	6.83	5.93
Al ₂ O ₃	0.07	0.08	0.24	0.41	0.31	1.11	1.23	1.50	1.90
Fe ₂ O ₃	0.60	0.65	12.60	9.20	5.08	8.06	9.92	9.70	12.08
FeO	8.15	8.70	1.02	2.18	6.29	1.94	1.35	2.28	0.58
MnO	1.85	1.89	5.67	2.07	2.68	2.74	2.44	2.78	1.93
MgO	12.38	12.34	13.16	11.27	11.73	12.48	13.48	10.39	10.53
CaO	24.40	24.05	24.24	26.86	27.99	29.55	28.25	27.22	28.75
BaO	9.86	9.71	4.38	3.86	3.25	4.85	4.85	5.85	3.60
SrO	0.28	0.25	0.16	0.22	0.15	0.18	0.22	0.24	0.18
ΣREE ₂ O ₃	1.63	1.38	0.62	1.22	0.85	1.15	1.35	1.08	1.20
Na ₂ O	-	-	-	-	-	-	-	-	-
K ₂ O	-	-	-	-	-	0.25	-	0.13	-
TiO ₂	-	-	-	-	-	-	0.13	0.02	0.08
P ₂ O ₅	0.04	0.06	0.03	0.05	0.01	0.02	0.04	0.08	0.37
CO ₂	32.80	32.10	27.30	34.4	27.22	27.66	27.32	28.33	29.25
SO ₃	5.28	5.22	2.29	2.57	1.68	2.55	2.55	3.16	2.95
H ₂ O ⁻	0.30	0.22	0.38	0.21	0.23	0.24	0.33	0.24	0.35
H ₂ O ⁺	1.10	1.72	4.48	2.32	1.20	1.02	0.98	-	-
Total	99.30	99.56	99.29	99.69	99.53	99.81	99.93	99.83	99.68

1. White carbonatite. 2. Brownish carbonatite 3. Samples of brownish carbonatite with some minor influence from country rocks (presence of some silicates). - = below detection limit

Table 2. Chemical analyses of trace elements from samples of Fazenda Varela Carbonatite (data - Au = ppb, other elements = ppm).

SAMPLE	VII.1.1.a	VII.1.2	II.2.1	II.4.2.a	I.2.3	II.2.2	III.4.2	JM.1	JM.5
Type	1	1	2	2	3	3	3	3	3
Au	35	27	13	15	14	22	30	25	33
As	13	10	2	5	6	8	11	5	8
Co	5	4	3	4	5	4	6	4	7
Cr	39	35	45	38	15	12	7	38	45
Hf	0.6	0.7	<0.5	0.5	<0.5	0.5	<0.5	0.5	<0.5
Mo	<5	<0.5	5	5	7	5	8	6	5
Sb	<0.6	<0.6	<1	<1	<1	<1	<1	<1	<1
Sc	19	46	13	15	12	10	8	15	13
Nb	66	75	115	58	90	20	250	98	125
Ta	3	2	1	2	8	5	10	2	1
Th	360	350	336	340	288	195	299	310	300
U	10.2	8.5	4.4	16.0	20.6	25.2	28.9	26.3	24.5
W	<3	<3	<3	<3	<3	<3	<3	<3	<3
Zn	540	505	430	450	350	398	400	450	430
Zr	106	110	100	98	142	125	110	98	100
Th/U	35	41	76	21	14	8	10	12	12
Nb/Ta	22	37	115	29	11	4	25	49	125

1. White carbonatite. 2. Brownish carbonatite 3. Samples of brownish carbonatite with some minor influence from country rocks.

Table 3. Chemical analyses of rare earth elements from samples of Fazenda Varela Carbonatite. Data in ppm.

SAMPLE	VII.1.1.a	VII.1.2	II.2.1	II.4.2.a	I.2.3	II.2.2	III.4.2	JM.1	JM.5
Rock type	1	1	2	2	3	3	3	3	3
La	5500	4656	1600	3148	2194	2726	3200	2560	2848
Ce	6800	5757	2700	5313	3702	5027	5900	4720	5251
Nd	1300	1101	760	1495	1042	1619	1900	1520	1691
Sm	134	113	88	173	120	207	244	195	217
Eu	30.0	25.4	21.6	42.5	29.6	50.8	59.6	47.7	53
Gd	106	89.7	63	124	86.6	124	146	117	130
Tb	8.6	7.3	7.6	15.0	10.4	11.2	13.1	10.5	11.7
Dy	22.0	18.6	26.1	51.4	35.8	29.6	34.8	27.8	31
Yb	1.3	1.1	0.5	1.0	0.7	0.9	1.1	0.9	1.0
Lu	0.32	0.30	0.13	0.31	0.22	0.25	0.28	0.24	0.27
La/Ce	0.81	0.81	0.59	0.59	0.59	0.54	0.54	0.54	0.54
LREE/HREE	99.58	99.59	53.11	53.06	53.00	58.03	57.88	57.80	57.83
La/Lu	17187	15520	12307	10154	9972	10904	11428	10666	10548
La/Yb	4230	4232	3200	3148	3134	3029	2909	2844	2848

1. White carbonatite. 2. Brownish carbonatite 3. Samples of brownish carbonatite with some minor influence from country rocks.

from the country rocks, as compared with chondrite composition, presents a strong enrichment of light (LREE) relative to heavy (HREE) elements, which is evident by the high LREE/HREE as well as La/Lu and La/Yb ratios (Tab. 3). The large enrichment on REE and on LREE relative to HREE has already been noticed by Scheibe & Formoso (1982). La is 10.000 times enriched in the carbonatite relative to chondrites. No anomalies were identified for Ce and Eu but a negative anomaly for Yb (Fig. 2) is evident. Scheibe & Formoso (1982) suggest that “The high absolute and relative content of light lanthanoids, added to other mineralogical and geochemistry characteristics of the occurrence, points out that these carbonatites represent the final stages of a fractionating process during the carbonatitic phase, and reinforces the possible existence of carbonatite generated during initial phases of differentiation in the Lages alkaline district.”

Alteration facies geochemistry – Tables 4 to 12 present the composition of weathered facies, represented by the initial alteration of carbonatite, alterite (saprolitic alteration) and laterite, in terms of major elements (Tabs. 4 to 6), trace elements (Tabs. 7 to 9) and rare earth elements (Tabs. 10 to 12).

Among the analyzed trace elements (Tab. 2), Th (up to 360 ppm) and associated U (up to

about 29 ppm) high contents must be highlighted, which is in agreement with the high radiometric values verified in this area (Scheibe, 1974). On the other hand, the very low Nb content, if compared with other carbonatites (Pereira, 1996), is connected to the very low proportion and random distribution of pyrochlore crystals.

REE analyses on samples from both pure carbonatites or those presenting some influence from the country rocks, as compared with chondrite composition, presents a strong enrichment of light (LREE) relative to heavy (HREE) elements, which is evident by the high LREE/HREE as well as La/Lu and La/Yb ratios (Tab. 3). The large enrichment on REE and on LREE relative to HREE has already been noticed by Scheibe & Formoso (1982). La is 10.000 times enriched in the carbonatite relative to chondrites. No anomalies were identified for Ce and Eu but a negative anomaly for Yb (Fig. 2) is evident. Scheibe & Formoso (1982) suggest that “The high absolute and relative content of light lanthanoids, added to other mineralogical and geochemistry characteristics of the occurrence, points out that these carbonatites represent the final stages of a fractionating process during the carbonatitic phase, and reinforces the possible existence of carbonatite

Table 4. Chemical analyses of major elements from samples of Fazenda Varela Carbonatite presenting an incipient alteration.

SAMPLE	I.3.2	II.2.5	III.4.4	III.4.5	III.5.2	III.4.6
SiO ₂	3.73	3.52	1.62	2.06	1.31	2.57
Al ₂ O ₃	0.77	0.46	0.14	0.26	0.05	0.55
Fe ₂ O ₃ *	18.83	16.33	16.52	14.15	19.52	17.30
FeO	ND	ND	ND	ND	ND	ND
MnO	3.67	2.31	2.31	1.88	1.79	2.25
MgO	5.15	2.79	1.24	2.56	1.65	4.20
CaO	26.10	30.80	29.05	25.14	28.14	24.78
BaO	7.60	6.66	8.33	10.05	8.3	6.6
SrO	0.18	0.16	0.20	0.18	0.20	0.15
Σ REE ₂ O ₃	1.87	1.20	1.74	2.49	1.51	1.71
Na ₂ O	-	-	-	-	-	-
K ₂ O	-	0.18	-	-	-	-
TiO ₂	0.01	-	-	-	0.01	-
P ₂ O ₅	0.19	0.02	0.02	0.02	0.51	0.03
CO ₂	22.44	25.55	26.56	20.33	19.96	21.33
SO ₃	3.96	3.47	4.47	4.05	4.94	3.47
H ₂ O-	0.52	0.55	0.69	0.55	0.69	0.63
H ₂ O+	4.65	5.62	6.67	16.11	11.14	14.23
Total	99.62	99.62	99.56	99.83	99.72	99.80

* Fe₂O₃ = total Fe. - = below detection limit

Table 5. Chemical analyses of major elements of alterite of Fazenda Varela Carbonatite.

SAMPLE	II.4.2.b	I.3.2.b	III.1.3	VII.1.1.b	XII.3.0	XIII.4.0
SiO ₂	4.34	6.02	10.98	5.69	3.77	10.97
Al ₂ O ₃	0.55	1.31	3.02	0.97	3.19	7.41
Fe ₂ O ₃ *	38.91	40.08	45.67	34.47	55.25	47.65
FeO	ND	ND	ND	ND	ND	ND
MnO	5.23	5.42	5.21	2.46	2.38	2.37
MgO	0.54	0.58	0.39	0.44	0.47	0.39
CaO	0.77	0.25	-	0.94	-	-
BaO	21.66	18.45	13.55	24.20	6.55	6.20
SrO	0.20	0.15	0.12	0.27	0.09	0.07
Σ REE ₂ O ₃	2.13	1.75	1.08	3.23	1.49	0.80
Na ₂ O	-	-	-	-	-	-
K ₂ O	-	-	0.71	0.51	-	0.26
TiO ₂	-	-	0.17	-	0.31	0.35
P ₂ O ₅	0.59	1.83	0.07	0.12	0.18	1.45
CO ₂	0.45	-	-	-	-	-
SO ₃	12.14	10.55	7.25	12.68	3.48	3.98
H ₂ O-	0.99	0.80	1.42	1.15	1.44	1.45
H ₂ O+	10.65	12.04	10.02	12.92	21.31	16.09
Total	99.15	99.23	99.66	99.85	99.91	99.44

* Fe₂O₃ = total Fe.

Table 6. Chemical analyses of major elements of laterite of Fazenda Varela Carbonatite.

SAMPLE	IV.1.0	X.3.0	X.4.2	XI.2.0	XII.6.0	XII.7.0	XIII.1.0	XIII.5.0
SiO ₂	2.28	4.25	3.60	2.09	4.16	5.3	3.12	4.03
Al ₂ O ₃	0.45	1.05	—	—	1.59	4.34	0.05	1.05
Fe ₂ O ₃ *	59.62	64.04	64.20	66.98	57.38	54.45	66.32	64.15
FeO	ND	ND	ND	ND	ND	ND	ND	ND
MnO	2.90	4.12	5.41	5.07	5.37	5.62	3.69	6.55
MgO	0.41	0.45	0.26	0.30	0.26	0.29	0.34	0.32
CaO	—	—	—	—	—	—	0.27	—
BaO	12.25	6.95	5.60	9.50	8.85	8.85	10.20	8.50
SrO	—	—	0.06	—	—	—	0.06	0.08
Σ REE ₂ O ₃	0.17	0.23	0.34	0.25	0.40	0.30	0.22	0.47
Na ₂ O	—	—	—	—	—	—	—	—
K ₂ O	—	—	—	—	—	—	—	—
TiO ₂	—	—	—	—	0.07	0.11	—	0.23
P ₂ O ₅	1.45	0.13	2.07	0.07	0.10	0.24	0.05	0.32
SO ₃	6.42	3.72	2.94	5.15	4.94	4.43	5.37	4.47
H ₂ O-	1.45	1.07	1.08	0.39	1.19	2.20	0.55	0.64
H ₂ O+	12.09	13.20	14.21	9.32	14.99	13.15	9.44	8.75
Total	99.49	99.21	99.77	9.12	99.30	99.28	99.68	99.56

* Fe₂O₃ = total Fe. — = below detection limit

Table 7. Chemical analyses of trace elements from samples of Fazenda Varela Carbonatite presenting an incipient alteration (Au = ppb, other elements = ppm).

SAMPLE	I.3.2	II.2.5	III.4.4	III.4.5	III.5.2	III.4.6
Au	66	44	32	130	25	48
As	8	14	16	72	24	28
Co	7	8	6	10	10	8
Cr	22	20	34	64	25	12
Hf	<0.5	<0.5	0.6	0.9	<0.5	<0.5
Mo	6	22	12	<5	8	<5
Sb	3.0	5.4	5.2	3.5	2.5	3.0
Sc	8.1	15	7.5	19	3.2	5.5
Nb	485	95	259	570	669	568
Ta	2	3	3	5	3	2
Th	280	580	350	331	450	375
U	5.8	3.4	8.5	20.0	7.5	4.6
W	<3	<3	<3	<3	<3	<0.3
Zn	450	500	520	670	430	320
Zr	268	139	85	109	107	114
Th/U	48	170	41	16	60	81
Nb/Ta	242	32	86	114	223	284

generated during initial phases of differentiation in the Lages alkaline district.”

Alteration facies geochemistry – Tables 4 to 12 present the composition of weathered facies, represented by the initial alteration of carbonatite, alterite (saprolitic alteration) and laterite, in terms of major elements (Tabs. 4 to 6), trace elements (Tabs. 7 to 9) and rare earth elements (Tabs. 10 to 12).

Table 8. Chemical analyses of trace elements of alterite of Fazenda Varela Carbonatite (Au = ppb, other elements = ppm).

SAMPLE	II.4.2.b	I.3.2.b	III.1.3	VII.1.1.b	XII.0	XIII.4.0
Au	75	84	66	130	32	86
As	26	14	12	72	24	15
Co	6	10	8	10	13	14
Cr	26	30	42	64	23	25
Hf	<0.5	<0.5	0.7	0.9	<0.5	0.5
Mo	<5	6.5	0.5	<5	<5	<5
Sb	3.0	<1.5	1.5	<1.5	3.0	<1.5
Sc	15	9.1	12	38	9.1	4.5
Nb	114	48.5	78	98	124	327
Ta	10	7	9	4	5	3
Th	650	725	585	717	680	490
U	27.8	24.4	28.6	20.0	33.4	29.8
W	<3	<3	<3	<3	<3	<3
Zn	450	540	485	1300	384	586
Zr	245	262	81	170	81	288
Th/U	23	30	20	36	20	16
Nb/Ta	11	7	9	24	25	109

Due to weathering process an accentuated Fe concentration occurs, that reaches 30 to 40% (total Fe₂O₃) for alterite and more than 60% for laterite. This Fe concentration is followed by Mn, Th and U concentration. This fact indicates that these elements are related to the Fe oxidized phases (goethite/hematite). The Th/U ratio increases very much in the samples with an incipient alteration and decreases in alterite and laterite facies. These aspects suggest that U is partially mobilized during the initial alteration, but it does not migrate much farther.

Ba, REE and P are enriched in alterite facies and strongly decrease in laterite facies. Ba and P are mostly concentrated in alterite as a consequence of barite and apatite stability relative to carbonates, but during the intense leaching that causes the laterite formation, these minerals are unstable and these elements are leached.

Despite synchysite's instability, REE tend to be adsorbed in the microcrystalline oxides of alterite facies due to the higher pH caused by the closeness to the rock alteration front. REE stay in the system and are relatively concentrated during the incipient carbonatite alteration (Tab. 10) and, mainly, in saprolite (Tab. 11). During laterite formation, as a consequence of lower pH (acid), REE tend to be highly mobilized and hence causing a significant decrease on their content (Tab. 12). Figures 2 to 5

Table 9. Chemical analyses of trace elements of laterite of Fazenda Varela Carbonatite (Data - Au = ppb, other elements = ppm).

SAMPLE	IV.1.0	X.3.0	X.4.2	XI.2.0	XII.6.0	XII.7.0	XIII.1.0	XIII.5.0
Au	26	79	24	30	34	22	19	26
As	25	27	15	25	30	27	13	25
Co	12	8	10	26	17	14	20	13
Cr	10	13	12	18	24	22	29	18
Hf	1.5	3.9	1.6	2.2	2.6	2.5	1.1	2.2
Mo	16	11	14	12	16	18	22	23
Sb	0.8	1.8	1.5	1.3	2.2	1.7	1.2	0.9
Sc	1.1	1.2	0.5	2.3	5.1	2.4	2.7	9.1
Nb	68	55.5	45.5	23.1	64.5	139	59	76
Ta	2	1	4	3	5	2	1	2
Th	980	941	868	835	797	780	638	694
U	33.3	25.1	32.5	42.2	49.3	23.4	32.5	51.2
W	8	10	7	8	9	7	5	8
Zn	1200	1600	1400	1300	1700	1500	2000	1500
Zr	169	349	141	27.1	169	163	65	250
Th/U	29	37	27	20	16	33	20	14
Nb/Ta	34	55	11	8	13	69	59	38

Table 10. Chemical analyses of rare earth elements from samples of Fazenda Varela Carbonatite presenting an incipient alteration. Data in ppm.

SAMPLE	I.3.2	II.2.5	III.4.4	III.4.5	III.5.2	III.4.6
La	3437	3100	4500	5600	3371	3825
Ce	5799	5300	7694	11000	6622	7513
Nd	1632	1400	2132	3700	2227	2527
Sm	189	171	248	493	297	336
Eu	46.4	41.8	66.7	117	70.4	79.9
Gd	136	121	176	278	167	190
Tb	16.3	13.6	19.7	24.8	14.9	19.9
Dy	56.1	43.1	62.6	68.5	41.2	46.8
Yb	1.1	1.2	1.7	3.3	2.0	2.3
Lu	0.28	0.21	0.35	0.66	0.42	0.50
La/Ce	0.59	0.58	0.58	0.51	0.51	0.51
LREE/HREE	52.9	55.9	56.2	55.7	55.8	55.0
La/Lu	12275	14762	12857	8485	8026	7650
La/Yb	3125	2583	2647	1697	1686	1663

show that the REE distribution trend in fresh carbonatite is not modified during rock alteration. However, the slope becomes gentler as a consequence of the gradational decrease of the LREE/HREE, La/Lu and La/Yb ratios, as can be seen in Tables 3, 10, 11 and 12. This fact shows that weathering modifies the partition of these elements, by leaching more LREE than HREE, in agreement with previous observations made by Formoso *et al.* (1989). In laterite facies, a Ce positive anomaly is observed (Fig. 5) and it is not present in fresh rock (Fig. 2), incipient alteration facies (Fig. 3) and even in the majority of the saprolite samples (Fig. 4). This fact can be explained by the stronger fixation power

Table 11. Chemical analyses of rare earth elements of alterite of Fazenda Varela Carbonatite. Data in ppm.

SAMPLE	II.4.2.b	I.3.2.b	III.1.3	VII.1.1.b	XII.3.0	XIII.4.0
La	5503	4520	2408	12000	1073	969
Ce	9408	7727	4730	12600	8880	4080
Nd	2485	2041	1591	2300	1761	1200
Sm	303	249	212	247	414	233
Eu	74.2	60.9	50.3	57.3	102	61.5
Gd	215	176	119	207	248	142
Tb	24.1	19.8	10.7	16.7	27	15.6
Dy	76.5	62.8	29.5	43.8	79.6	52
Yb	2.1	1.7	1.4	2.8	10.0	8.8
Lu	0.42	0.32	0.33	0.63	1.4	1.2
La/Ce	0.58	0.58	0.51	0.95	0.12	0.23
LREE/HREE	55.9	56.0	55.9	100.4	33.4	29.8
La/Lu	13102	14125	7297	19048	766	808
La/Yb	2620	2659	1720	4286	107	110

of this element due to its oxidation from Ce^{3+} to Ce^{4+} .

Mineral chemistry of alteration products of Fazenda Varela Carbonatite

Fe oxides and hydroxides (hematite and goethite), the main weathering products of Fazenda Varela Carbonatite, were analyzed in an electron microprobe (Tabs. 13 and 14). For goethite (Tab. 13), the electron microprobe analyses were done not taking the H_2O content into account, which was separately determined by heating. The results attest to a REE decrease but do not confirm the high Th and U content verified in the whole rock analyses undertaken in both goethite and hematite. This fact would indicate that U and Th would be associated with poorly crystalline phases. Goethite and hematite present low Al_2O_3 content which is, anyway, significant if the initial low content in the rock is taken into account. Due to the absence of clay minerals, the small present amount of Al follows Fe and is fixed in its minerals. In the same way, Mn also follows Fe and is thus part of goethite and hematite.

THE CATALÃO I ALKALINE-CARBONATITIC MASSIF

Geological setting

The Catalão I Alkaline-Carbonatitic Massif is situated at 18°08' S and 47°48' W, in southeastern Goiás State, and belongs to Alto Parnaíba Alkaline

Table 12. Chemical analyses of rare earth elements of laterite of Fazenda Varela Carbonatite. Data in ppm.

SAMPLE	IV.1.0	X.3.0	X.4.2	XI.2.0	XII.6.0	XII.7.0	XIII.1.0	XIII.5.0
La	103	140	207	181	290	218	230	570
Ce	887	1200	1774	1500	2400	1800	1000	2400
Nd	296	400	591	298	476	357	449	706
Sm	93.1	126	186	70.0	112	84.0	106	137
Eu	22.5	30.4	44.9	17.2	27.5	20.6	24.8	36.2
Gd	41.4	—	82.8	41.9	67	50.3	51	84
Tb	3.6	5.2	7.7	4.6	7.3	5.5	5.1	9.2
Dy	11.3	15.3	22.6	13.4	21.5	16.1	14.4	30.6
Yb	3.0	4.0	5.9	1.7	2.7	2.0	1.7	5.2
Lu	0.45	0.52	0.82	0.22	0.37	0.33	0.22	0.7
La/Ce	0.12	0.12	0.12	0.12	0.12	0.12	0.23	0.24
LREE/HREE	23.5	23.4	23.4	33.4	33.4	33.4	25.0	29.7
La/Lu	228.9	269.2	252.4	822.7	783.8	660.6	1045.5	814.3
La/Yb	34.3	35.0	35.1	106.5	107.4	109.0	135.3	109.6

Province. This province has twelve massifs associated with more than 250 kimberlitic pipes lined up along a N 50° W magnetometric anomaly that is longer than 200 Km (Almeida, 1993). These alkaline rocks are situated among Amazon, São Francisco and Rio de La Plata cratons, in the northwestern part of the Paraná Basin (Fig. 1).

Catalão I Massif intrudes micaschists with amphibolitic and quartzitic lenses of Precambrian rocks that belong to Araxá Group. Radiometric

studies of these alkaline rocks have yielded ages around 80 My according to Amaral *et al.* (1967) and Sonoki & Garda (1988).

Field observation and interpretation of laboratory analyses agreed with Baecker (1983) descriptions, and have rendered possible the identification of three magmatic events: (1) Phoscorite and pyroxenite; (2) Sövitic carbonatite; (3) Magnesium carbonatite. Between the Sövitic (second magmatic event) and Magnesium (third magmatic event) carbonatites three hydrothermal events have occurred and are characterized, respectively, by apatite veins, quartz veins and barite veins. After the magnesium carbonatite intrusion (latest magmatic event) another hydrothermal event has occurred and is characterized by quartz veins. Weathering represents the latest event.

1. Phoscorite and pyroxenite, formed in the first magmatic event, are composed of apatite, magnetite, olivine (crisolite) and rarely of perovskite, which is identified also in the strongly altered pyroxenite. These rocks were strongly affected by a hydrothermal process, which is responsible for the transformation of olivine and pyroxene into ferriphlogopites (Fe^{3+}). The hydrothermal fluid was K-rich (potassic metassomatism) and oxidant. Pyrochlore and magnetite were formed during this event.

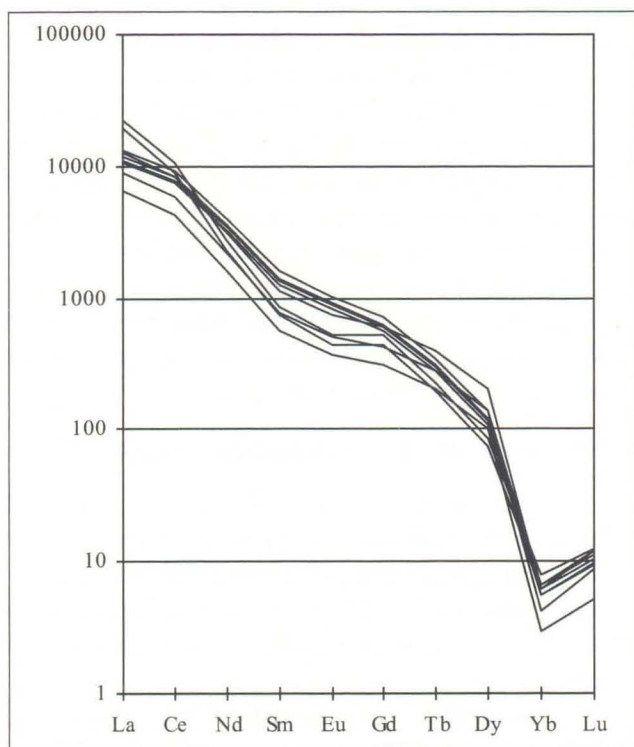


Figure 2. REE distribution in samples of Fazenda Varela Carbonatite (Table 3). Normalized to chondrite.

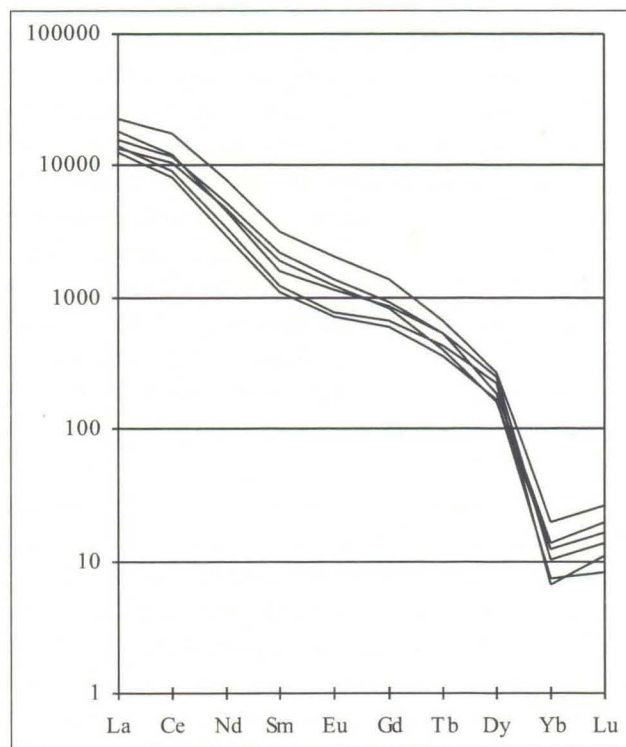


Figure 3. REE distribution in samples of Fazenda Varela Carbonatite presenting an incipient alteration. Normalized to chondrite.

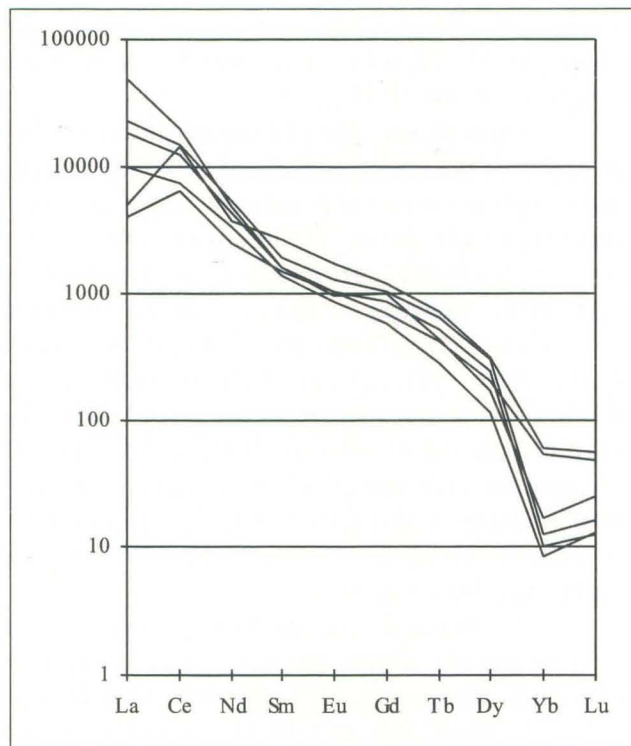


Figure 4. REE distribution in samples from alterite of Fazenda Varela Carbonatite. Normalized to chondrite.

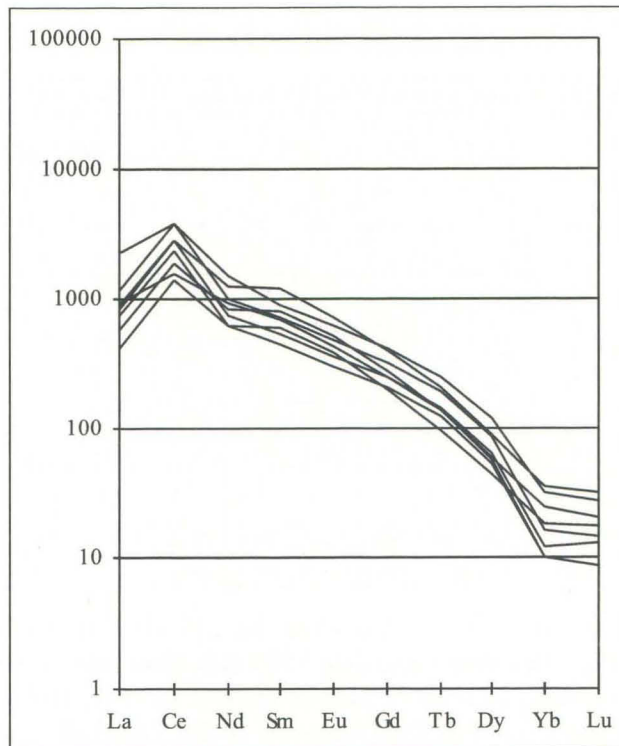


Figure 5. REE distribution in samples from laterite of Fazenda Varela Carbonatite. Normalized to chondrite.

2. The second magmatic event comprises centimetric carbonatite veins that crosscut the previous rocks. They are composed of apatite, magnetite and pyrite in alternated calcite and dolomite layers that are here understood as associated to the variations in the calcium and magnesium activities during the crystallization. A hydrothermal event, younger than the magmatic event, originated veins of apatite and hence phosphate mineralization of Catalão I Massif. The thickness of these veins are variable and they contain magnetite and quartz. Pyrochlore and titanite are rarely observed. Pyrochlore textures and composition suggest that this mineral was formed only during the second event. Later Hydrothermal events formed 10 cm thick quartz veins, containing apatite and barite as accessory minerals, and 30 cm thick barite veins.

3. The third magmatic event is represented by a widespread network of berforsitic carbonatite veins of variable thickness, usually thinner than 1 meter. Several minerals were transformed during this last event. Apatites were partially digested and olivines that survived from previous alteration processes were partially transformed into serpentines. Associated with the previous hydrothermal process, this dolomitic event is responsible for the

transformation of perovskite in anatase. A younger hydrothermal event is represented by a rock comprising more than 50% of quartz and here named "silicite". Different secondary phosphates from the plumbogummite group were observed between the quartz grains. Oxygen analyses of this quartz (dO_2), and field observations, were not enough to decide between a hydrothermal or a supergenic origin for this rock. Its association with barite, coupled with the presence of unaltered magnetite grains, are indications of a hydrothermal origin, whereas the horizontal layered position, and its association with secondary phosphates suggest weathering processes. Probably, both hydrothermal and a later supergenic processes are responsible for the formation of "silicite" minerals.

Mineralogy of the carbonatitic events

Taking into account the above mentioned carbonatite definitions, two types of carbonatites (2nd and 3rd magmatic events) are present in Alkaline-Carbonatitic Catalão I Massif. Carbonatites occur as dikes and a continuous carbonatite body was not identified there.

Banded carbonatite (2nd magmatic event) – It comprises dikes of varied thickness, often more than 10 cm thick. These dikes are

Table 13. Chemical composition of goethite crystals through electron microprobe analyses of alterite of Fazenda Varela Carbonatite.

Point	52	53	54	55	56
TiO ₂	0.02	0.02	0.01	0.01	0.00
Al ₂ O ₃	0.28	0.37	0.28	0.56	0.14
Cr ₂ O ₃	0.00	0.00	0.00	0.03	0.01
Fe ₂ O ₃	86.84	86.41	85.08	80.62	87.38
La ₂ O ₃	0.00	0.10	0.00	0.00	0.02
Ce ₂ O ₃	0.00	0.02	0.02	0.06	0.00
ThO ₂	0.00	0.05	0.02	0.00	0.00
MnO	0.58	0.51	0.83	0.76	0.49
H ₂ O	11.82	11.94	12.90	17.73	11.94
Total	99.54	99.43	99.14	99.78	99.98

composed by light gray bands of calcium carbonatite (@0,5 cm thick), with apatite and magnetite, and dark bands of dolomitic carbonatite (@1 cm thick), including a larger proportion of apatite and magnetite, the latter accounting for the color differences. The mineralogical transition between calcitic and dolomitic bands has a gradational rather than abrupt nature. The carbonatite-banded texture was not caused only by the magmatic flow but it is mainly due to the alternated crystallization of calcitic and dolomitic phases. Rare pyrite grains were identified in the dolomite bands. These banded carbonatite veins were the cause of the transformation of phoscorite and forsterite olivines (1st magmatic event) into phlogopites, bowlingites and serpentines. However, this alteration is restricted if compared with the alteration related to beforsitic carbonatite. Locally, the banded carbonatite veins are cut by late dolomitic veins that also cross cut one glimmeritic breccia product of the foscortite alteration by the banded carbonatite dikes.

Beforsitic carbonatite (3rd magmatic event) – This carbonatite contains varied amounts of pyrite, sometimes in excess of 30%, small amounts of baddeleyite and tabular and transparent aggregates of strontianite. During its uprising, the carbonatitic magma has engulfed significant amounts of the hosted rocks. This fact is attested by the presence of apatite, magnetite, quartz, pyrochlore and barite inclusions displaying corroded to partially destroyed borders and often forming plasmas of complex composition. Serpentine derived from olivine alteration are also identified. This magmatic event is also recorded by the presence of dolomite and pyrite along the cleavage planes of the country rock phlogopite.

Table 14. Chemical composition of hematite through electron microprobe analyses of laterite of Fazenda Varela Carbonatite.

Point	57	59	60	61
TiO ₂	0.01	0.01	0.01	0.00
Al ₂ O ₃	0.25	0.32	0.67	0.16
Cr ₂ O ₃	0.00	0.00	0.04	0.01
Fe ₂ O ₃	98.06	97.75	97.44	98.16
La ₂ O ₃	0.00	0.00	0.00	0.00
Ce ₂ O ₃	0.00	0.00	0.00	0.00
ThO ₂	0.13	0.04	0.07	0.04
MnO	1.08	0.95	0.91	0.55
Total	99.53	99.09	99.16	98.90

In some cases, carbonatite dikes present carbonate grains with distinct orientation at border and central portions. This pattern shows that the surrounding hosted rocks were much colder than the carbonatite during its uprising. Wherever reaction took place, carbonate crystals are smaller and present irregular surfaces and borders.

In several places metaphoscorites and pyroxenites (1st magmatic event) were altered by beforsite intrusion. In the titanium zone, perovskite was altered into anatase; both phoscorite olivines and pyroxenite pyroxenes were transformed either into phlogopites or plasmas (mineral or the mixing of minerals with colloidal dimensions). These plasmas are the result of either the reaction between pyrite and phlogopite or the mixture of olivine-derived phlogopites with magnetites altered by carbonatite.

Magnesium carbonatite action is intense along the entire profile although a stronger influence is perceived in the probes at depths of 200 to 300 meters.

Geochemistry

Major, minor and trace elements (X-ray fluorescence and atomic absorption spectrometry) and rare earth elements (I.C.P.) chemical analyses of carbonatite samples, added to Imbernon's (1993) analytical results also from carbonatites, are shown in tables 15 to 17.

The comparison of the results presented in Table 15 with those published by Gold (1966), who organized the results of 200 analyses on carbonatites from 55 different localities, show in a general sense, that Catalão I carbonatites are poor in terms of Al, Mn, Na and K content. Similar results can be achieved by comparing the Catalão I results with those presented by Wooley & Kempe (1989).

Carbonatite enrichment in terms of some elements may be caused by either country rock contamination or its own original composition. In some cases it is impossible to indicate the origin of these elements. Samples presenting large anomalies in terms of Cr, Ni, Co, Cu, Li and Zr enrichment (A1CP, Tab. 16) or high values of the Cu and Co content (CF and 11, Tab. 16) were identified. The existence of sulphides in carbonatite is here used to explain the presence of Cu whereas contamination from metaphoscorites could be used to explain the presence of Cr, as suggested by the presence of chromite in the breccia cross cut by this carbonatite.

Banded carbonatite (2nd magmatic event) is richer in Cr and Ni, probably because it has replaced a glimmeritic breccia (metasomatized phoscorite) bearing chromite and olivine remains. In banded carbonatite minor elements, with the exception of Ba, are concentrated in magnesium carbonatite. SiO₂, TiO₂, Fe₂O₃ and MnO enrichment in Mg-carbonatite is in agreement with Woolley & Kempe's (1989) observations, which were based on 400 chemical analyses of carbonatites from several worldwide distributed alkaline massifs. To them, up to this moment, there is no explanation for the presence of large amount of Nb (more than 1200 ppm) in Ca-carbonatites and Fe-carbonatites. Taking into account the very low Nb content of carbonatitic veins (Tab. 16) and the presence of a Nb mineralization in Alkaline-Carbonatite Catalão I Massif, it is possible to assume that carbonatite is not the cause of the economical concentration of this element.

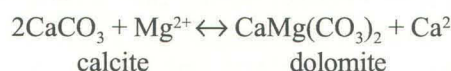
Rare earth elements (REE) distribution in the analyzed samples from Catalão I Carbonatite is shown in figure 6. It is possible to visualize that banded carbonatite is very poor in terms of REE content and that Mg-carbonatite bands are richer than Ca-carbonatite in terms of any REE. The REE distribution when normalized to chondrite do not indicate any anomaly in the distinct signatures. However, the Eu/Eu* ratios are lower than one (Tab. 17).

Ca-carbonatite (A1CB, Tab. 17) is extremely poor in any REE if compared with the Mg-carbonatite samples. Relative to any other analyzed type, Ca-carbonatite has the smallest amount of Mg, whereas phoscorite-related carbonatite (11, Tab. 17) is the richest one in terms of Mg and REE content. This REE rise is due to pyrochlore enrichment which is the also cause for the Nb increase in this sample.

Ca-carbonatite of banded carbonatite is very poor in terms of trace elements. The cause for the partition of the different elements in these phases is well described in alkaline rock literature: as the Ca-carbonatite is the first one to crystallize it becomes poorer in several elements, mostly REE which are concentrated in the final, lower temperature phases.

Larger P concentration in Mg-carbonatite of the banded sample is due to the higher amount of apatite grains. It is probable that apatite grains are also the cause for the larger concentration of REE within these bands.

The alternate nature of calcitic and dolomitic bands is an important fact as it brings out substantial information about the genesis of carbonatitic magma. According to Holland & Malinin (1979), dolomite does not crystallize simply by cooling, some other mechanism being necessary for crystallization to take place. They showed that calcite and dolomite crystallize within a wide temperature interval, and that the degree of calcium and magnesium activity is the most important factor controlling the crystallization of these minerals. To generate carbonatite with alternate calcite and dolomite bands it is necessary that Ca²⁺ and Mg²⁺ be near to the equilibrium conditions. Changes in the activity of these elements make the following chemical reaction operate from left to right and from right to left in alternate ways:



and the equilibrium equation is:

$$K_e = \frac{a_{\text{Ca}^{2+}}}{a_{\text{Mg}^{2+}}}$$

Holland & Malinin (1979) quoted that strontianite seems to precipitate at temperatures near or lower than 100°C and that it is very difficult for hydrothermal strontianite to crystallize at temperatures higher than 200°C. Therefore, the presence of this mineral in late dolomitic carbonatites is a reason for assuming that probably Catalão I Mg-carbonatites have crystallized at lower temperatures than early carbonatites.

The transformation of olivine into serpentine, caused by carbonatite intrusion in phoscorites, may be defined (after Deer *et al.*, 1966) as follows:

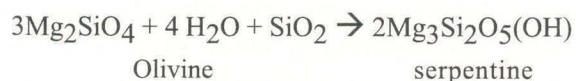


Table 15. Chemical analyses of major elements of Catalão I Carbonatite.

SAMPLES	A1CB	11	A1CP	CF	A1C*
SiO ₂	2.99	2.34	7.95	1.06	1.3
Al ₂ O ₃	0	0	0	0	<0.1
CaO	37	11.9	21.5	18	44.8
MgO	2.4	18.3	15.4	15	6
MnO	0.01	0.23	0.24	0.22	0.19
Na ₂ O	0.06	0.24	0.07	0.26	0.07
K ₂ O	0.03	0.5	0.49	0.12	0.1
TiO ₂	0.01	0.13	1.16	0.24	<0.05
P ₂ O ₅	0.06	0.45	4.52	5.11	2.7
Fe ₂ O ₃ T	0.11	9.05	10.3	15.5	5
FeO	n. a.	n. a.	n. a.	n. a.	0.44
BaO	0.1	7.5	0.1	1.2	0.25
F	n. a.	n. a.	n. a.	n. a.	0.24
H ₂ O-	16.9	16.8	16.4	16.7	n. a.
P. F.	41.5	31.4	22.5	27.9	38.02
Total	101.2	98.9	100.6	101.3	99.01

A1CB = Ca-carbonatite.

11 = Mg-carbonatite associated with phoscorite.

A1CP, CF, A1C* = Mg-carbonatites

Table 16. Chemical analyses of minor elements of Catalão I Carbonatite.

SAMPLES	A1CB	11	A1CP	CF	A1C*
Cr	<5	<5	191	7	<20
Ni	24	24	64	n. d.	<24
Co	n. d.	140	43	101	n. a.
Li	<5	0	27	<5	n. a.
Cu	12	195	67	225	n. a.
Pb	<10	n. d.	n. d.	n. d.	n. a.
Zn	16	56	169	170	n. a.
Ba	1039	75000	1038	12000	2508
Sr	801	6880	4973	5104	4280
Nb	7.1	573	124	278	1140
V	0	257	125	154	n. a.
Zr	68.7	668	1011	657	220

A1CB = Ca-carbonatite. 11 = Mg-carbonatite associated with phoscorite.

A1CP, CF, A1C* = Mg-carbonatites

The hydration reaction related to the transformation of olivine into serpentine shows the presence of water in the rock. In temperatures over 450°C, CO₂ and H₂O are completely miscible, except under very high pressure. According to Holland & Malinin (1979), in highly alkaline solutions, calcite solubility increases with

Table 17. Chemical analyses of rare earth elements of Catalão I Carbonatite.

SAMPLE	A1CB	11	A1CP	CF	A1C*
La	70.5	976	435	865	669
Ce	108	2159	977	1728	1423
Nd	35.3	832	432	836	531
Sm	3.4	92.3	53.2	131	63.9
Eu	0.64	16.5	11.4	29.5	12.4
Gd	2.2	42.5	31.4	82.3	31.3
Dy	1	16.2	15.6	38.5	12.8
Ho	0.1	2.2	2.6	5.4	2.2
Er	0.3	3.7	4.2	6.8	3.9
Yb	0.1	0.8	1.7	1.9	1.05
Lu	0.02	0.1	0.19	0.2	0.13
Σ REE	221.5	4141.3	1964.2	3724.6	2750.6
La/Lu (n)	366	830	237	408	171
La/Sm (n)	13	6.65	5.14	4.15	6.59
Eu/Eu* (n)	0.67	0.7	0.79	0.81	n. c.

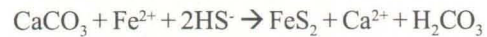
A1CB = Ca-carbonatite.

11 = Mg-carbonatite associated with phoscorite.

A1CP, CF, A1C* = Mg-carbonatites

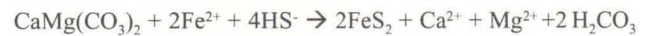
temperature and CO₃²⁻ concentration. The effervescence and changes of the a_H⁺, caused by interaction with the country rocks, are important mechanisms for the formation of that mineral. A decrease of the H⁺ activity causes an increase of CO₃²⁻ and may lead to precipitation of another carbonate.

The presence of pyrite in carbonatites, particularly in Mg-carbonatites, may be due to HS⁻ reactions, controlled by O₂ fugacity, as exemplified in following reactions for calcite and dolomite:



calcite

pyrite



dolomite

pyrite

During the serpentinization process caused by carbonatite intrusion, olivines became orange colored near pyrites, therefore attesting the occurrence of previous reactions during carbonatite crystallization.

According to Santos & Clayton (1995), results of oxygen and carbon isotope analyses of Catalão I carbonatites suggest that these rocks were formed at temperatures lower than 200°C, involving fluids with high H₂O/CO₂ ratios, and were contaminated by the surrounding country rocks. Similar phenomena were identified by Kubicki & Ryka

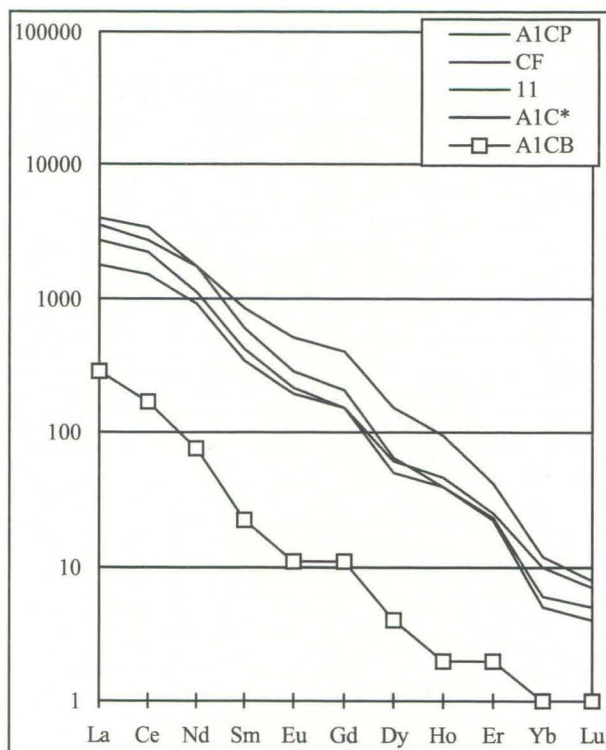


Figure 6. REE patterns of Catalão I carbonatites. Normalized to chondrite. A1CP, CF, 11 and A1C* = Mg-carbonatites; A1CB = Ca-carbonatites.

(1987) in carbonatites associated with ultramafic rocks in Tajno (Poland).

In the analyzed samples strontium is mainly associated with dolomite in banded carbonatite. This fact implies a certain scarcity of this element in calcite. A comparison of the obtained data with those presented by Kapustin (1982) indicates that strontium content is similar to that obtained for early-phase carbonatites, with the exception of the aforementioned calcitic facies. On the other hand, barium content is extremely high relative to the mean barium content of carbonatites from other localities, and therefore could explain the relatively lower Sr/Ba ratios of the analyzed samples if compared with ratios quoted in literature.

The extremely high Ba content in Mg-carbonatites (CF and 11, Tab. 16) is due to the probable presence of barite inclusions related to the hydrothermal event, as was attested by optical microscopy.

DISCUSSION ABOUT THE CARBONATE MINERALS

Taking into account that carbonates are the main components of Fazenda Varela and Catalão I

carbonatites, their chemical composition was detailed through electron microprobe analyses.

Chemistry of the rhombohedral carbonates from Fazenda Varela Carbonatite

Analytical results of the rhombohedral carbonates (ankerite, Fe-dolomite and dolomite) from Fazenda Varela carbonatite are presented in tables 18 and 19, with the structural formulas calculated for 6 oxygen.

The composition of zoned rhombohedral carbonates changes from the core to the outer parts, generally being their center Ca-poorer and Fe-richer (Tab. 18). These carbonates are characterized by Fe-dolomites bands, which eventually change to dolomite bands, whereas ankerite occurs only in the central portions of some crystals (Fig. 7). Both Fe-dolomite and ankerite have a significant Mn content, which surpasses the Fe content in some bands of these carbonates.

The Fe-dolomite, ankerite and dolomite structures are similar to that of calcite, although, in a more detailed view, some differences can be noticed as they present two sites (A and B). Site A is entirely occupied by Ca whereas site B, the smaller one, is occupied by Mg in dolomite, Mg+Fe+Mn in Fe-dolomite and Fe+Mn in ankerite (Reeder, 1990). Therefore, dolomite and ankerite constitute a series formed by Mg substitution from site B by (Fe+Mn). According to Deer *et al.* (1967), a continuous Mg replacement from dolomite structure by Fe (and also by Mn) occurs towards ankerite composition. The mineral is called ankerite whenever its site B contains a proportion of Mg: (Fe+Mn) \leq 4:1, and Fe-dolomite when the proportion is greater than 4:1 (Deer *et al.*, 1967). Fe-dolomites and ankerites present an excess of CaCO_3 relative to their ideal formulas. Considering that site A is entirely occupied by Ca, this fact indicates that site B is occupied not just by Mg and/or Fe+Mn but also by a certain amount of Ca. On the other hand, the total amount of CaCO_3 in these minerals changes as a consequence of their crystallization temperature (Goldsmith, 1990) but it is rarely larger than 57% in weight (Reeder, 1990). Most of the analyzed points in dolomites, Fe-dolomites and ankerites present compositions within this compositional range (Tab. 18).

The interstitial, clean rhombohedral carbonates are predominantly calcite, Mg-calcite and dolomite, and rarely Fe-dolomite (Tab. 18 and

Table 18. Chemical composition (%) and structural formulas, calculated for 6 oxygen (2CO_2), of zoned rhombohedral carbonates from Fazenda Varela Carbonatite. Analyses undertaken in an electron microprobe. Classification based on Ca, Mg and Fe+Mn molecular proportions (Goldsmith, 1990; Reeder, 1990; Deer et al., 1967).

Point *	Ia	Ib	Ic	Id	Ie	IIa	IIb	IIc	Va	Vb	Vc	Vd	Ve	IVa	IVb	IVc	IVd	IVe
CaO	37.7	32.1	31.9	31.8	31.6	32.0	30.3	30.3	31.1	31.9	30.5	34.2	34.8	27.6	30.6	31.1	30.5	33.1
MgO	9.56	16.2	14.3	14.8	15.2	14.4	19.2	19.4	14.2	14.9	19.6	13.0	16.8	8.84	8.83	15.0	15.8	17.7
SrO	0.092	0.155	0.154	0.254	0.228	0.218	0.781	0.682	0.051	0.130	0.316	0.198	0.098	0.118	0.160	0.347	0.078	0.425
BaO	0.190		0.076	0.061		0.238	0.233				0.161		0.040	0.087			0.038	
Fe_2O_3	6.40	3.21	9.11	8.23	7.77	8.83	3.27	3.29	10.37	8.16	2.85	4.36	2.17	21.96	18.81	9.17	8.97	2.46
MnO	2.862	2.605	0.733	0.614	0.564	0.989	0.100	0.112	1.197	0.677	0.045	0.094	0.041	1.851	1.628	0.628	0.436	0.138
Cr_2O_3	0.001	0.008						0.128	0.030				0.008	0.047			0.076	
La_2O_3		0.034		0.342				0.274	0.371			1.901		0.157		0.391		
Ce_2O_3	0.146	0.203			0.115	0.180	0.052	0.138		0.098	0.259	3.457	0.086	0.058		0.164		0.017
S	56.93	54.51	56.28	56.18	55.49	56.79	53.90	54.34	57.29	55.83	53.68	57.26	54.01	60.68	60.05	56.89	55.91	53.92
CO_2^{**}	43.6	45.4	43.7	44.0	44.0	44.0	46.0	46.3	43.6	44.0	46.3	43.1	46.3	38.6	39.9	44.0	44.0	46.3
Total	100.53	99.91	99.98	100.18	99.49	100.79	99.90	100.64	100.89	99.83	99.98	100.36	100.31	99.28	99.95	100.89	99.91	100.22
N. of cations																		
Ca	1.4	1.1	1.1	1.1	1.1	1.1	1.0	1.0	1.1	1.1	1.0	1.2	1.2	1.1	1.2	1.1	1.1	1.1
Mg	0.48	0.78	0.72	0.74	0.75	0.71	0.91	0.91	0.71	0.74	0.92	0.66	0.79	0.50	0.48	0.75	0.78	0.84
Sr	0.002	0.003	0.003	0.005	0.004	0.004	0.014	0.013	0.001	0.003	0.006	0.004	0.002	0.003	0.003	0.007	0.002	0.008
Ba	0.003	-	0.001	0.001	-	0.003	0.003	-	-	-	0.002	-	0.001	0.001	-	-	0.001	-
Fe	0.076	0.039	0.12	0.10	0.10	0.11	0.039	0.039	0.13	0.10	0.034	0.056	0.026	0.31	0.26	0.12	0.11	0.029
Mn	0.082	0.071	0.021	0.017	0.016	0.028	0.003	0.003	0.034	0.019	0.001	0.003	0.001	0.060	0.051	0.018	0.012	0.004
Cr	-	-	-	-	-	-	-	0.002	-	-	-	-	-	0.001	-	-	0.001	-
La	-	-	-	0.002	-	-	-	0.002	0.002	-	-	0.012	-	0.001	-	0.002	-	-
Ce	0.001	0.001	-	-	0.001	0.001	-	0.001	-	0.001	0.002	0.022	0.001	-	-	0.001	-	-
C	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Classific.	Ankerite	Fe-dolom.	Fe-dolom.	Fe-dolom.	Dolomite	Fe-dolom.	Dolomite	Dolomite	Fe-dolom.	Fe-dolom.	Dolomite	Dolomite	Dolomite	Ankerite	Ankerite	Fe-dolom.	Fe-dolom.	Dolomite

I to IV represent different minerals; a, b, ..., g indicate bands from the crystal core towards its periphery.

** CO_2 estimated using ideal formula $[(\text{Mg,Ca})(\text{CO}_3)_2]$

Table 19. Structural formulas, calculated for 6 oxygen, of rhombohedral carbonates from Fazenda Varella Carbonatite including the clean, interstitial type as well as the type that surrounds the synchisite. Analyses undertaken in an electron microprobe. Classification based on Ca, Mg and Fe+Mn molecular proportions (Goldsmith, 1990; Reeder, 1990; Deer *et al.*, 1967).

Point *	IVf	IVg	IIIa	IIIb	IIIc	IIId	VIa	VIb	VIc	VIId	VIIa	VIIb
CaO	50.2	48.2	42.4	44.9	31.2	42.9	47.0	48.3	30.9	30.1	51.0	38.9
MgO	2.42	3.57	4.30	1.28	13.54	2.74	2.30	2.92	19.59	15.00	3.06	3.82
SrO	-	0.088	-	0.064	0.076	0.034	-	0.021	0.921	0.164	0.145	0.275
BaO	-	-	0.209	-	-	-	0.476	0.069	-	0.098	0.107	-
Fe ₂ O ₃			11.4	9.69	12.7	14.4	3.26	1.50	0.882	11.8	0.950	13.0
MnO	2.99	3.55	0.381	3.34	0.410	0.659	1.35	3.79	-	0.235	-	0.377
Cr ₂ O ₃	-	0.083	0.150	0.014	0.007	-	3.007	0.243	-	-	0.053	0.220
La ₂ O ₃	0.098	-	0.138	0.400	0.144	0.061	0.246	-	0.360	0.145	0.733	0.740
Ce ₂ O ₃	0.148	-	-	0.093	-	0.199	0.588	0.181	0.052	0.065	0.558	0.246
S	55.9	55.4	58.9	59.8	58.1	61.0	58.2	57.0	52.7	57.6	56.7	57.6
CO ₂ **	44.0	44.0	41.5	41.5	43.1	41.1	41.5	44.0	46.3	43.6	44.0	42.9
Total	99.9	99.5	100.5	101.3	101.3	102.1	99.7	101.0	99.0	101.2	100.7	100.5
N. of cations												
Ca	1.8	1.7	1.6	1.7	1.1	1.6	1.8	1.7	1.0	1.1	1.8	1.4
Mg	0.12	0.18	0.23	0.07	0.69	0.15	0.12	0.14	0.92	0.75	0.15	0.20
Sr	-	0.002	-	0.001	0.002	0.001	-	-	0.017	0.003	0.003	0.006
Ba	-	-	0.003	-	-	-	0.007	0.001	-	0.001	0.001	-
Fe	-	-	0.15	0.13	0.16	0.19	0.04	0.02	0.01	0.15	0.01	0.17
Mn	0.084	0.100	0.011	0.100	0.012	0.020	0.040	0.107	-	0.007	-	0.011
Cr	-	0.001	0.002	-	-	-	0.042	0.003	-	-	0.001	0.003
La	0.001	-	0.001	0.003	0.001	-	0.002	-	0.002	0.001	0.005	0.005
Ce	0.001	-	-	0.001	-	0.001	0.004	0.001	-	-	0.003	0.002
C	2	2	2	2	2	2	2	2	2	2	2	2
Classific.	Calcite	Calcite	Fe-Calcite	Fe-Calcite	Fe-dolom.	Fe-Calcite	Calcite	Calcite	Dolomite	Fe-dolom	Calcite	Fe-Calcite

* III, IV, VI, VII represent different minerals; a, b, ..., g indicate bands from the crystal core towards its periphery.

** CO₂ estimated using ideal formula [(Mg,Ca)(CO₃)₂]

Fig. 7). According to Reeder (1990), Mg-calcite is an incomplete solid solution of calcite and dolomite. Taking into account the structural limitations for substitution of Ca by Mg, as a consequence of their distinct ionic radius, this solid solution occurs just as small proportions of MgCO₃ within the calcite structure. The substitution of Mg by Ca in dolomite site B is also limited and it produces Ca-dolomites (Reeder, 1990). According to Goldsmith (1990), MgCO₃ solubility in calcite is dependent on the temperature, being larger at higher temperatures. In site B, CaCO₃ solubility of the dolomite structure is also related to the temperature, but its growth with an increase of temperature is very limited due to the fact that the Ca ionic radius generates a structural disorder.

Calcites and dolomites from Catalão I Carbonatite

The study of Catalão I Carbonatite was complemented by a detailed analyses of calcites and dolomites. Electron microprobe results were recalculated to structural formulas of 6 oxygen (Tab. 20). Well-crystallized dolomites (from 15 to 24 in Tab. 20) present a composition similar to the poorly crystallized ones, which microscopically resemble a white plasma with underdeveloped optical proprieties.

Fluorescence observation of different carbonate samples through cathodoluminescence analyses has shown that not all grains from one sample are fluorescent and the fluorescence intensity is widely

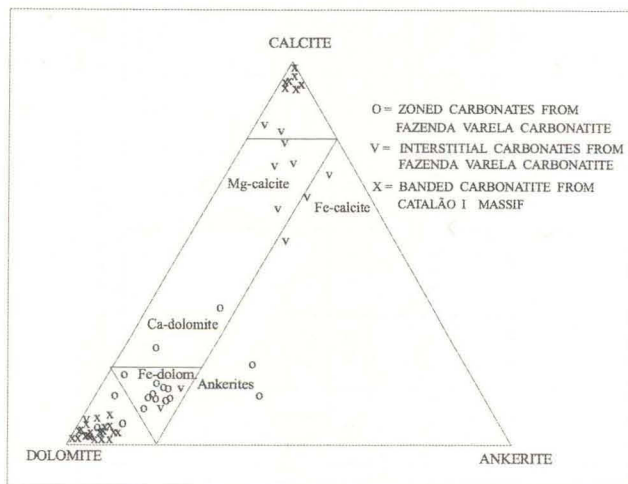


Figure 7. Rhombohedral carbonates classification based on CaCO_3 , $\text{CaMg}(\text{CO}_3)_2$ and $\text{Ca}(\text{Fe,Mn})(\text{CO}_3)_2$ relative proportions. Adapted after Goldsmith (1990); Reeder (1990) and Deer *et al.* (1967).

varied and always with a dark red color. This analytical approach has rendered possible the identification of zoned grains, which were not identified using other analytical methods.

The comparison of the obtained chemical results (Tab. 20) with those published by Kapustin (1980, 1982), relative to calcite and dolomite analyses from several sites, allows to present some additional comments, as follows: Catalão I calcites are much richer in strontium and their Ba content is similar to the mean content presented by Kapustin (1982). According to this author, Sr/Ba ratio is, in average, 8,93 in calcites whereas in Catalão I samples that contains Ba this ratio is widely varied (6,57 to 18,44). Grains with a very low amount of Ba and hence very high Sr/Ba ratios were also observed. Kapustin (1982) stated that Sr-rich calcites are characteristic of the initial phases carbonatites. Ba mean content of Catalão I calcites (518 ppm) is much smaller than the average of 47 calcites (1060 ppm) analyzed by Quon, 1965 (apud Pouliot, 1970). The dolomites associated with calcites in banded carbonatite, as well as all other analyzed dolomites, are Sr- and Ba-richer than those presented by Kapustin (1982) although Sr/Ba ratios are smaller. This fact leads to the conclusion that, in banded carbonatite, Sr is preferentially associated with calcite whereas Ba is related to dolomite.

In dolomitic veins that cross cut banded carbonatite, the Sr/Ba ratio decreases to values between 1,07 and 3,66, due to a significant increase in Ba proportion, supporting the hypothesis that this element is enriched during the late phases. On the

other hand, Sr content is similar in both veins and banded carbonatite. In both calcite and dolomite, Ba content is smaller than Sr content, according to data presented in previous papers dealing with carbonatites from other sites.

Fe and Mn are mostly associated with dolomite, and not with calcite of banded carbonatite, but dolomitic veins that cross cut this carbonatite do not get richer in these elements. In Oka Alkaline Massif (Canada) low Mn content is characteristic of late calcites and, according to Kapustin (1982), first generation dolomites present an FeO content smaller than 2,5%.

Chemistry of the synchysite from Fazenda Varela Carbonatite

The synchysite ideal formula is $[(\text{REE})\text{Ca}(\text{CO}_3)_2\text{F}]$, that means a structural proportions REE:Ca, represented by the number of cations, about 1:1. Table 21 shows that, in synchysite's structural formula, for each structural unit couplet (2CO_3), Ca occupies from 1,0 to slightly more than 1,1, Ce around 0,5 and La from 0,27 (in brownish carbonatite) to 0,40 (in white carbonatite). Mg is almost absent and Sr, Cr and Ba occur in small amounts. Taking into account that brownish carbonatite seems to represent the oxidized product of white carbonatite, it is possible that this process has removed part of the La from synchysite. Ce changes its oxidation state from Ce^{3+} to Ce^{4+} and it is possibly co-precipitated with Fe and Mn which form poorly crystallized oxides closely related to carbonate.

CONCLUSIONS

- Fazenda Varela carbonatites and carbonatites associated with Catalão I Alkaline Massif have some similarities in terms of their occurrence, as both occur as complex dike systems, but they have important compositional differences. Fazenda Varela carbonatite is dominantly an Fe-carbonatite, associated with dolomite carbonatite. On the other hand, in Catalão I Alkaline Massif, two generations of carbonatite were identified. The first one alternates calcitic and dolomitic bands whereas the second one is exclusively beforssitic.
- Mineralogical composition of Fazenda Varela carbonatite is characterized by the association of Fe-carbonates (ankerite and Fe-dolomite), with

Table 20. Chemical analyses of calcites and dolomites from Catalão I Alkaline Massif. Structural formulas calculated for 6 oxygen and analyses undertaken in an electron microprobe. Classification based on Ca, Mg and Fe+Mn molecular proportions (Goldsmith, 1990; Reeder, 1990; Deer et al., 1967).

Points	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	21	22	23	24
SiO ₂	0	0	0.131	0	0.035	0.014	0	0	0.02	0.029	0	0	0.007	0.006	0	0	0	0.027	0	0	0.002	0.01	0.019
CaO	31.3	31.9	54.9	31	54.9	55.9	53.6	55.3	29.6	28.9	29.1	30.4	56.9	57.3	28.9	28.7	28.7	28.8	28.9	28.7	30.1	29.5	29.6
MgO	18.0	17.4	-	19.1	0.381	0.100	0.352	0.198	20.0	20.4	20.2	19.6	0.019	0.081	21.9	20.7	20.8	21.0	20.2	20.8	21.6	21.9	20.1
SrO	1.07	0.827	1.09	0.913	1.97	0.389	2.23	0.467	1.33	1.53	1.39	0.997	0	0.389	2.27	1.50	2.05	0.696	0.667	2.13	1.42	2.25	0.306
Al ₂ O ₃	0.002	0	0	0	0	0	0	0.011	0	0.017	0	0	0	0.004	0.002	0.002	0	0	0.025	0	0	0	0
FeO	0.78	2.39	0.128	0.61	0.056	0.064	0.104	0	0.876	0.867	0.859	0.604	0	0	0.903	1.04	0.644	1.04	1.67	1.18	1.12	0.18	1.70
MnO	0.18	0.05	0.043	0.444	0.059	0.102	0	0.034	0.165	0.131	0.147	0.103	0	0	0.636	0.423	0.177	0.413	0.666	0.48	0.310	0.264	0.606
BaO	0.614	0.970	0.155	0.461	0.104	0	0	0	0.512	0.869	0.461	0.871	0	0.104	0	0.357	0.204	0.051	0	0	0	0.460	0
Ce ₂ O ₃	0.039	0.078	0.704	0.078	0	0	0	0.039	0	0	0	0	0.079	0.197	0.194	0	0.155	0	0	0	0.078	0.039	0
La ₂ O ₃	0.412	0	0.554	0	0.185	0	0.554	0	0.046	0	0	0	0	0	0.137	0	0.274	0	0	0	0	0.229	0.183
S	52.42	53.62	57.71	52.61	57.69	56.57	56.84	56.05	52.55	52.74	52.16	52.58	57.01	58.08	54.94	52.72	53.00	52.03	52.13	53.29	54.63	54.83	52.51
CO ₂ *	47.6	46.4	43.1	47.4	42.4	43.4	43.1	43.9	47.4	47.2	47.8	47.4	43	41.9	45.5	47.3	47	47.9	47.9	46.7	45.4	45.1	47.4
Total	100.02	100.02	100.81	100.01	100.09	99.97	99.94	99.95	99.95	99.94	99.96	99.98	100.01	99.98	100.44	100.02	100.00	99.93	100.03	99.99	100.03	99.93	99.91
N. of cations																							
Si	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ca	1.05	1.08	1.96	1.03	2	2.01	1.95	1.98	0.99	0.96	0.97	1.02	2.05	2.09	0.98	0.96	0.96	0.95	0.96	0.96	1.01	1.00	0.98
Mg	0.84	0.82	-	0.89	0.02	-	0.02	0.01	0.93	0.95	0.93	0.91	-	-	1.01	0.96	0.97	0.97	0.93	0.97	1.02	1.04	0.93
Sr	0.02	0.02	0.02	0.02	0.04	0.01	0.04	0.01	0.02	0.03	0.02	0.02	-	0.01	0.04	0.03	0.04	0.01	0.01	0.04	0.03	0.04	0.01
Al	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe ₂ ⁺	0.02	0.06	-	0.02	-	-	-	-	0.02	0.02	0.02	0.02	-	-	0.02	0.03	0.02	0.03	0.04	0.03	0.03	-	0.04
Mn	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	0.02	0.01	-	0.01	0.02	0.01	0.01	0.01	0.02
Ba	0.01	0.01	-	0.01	-	-	-	-	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-	-	-	0.01	-
Ce	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
La	-	-	0.01	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	2.03	2.00	1.99	2.01	1.97	1.99	1.99	2.00	2.01	2.01	2.02	2.01	1.97	1.95	1.96	2.01	2.00	2.02	2.02	1.99	1.95	1.95	2.01
Classif.	Dolom.	Dolom.	Calcite	Dolom.	Calcite	Calcite	Calcite	Calcite	Dolom.	Dolom.	Dolom.	Dolom.	Calcite	Calcite	Dolom.	Dolom.	Dolom.	Dolom.	Dolom.	Dolom.	Dolom.	Dolom.	Dolom.

* CO₂ estimated using ideal formula [(Mg,Ca)(CO₃)₂]

Table 21. Chemical composition (%) and structural formulas, calculated for 6 oxygen, of synchysites from Fazenda Varela Carbonatite. Analyses undertaken in an electron microprobe.

ROCK			Brown	Carbonatite							White	Carbonatite					GENERAL
	13	14	15	16	17	18	19	20	MEAN	37	38	39	40	41	42	MEAN	MEAN
CaO	14.13	14.42	14.42	14.42	14.23	14.42	15.11	14.23	14.42	10.10	11.77	12.07	12.75	13.73	12.66	12.18	13.30
MgO	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.10	0.00	0.01	0.02	0.01
SrO	0.52	0.40	0.48	0.80	0.68	0.74	1.18	0.65	0.68	0.63	0.53	0.71	0.61	0.79	0.78	0.67	0.68
BaO	0.04	0.01	0.03	0.00	0.00	0.00	0.11	0.04	0.03	0.00	0.13	0.00	0.61	0.00	0.00	0.12	0.08
Fe ₂ O ₃	2.68	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.38	0.00	0.00	1.38	2.13	0.00	0.00	0.59	0.48
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.29	0.25	0.32	0.13	0.22	0.17	0.22	0.21	0.23	0.35	0.41	0.41	0.60	0.34	0.49	0.43	0.33
La ₂ O ₃	20.70	20.99	20.80	20.50	21.49	20.99	19.23	20.99	20.71	31.59	30.22	28.35	26.78	24.72	29.04	28.45	24.58
Ce ₂ O ₃	40.52	41.99	42.38	42.48	40.81	41.70	41.30	42.58	41.72	38.46	36.79	35.91	35.12	38.36	35.91	36.76	39.24
S	78.88	78.07	78.43	78.34	77.77	78.02	77.15	78.69	78.17	81.14	79.85	78.84	78.71	77.94	78.89	79.23	78.70
CO ₂ *	19.25	18.97	18.97	19.06	18.88	18.97	19.43	18.97	19.06	16.66	17.58	17.86	18.51	18.60	18.05	17.88	18.47
F *	4.44	4.53	4.53	4.44	4.53	4.53	3.70	4.53	4.41	4.07	3.70	3.79	4.07	4.35	3.98	3.99	4.20
Total	102.58	101.58	101.93	101.85	101.18	101.53	100.29	102.20	101.64	101.87	101.13	100.50	101.29	100.89	100.91	101.10	101.37
N. ions																	
Ca	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.1	1.1	0.9	1	1	1	1.1	1	1	1.1
Mg	0.002	-	-	-	-	-	-	-	-	0.002	-	0.002	0.011	-	0.001	0.003	0.001
Sr	0.022	0.017	0.02	0.034	0.029	0.032	0.049	0.027	0.029	0.03	0.024	0.032	0.027	0.034	0.035	0.03	0.029
Ba	0.001	-	0.001	-	-	-	0.003	0.001	0.001	-	0.004	-	0.018	-	-	0.004	0.002
Fe	0.073	-	-	-	0.009	-	-	-	0.01	-	-	0.04	0.06	-	-	0.017	0.013
Mn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Cr	0.008	0.007	0.009	0.004	0.007	0.005	0.006	0.006	0.007	0.011	0.013	0.013	0.018	0.01	0.015	0.013	0.01
La	0.27	0.28	0.28	0.27	0.29	0.28	0.25	0.28	0.28	0.48	0.44	0.4	0.37	0.34	0.41	0.4	0.34
Ce	0.53	0.56	0.57	0.57	0.55	0.56	0.54	0.57	0.56	0.58	0.53	0.51	0.48	0.52	0.5	0.52	0.54
C	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
F	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1

* CO₂ and F estimated using the synchysite ideal formula [(REE)Ca(CO₃)₂F].

dolomite bands and veins (eventually calcite in the interstitial spaces), minor amounts of synchysite (Ca and REE carbonate) and associated barite. Catalão I carbonatites are essentially composed by zoned calcite and dolomite. Apatite and pyrochlore occur as accessory minerals in Catalão I carbonatite and as very rare accessory minerals in Fazenda Varela carbonatite.

- Ba and SO₃ high concentration and P low content are characteristic of Fazenda Varela carbonatite. Sr and REE content are so high that makes them major elements, the former one probably associated with Ca in the rhombohedral carbonates and the latter ones with synchysite. Among other elements, Th and U are important components whereas Nb occurs in very low amounts. REE composition, relative to chondrites, presents a strong enrichment of the light ones (LREE) relative to the heavy ones (HREE). Ce and Eu anomalies were not found but a clear Yb negative anomaly is evident.
- Catalão I carbonatites are poor in Al, Mn, Na and K. Anomalous Cr, Ni, Co, Cu, Li and Zr-rich samples do occur as well as samples presenting high amounts of Cu and Co. Presence of Cu is due to presence of pyrite whereas Co high proportion is supposed to represent contamination processes. Nb content in carbonatitic veins is very low and suggests that these rocks are not the cause for the economic concentration of this element in Catalão I Alkaline-Carbonatitic Massif. Sr is mostly associated with dolomite in banded carbonatite, causing the shortage of this element in the calcitic phase. Banded carbonatite is relatively REE-poor and magnesium carbonatite bands are richer in all REE than the associated calcium carbonatite. There are no anomalies in the distinct signatures although calcium carbonatite is extremely poor in all REE.
- Weathering on the Fazenda Varela carbonatite is intense and is represented by alterite, formed under present-day climate, and laterite, as the product of previous climatic conditions. In Catalão I, the weathering does not generated expressive residual products, because carbonatites were dissolved without producing an alteration cap due to carbonate (calcite and dolomite) dissolution.
- The alterite formed by Fazenda Varela carbonatite alteration is composed almost exclusively by goethite, a neoformed mineral through Fe-

carbonate degradation, with no clay minerals and unaltered barite. Laterite is composed by hematite and goethite, being hematite the dominant mineral when laterite is more compact and goethite when it is more friable. Goethite develops by secondary hydration under present-day climate.

- The main geochemical effect of weathering on Fazenda Varela carbonatite consists in the fixation and enrichment of Fe, as well as Mn, Th and U, in both alteration facies (alterite and laterite). As U and Th are not important elements neither in goethite or hematite, it is possible to conclude that these elements are associated with the oxidized, amorphous or poorly crystallized phases. Ba, REE and P are retained in alterite and present large losses in laterite due to the following causes: REE are liberated from synchysite, retained by adsorption in alterite and leached from laterite due to pH control. Ba and P are retained in alterite due to barite's and apatite's high resistance to alteration and they can only be lixiviated when these minerals become unstable.

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