

Niobium mineralization of Catalao I carbonatite complex, Goias, Brazil

Hideo HIRANO*, Masaharu KAMITANI**,
Takeo SATO* and Sadahisa SUDO*

HIRANO, H., KAMITANI, M., SATO, T. and SUDO, S. (1990) Niobium mineralization of Catalao I carbonatite complex, Goias, Brazil. *Bull. Geol. Surv. Japan*, vol. 41(11), p. 577-594.

Abstract: Catalao I carbonatite complex (83 Ma) and related ore deposits were studied paying special attention to their mode of occurrence.

This complex composed of ultramafics and carbonatites, intruded into the Proterozoic metamorphics as a stock with 6 km in diameter in the surface exposure. Formation history of the constituent rocks were classified into the following three stages; the earliest ultramafics, then carbonatites and the latest hydrothermal products. Peridotites were solidified from silicate magma during the ultramafic stage, then some were changed to serpentinite. Carbonatitic magma intruded into the ultramafics at the shallow depth in the form of networks, and changed the host ultramafics to phlogopite rocks by alkaline metasomatism. Phoscolite, the main parent rocks for Nb-minerals, was formed from phoscolitic melt which was segregated immiscibly from the carbonatitic magma due to extensive loss of the alkaline components from the carbonatitic magma. Niobium was selectively concentrated in the phoscolitic melt and then crystallized as pyrochlore.

After denudation of these rocks, strong weathering made development of a thick decomposed crust over the complex and considerable amount of Nb and P were concentrated in the middle zone of the weathering profiles. The circular remnant of quartzite surrounding the complex preserves thick weathered soils which were originally derived from the subvolcanic facies of the complex. These geologic features are essentially the same as those of the Araxa complex which has the largest Nb-ore reserves in the world.

1. Introduction

Carbonatites, which are volumetrically insignificant among the igneous rocks have been a major source for rare metals such as Nb, REE, Sr, Zr, Ti, U and Th (HEINRICH, 1966; DEANS, 1966, 1978; COOK, 1984). Carbonatites contribute especially to niobium. The Nb production from carbonatites reached more than 98% among whole rock types in 1986 (CUNNINGHAM, 1987).

There is a remarkable concentration of carbonatites around the Parana basin in southern

Brazil (Fig. 1). All of them are products of the alkaline igneous activity in the Mesozoic age (ULBRICH and GOMES, 1981; BERBERT, 1984). They are divided into three groups on the locality and the detailed age of emplacement. The earliest carbonatite activity occurred in the coastal region, then followed in the inland and finally in the coast (Table 1). Mineral deposits originated from the carbonatites show characteristic features in each three groups as shown in Table 1. The inland group including the Catalao I and the Araxa are characterized by the variety of commodity and their amounts.

In this paper we will describe the niobium ore deposit in the Catalao I complex comparing with that of the Araxa, and intend to clarify the geologic features which have developed the exceptionally high-grade Nb ores in the central

* Mineral Resources Dept., Geological Survey of Japan.

** Geological Museum, Geological Survey of Japan.

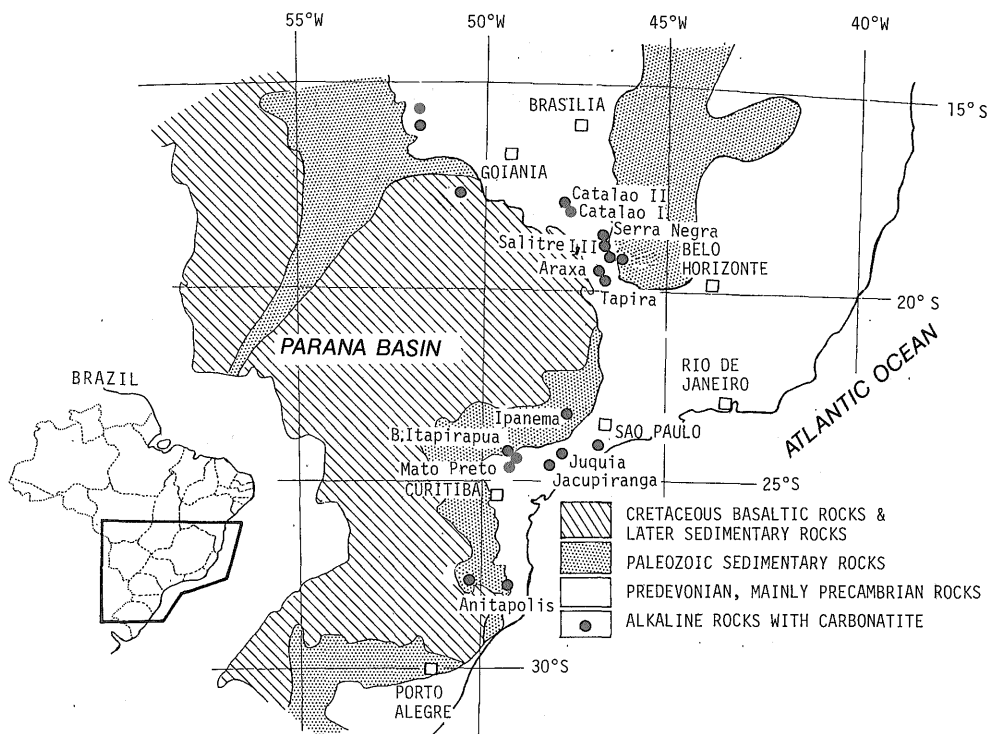


Fig. 1 Distribution of alkali-carbonatite complexes in southern Brazil.

part of the Brazil.

2. Geology

Catalao I complex * is located at 18°08'S and 47°48'W, 20 km northeast from the Catalao city and 10 km north from the Ouvidor town in the Goias State. This complex intruded into the Araxa group of the middle Proterozoic mica schist and quartzite.

Topographically this intrusion is situated in the central plateau of a caldera-like ring structure with 6 km diameter (Fig. 2). The circular ridge, "somma" is composed of alkali-metasomatized quartzite surrounded by mica schist. As shown in Fig. 2, schistosity of the metamorphics shows a concentric structure which is parallel to outline of the Catalao I com-

plex. This pattern may indicate that quartzite was apparently overlain by the mica schist and the metamorphics were extensively rolled up by intrusion of the complex. The complex bounds on quartzite with about 65° outward-dip on the surface (BECKER, pers. communication).

Alkaline metasomatism (fentization) caused by the intrusion of the Catalao I complex extends to 1 to 2 km width from the border, where aegirine, arfvedsonite, and alkali-feldspar have been newly formed in the metamorphics (CARVALHO, 1974).

The complex was deeply weathered and covered by the thick decomposed crust. Although drilling is the only way to obtain direct information on the fresh rock association, the weathered surface evidence also indicates concentric or crescent distribution of the rock-association of the complex.

The laterite rich in vermiculite is distributed along the eastern margin of the complex and anatase-rich soil is developed at the north-eastern rim of the complex. On the central part

* Another complex called the Catalao II is located 15 km north to the Catalao I, which seems to have similar geologic features but has not been exploited yet.

Table 1 Mineral resources associated with carbonatites in southern Brazil

Igneous complex	Age of intrusion (Ma)	Phosphorous		Niobium		Titanium		Rare Earth		Vermiculite		Fluorite	
		Resr. × 10 ⁶ t	Grade P ₂ O ₅ %	Resr. × 10 ⁶ t	Grade Nb ₂ O ₅ %	Resr. × 10 ⁶ t	Grade TiO ₂ %	Resr. × 10 ³ t	Grade TRE%	Resr. × 10 ⁶ t	Grade %	Resr. × 10 ⁶ t	Grade CaF ₂ %
COAST	JACUIRANGA (SP)	89	6.15										
	JUQUIA (SP)	2	16.0										
	IPANEMA (SP)	117	6.73							5	20.0		
INLAND	ANITAPOLIS (SC)	259	4.86										
	CATALAO I (GO)	306	7.96	19	1.08	6	19.9	2000	12.0	5	14.0		
	ARAXA (MG)	460	15.1	462	2.48								
	TAPIRA (MG)	921	8.3	166	1.18	95	17.7	546	10.5				
	SALITRE I (MG)	83				84	23.3						
COAST	SALITRE II (MG)	79				92	13.0						
	SERRA NEGRA (MG)	82				200	27.7						
	BARRA DO ITAPIRAPUA (PR)	—							0.94				
MATO PRETO (PR)	67										2.8	58	

GO, GOIAS; MG, MINAS GERAIS; PR, PARANA; SC, SANTA CATARINA; SP, SAO PAULO.

Data mainly from RODRIGUES and LIMA (1984).

of the complex, argillaceous sediments fill up small-scale depressions; dolines and karst valleys. Niobium ores are concentrated in the weathered crust of the core part and phosphorus ores are in the innerpart. The distribution pattern of the minerals probably indicates a concentric zonation on the fresh rocks of the complex; phlogopite-rich titaniferous rocks occupying the border zone, apatite-rich carbonatites of the inner part and Nb-rich carbonatites in the core part of the complex.

Intrusion age of the complex is determined as 82.9 ± 4.2 Ma with a K-Ar method (HASUI and CORDANI, 1968). After the intrusion, the complex was subjected to subaerial erosion and weathering during the Tertiary age. The weathered crust on the complex has been saved from the erosion by the surrounding ridges of quartzite which is more resistant than mica schist.

3. Catalao I Complex

The concentric zonation of the fresh rocks was inferred to the Catalao I complex using the surface geologic data. Nb- and P-rich rocks may be concentrated in the inner parts, and phlogopite-rich titaniferous rocks occupy the border of the complex. This pattern may be essentially the same as that of the Araxa complex shown by FILHO *et al.* (1984).

Some drill cores of unweathered rocks were kindly provided for our study by Mineracao Catalao de Goias Ltd. All of them were collected from three drill holes located in the central part of the complex (Fig. 3). Unweathered samples were examined by staining carbonates (ALIZARIN red S; e.g. FRIEDMAN, 1959), and microscopic and X-ray powder diffraction methods.

3.1 Petrography

The nomenclature by Streckeisen (1980, p. 204) is adopted here for igneous carbonatites which contain more than 50% by volume of carbonate minerals. Carbonate-poor rocks composed mainly of apatite, magnetite and mafic silicates are called phoscolite if the rocks are of magmatic origin, but metaphoscolite if metasomatic processes are prominent

CATALAO

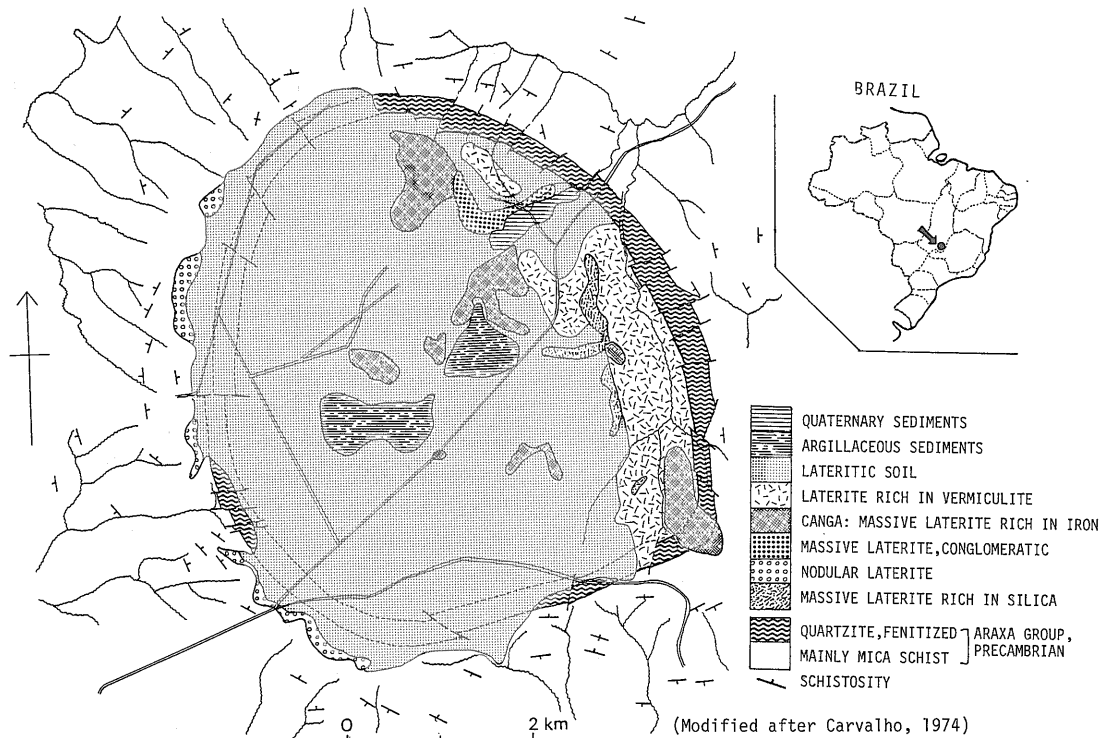


Fig. 2 Surface geologic map of Catalao I complex, Goiás state.

(VARTAINEN and PAARMA, 1979).

Unweathered rocks from the central part of the complex are classified into three groups based on their texture and mineralogy.

A. Ultramafic rocks and their metasomatized rocks

B. Phoscolite

C. Carbonatite

Their volumetric ratios are estimated using two drill cores from the central part of the complex as follows;

Drill hole	(Depth)	Ultramafics	Phoscolite	Carbonatite
47E29N	(103-295 m)	47%	47%	6%
51E33N	(390-606 m)	35	53	12
Mean		41	50	9

Their modes of occurrence are schematically shown in Fig. 4. High concentration of network-like phoscolite is one of the characteristic features in the central part of this complex.

3.2 Ultramafics and their metasomatized rocks

(a) Ultramafics

Ultramafic rocks are massive, pale yellowish green and completely altered to serpentine/clay mineral and carbonate. They are commonly intruded by networks of carbonatitic dikes and veins, where Liesegang banding is developed parallel to the veinlets. Original rocks are thought to be peridotite and pyroxenite derived from silicate magma (CARVALHO, 1974; BAECKER, 1983).

(b) Phlogopite rock

This is massive and brown in color and composed essentially of fine-grained phlogopite with fine- to medium-grained magnetite. Some parts of this rock are composed of medium-grained phlogopite, which may correspond to "glimmerite" called by resident geologists (e.g. CARVALHO, 1974). Phlogopite rocks are alkali metasomatized ones derived from peridotite

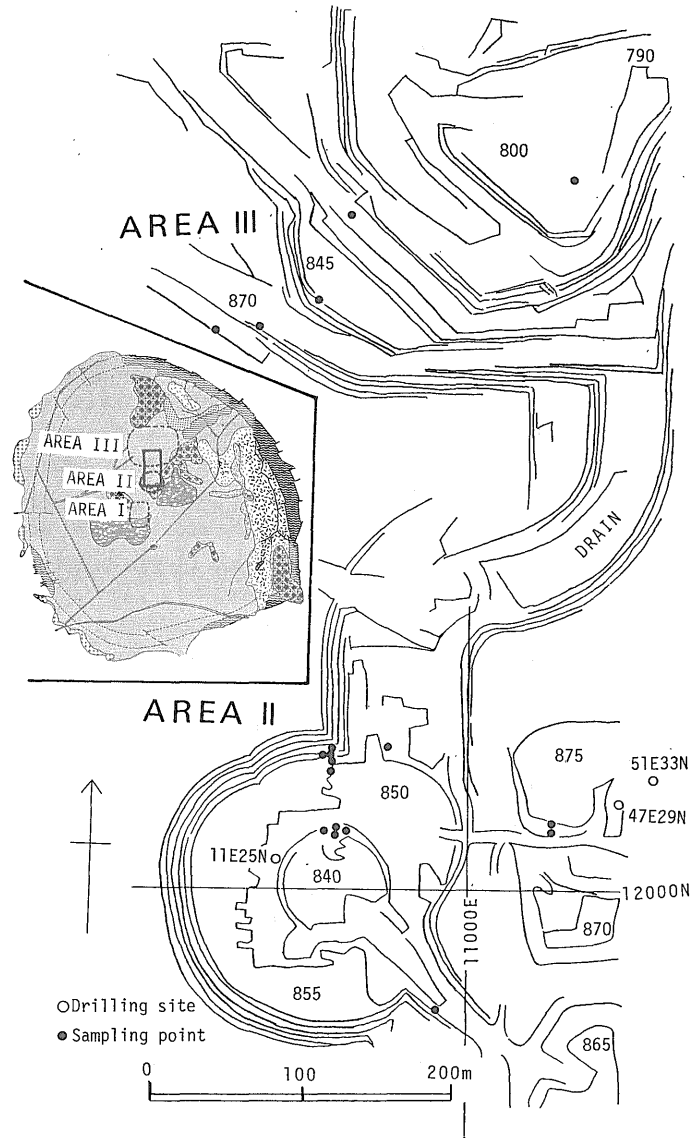


Fig. 3 Open pits of Area II and Area III of Catalao I complex, showing drill site and sampling locality.

and pyroxenite. They are developed as a kind of reaction zone between the host ultramafics and carbonatitic dikes. Phlogopitization related to the intrusion of carbonatite into pyroxenite is observed in many carbonatite complexes such as Oka, Canada and Jacupiranga, Brazil. Phlogopitization of pyroxenite is a kind of fenitization caused by intrusion of carbonatite and it is a proof for common existence of alkali-

rich carbonatite magma (GITTINS *et al.*, 1975).

(c) Pegmatitic phoscolite

Pegmatitic phoscolite occurs as vein-like rocks developed in ultramafics and phlogopite rocks. It contains coarse-grained magnetite, apatite, ilmenite and phlogopite or aggregates of fine-grained phlogopite. No pyrochlore is contained in this rock. Amount of constituent minerals is variable; apatite is little in

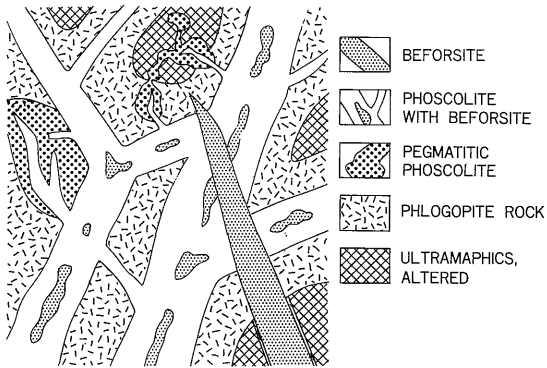


Fig. 4 Schematic mode of occurrence of phoscolite and beforosite intruding into ultramafics. Width of this figure corresponds to 1 to 10 meters. Phlogopite rock and metaphoscolite are formed as metasomatic halos along phoscolite dikes.

metaphoscolite developed in ultramafics and commonly abundant in that occurring near phoscolitic dikes. Magnetite commonly contains exsolution of ilmenite lamellar indicating the crystallization of magnetite under high-Ti/high-temperature conditions (BAECKER, 1983).

3.3 Phoscolite

Phoscolite is a carbonate-poor igneous rock which contains apatite, magnetite and mafic

silicates (RUSSEL *et al.*, 1954; VARTIAINEN and PAARMA, 1979). In the case of the Catalao complex, it occurs as dark-gray, fine- to medium-grained dikes and veins accompanying thick reaction zones of phlogopite. As already shown, phoscolite occupies a considerable volume (about 50%) of the central part of the complex.

Phoscolite includes lens- and "amygdule"-like aggregates of beforosite (Plate I-1). Main parts of phoscolite dikes show a typical igneous texture of medium grained (Plate I-2). At the boundary with beforosite, phoscolite shows partly a bunch of grapes texture, which is composed of radial crystal of apatite and phlogopite with crusts of magnetite (Plates II-3 and II-4). This texture indicates that of liquid-immiscibility between phoscolitic liquid and carbonatitic liquid as already revealed by Lapin (1982) and Lapin and Vartiainen (1982).

The constituent minerals showing a holocrystalline igneous texture (Plate I-2), are euhedral tabular phlogopite, prismatic apatite and anhedral magnetite with small amounts of carbonates and pyrochlore (Fig. 5). It is sometimes observed that radiating clusters of apatite and book-like crystals of phlogopite in phoscolite cross the boundary between phoscolite and beforosite. Magnetite is often concentrated as a crust along the margin of

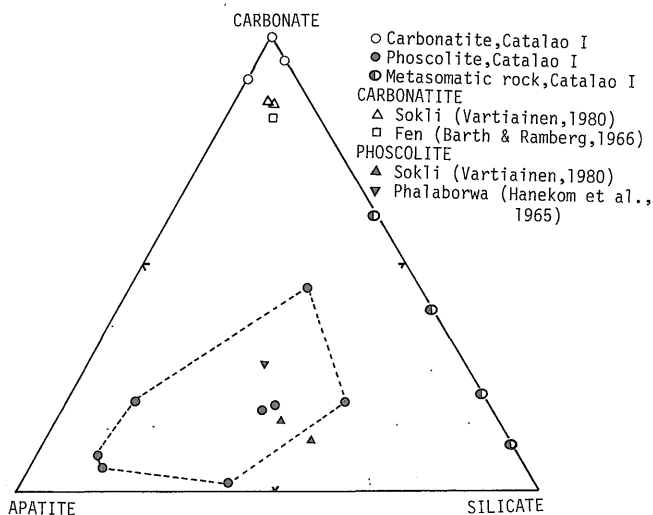


Fig. 5 Carbonate-apatite-mafic silicate diagram showing compositions of carbonatite, phoscolite and metaphoscolite.

phoscolite. Dolomite is the main carbonate minerals in phoscolite, and occurs interstitially or as "amygdules" in the center of the phoscolite dikes.

Pyrochlore, a main Nb-mineral in the unweathered rocks, is selectively concentrated in phoscolite (Fig. 6). An average content of pyrochlore in 6 phoscolite samples rich in pyrochlore is 12 modal % which corresponds to 7 to 8 wt. % Nb_2O_5 . This considerably high value, however, is not a mean of whole phoscolite in the central part of the complex, but likely to that of the highest group of Nb-rich phoscolite.

Phoscolite in the Araxa complex is also the major host rock of pyrochlore, which occurs in the core part of the complex (FILHO *et al.*, 1984).

3.4 Carbonatite and carbonate rocks

This group contains dolomite-carbonatite (beforsite), magnesite-beforsite, sovite and hydrothermal veins of carbonates. Calcite-carbonatite corresponding to sovite defined by Streckisen (1980) is not found within our limited numbers of samples from the central part of the complex, though it was reported in previous works (e.g. CARVALHO, 1974).

(a) Beforsite

This rock is a coarse- to medium-grained carbonatite which occurs as dike with sharp contact with host ultramafic rocks, and occurs as amygdules in phoscolite. It is composed of subhedral dolomite and norsethite with small amounts of pyrite and phlogopite. Norsethite, $(\text{Ba}, \text{Mg})(\text{CO}_3)_2$, which shows partly similar peaks on X-ray diffraction pattern to those of calcite (Fig. 7) is newly found in beforsite. Norsethite is commonly distributed as anhedral, coarse to medium-grained crystals in beforsite. Pyrochlore and apatite are also present.

Beforsite dikes intruding into ultramafics are commonly associated with thinner reaction zones of phlogopite, compared with that of phoscolite dikes. Beforsite is estimated to be 5 to 10 volume % in the central part of the complex.

(b) Magnesite-beforsite

Magnesite-beforsite is fine grained, and mainly composed of dolomite with magnesite, phlogopite, magnetite and pyrite. No apatite

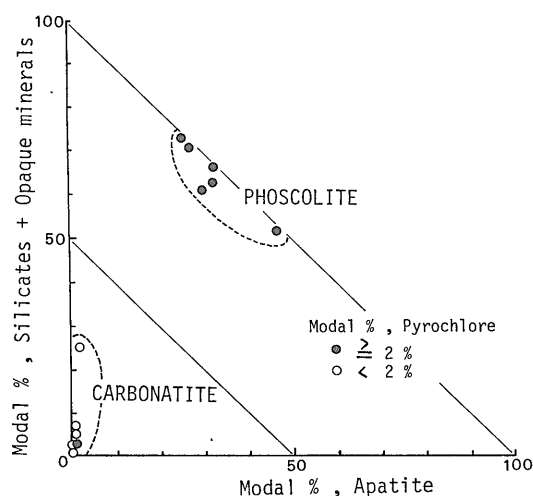


Fig. 6 Apatite-(mafic silicates + opaque minerals) diagram showing compositional fields of phoscolite and carbonatite from Catalao I complex.

was found in this rock. Carbonate rocks without apatite in the Catalao complex are labeled as the products in late magmatic or hydrothermal stage (GIERTH *et al.*, 1985).

(c) Dolomitic sinter and others

Dolomitic sinter, "cocard", occurs as compact veinlets filling cracks of ultramafics and carbonatites. It is composed of rhythmic banding of cryptocrystalline domoite with calcite. Because of its colloform texture, the cocard is thought to be a product precipitated from hot spring.

4. Weathering profiles and concentration of Nb and P

4.1 Weathering profile

Since the intrusion in Cretaceous age, the Catalao complex have been weathered and eroded under subaerial conditions. The effusive facies of the complex such as tuff breccias and lavas, were thus eroded out as well as mica schist near the complex. Quartzite surrounding the complex remained as a circular ridge, because of its resistibility more than mica schist. Consequently the weathered crust surrounded by the circular ridge has developed above the

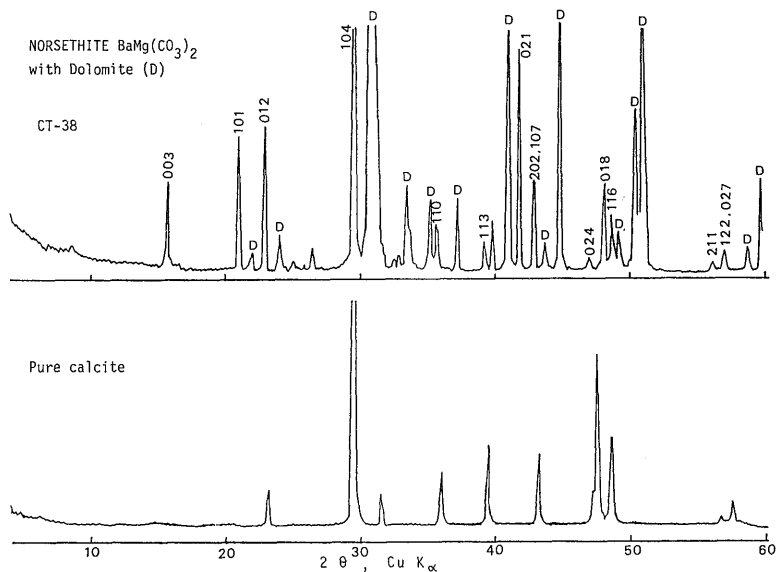


Fig. 7 X-ray powder diffraction pattern of norsethite in beforosite, comparing with that of calcite.

complex with residual soils being about 100 m thick in average.

Soil profiles can be seen in the areas II and III and they are classified into five horizons depending upon their features and mineral composition;

Zone	Level	Thickness (aver.)
Laterite and lateritic soil	890-870 m	10-40 m (20 m)
Pisolithic soil	870-855 m	5-30 m (15 m)
Banded soil	855-820 m	25-40 m (35 m)
Mica-rich soil	820-810 m	5-20 m (10 m)
Decomposed rock	810-800 m	10 m (10 m)

The upper two horizons are characterized by leaching-out of many components except for aluminum and ferric iron. The banded soil horizon is enriched in Ca, Ba, Nb and P. The lower two horizons are characterized by argillization. The ground-water table at the area II varies from 840 m to 810 m above the sea level, which correspond to the middle and the bottom of the banded soil horizon, respectively. The schematic soil profile and its mineral compositions are shown in Fig.8 and Table 2.

Going up the profile showing in Table 2, it is clear that vermiculite (2:2 type mineral) disap-

pears and kaolinite (1:1 type mineral), gibbsite and goethite appear.

(a) Laterite and lateritic soil zone

This zone constitutes the top of the soil profile in this area and is characterized by its red to reddish brown color. Laterite zone is composed of gibbsite, kaolinite, alunite, goethite and hematite. Anatase is also concentrated in this zone. Thin hard layers of goethite pitholith, "canga", are partly developed in the upper part of the laterite zone. Blocks of iron concretion are also observed in the bottom of this zone.

Lateritic soil, being softer than the laterite, is partly developed on the laterite zone. It includes few iron concentrates and is likely to be formed as reworked soil beds in small depressions such as doline and uvala.

(b) Pisolithic soil zone

This zone is characterized by high-concentration of sub-rounded pisoliths with light gray color. The pisoliths are composed mostly of iron- and aluminum-hydroxides, such as goethite, alunite and kaolinite. In spite of the highest concentration of iron, this zone is not dark in color but light gray. The mineral assemblage of this zone is essentially the same as that of the laterite zone (Table 2).

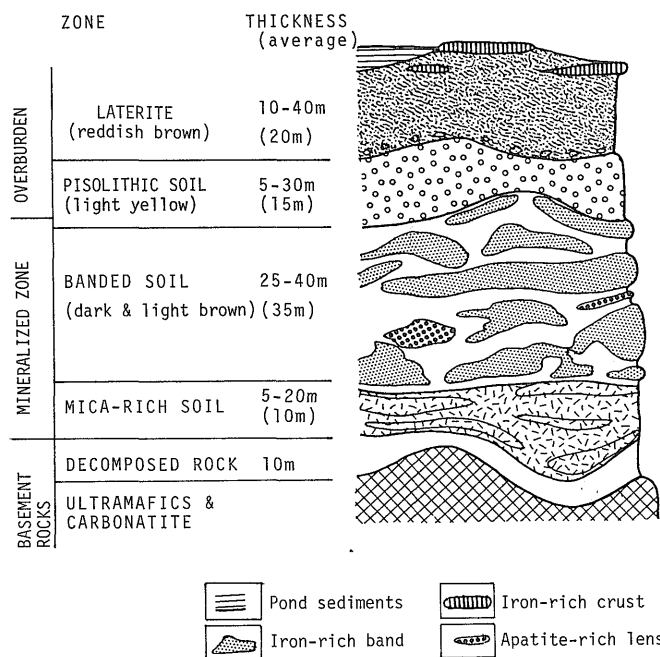


Fig. 8 Schematic soil profile of weathering crust over Catalao I complex.

(c) Banded soil zone

This zone is characterized with massive and hard lenses which have banding structures of the light and dark brown color. It is composed of apatite, goethite, magnetite and barite with pandaite (bariopyrochlore). Apatite accumulates in hard phosphocrate lenses which often contain more than 30% P₂O₅. Quartz is partly concentrated in silicate forming irregular lenses in this zone, which is called as "silexite" by resident geologists. Pandaite is also concentrated especially in the upper half of this zone.

(d) Mica-rich soil zone

This zone is a transitional zone between the banded soil zone and decomposed rock zone. It is characterized with vermiculite. Although primary apatite and magnetite are partly remained, most of the silicate minerals of the original rocks are changed to clay minerals such as vermiculite.

(e) Decomposed rock zone

This zone, developed just above the fresh rocks, is light yellow and composed of vermiculite, barite, apatite and magnetite partly

associated with veinlets of secondary calcite and dolomite. Quartz, kaolinite and goethite are rarely observed in this zone. This zone was probably subjected constantly to water-saturated horizon under the reduced condition.

4.2 Differential thermal analysis

Differential thermal analysis (DTA) was carried out on the weathered samples. The result is shown in Fig. 9. Differential thermal (DT) curves for two samples from the upper horizon indicate high concentration of aluminous clay minerals. CT-48 gives distinct endothermal and exothermal peaks of gibbsite and kaolinite. DT curve of CT-49 shows peaks of goethite and kaolinite.

The samples from the middle horizon contain lots of goethite, apatite and barite instead of clay minerals as shown in Table 2. The DT curves show only the typical pattern of goethite. The peak temperature of goethite decreases with the depth collected the samples (CAT-08 to CT-50). This may reflect the particle size of goethite which indicates degree of the weathering. MACKENZIE (1957, p. 300) has already

Table 2 Vertical variation of minerals in the soil horizon on Catalao I complex

WEATHERING HORIZON sp. no., level	LATERITIC SOIL & LATERITE			PISOLITHIC SOIL			BANDED SOIL						DECOMPOSED ROCKS CT-54, 800 m	BASEMENT ROCKS (ULTRAMAFICS & CARBONATITES)
	CT-48, 880 m	CT-62, 872 m	CAT-09, 870 m	CT-63, 871 m	CT-49, 870 m	CAT-08, 865 m	CAT-07, 860 m	CAT-05, 855 m	CAT-03, 845 m	CAT-04, 845 m	CAT-10, 845 m	CT-50, 845 m		
MINERAL														
KAOLINITE	#	+		+	+					+				
GIBBSITE	+				+									
ALUNITE	#	+	#	#	+		+		+					
QUARTZ	+	+	+	+	+	+	+	+	+	+	#	+		
ANATASE	+	+	+	+	+	+				+				
GOETHITE	+	#	#	+	#	#	+	+	+	+	+	#		
HEMATITE	+	+	+			+	+	+	+	+	+			
MAGNETITE		+	#				#						+	#
ILMENITE								+	+					+
VERMICULITE									+				#	+
BARITE						+	+				#		+	+
APATITE (F)									+	+		#	+	+
PANDAITE						+	+	+				+		
PHLOGOPITE														#
CALCITE													+	+
DOLOMITE													+	+
MAGNESITE														+
NORSETHITE														+
PYROCHLORE														+
SULPHIDES														+

Dominant + Major + Minor

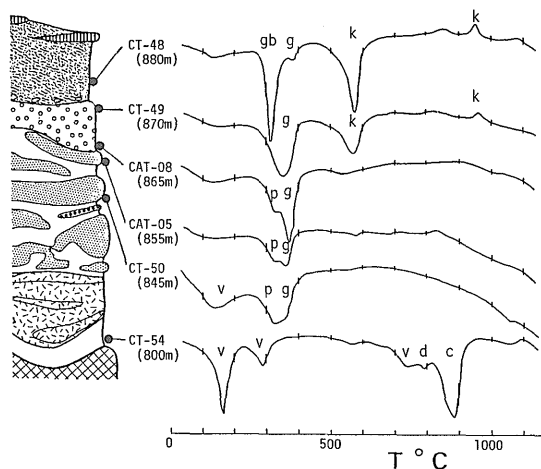


Fig. 9 DTA curve for some samples from the soil horizon on Catalao I complex.

Abb: c, calcite; d, dolomite; g, goethite; gb, gibbsite; k, kaolinite; p, bariopyrochlore; v, vermiculite. Symbols are those in Fig. 8.

pointed out that the peak temperature increases with the particle size of goethite in 300 to 400°C region.

At the bottom of the weathering horizon, silicate minerals of the original rocks are altered to clay minerals and vermiculite. Carbonate minerals of the parent rocks are dissolved under the weathering processes and partly precipitated as veinlet in the clay minerals. The DT curve of CT-54 shows lower endothermic peaks of vermiculite (166°C, 288°C) and those for the mixture of calcite, dolomite and vermiculite (886°C).

4.3 Chemical composition

Average chemical compositions for weathered zones are given in Table 3*.

The uppermost laterite zone is composed mainly of Al_2O_3 , total Fe_2O_3 (T. Fe_2O_3) and TiO_2 . The pisolithic soil zone shows the highest concentration of T. Fe_2O_3 . These two zones are characterized by leaching of most components except for Al_2O_3 , T. Fe_2O_3 and TiO_2 . The banded soil zone is enriched in Ba, P and Nb. The

mica-rich soil and decomposed rock zones are chemically similar to each other and those of the basement complex except for CO_2 and alkali and alkali-earth elements.

From the economical point of view, Nb, P, Ti and REE are important in this complex (e.g., BAECKER, 1983). REE is concentrated in monazite, rhabdophanite and apatite in the pisolithic soil and banded soil zones. Ti is enriched as anatase in the uppermost zone.

Niobium (Nb) and phosphorus (P) are essentially concentrated in pandaite and apatite, respectively. They have been mined and their chemical data have been accumulated by the mining companies. Some chemical data provided by the companies are shown in Fig. 10.

Nb: The distribution of Nb_2O_5 in the weathering profile of the area II is shown in Fig. 10. In comparison with the fresh rocks, Nb_2O_5 is accumulated in the pisolithic and banded soil zones. This chemical result corresponds to our observation that pandaite is detectable using with X-ray diffractometer in some powdered specimens from the lower part of the pisolithic soil zone as well as from the banded soil zone. Nb_2O_5 decreases in the upper horizon. It may be attributed to leaching under the weathering.

Fresh rocks overlain by the weathering zones show the higher content of Nb in comparison with the average of the lower horizon (mica-rich and decomposed rock zones). It may be due to the heterogeneity of the rock associations.

P: Distribution of P_2O_5 is also shown in Fig. 10. The upper horizon of both the areas shows low P_2O_5 contents, indicating the strong leaching for most components under the weathering processes. The banded soil horizon of both the area is distinctly enriched in P_2O_5 .

Comparing with the area II, the area III contains high P_2O_5 in the lower half of the horizons including the banded soil zone. This may be attributed to heterogeneity of the parent rocks; the central part of the complex contains less P_2O_5 than the main part of the complex in average.

* The data are rather statistically insufficient because the specimens for chemical analyses were mostly collected from the apatite-rich parts of the banded soil zone.

5. Discussion

(1) Evolutionary sequence of the complex

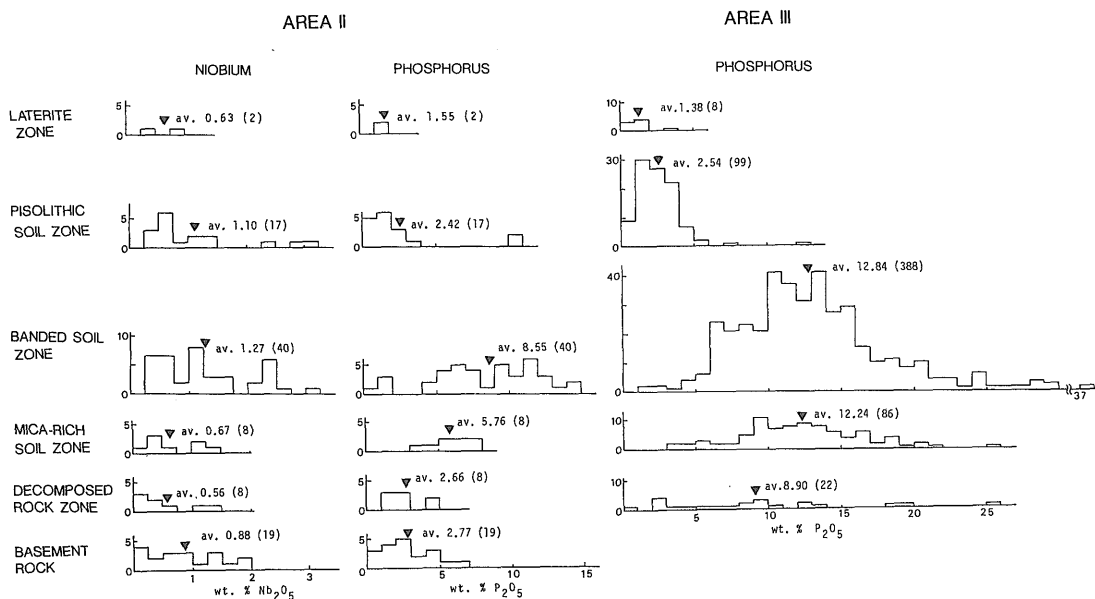


Fig. 10 Distribution of niobium and phosphorus of the weathering profile at Area II and Area III of the Catalao I complex. Number in parentheses showing numbers of analysed samples.

Formational sequence of the Catalao I complex has been considered by some authors (e.g., ÇARVALHO, 1974; BAECKER, 1983; GIERTH *et al.*, 1985). According to their results, three main stages are commonly recognized on the formation of the complex; the earliest ultramafic stage, then, the carbonatitic stage and the latest hydrothermal stage.

We have reached a similar conclusion, and our interpretation is as follows;

In the ultramafic stage, peridotite was emplaced from silicate magmas. Phlogopite-titaniferous rocks assumed by surface geology are likely to be products of this stage. During cooling of the silicate intrusion, some parts of the ultramafics were changed to serpentinite.

The carbonatitic stage is rather complicated because of successive and repeated intrusion. Carbonatitic magmas intruded as networks into the ultramafics where fissures and cracks were developed. Well-developed fissures in the ultramafics indicate that the intrusion of the carbonatites occurred at shallow depth. Phlogopitization of the ultramafics is intimately linked with intrusion of the carbonatitic rocks;

phlogopite zone was developed in the host ultramafic rocks along conduits for the carbonatitic magmas. Pegmatitic metaphoscolite was also formed locally along the conduits.

In the early carbonatitic stage, phoscolitic melt separated immiscibly from the carbonatitic magma. The residue evolved to the magma rich in dolomitic composition which is poor in phosphorous.

Crystallization of carbonate minerals would have continued progressively; first by direct precipitation from carbonatitic magma and later from hydrothermal fluid.

(2) Nb-concentration process

The Catalao I complex has following features; (a) Quartzite ring surrounds the complex, (b) Nb-ore deposit occurs in the middle horizon of the thick weathering crust on the core part of the complex, and (c) network phoscolite is the source rock for the Nb-ore deposit.

Therefore, following two stages are considered on the Nb-concentration of the Catalao I complex; the early one is igneous and the late weathering.

A weathering process contributed to enrich

Table 3 Chemical composition of samples from the weathering crust on the Catalao I complex

LATERITE		PISOLITHIC	BANDED	DECOMPOSED	(Detection limit)	LATERITE	PISOLITHIC	BANDED	DECOMPOSED
(No of samples)	(1)	SOIL	SOIL	ROCK	ppm	(1)	SOIL	SOIL	ROCK
		(3)	(12)	(1)			(4)	(10)	(1)
SiO ₂	18.48	4.42	15.84	20.63	Ag (2)	—	<2	4	—
TiO ₂	6.04	2.03	2.41	4.18	Be (1)	—	<2	14	—
Al ₂ O ₃	25.50	6.17	1.36	1.45	Cd (1)	—	1	15	—
T. Fe ₂ O ₃	30.22	63.69	32.60	11.68	Co (10)	—	17	95	—
MnO	0.19	1.69	0.91	0.22	Cr (1)	—	240	480	—
MgO	0.38	0.58	0.92	19.05	Cu (5)	—	103	183	—
CaO	0.15	0.28	20.00	19.10	Mo (1)	—	2	6	—
Na ₂ O	0.21	0.18	0.26	0.01	Ni (5)	—	87	252	—
K ₂ O	0.10	0.07	0.11	0.21	Pb (2)	—	34	557	—
P ₂ O ₅	3.43	3.47	15.28	4.49	Sr (2)	4300	3730	6150	2000
BaO	1.52	3.69	3.24	0.15	V (1)	—	425	411	—
SrO	0.51	0.44	0.73	0.24	Zn (2)	—	649	495	—
ZrO ₂	0.05	0.07	0.16	0.06	U (0.1)	—	100	255	—
Nb ₂ O ₅	—	0.76	1.31	—	Th (0.1)	—	395	410	—
Ta ₂ O ₅	—	0.01	0.01	—	Sc (0.5)	106	72	103	36
T. RE ₂ O ₃	0.77	1.51	1.09	0.23	La (0.1)	2100	5170	2450	498
LOI	11.25	8.05	2.89	16.48	Ce (3)	3080	6630	4780	1050
Total	98.84	97.10	99.12	98.38	Nd (10)	1230	970	2020	540
					Sm (0.1)	167	192	265	96
					Eu (0.2)	39	22.4	67	18
					Yb (1)	7.0	2.0	4.3	2.1
					Lu (0.05)	1.2	0.67	0.87	0.20

LOI: Loss of ignition

—: Not determined

Neutron activation method for rare earth elements and ICP for other elements

niobium as well as phosphorus in some soil horizons. During the weathering, quartzite remained as a eroded remnant and preserved the residual soils derived from the subvolcanic part of the complex.

The distribution of the deposits is limited to the core part of the Catalao I complex, where network phoscolite has widely developed in the ultramafics. As shown in Fig. 10, the bulk fresh rocks from the core part of the complex are estimated to be 0.88% Nb₂O₅. The essential source rock of niobium is phoscolite. The average content of the highest Nb-phoscolite of the complex is estimated to be as high as 7 to 8 wt.% Nb₂O₅ as mentioned before.

High concentration of niobium in phoscolite indicates that niobium is concentrated selectively in phoscolitic melt relative to carbonatitic melt during the process of liquid immiscibility. This may coincide with high solubility of niobium oxide hydrate (Nb₂O₅·nH₂O) in hot phosphoric acid.

The original magma for carbonatite is estimated to be highly alkaline (GITTINGS *et al.*, 1975) and chemically similar to natrocarbonatite lava of Ordinyo Lengai volcano in Tanzania (e.g. DAWSON, 1966; LEBAS, 1977, 1981). If alkali carbonatite magma intrudes into the host rocks at shallow depth associating with intense fracturing, alkaline components of the magma may intensively emanate to the host rocks and produce fenetization and phlogopitization of the host rocks. During the rapid extraction of alkaline components, phoscolitic melt may separate immiscibly from the parent carbonatitic magma. This may coincide the field evidences from the Catalao I complex showing intense fracturing and alkali-metasomatism along the carbonatitic dikes.

The Araxa complex being the world's largest known niobium reserves shows similar geologic features to those of the Catalao I, referring previous works (PARAISO and FUCCIO, 1981; FILHO *et al.*, 1984).

It is concluded that two Nb-concentration processes, igneous and weathering, have been successfully progressed in both the Catalao I and the Araxa complexes situated in the central part of Brazil.

Acknowledgements We express our gratitude to Drs. Carlos Oiti BERBERT and Kiomar OGUINO of Departamento Nacional da Producao Mineral (DNPM), who have made every effort for cooperative research work between DNPM and Geol.Surv.Japan. One of the authors (H.H.) would like to thank Messrs. Manfred L. BAECKER and Luis C. ASSIS of Mineracao Catalao de Goias Ltd. and Jarbas J. A. MELO of Copebras S. A. for providing the drill core samples, documents on the ore deposits and for helpful discussion of mineralogical aspects of the study. Special thanks go to Mr. Armando Silva NEIBA of Goias branch, DNPM for his excellent assistance during our field trip.

References

- BAECKER, M. L. (1983) A mineralizacao de niobio do solo residual lateritico e a petrografia das rochas ultramaficas-alcaldas do domo de Catalao I, Goias. 113 p. Master thesis of Dept. Geoscience, Univ. Brasilia.
- BARTH, T. F. W. and RAMBERG, I. B. (1966) The Fen circular complex In Tuttle, O. F. and Gittins, J. eds., *Carbonatites*, p. 225-257. John Wiley and Sons, New York.
- BERBERT, C. O. (1984) Carbonatites and associated mineral deposits in Brazil. *Geol. Surv. Japan, Rept.* no. 263, p. 269-290.
- CARVALHO, W. T. (1974) Aspectos geologicos e petrograficos do complexo ultramafico-alkalino de Catalao I, Go., Anais do 28 Congr. Bras. Geol., vol. 5, p. 107-123.
- COOK, P. J. (1984) Spatial and temporal controls on the formation of phosphate deposits—a review—. In Niagu, J. O. and Moor P. B. eds., *Phosphate minerals*. p. 242-274. Springer-Verlag.
- CUNNINGHAM, L. D. (1987) Columbian and Tantalum, In *minerals yearbook* p. 291-302. Bureau of Mines, U.S. Dept. of Interior.
- DEANS, T. (1966) Economic mineralogy of African carbonatites. In Tuttle, O. F. and Gittins, J. eds., *Carbonatites*, p. 385-413, John Wiley and Sons, New York.
- (1978) Mineral production from carbonatite complexes: world review—Proceedings of the First International Symposium on Carbonatites, p. 123-133. DNPM, Brasilia.

- FAWLEY, A. P. and JAMES, T. C. (1955) A pyrochlore (columbium) carbonatite, southern Tanganyika. *Econ. Geology*, vol. 50, p. 571-585.
- FILHO, A. I., LIMA, P. R. A. dos S. and SOUZA, O. M. (1984) Aspectos da Geologia do Complexo Carbonatítico do Barreiro, Araxá, MG, Brasil. p. 19-44. Companhia Brasileira de Metalurgia e Mineração (CBMM), São Paulo.
- FRIEDMAN, G. M. (1959) Identification of carbonate minerals by staining methods. *Jour. Sed. Petrol.* vol. 29, p. 87-97.
- GERTH, E. Leonardos O. H. Jr and BAECKER, M. L. (1985) Some mineralogical characteristics of the main constituents of the unweathered section of the carbonatite complex Catalao I, Goiás, Brazil. In Contribuições a Geologia e a Petrologia. p.45-48. Companhia Brasileira de Metalurgia e Mineração (CBMM). Belo Horizonte.
- GITTINS, J. Allen, C. R. and COOPER, A. F. (1975) Phlogopitization of pyroxene: its bearing on the composition of carbonatite magmas. *Geol. Mag.* vol. 112, p. 503-507.
- GOLD, D. P., VALLEE, M. and CHARETTE, J. P. (1967) Economic geology and geophysics of the Oka alkaline complex, Quebec. *Canad. Inst. Mining Metal. Bull.* vol. 60, p. 1131-1144.
- HANEKOM, H. J., VANSTADEN, G. M. V., SMIT, P. J. and PIKE, D. R. (1965) The geology of the Palabora igneous complex. *Geol. Surv. Rep. South Africa, Mem.*, no. 54, 185p.
- HASUI, Y. and CORDANI, U. G. (1968) Idades Potássio-argônio de rochas eruptivas Mesozoicas do oeste mineiro e sul de Goiás. In congress Brasileiro de Geologia, 22, Belo Horizonte, p. 139-143.
- HEINRICH, E. W. (1966) *The geology of carbonatites*. 555 p. Rand McNally and Co., Chicago.
- LAPIN, A. V. (1982) Carbonatite differentiation processes. *Internat. Geology Rev.*, vol. 24, (9), p. 1079-1089.
- LAPIN, A. V. and Vartiainen, H. (1982) Orbicular and spherulitic carbonatites from Sokli and Vuorijärvi. *Lithos*, vol. 16, p. 53-60
- LEBAS, M. J. (1977) *Carbonatite-nephelinite volcanism*. 347 p. Wiley, New York.
- (1981) Carbonatite magmas. *Mineral. Mag.* vol. 44, p. 133-140.
- MACKENZIE, R. C. ed. (1957) *The differential thermal investigation on clays*. 456p. Mineralogical Society, London.
- PARAISO, O. S. and FUCCIO, R. (1981) Mining, ore preparation and ferro-niobium production at CBMM. In Proceedings of the Internat. Symp. *Niobium 81*, held in San Francisco, Calif. ed. by Stuart, H. p. 113-132. Metallurgical Soc. AIME.
- RODRIGUES, C. S. and LIMA, P. R. A. dos S. (1984) Complexos carbonatíticos do Brasil: Geologia. p. 1-17. Companhia Brasileira de Metalurgia e Mineração (CBMM), São Paulo.
- RUSSELL, H. D., HIEMSTRA, S. A. and GROENEVELD, D. (1954) The mineralogy and petrology of the carbonatite at Loolekop, eastern Transvaal. *Transac. Geol. Soc. South Africa*, vol. 57, p. 197-208.
- STRECKEISEN, A. L. (1980) Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites and melilitic rocks, IUGS Subcommission on the Systematics of igneous rocks. *Geol. Rundsch.*, vol. 69, p. 194-207.
- ULBRICH, H. H. G. J. and GOMES, C. B. (1981) Alkaline rocks from continental Brazil. *Earth-Science Rev.*, vol. 17, p. 135-154.
- VARTIAINEN, H. (1980) The petrography, mineralogy and petrochemistry of the Sokli carbonatite massif, northern Finland. *Geol. Surv. Finland Bull.*, no. 313, 126p.
- and PAARMA, H. (1979) Geological characteristics of the Sokli carbonatite complex, Finland. *Econ. Geol.*, vol. 74, p. 1296-1306.

ブラジル国カロン I カーボナタイト複合岩体のニオブ鉱化作用

平野英雄・神谷雅晴・佐藤壮郎・須藤定久

要 旨

カロン I カーボナタイト複合岩体(貫入年代: 83 Ma)とそれに伴う鉱物資源の産状記載をおこない、ニオブ(Nb)の鉱化作用について考察した。複合岩体は、まずストック状のかんらん岩が形成され、次いで、その内部にカーボナタイト質マグマが脈状に貫入し、リン酸塩マグマと炭酸塩マグマに分離し、固結した。この液相分離の際に、ニオブは選択的にリン酸塩マグマに濃縮した。その後強い風化作用によりニオブは風化土壌の特定の層準に濃集した。このような2段階のニオブ濃縮モデルは、世界最大のアラシャ(Araxa)ニオブ鉱床にも適用できることをしめした。

(受付: 1990年3月27日; 受理: 1990年9月1日)

Plate I

- 1 Phoscolite (gray) and beforosite (white). Scale: cm.
- 2 Phoscolite showing a holocrystalline igneous texture with apatite (ap), magnetite (mt), phlogopite (ph) and pyrochlore (pc). In plane-polarized light. Specimen no.: CT-79 (51E33N, -501.3 m).

Plate II

- 3 Beforosite (lower half) and semi-spherulitic phoscolite showing a texture of liquid immiscibility. Some radial crystals of apatite cross a smooth boundary between phoscolite and beforosite. Abbr: ap, apatite; cb, carbonate minerals (dolomite and norsethite); mt, magnetite; pc, pyrochlore; ph, phlogopite. In plane-polarized light. Specimen no.: CT-86 (51E33N, -566.3 m).
- 4 Beforosite (right side) and semi-spherulitic phoscolite showing a texture of liquid immiscibility. Abbr: ap, apatite; cb, carbonate minerals (dolomite and norsethite); mt, magnetite; pc, pyrochlore; ph, phlogopite. 4A, in plane-polarized light; 4B, in cross-polarized light. Specimen no.: CT-36 (47E29N, -277 m).

