

COMPOSITION OF BRAZILIAN APATITE FROM A CARBONATE-SILICATE PHOSPHATE ORE

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ABSTRACT

The influence of chemical and morphological heterogeneities of apatite in froth flotation concentration is very relevant. Therefore, twelve apatite concentrates from deeper parts of the Tapira Mine, Minas Gerais State (SE Brazil) were characterized using the techniques: optical microscopy, X-ray diffraction, chemical analyses, microanalyses (WDS) and infrared spectrometry. The goal was to determine the types and compositions of the apatites and their relations with the gangue minerals. The phosphate ores studied are rich in silicates and carbonates and were divided in four groups depending on their mineralogical characteristics and alteration degree and were named as: slightly altered clinopyroxenite, micaceous clinopyroxenite, argillaceous clinopyroxenite and clinopyroxenite rich in magnetite and perovskite. The purified apatite concentrates were obtained in the laboratory by means of a combination of techniques: flotation and heavy liquid separation. The product obtained between the densities 2.95g/cm^3 and 3.32g/cm^3 was cleaned in a Frantz Isodynamic Magnetic Separator. All the 12 apatites studied show substitutions of Ca^{2+} mainly by Sr^{2+} and rare-earth elements and also by Na^+ , Mg^{2+} and Fe^{2+} ; of the PO_4^{2-} group by SiO_4^{4-} and CO_3^{2-} and of F^- by OH^- . The apatite is classified as carbonate-strontium-fluor-hydroxylapatite, is essentially original (not secondary), is well formed and commonly shows fluid and carbonate inclusions (mainly calcite and locally strontianite). Inclusions of barite, monazite, ilmenite, zirconolite, nontronite, pyroxene, perovskite and K-feldspar are locally observed. Apatite normally has a smooth surface with the exception of some apatites from argillaceous clinopyroxenite that show rough surface. The fact that the apatites are original and do not show association with secondary types suggest that these samples would have a good performance in froth flotation concentration. However, the problems could be their selectivity in relation to gangue minerals and the presence of carbonates as inclusions and veinlets in apatite crystals.

Keywords

Phosphate, Apatite, Crystal Chemistry

INTRODUCTION

The Tapira mine is located in the northern portion of the Tapira Ultramafic-alkaline-carbonatitic Complex, Western Minas Gerais State (SE Brazil), at approximately 35Km south-southeast of the town of Araxá. It is one of several alkaline-carbonatitic complexes of the Alto Paranaíba Province and was emplaced approximately 70m.y. ago (Hasui & Cordani, 1968) in the Precambrian metasedimentary rocks of the Canastra Group. The mine is an important ore deposit of phosphate and titanium and is the result of the supergenic enrichment of ultramafic rocks (mainly clinopyroxenites and peridotites) rich in these elements. The total geological reserve of phosphate ore is estimated in 1.2 billion tonnes, with the average grade of 8.2% of P_2O_5 .

The Tapira deposit is deeply weathered due to the tropical climate and the phosphate ore shows a complex mineralogical association and low apatite grade because of its igneous origin. The clinopyroxenites are the main rock type, showing facies variations defined by the different modal proportions of the essential minerals clinopyroxene, mica-like minerals, perovskite, apatite and magnetite. The concentration of the apatite ore is carried out by froth flotation which is greatly influenced by the physical, chemical and crystallinity degree characteristics of the apatite (Rodrigues and Brandao, 1993) and by the gangue minerals.

The goal of this work was to characterize the types and compositions of the apatite present in the 12 samples of carbonate-silicate phosphate ore from deeper parts of the Tapira mine and the relationship between the apatite and the gangue minerals (mainly carbonates). A thorough knowledge of the apatite characteristics is fundamental to the understanding of this mineral's behavior during the froth flotation process and can contribute to obtaining an apatite concentrate with better grade and recovery.

EXPERIMENTAL

Twelve apatite concentrates produced from 12 samples of different kinds of clinopyroxenites collected from deeper parts of the Tapira Mine, Minas Gerais State (SE Brazil) were used in this study. The purified apatite concentrates were obtained in the laboratory by means of a combination of techniques: flotation in a Denver cell and heavy liquid separation (tetrabromoethane, $d= 2.95g/cm^3$ and methylene iodide, $d= 3.32g/cm^3$). The product obtained between the $2.95g/cm^3$ and $3.32g/cm^3$ densities was cleaned in a Frantz Isodynamic Magnetic Separator (currents from 0.25A to 1.50A).

All the 12 apatite concentrates were submitted to X-ray diffraction (Phillips model PW3710) analysis to assess their purity. Polished thin sections were prepared for mineral composition and microstructure studies of the apatites using optical (Leitz Ortoplan) and electron microscopy (SEM JEOL model JSM-5410 with EDS Noran model TN-M3055). Selected apatite crystals from each sample were analyzed using a JEOL model JXA8900RL electron microprobe. The analyses were performed under an accelerating voltage of 15KV and a beam current of 20nA, using a 5 μ m diameter beam. Natural and synthetic mineral standards were employed; counting times ranged from 10 to 30s depending on chemical concentration. Infrared spectrometry (Bomem Hartmann & Braun, model DA8) was used to assist in the apatite structure determination. The samples were prepared using the KBr pellet transmission method.

Chemical analyses of major elements in the ore samples were determined by X-ray fluorescence spectrometry (Philips model PW2404) and F by ion specific electrode analysis. The elements Ba, Sr, Nb and rare-earth (REE) were analyzed by energy-dispersive spectrometry (with americium²⁴¹ excitation source – Kevex system).

RESULTS AND DISCUSSIONS

Petrography of clinopyroxenites from which the apatite concentrates were obtained

Based on the mineralogical characteristics and the alteration degree the clinopyroxenites samples were divided in four groups of ores: slightly altered clinopyroxenite (samples 2, 5 and 10), micaceous clinopyroxenite (samples 1, 4 and 9), argillaceous clinopyroxenite (samples 11 and 12) and clinopyroxenite rich in magnetite and perovskite (samples 3, 6, 7 and 8) (Chula *et al.*, 2003 and Chula *et al.*, 2004). The chemical analyses of these samples are displayed in Table 1 and are consistent with the mineral assemblages identified.

Table 1 – Chemical analysis (%) of the different kinds of clinopyroxenite (cpx) from the Tapira mine

	2	5	10	1	4	9	11	12	3	6	7	8
P ₂ O ₅	3.42	3.44	9.60	6.84	3.85	5.29	11.80	6.37	8.96	6.87	5.91	5.89
Fe ₂ O ₃	16.80	13.80	12.10	14.70	15.20	19.50	26.30	26.83	17.70	19.30	13.90	17.40
MgO	10.30	11.90	4.63	11.90	11.30	8.58	1.32	6.15	7.80	5.68	5.25	5.15
CaO	24.40	25.20	31.10	20.30	20.80	16.80	16.80	11.30	28.10	26.60	27.30	27.40
Al ₂ O ₃	1.11	1.75	0.70	2.43	3.44	1.72	4.26	5.87	0.66	0.78	0.40	0.41
SiO ₂	26.04	27.58	19.30	30.70	26.80	34.10	16.80	23.56	13.48	18.49	19.30	15.50
TiO ₂	7.57	3.31	3.72	7.03	6.34	9.88	11.80	12.04	12.80	10.20	14.30	17.60
Na ₂ O	1.33	0.89	0.50	0.45	0.10	0.37	0.10	0.43	0.94	0.20	0.14	0.12
K ₂ O	0.41	0.18	0.51	0.70	1.50	0.25	0.18	1.46	0.22	0.08	0.18	0.11
MnO	0.23	0.20	0.24	0.19	0.24	0.23	0.43	0.31	0.20	0.28	0.24	0.23
BaO	0.05	0.07	0.40	0.06	0.14	0.04	0.16	0.14	0.04	0.05	0.21	0.10
SrO	0.17	0.13	0.73	0.23	0.27	0.18	0.23	0.25	0.34	0.24	0.34	0.25
Nb ₂ O ₅	0.11	0.06	0.10	0.01	0.07	0.09	0.17	0.08	0.16	0.11	0.11	0.12
REE	0.45	0.23	0.72	0.48	0.32	0.50	0.88	0.33	0.77	0.57	0.69	0.78
F	0.14	0.13	0.25	0.24	0.23	0.14	0.21	0.60	0.24	0.22	0.14	0.13
LOI	9.01	9.75	16.30	3.64	9.57	4.19	8.98	6.04	9.75	11.40	13.30	10.80
CaO/P ₂ O ₅	7.13	7.33	3.24	2.97	5.40	3.18	1.42	1.77	3.14	3.87	4.62	4.65
Total	101.5	98.60	101.0	100.0	100.3	101.9	100.5	101.9	102.3	101.2	101.8	102.1

REE: rare-earth elements; LOI: loss of ignition

Samples 2, 5, 10 = slightly altered cpx; samples 1, 4, 9 = micaceous cpx; samples 11, 12 = argillaceous cpx; samples 3, 6, 7, 8 = cpx rich in magnetite and perovskite

The slightly altered, micaceous and argillaceous clinopyroxenites and clinopyroxenite rich in magnetite and perovskite show green, green to ochre/yellowish, ochre-yellowish to light green and ochre/brownish to reddish color, respectively, and show granular texture and fine to coarse grains. The slightly altered clinopyroxenite frequently appears in contact with

the micaceous clinopyroxenite and is commonly cut by veinlets of carbonates and, locally, quartz, in variable directions. The clinopyroxenite rich in magnetite and perovskite occurs in the form of concordant bodies or cutting the other clinopyroxenites or as irregular bodies inside these rocks. These samples are also commonly cut by veinlets of carbonates and, locally, quartz, in variable directions.

These different kinds of ores show similar mineralogy (diopside, apatite, carbonates, micaceous minerals, magnetite, perovskite and anatase) although the modal proportions of the minerals are variable. Garnet (melanite) occurs only in sample 4 and smectite (nontronite) in samples 11 and 12. Very low amounts of amphibole, quartz, ilmenite, hematite, goethite, zircon, pyrite, titanite, monazite, barite, zirconolite, Mn, Ba and Fe oxide (probable hollandite and/or romanechite) and secondary phosphates of the rhabdophane and crandallite groups are locally observed.

Micaceous minerals were identified mainly as mixed-layer phyllosilicates (phlogopite/vermiculite and locally biotite/vermiculite) and pure vermiculite. Pure phlogopite and chlorite were also observed. The carbonates were identified as calcite, dolomite and magnesium calcite when they appear as veinlets cutting the other minerals and generally as calcite and locally as strontianite (sample 4 and rarely in sample 10) when they occur as inclusions mainly in apatite.

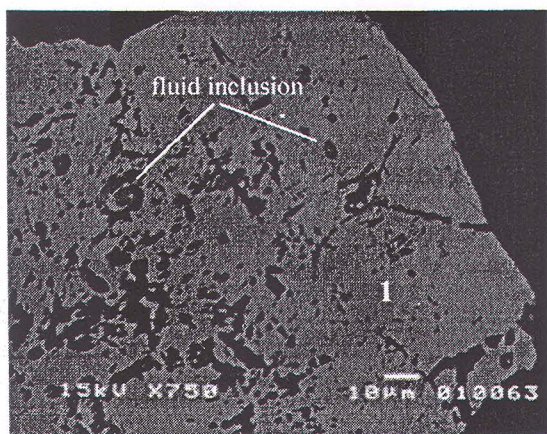
Apatite Characterization

Optical and electron microscopy studies showed that in all 12 samples apatite is disseminated within the rock, filling the intergranular spaces or as inclusions in magnetite, pyroxene/amphibole, micaceous minerals, goethite, perovskite, garnet and nontronite and appears either as isolated crystals or in aggregates. These characteristics indicate that apatite is one of the first minerals to form. Apatite shows variable granulation (0.02mm to 2.5cm), is commonly anhedral or locally prismatic or hexagonal in shape.

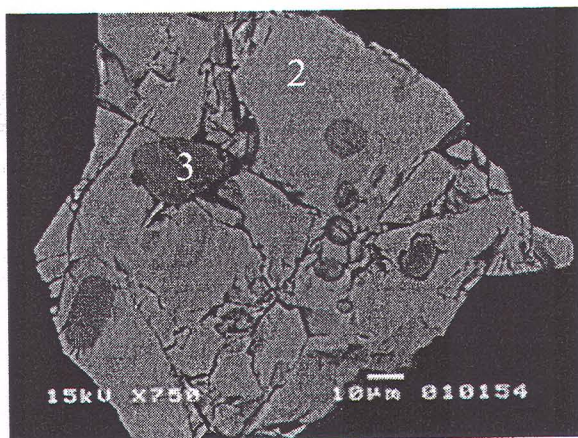
The apatite is well formed, normally has smooth surfaces with the exception of the apatites from sample 12 (argillaceous clinopyroxenites) that show a rough surface, what indicates the beginning of dissolution (Figure 1a – sample 12). Apatite shows mainly a clear aspect, although some grains display fluid inclusions and commonly inclusions of calcite (Figure 1b – sample 9). Barite, strontianite, monazite, ilmenite, zirconolite, nontronite, pyroxene, perovskite and K-feldspar also occur as inclusions. Partial coverings by goethite thin crusts are observed in less than 2-5% of the apatite grains.

Apatite crystals in most samples (exceptions are samples 1, 9, 11 and 12) are very fractured and cut by veinlets of carbonates, carbonates plus quartz or locally just by quartz veinlets, which sometimes subdivide the crystals (Figure 1c – sample 6). These features are observed in all size fractions, but below the $-0.210\text{mm} + 0.149\text{mm}$ fraction, the carbonates appear mainly as free grains and the apatite liberation increases. In some veins there is a composition zoning in carbonates, varying from dolomite to calcite.

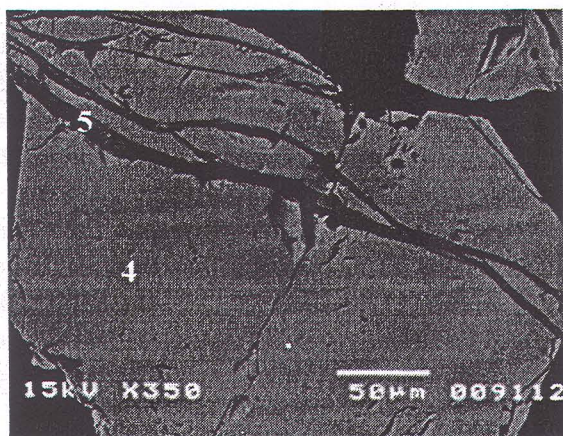
All the characteristics of the apatite crystals demonstrate that this mineral is essentially original (not secondary), although electron microscopy studies locally show some apatite grains with different gray shades, indicating different concentrations of Sr and rare-earth elements, suggesting more than one generation of original apatite (Figure 1d – sample 11).



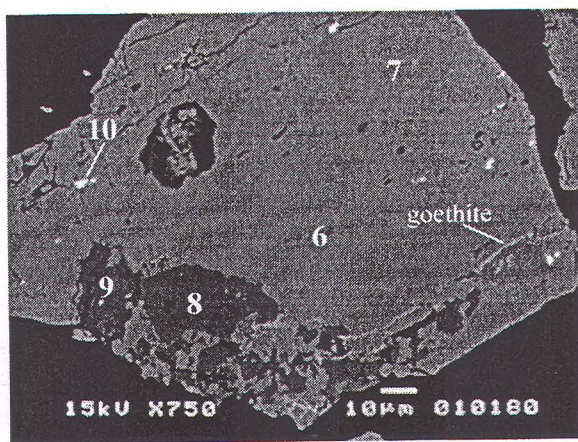
(a)



(b)



(c)



(d)

Area	CaO	SiO ₂	MgO	SrO	BaO	FeO	P ₂ O ₅	REE	CO ₂	TiO ₂	K ₂ O	Al ₂ O ₃	Mineral
1	53.0	0.0	0.0	3.2	0.1	0.0	42.7	1.0	-	0.0	-	-	apatite
2	57.5	0.4	0.0	1.1	0.5	0.0	39.7	0.8	-	0.0	-	-	apatite
3	54.6	-	0.3	1.2	0.5	0.6	-	-	42.8	-	-	-	calcite
4	57.8	0.5	-	0.8	-	0.2	40.1	0.4	-	0.2	-	-	apatite
5	55.6	0.3	0.8	0.1	0.1	0.0	-	-	43.1	-	-	-	calcite
6	57.9	0.2	0.1	0.9	0.0	0.3	40.5	0.0	-	0.0	-	-	dark apatite
7	57.1	0.0	0.0	1.2	0.0	0.1	40.2	1.1	-	0.3	-	-	light apatite
8	-	63.7	-	-	-	-	-	-	-	-	19.9	16.4	K-feldspar
9	3.7	53.9	2.3	-	-	36.3	-	-	-	-	-	3.8	nontronite
10	8.9	0.3	0.1	0.9	1.9	0.6	31.2	50.6	-	5.4	-	-	monazite

Figure 1 – Backscattered electrons image of apatite from clinopyroxenites of the Tapira mine: (a): apatite with rough surface (sample 12). (b): apatite with inclusions of calcite (sample 9). (c): apatite cut by calcite veinlets (sample 6). (d): apatite with different gray shades showing inclusions of monazite, nontronite and alkali feldspar (sample 11).

Numbers in the images correspond to the EDS microanalyses in the table.

Apatite composition

In Table 2, microprobe analyses are given for each one of the 12 apatites originating from the 12 samples of clinopyroxenites from the Tapira mine. This table also shows the structural formula of apatite calculated with the oxides obtained by microprobe analyses.

Substitutions of Ca^{2+} mainly by Sr^{2+} and rare-earth elements are observed in all 12 apatites, with minor Na^+ , Mg^{2+} and Fe^{2+} contents. Substitutions of the PO_4^{2-} group by SiO_4^{4-} and of F^- by OH^- were also detected. Although the analyses sum up to 100%, the infrared spectrometry studies indicated the presence of carbonate substituting for phosphate (Figure 2). The infrared spectrometry studies also indicated the presence of OH^- in the apatite structure. The PO_4^{3-} ion is characterized by the absorption peaks at 602-571 to 575 cm^{-1} (triply degenerate asymmetric bending – ν_4), 961 cm^{-1} (symmetric stretching – ν_1), 1092-1038 to 1042 cm^{-1} (triply degenerate asymmetric stretching – ν_3) and 1991-2003-2080 cm^{-1} ($\nu_1 + \nu_3$). The OH^- is characterized by the bands at 718-737 cm^{-1} and 3539-3546 cm^{-1} and the CO_3^{2-} by the bands at 876-880 cm^{-1} , 1420 and 1466 cm^{-1} . The OH^- stretching peak at 3539-3546 cm^{-1} and the libration peak at 718-737 cm^{-1} are typical of a fluor-hydroxylapatite (Santos & Clayton, 1995; Comodi *et al.*, 1999) because they are shifted when compared with a hydroxylapatite whose OH^- stretching peak appears at 3560-3570 cm^{-1} and the libration peak occurs at 630-635 cm^{-1} .

The results of WDS (wavelength-dispersive spectrometry) microanalysis together with infrared spectrometry indicated that the apatite is a carbonate-strontium-fluor-hydroxylapatite (McClellan, 1980). The average content of SrO in the apatite varies from 0.66% to 1.37%; F from 1.02% to 1.82% and the REE_2O_3 content is <1% (0.26% to 0.77%) in most of the samples, with the exception of sample 10 – slightly altered clinopyroxenites (1.93%), samples 4 and 9 – micaceous clinopyroxenites (1.00% and 1.45%, respectively) and sample 8 – clinopyroxenite rich in magnetite and perovskite (1.47%).

The apatite floatability can be influenced by several factors, such as apatite composition, crystal size, degree of crystallinity, the collectors and depressants used in the flotation process and pH values. The gangue minerals, i.e. the non-apatite minerals: carbonates and others calcium-bearing minerals, iron-magnesium minerals, etc., and the partial coverings by goethite thin crusts can also interfere in the apatite flotation performance.

The chemical replacements in apatite can modify the values of the unit cell parameters, the density and the crystal stability. The substitution of PO_4^{3-} by CO_3^{2-} has a destabilizing effect on the apatite structure which results in increased solubility. The substitution of Ca^{2+} by Sr^{2+} increases the apatite density. Studies by Rodrigues & Brandão (1993) showed an increasing of the unit cell parameters a (9.4016Å) and c (6.8929 Å) in apatites from Tapira what can be mainly explained by the substitution of Ca^{2+} by Sr^{2+} and REE^{3+} . The replacement of PO_4^{3-} by CO_3^{2-} causes a decrease in the unit cell parameter “ a ” and an increase in “ c ” and the substitution of F^- by OH^- causes an expansion in “ a ” and a contraction in “ c ”.

The following main characteristics of apatite: that they are essentially original, well formed, normally with smooth surfaces, mainly with a clear aspect and showing partial coverings by goethite thin crusts in less than 2-5% of apatite grains, suggest that these samples would have a good performance in the froth flotation process. One of the problems could be the presence of carbonates as small inclusions in apatite or as veinlets what would contaminate the apatite concentrate, since an excessive grinding of the ore would be needed to liberate them. However, as the major part of the carbonates appears as free grains, the use of more selective collectors such as sulphosuccinates and sulphosuccinamates instead of vegetable saponified oils would produce cleaner concentrates (Barros *et al.*, 2001).

Table 2 – Electron probe microanalysis of apatites from different types of clinopyroxenite

Oxide (%)	Slightly altered clinopyroxenite			Micaceous clinopyroxenite			Argillaceous clinopyroxenite		Clinopyroxenite rich in magnetite and perovskite			
	2	5	10	1	4	9	11	12	3	6	7	8
SiO ₂	0,32	0,41	0,66	0,44	0,43	0,51	0,25	0,44	0,49	0,40	0,41	0,31
FeO	0,06	0,06	0,04	0,04	0,06	0,03	0,04	0,04	0,05	0,03	0,07	0,04
MgO	0,01	0,02	0,03	0,03	0,03	0,01	0,01	0,01	0,03	0,03	0,03	0,03
CaO	54,26	53,39	52,00	53,68	53,65	52,31	54,41	53,66	54,35	53,67	53,91	52,21
SrO	1,26	0,92	1,20	1,16	1,12	1,18	0,88	1,30	1,02	0,76	0,66	1,37
Na ₂ O	0,05	0,12	0,22	0,10	0,12	0,17	0,05	0,05	0,06	0,06	0,06	0,31
P ₂ O ₅	41,75	42,03	40,48	40,96	42,27	41,38	42,78	42,14	42,50	41,91	42,24	42,21
Y ₂ O ₃	0,01	0,02	0,04	0,01	0,02	0,04	0,00	0,00	0,01	0,00	0,01	0,01
La ₂ O ₃	0,08	0,21	0,48	0,12	0,22	0,37	0,03	0,13	0,08	0,03	0,05	0,31
Ce ₂ O ₃	0,22	0,44	1,19	0,28	0,61	0,87	0,16	0,37	0,21	0,17	0,18	0,94
Pr ₂ O ₃	0,09	0,06	0,08	0,12	0,07	0,08	0,05	0,04	0,01	0,04	0,02	0,09
Nd ₂ O ₃	0,05	0,06	0,18	0,02	0,10	0,13	0,04	0,06	0,03	0,02	0,05	0,13
F	1,82	1,26	1,16	1,81	1,54	1,09	1,15	1,47	1,04	1,02	1,13	1,53
H ₂ O	0,91	1,17	1,18	0,89	1,05	1,23	1,25	1,09	2,71	1,29	1,24	1,04
Cl	0,01	0,01	0,00	0,01	0,01	0,01	0,01	0,01	0,02	0,01	0,02	0,01
	100,91	100,19	98,93	99,67	101,30	99,40	101,10	100,78	102,60	99,44	100,08	100,55
O=F,Cl	0,77	0,53	0,49	0,76	0,65	0,46	0,49	0,62	0,44	0,43	0,48	0,68
total	100,14	99,65	98,44	98,91	100,65	98,93	100,61	100,16	102,16	99,01	99,60	99,86
Atoms to 26 oxygens												
P	5,96	6,01	5,92	5,93	6,00	5,99	6,03	6,00	5,82	6,01	6,01	6,04
Si	0,05	0,07	0,11	0,08	0,07	0,09	0,04	0,07	0,08	0,07	0,07	0,05
total	6,02	6,07	6,03	6,00	6,07	6,07	6,07	6,07	5,90	6,07	6,08	6,10
Fe ²⁺	0,01	0,01	0,01	0,01	0,01	0,00	0,01	0,00	0,01	0,00	0,01	0,01
Mg	0,00	0,01	0,01	0,01	0,01	0,00	0,00	0,00	0,01	0,01	0,01	0,01
Ca	9,81	9,65	9,62	9,83	9,63	9,58	9,71	9,66	9,42	9,73	9,71	9,46
Sr	0,12	0,09	0,12	0,12	0,11	0,12	0,08	0,13	0,10	0,07	0,06	0,13
Na	0,01	0,03	0,06	0,03	0,03	0,04	0,01	0,01	0,01	0,01	0,02	0,08
Y ³⁺	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
La ³⁺	0,01	0,01	0,03	0,01	0,01	0,02	0,00	0,01	0,00	0,00	0,00	0,02
Ce ³⁺	0,01	0,03	0,07	0,02	0,04	0,05	0,01	0,02	0,01	0,01	0,01	0,06
Pr ³⁺	0,01	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01
Nd ³⁺	0,00	0,00	0,01	0,00	0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,01
total	9,98	9,84	9,94	10,02	9,85	9,84	9,83	9,85	9,56	9,85	9,83	9,78
F	0,97	0,67	0,63	0,98	0,82	0,59	0,60	0,78	0,53	0,54	0,60	0,82
OH	1,02	1,32	1,37	1,02	1,18	1,41	1,39	1,22	1,46	1,45	1,39	1,18
Cl	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00
total	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00	2,00

Other gangue minerals identified in the samples (oxides and silicates) probably would not cause problems in the froth flotation of apatite, with the exception of nontronite in argillaceous clinopyroxenites what could contaminate the concentrate by entrainment and cause an increase in reagents consumption.

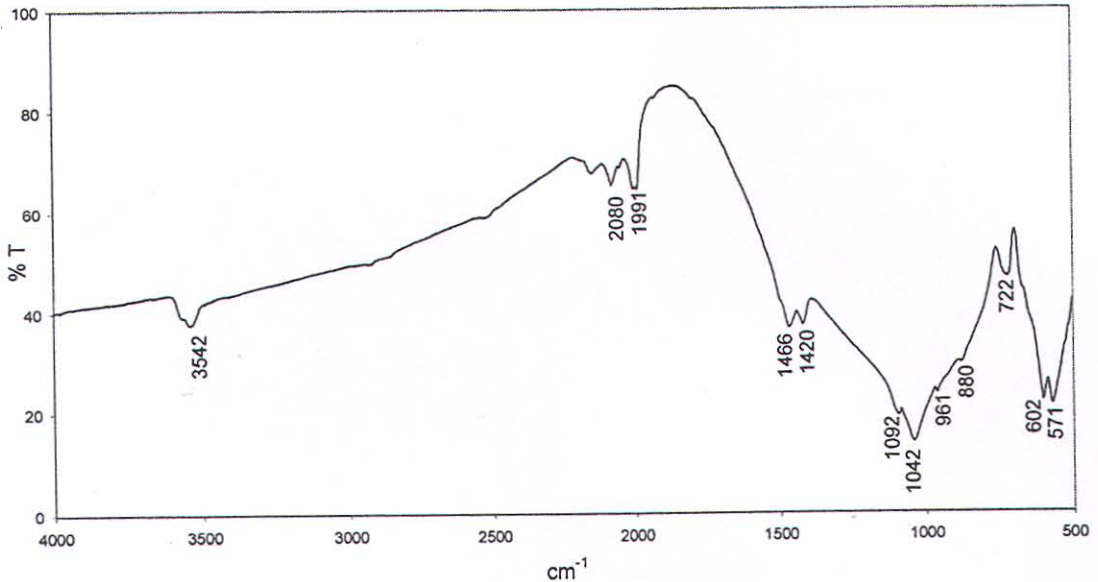


Figure 2 – Typical infrared spectrum (transmission) of an apatite concentrate (sample 7) from the Tapira mine-MG.

CONCLUSIONS

The apatite characteristics observed in all the 12 samples studied indicate that this mineral is essentially original (not secondary) and was one of the first minerals to form, since it appears as inclusions in the other minerals: pyroxene/amphibole, magnetite, micaceous minerals, nontronite, goethite, garnet and perovskite. The apatite normally has smooth surfaces with the exception of some apatites from the argillaceous clinopyroxenite that show rough surfaces what indicate the beginning of dissolution. The apatite crystals are normally clean, although fluid inclusions and inclusions of carbonate (mainly calcite and locally strontianite) are commonly. Inclusions of barite, monazite, ilmenite and zirconolite are locally observed. Partial coverings by goethite thin crusts can be observed only in less than 2-5% of the apatite grains. Among the ore types studied, the apatite present in the clinopyroxenite rich in magnetite and perovskite shows the clearest aspect and the apatite of sample 11 (argillaceous clinopyroxenite) exhibits the greatest quantity of inclusions, identified as monazite, barite, nontronite, calcite, ilmenite, zirconolite, ankerite and alkali feldspar.

All the 12 apatites studied are classified as carbonate-strontium-fluor-hydroxylapatite and show substitutions of Ca^{2+} mainly by Sr^{2+} and REE^{3+} and also by Na^+ , Mg^{2+} and Fe^{2+} ; of

the PO_4^{2-} group by SiO_4^{4-} and CO_3^{2-} and of F^- by OH^- . The average SrO content varies between 0.66% and 1.37% and that of F between 1.02% and 1.82%. The REE_2O_3 contents are less than 1% in most samples, with the exception of apatite from sample 10 – slightly altered clinopyroxenite (1.93%), sample 9 – micaceous clinopyroxenite (1.45%) and sample 8 – clinopyroxenite rich in magnetite and perovskite (1.47%).

Although the apatite is essentially original, electron microscopy studies locally show some apatite grains with different gray shades, indicating different concentrations of SrO and rare-earth elements, what can suggest more than one generation of the original apatite.

The apatite characteristics indicate that it would have a good performance in the froth flotation process. However, the problems could be: the selectivity in relation to gangue minerals, mainly in the samples having high amounts of carbonates occurring either as isolate grains or as inclusions or veinlets within the apatite crystals. Also, the clay mineral nontronite could pose problems by increasing reagents consumption and contaminating the final concentrate by entrainment.

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