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STUDY OF THE MANGANESE ORES OF THE SERRA DO NAVIO DISTRICT. — AMAPA' — BRAZIL

por
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ABSTRACT

A general review of the literature on the Serra do Navio district is made, (including some unpublished reports) and the mineralogy and texture of over 50 samples of ores, protores and country rocks are studied and their main features described.

Two minerals, namely graphite and tephroite, not yet recorded in previous works, were found. Lithiophorite, which had been determined in X-ray diffraction analyses, was identified in polished sections.

Conclusive evidences for a supergene or hypogene origin of the ore were not found, but the available evidences point toward a supergene origin of most of the ore, if not all.

Specimens containing weathered spessartite crystals were studied and it is concluded that, though giving rise to some manganese oxide, spessartite should, more properly, be considered as an undesirable constituent of the protore. It is suggested that tephroite might have been a significant source of ore, and that rhodochrosite, found at depth in recent drill holes, probably played a very important part in the formation of the ore. The point is made that other carbonates, mainly calcite, commonly present in the protore, also helped in the formation of ore not only giving off CO_2 during weathering but also enabling solutions to percolate more easily downward.

INTRODUCTION

The principal aim of this work was to study and interpret the mineralogy, textures, and structures of over fifty samples collected from the Serra do Navio manganese deposits, and, on the base of these observations and interpretations combined with field information secured from publications by other workers, to give an acount for the genesis and control of ore deposition. Laboratory work consisted of microscopic studies of thin and polished sections, heavy liquid and electromagnetic separations, determinations of specific gravities and refractive indexes, and some microchemical tests. A few samples were analysed by X-ray diffraction, spectroscopic and chemical methods.

The writer is indebted to Thomas Tieh for much profitable discussion. Professors C. Osborn Hutton, Iphigênio S. Coelho and Charles F. Park Jr. were generous advisors. Mr. John V. N. Dorr II very kindly made the critical reading of the typescript and contributed many sound suggestions. The author wishes also to express his gratitude to his colleagues of the Instituto de Pesquisas Radioativas for their help with chemical, spectrographic and X-ray diffraction analyses.

DESCRIPTION OF THE SERRA DO NAVIO MANGANESE DEPOSITS

The manganese deposits of Serra do Navio lie approximately at latitude 1° North, longitude 52° West, in the center of the Federal Territory of Amapá, Brazil. They are now connected by railroad to the port of Santana, some 200 kilometers to the southeast, on the banks of the North Channel of the Amazon river. Santana can be reached by car from the town of Macapá, capital of the Territory, which is some 20 kilometers to the north. Macapá, in turn, is regularly connected by plane to the city of Belém and through Belém to other parts of the world.

According to Dorr et al. (3), manganese ore in the region was first noticed by Snr. Mário Cruz, a local woodsman and prospector, in 1941. He was travelling along the Amapari river and, without knowing what the material was, took a piece of ore to use as ballast in his canoe. Five years later, when Hanna Co. began prospecting for iron ore in the Territory, Cruz recalled that piece of heavy rock he had found. He recovered the material and brought it to the Governor of the Territory, Capt. Janary Nunes, who sent a sample to be analysed, and it was found to contain over 55 percent manganese. In 1947 the Brazilian Government granted a concession to explore and develop the deposits to Indústria e Comércio de Minérios S. A. — ICOMI — producers of iron and manganese ores in the State of Minas Gerais. Later on, Bethlehem Steel Co. became ICOMI's associate in the project. The preliminary survey, including basic geological work, over 9,000 meters of diamond drilling, construction of the railroad and port, mining equipment, and so on, were finished in 1956. Production started in October of the same year, and since January 1957 the mine has been producing 2,000 metric tons of manganese ore averaging about 50 percent Mn daily.

From Santana to Porto Platon, which is halfway between the Amazon river and the mine, the railroad crosses a slightly dissected plain formed by deeply weathered river sediments covered by thin savannah-grass. This area is wholly useless to people and animals, for the soil has been so completely leached of its mineral contents that the land is entirely lost for agricultural and cattle-raising purposes.

Westward of Porto Platon, the crystalline shield appears, producing a radical change in topography and vegetation. From there on, the country is hilly and densely forested, with a growing number of people living along the railroad sides. They have a primitive agriculture, live in very poor wood-houses and many of them work in near-by cassiterite and gold placers.

Dorr et al. (3), describing the major physiographic elements bearing on the ore deposits, observed that in the Serra do Navio district

> ...there appears to exist an ancient erosion surface of low relief now being destroyed by the rejuvenated Amapari and its tributaries. A general concordance in elevation of the flat-topped ridges and plateaus over an area of tens os square kilometers suggests that a peneplain must have been present in this region before regional tilting initiated a new erosion cycle.

The region is drained by the Araguarí and Amaparí rivers the waters of which join some 15 kilometers west of Porto Platon, and, after making a sharp turn in direction, run directly into the Atlantic Ocean. The Amaparí cuts across the maganese deposits where its elevations is about 90 meters.

The climate at Serra do Navio is warm and humid though not depressing. The average annual precipitation is around 230 cm (90 inches), unevenly distributed throughout the year. During the dry season rainfall gets as low as 5 cm (2 inches) a month, whereas during the wet season — February through July — it gets as high as 20 to 50 cm (8-20 inches) monthly (13).

Health conditions both at Santana and Serra do Navio are now excellent. The concessionaire maintains there one of the best hospitals of the northern part of Brazil; and according to official figures, displayed proudly by the medical staff, the town of Serra do Navio in spite of having the highest birthrate of Brazil, has also the lowest infant mortality rate of the whole country.

GEOLOGIC ENVIRONMENT

The regional geology of the Territory or Amapá is little known. Most of it lies within the crystalline complex forming the Guiana shield, which is generally thought to be Precambrian in age. The local geology of the Serra do Navio area is now known in some detail through studies done by the concessionaire, but results of these studies have not yet been published. The only materials available to the author were a few publications by several geologists who have visited or worked in the district. The latest of such publications are those by Park (1956), Nagell and Seara (1958), and Martin (1959).

Martin's paper is a very brief description of some structural features of the orebodies, with a proposed hypothesis for the origin of the ore.

In his paper, Park described the geology of the area as follows:

> The Serra do Navio manganese deposits lie within the Crystalline complex forming the Guiana highlands. Outcrops of rocks are unusual in the area except for scattered exposures visible at low water in the beds of the Araguari and Amapari rivers and at waterfalls along their tributaries. Bedrock is effectively masked by heavy vegetation and lateritic soils. It is only where the debris is removed by running water that fresh or comparatively fresh

> underlying rocks can be seen. In the imediate vicinity of the ore deposits, the rocks exposed in gullies, shallow prospect holes, and encountered in diamond drill cores are predominantly amphibolites, mica schists, pyroxenites, and quartzites, with occasional showing of diabase and gabbro. Much of the surrounding region is underlain by granitic gneiss. Exposures are too scattered and obscure to permit comment on the distribution and sequence of the various rocks. Correlation of rock types between diamond drill holes was not possible and a recognizable stratigraphic sequence is not yet established.

Park also observes that the regional trend of these metamorphic rocks is north-northwest, and they dip moderately to the northeast.

To this general picture Nagell and Seara (11) add that the top of the ridges are covered by a thick layer of structureless, red, argillaceous material that reaches depths of about 30 meters. This saprolite is underlayed by rocks composed of clay and iron oxides with some quartz and garnet still exhibiting significant weathering. Fresh country rock can only be found 60 to 100 meters below the surface.

According to Nagell and Seara (11), the several lenses of ore are distributed in the area forming a "Y" (Fig. 1) about six miles long and two miles wide on the top of the "Y". This distribution is different from that described in earlier publications and is probably the result of a more complete investigation of the vicinity of the main ore zone. Nagell and Seara do not give detailed information on the new northern leg of the "Y", though it is clear from their map that it is formed by six lenses of "rolamentos" (detrital ore), which are not only at higher levels than the main belt but also crosscut the general trend of the region.

The general trend of the principal ore belt — north-northwest — coincides with that of the surrounding rocks. Maximum width of ore across the outcrops is about 200 meters. The belt is divided by the Amapari river and the most important orebodies lie to the east. Individual bodies seem to form lenses within the amphibolite. The largest and most consistent of these lenses is that along the crest and high flanks of Terezinha ridge, where ore crops out over a distance a 1.500 meters. The contact between orebodies and underlying altered schist is very irregular with sharp projections

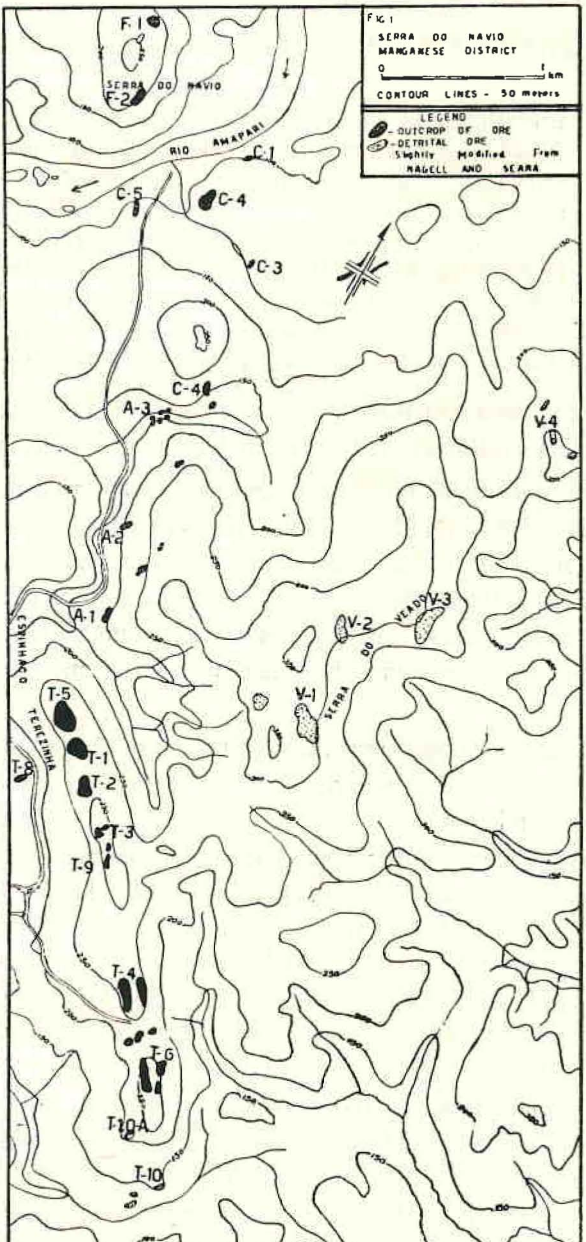
FIG 1
SERRA DO NAVIO
MANGANESE DISTRICT
0
1 km
CONTOUR LINES - 50 meters
LEGEND
- OUTCROP OF ORE
- DETRITAL ORE
Slightly Modified From
NAGELL AND SCARA
F-1
F-2
SERRA DO NAVIO
RIO AMAPARI
C-1
C-5
C-4
C-3
C-4
A-3
A-2
A-1
V-4
V-2
V-3
SERRA DO VEADO
V-1
ESTINHACO
TEREZINHA
T-5
T-1
T-8
T-2
T-3
T-9
T-4
T-6
T-10-A
T-10
T-11

Fig. 1

pointing downward. No ore has been found in contact with fresh rock and only a few orebodies reach depths of 60 meters (11).

Most outcrops consist of hard massive manganese oxide with altered remnants of garnetiferous rock and irregular tiny patches of whitish clay material. Boulder ore is economically important along the flanks of steep slopes and at the bottom of cliffs. Small concretionary nodules, known in Cuba as granzon, are widely distributed in the soil near manganese orebodies. Ore crops out at, or near, the crest of the ridges and it clearly controls the local relief.

On the basis of the geological data available at that time, Park in 1956 explained the distribution and character of the individual lenses as closely related to a zone of synclinal folding, and that folding and faulting have given rise to the present attitudes of the ore belt and individual orebodies. He also found that the orebodies give a slight hint of stratigraphic control.

Nagell and Seara (11) also agree on this stratigraphic control. They point out that the contacts between ore and altered country rock always follow the original stratification of the rock, and the local structures within the orebodies also follow the general trend of the region.

Martin (9), who has recently made a study of the structure of the orebodies, arrives at the conclusion that "there are indications that the orebodies T-1 to T-10 are remnants of an anticlinorium accentuated by thrust faulting. Remnants of a synclinorium of a similar nature might be expected somewhere else." He also observed that all faults in the area are strike faults, no cross-cutting faults were found, and he thinks they are not necessary to explain the distribution of the orebodies.

LABORATORY STUDY OF ROCKS AND ORES FROM THE AREA

The Serra do Navio suite in the Stanford Ore Deposits laboratory, on which most of this study is based, comprises some 50 specimens, which were in part collected by John Van N. Dorr II, in 1948, and, in part, by Charles F. Park Jr. in 1955. Samples collected by Dorr are mainly rocks and ores taken from the surface and from shallow prospect holes. Those collected by Park are chiefly drill cores.

In this collection there are typical examples of practically all rocks reported in the literature on the deposit. Most of the minerals identified in previous studies were found in the present investigation. The few exceptions are scapotite, reported by Scorza (14), manganite by Leinz (8), and ramsdellite, identified in the Cleveland laboratory (7). Two other important minerals, namely graphite and tephroite, which are not recorded in the literature, were identified during this study.

The rocks were identified as: granitic gneiss, quartzite, amphibolite, pyroxenite, gabbro, mica schist, diabase, and highly metamorphosed volcanic rocks.

The presence of garnets of one type or another is a common feature of these rocks. Only in the granitic gneiss and in the diabase were they not found. Tourmaline is present in some samples and it is an important constituent of a quartz-muscovite schist (Fig. 2) and a highly metamorphosed tuff (Fig. 3). Graphite was found in several preparations (Fig. 2, Fig. 3 and Fig. 12). Its presence was first noted

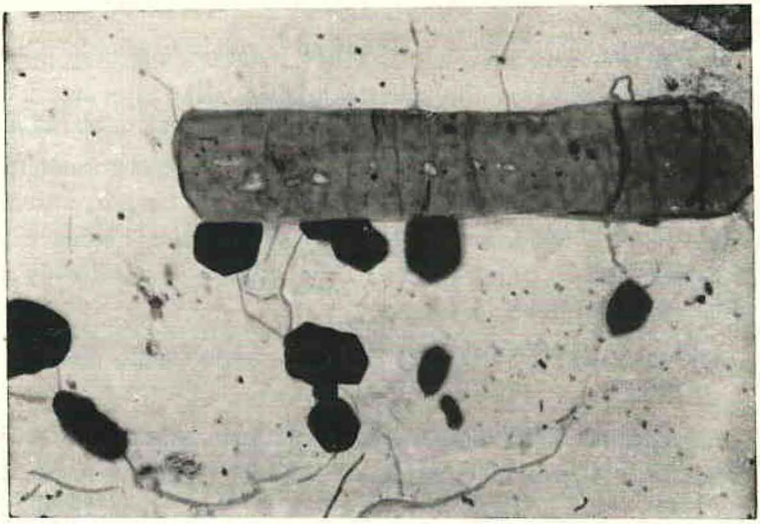

Fig. 2 — Tourmaline (gray) and graphite (black) in a quartz-sericite schist (grayish background). X 237, parallel light, OD-27583, Chumbo C-2, DH 27, 122 ft.

when the mineral floated on the surface during routine elutriation. Its determination was confirmed by X-ray difraction.

Sillimanite is found in a garnet-sillimanite-biotite schist (DH 18, 120 ft, C-2). Tremolite is the principal constituent of a sample of amphibolite (C-2, DH, 160 ft). Pyrite is present in small amounts in many preparations. Arsenopyrite was identified in two samples and it is probably present in many others. Some rocks have undergone appreciable chloritization, sericitization, and silicification. Some of the specimens exhibit veins of zeolites, adularia, and carbonates (probably calcite). Hematite was noted in a quartz-mica schist; the mineral occurs with pyrite in a veinlet cutting a garnet crystal.

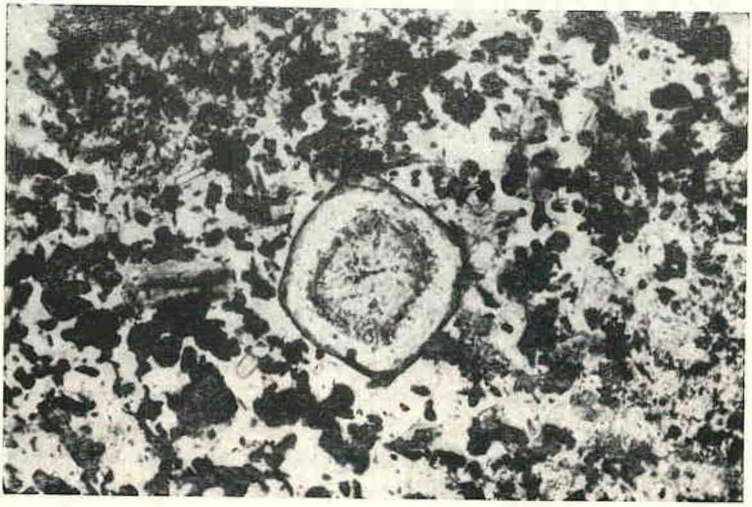

Fig. 3 — Spessartite grain with opaque inclusions of graphite (?) in the central zone and fresh borders. The rock is a highly metamorphosed tuff. Small prismatic crystals are tourmaline. Part of the opaque material outside the garnet crystal is graphite and part is manganese oxide. X 100, parallel light, OD 27575, C-2, DH 7, 152 ft.

Manganese oxide is found in many samples of the country rock and in samples of gondite. Its most striking feature is that it develops along the grain boundaries of the gangue minerals and replaces the latter. Quartz and garnet seem to be the most refractory minerals to this replacement. Veinlets of manganese oxide cutting across garnet and quartz crystals are also common. (Fig. 4 and Fig. 5).

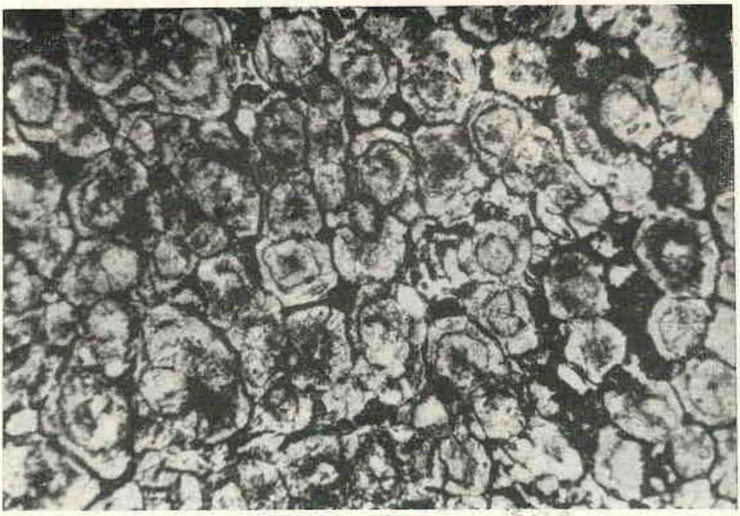

Fig. 4 — Gondite with some manganese oxide (black) introduced along the grain boundaries of garnet and quartz crystals. Note that most garnet grains display inclusions of graphite (?) following crystallographic directions. X 30, parallel light, OD 27564, near Antunes deposit.

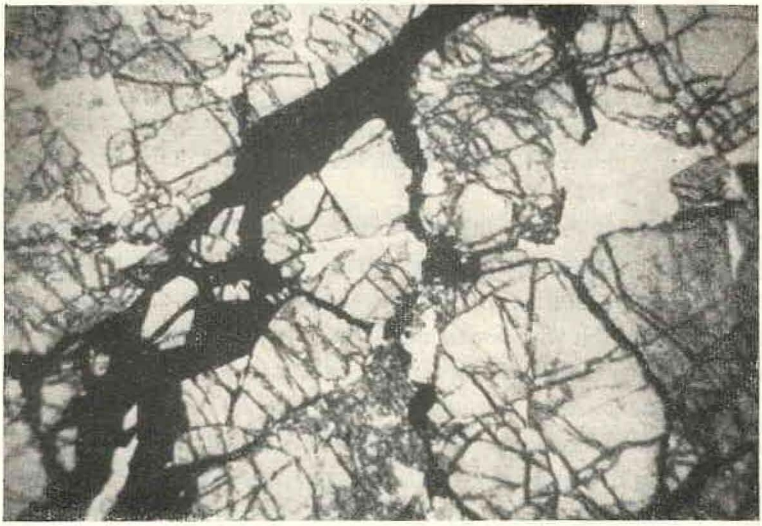

Fig. 5 — Manganese oxide (black) crossing originally interlocking spessartite crystals (light gray). X 16, parallel light, OD 27576, C-2.

DESCRIPTION OF THE ORES

The ores display a great variety of textural and structural features. They range from hard, compact material, nearly structureless, with high specific gravity, to soft, less dense types. Most of the ore is in the form of colloform aggregates, with colloform and mammilary textures. Cavities are abundant. Close inspection of some specimens reveals that the cavities are partially filled by successive layers of colloform microcrystalline manganese oxide, and layers of pyrolusite growing normally to the colloform bands.

Most of the ore is deep gray with a luster ranging from earthy to brilliant metallic. Some samples have a reddish tinge produced by iron oxide. Whitish patches of clay material and remnants of garnet crystals can be found in nearly all samples of ore. One specimen, the largest of the suite, gives a good suggestion of bedding.

MINERALOGY

As it has been emphasized by Park (13), a complete study of the manganese minerals of the Serra do Navio district has not yet been attempted. References to the subject in the literature are somewhat contradictory.

In 1948, Viktor Leinz (8), in one of the first description of the deposit, mentioned spessartite, pyrolusite, psilomelane, and manganite as being the only manganese minerals he could find in the ore. The presence of neither psilomelane nor manganite have been confirmed by later workers. Leinz described manganite as occurring in acicular crystals replacing garnet, and he stated that manganite represents a stage in the transformation of garnet into pyrolusite. Judging from his description and from the microphotograph in his paper, it seems to this writer that this acicular mineral is the same found in samples OD 27566 (Fig. 6 and Fig. 7) and IPR 2064 (Fig. 17 and Fig. 18). This material was separated as well as possible from the garnet and analysed chemically and by X-ray diffraction, when it was found to be amorphous (gave no definite X-ray pattern) and to contain less silica and more alumina than spessartite.

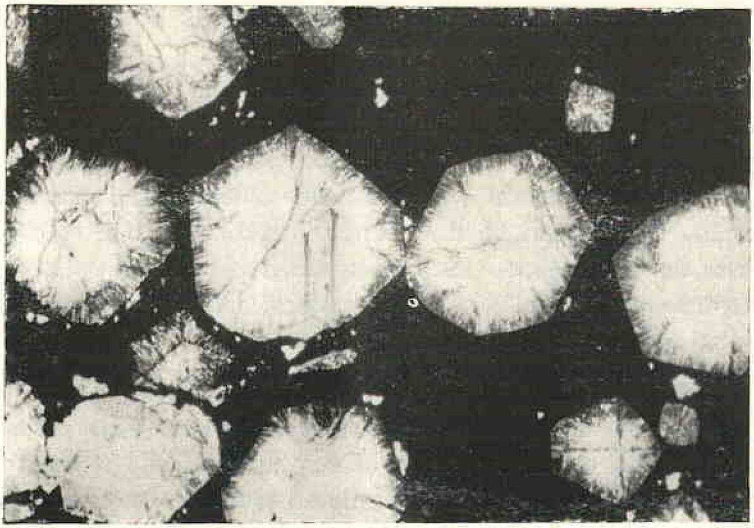

Fig. 6 — Spessartite crystals (white) with amorphous alumina-rich material along the borders, rhodochrosite (gray) and clay material (white) in the center. Black background is formed by manganese and iron oxides. See also Fig. 16. X 24, parallel light, OD 27566, T-1, DH-3. 255 ft.

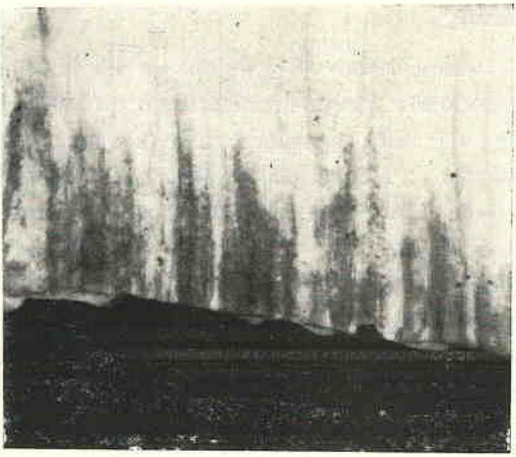

Fig. 7 — The same as Fig. 6 (above) with higher magnification. The acicular black areas in the photo (actually white in the hand specimen) are formed by amorphous alumina-rich material. X 337, parallel light.

Scorza (14), in 1949, found that the main manganese ore mineral in the Serra do Navio district is cryptomelane.

J. M. Axelrod of the United States Geological Survey (in Dorr et al., 3) confirmed the presence of cryptomelane during his X-ray diffraction studies; lithiophorite was also reported, but not pyrolusite.

A sample of ore was submitted to the micro-optical section of the Squier Signal Laboratory, Signal Corps, United States Army (in Dorr et al., 3), where the material was examined by electron microscopy, X-ray diffraction, and emission spectroscopy with the following results: "The material is fairly pure manganese dioxide, predominantly alpha (cryptomelane) phase, quite well crystallized. Gamma phase, if present at all, is minor. The presence of lithiophorite was not confirmed."

It was also concluded that the beta phase MnO_2 (pyrolusite), if present at all, is very minor.

In 1956, Park (13) reported that fresh garnet had been studied by D. E. Lee who concluded: "The garnet is very nearly 90 pct spessartite, with the remaining 10 pct made up of grossularite and almandine." Park also stated that "small quantities of hausmannite (?) were noted by Lee in the spessartite rock . . .".

In 1956, 30 samples were analyzed by X-ray diffraction in Brazil when the concessionaire was testing the ore to see if it were suitable for battery ore (7). It was concluded that cryptomelane and lithiophorite are the principal manganese minerals in the Chumbo area, whereas pyrolusite is the most abundant manganese mineral in the Terezinha area, where lithiophorite occurs only in minor amounts. At the same time, it was determined that the granzon material is formed by pyrolusite and nacrite. Other interesting information from the same source is that one sample studied by X-ray diffraction in the Cleveland laboratory in 1955 was said to contain 30 pct ramsdellite. No ramsdellite was found in the analyses done in Brazil.

As it is indicated by Sorem and Cameron (17), the study of manganese oxide ores can only be done appropriately by combining microscopic study of polished sections with mineral identification by X-ray diffraction. Unfortunately, this technique could not be used as a routine practice in the present investigation, which was mainly

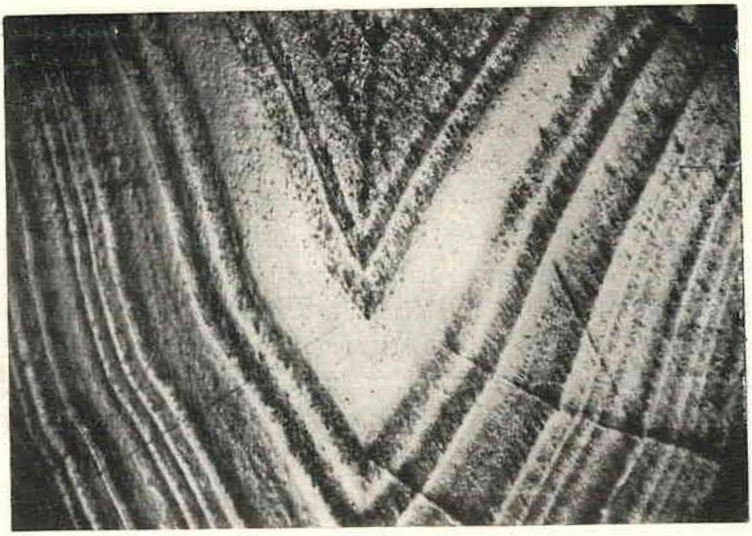

Fig. 8 — Polished section showing colloform cavity-filling ore. Pyrolusite (light gray) and cryptomelane (dark gray) in alternated layers. X 4, plain light, OD 27560, Cancão.

Fig. 9 — Colloform deposition of manganese oxides. Cryptomelane (gray) and pyrolusite (white). X 4, plain light, Serra do Navio, OD 30152.

restricted to thin-section and polished section examinations. X-ray diffraction was only used in the identification of a few minerals.

The following is a description of the manganese minerals identified during the present study.

Cryptomelane — Found typically in continuous colloform layers banded with layers of pyrolusite and, sometimes, goethite (Fig. 8 and Fig. 9). Recognized by its cryptocrystalline nature and relatively low reflectivity. Abundant.

Pyrolusite — Found in colloform bands (Fig. 8 and Fig. 9) and also in aggregates of prismatic crystals (Fig. 10). Anisotropic with high reflectivity, Ar = 5° (in air and using white light), distinct dispersion with r > v, and hardness ranging from C to E in Short's scale. In hand specimen pyrolusite can be seen in well developed crystals (polianite) covering the walls of cavities.

Fig. 10 — Pyrolusite (white, different shades of gray and black) in prismatic crystals. X 4, plain light, Terez., OD 27591.

Lithiophorite — This mineral is reported in several X-ray analyses of the Amapá ores but had not yet been identified in polished sections. The author found two of his specimens contained the mineral (Fig. 11). The identification was based on:

a — Strong bireflectance in oil from dark gray (nearly black) to grayish white; b — Strong anisotropism with four extinctions per revolution; c — Ar = 35° (in oil and white light); d — No dispersion and no internal reflection. As indicated by Sorem and Cameron (16), the color changes from pale blue to pale yellow when the mica plate is inserted and the stage is rotated. Most commonly the mineral occurs in aggregates of very small flakes, though some isolated grains were seen mixed with other manganese oxides. In both samples the mineral constitutes less than 1 pct of the ore. One of them was taken from an outcrop in the Chumbo area, but the other came from a drill hole core 75 meters below the surface.

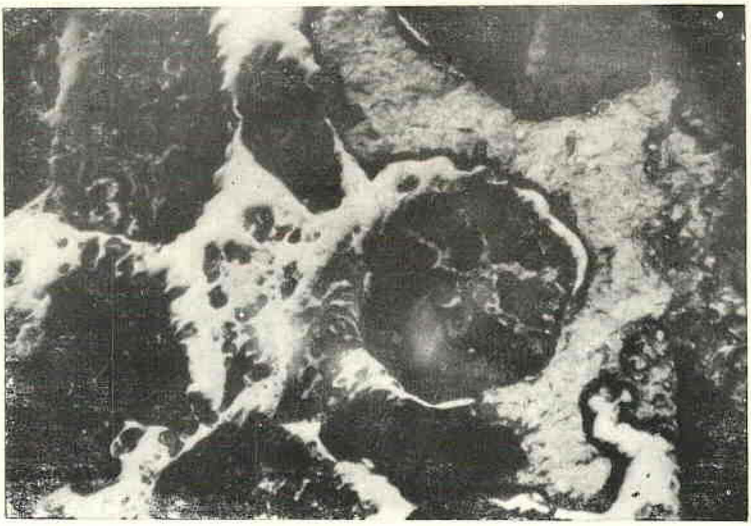

Fig. 11 — Polished surface showing aggregates of lithiophorite flakes (medium gray on the right side and top) and pyrolusite (white). Garnet crystals (black) are being replaced by maganese oxide. X 100, Plain light, Cachoeira near Chumbo, OD 27552.

Tephroite — Found in only one sample where it constitutes about 80 pct of the rock, with the remaining 20 pct made up of carbonate, garnet and graphite. It was first identified as picrotephroite, which is the magnesianrich variety of tephroite, but later on a chemical essay revealed the presence of less than 5 pct MgO, whereas normal picrotephroite carries more then 10 pct MgO. Finally, X-ray diffraction confirmed the determination as tephroite (analyst: Clécio Murta).

The mineral is slightly pink in transmitted light (the hand specimen is dark gray) and is not pleochroic. Some individuals are nearly 1.0 cm long, and the boundaries between adjacent grains are irregular and interlocking. It has negative elongation, parallel extinction and a good parting (?) normal to the elongation dividing the crystal into small lenses (Fig. 12 and Fig. 13). Other properties are: Biaxial, negative, 2V = 64°, Nz = 1.78, Nx = 1.756, birefringence = 0.024, and G = 3.90.

A complete chemical analysis of the rock ran as follows:

		%
SiO_2	—	26.1
FeO	—	3.2
Al_2O_3	—	2.3
TiO_2	—	0.1
MnO	—	49.9
CaO	—	5.3
MgO	—	4.8
Ig.	—	7.0
TOTAL		98.7

(Analysts: Prof. Cássio Pinto,
Edith Moysés and
Josephina B. Fernandes).

It should be observed that when calcined at 900°C for 10 minutes the rock-powder presented a loss of weight of 7%, but after 20 minutes of calcination the color changed from ash-gray to black with the formation of an amorphous manganese oxide and the loss of weight was reduced to only 5%.

Spessartite — Garnets are abundantly distributed in both ores and country rocks. They range from almost colorless to pink, and from euhedral to completely anhedral. As has been determined by Lee (13), the fresh garnets within the ore are nearly pure spessartite. But spessartite is also found outside the ore in the country rock. In the case, for example, of a pink garnet that occurs in large crystals (a few millimeters in diameter) in the sillimanite-quartz-biotite schist OD 27580, the refractive index and specific gravity are essentially the same as for pure spessartite.

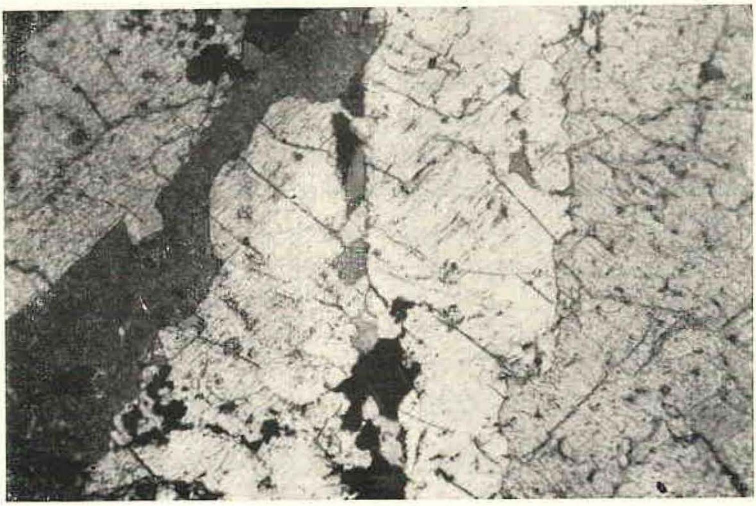

Fig. 12 — Large crystals of tephroite (different shades of gray). The vertical vein in the center is formed by calcite. Small black dots are graphite. Some of the black areas on the left side are garnet crystals, others are graphite. X 30, X nicols, OD 27581, Chumbo C-2, DH 26, 148 ft.

Spessartite crystals in the Serra do Navio ores very commonly display inclusions of other minerals. The most important of these inclusions are:

In some places manganese oxide is clearly replacing garnet along the borders or along crystallographic directions (Fig. 14). In some other cases, small spots of manganese oxide are seen inside garnet crystals.

Garnet crystals with fresh borders but displaying opaque inclusions paralleling the outlines of the grains are very abundant (Fig. 3 and Fig. 4). These inclusions are thought to be *graphite,* though it was not possible to determine the mineral with certainty.

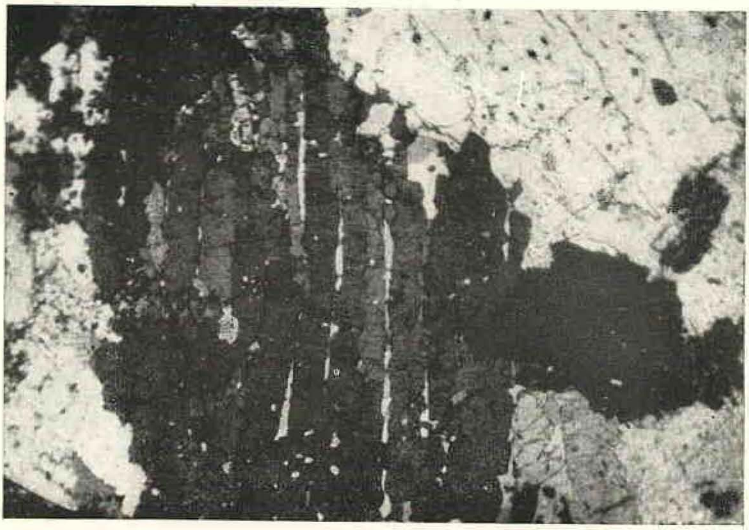

Fig. 13 — Calcite (vertical veinlets) distributed along crystallographic directions in tephroite. The large black area is a crystal of tephroite at extinction. X 30, X nicols, same specimen than Fig. 12.

It is interesting to note that similar inclusions are present in garnet crystals of the Indian deposits described by Fermor (5), and of the Lafaiete district, Brazil, described by Derby (2) in 1901. Derby's reference to these inclusions is:

> Under the microscope the rock is seen to be composed almost exclusively of closely appressed idiomorphic grains of white garnet showing a clear border but with the center highly charged with a black opaque powder that appears to be graphite.

Another type of inclusion found in the central part of manganese-rich garnet crystals with fresh borders is gibbsite. It occurs in aggregates of small grains, just large enough to permit exact determination by routine optical methods (Fig. 15). The mineral was probably formed by the break down of spessartite into manganese oxide, silica, and aluminum hydroxide.

Some specimens from Terezinha ore body display a large number of well shaped pseudomorphs of an amorphous *alumina-rich material*

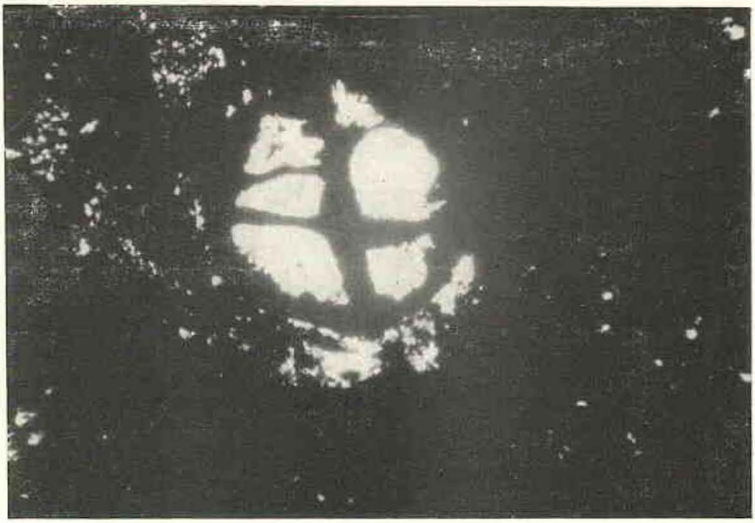

Fig. 14 — Spessartite crystal (white, center) replaced along the borders and along crystalographic directions by manganese oxide (black). Small white dots are remnants of garnet, and chlorite. X 100, paralled light, OD 27558, Chumbo.

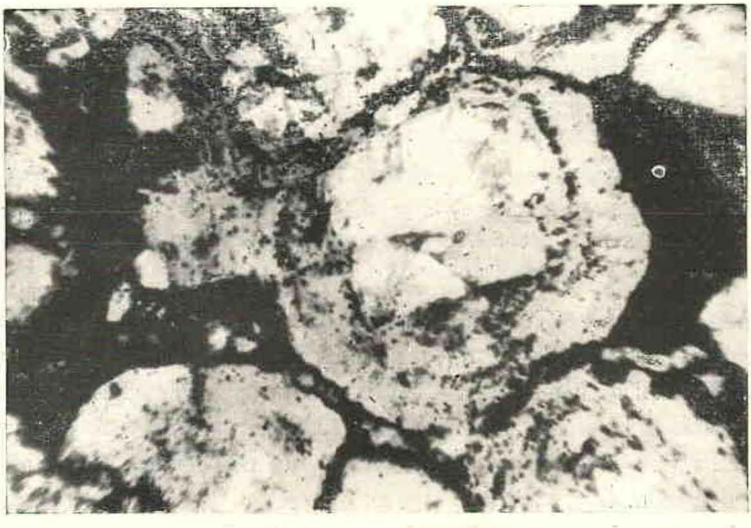

Fig. 15 — Inclusions of gibbsite (white) and graphite (?) (black) in spessartite (gray). X 100, nicols at 45°, OD 27564, Antunes.

after spessartite. (Fig. 6, Fig. 7, Fig. 17 and Fig. 18). The grains are cream-white on the outside and, when broken, shown a loose radial structure of acicular "crystals".

The interpretation was given that, subject to weathering, spessartite releases silica plus manganese and has alumina concentrated as an insoluble residue. This conclusion was partially confirmed by chemical assays which compare as follows with theoretical spessartite:

	Theoretical spessartite	Weathered spessartite
Silica	36.4%	25.4%
Alumina	20.6%	34.8%
Fe_2O_3	—	1.2%

(Analyst: Edith Moysés)

In specimen OD 27566 (Fig. 6 and Fig. 7) the wathering process has just started, but in sample IPR 2064 (Fig. 17 and Fig. 18) the garnet grains were almost completely replaced and only small, irregular fragments of spessartite could be seen in the central part of the grains.

An X-ray diffraction pattern of material estimated to contain more than 95 pct of the white acicular grains showed only the lines of spessartite. The film was considerably darkened suggesting the presence of an amorphous substance and it was finally concluded that, though acicular, the grains had no crystalline structure (analyst: Clécio Murta).

A spectrographic analysis gave Mn, Al and Si as principal constituents (analysis: Zilda Rabello).

Patches of *clay* material are also common inclusions in spessartite grains. The material is extremely fine-grained and appears isotropic (Fig. 6).

Carbonate (*rhodochrosite?*) is found in the same sample in which the amorphous silica is present (Fig. 6 and Fig. 16). It occurs along certain lines clearly related to crystallographic directions of the garnet crystals.

Other kind of inclusions, too fine-grained to be identified, are also found in the spessartite garnets.

Rhodochrosite (*?*) — As mentioned above, the garnet of one specimen has inclusions of a carbonate which is thought to be rhodochrosite (Fig. 6 and Fig. 16). The material is fine-grained and uniaxial negative with high birefringence. It was not washed off by concentrated HCl, and only began effervescing when the slide was slightly heated. According to this test the mineral is either dolomite, magnesite, or rhodochrosite. Considering that rhodochrosite has been found in depth in the deposit, and that associated minerals in the specimen are high in manganese, the carbonate is more likely to be rhodochrosite than dolomite or magnesite.

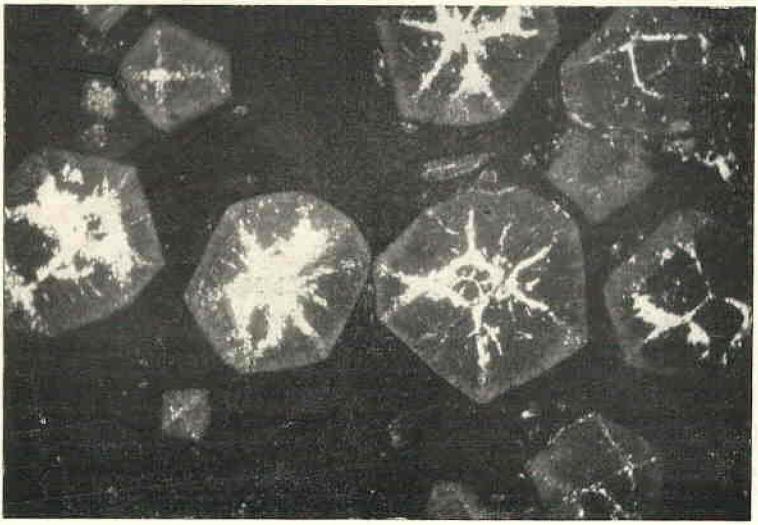

Fig. 16 — The same field as Fig. 6 with crossed nicols. Rhodochrosite? (white) clearly distributed inside spessartite crystals (dark gray) with reference to crystallographic direction. An amorphous alumina-rich mineral forms the light-gray, ribbon-shaped areas around garnet grains. Black background is mainly manganese oxide.

Textures of the Ores — Under the microscope two kinds of ores are easily distinguished by their textures: cavity filling ore and replacement ore. The former is indicated by the presence of delicate colloform bands, vugs, and cavities. Actually, most of the ore is formed by successive layers of manganese oxides, sometimes intercalated with layers of goethite, filling vugs and cavities. (Fig. 8 and Fig. 9). The second type is characterized by the presence of grains of garnet, quartz, and some other few gangue minerals. Veins of manganese oxide cut across these minerals or replace them along the borders (Fig. 4, Fig. 5, Fig. 11, Fig. 14 and Fig. 15). When the amount of manganese is not great enough to destroy the characteristics of the rock undergoing replacement, it is always more or less clear that the manganese oxides were mainly introduced along the grain boundaries of the gangue minerals (including spessartite in this category).

ORIGIN OF THE ORE

References in the Literature — In his paper published in 1948, Leinz (8) attributed the manganese oxide deposits of the Serra do Navio district to the weathering of the gondite. He gives considerable importance to spessartite as a source of ore, though he admits that other manganese minerals might have made significant contributions.

In 1949, Dorr, et al. (3) agreed with Leinz that the available evidences pointed toward the manganiferous silicates and, possibly, other manganiferous minerals, as being the source of the ores. However, they emphasized that some observed facts did not appear to fit well with this hypothesis. First, fresh garnets are found within the ore, and second, the manganese oxide is not concentrated along the contact of the gondite with the relatively impermeable rocks which form the foot-wall. They believed one or more other manganese minerals should be found at depth, and suggested rhodochrosite and alabandite as the more probable ones.

Park (13), in 1956, concluded that spessartite could hardly be considered as being the only source of manganese oxide, and that other mineral, or minerals, must have played a large part in the development of the ore. To the evidences previously found, Park added that the amount of alumina in the ore is not as high as should be expected if all the ore had been derived from the decomposition of spessartite.

Nagell and Seara (11) state the two general hyotheses — namely hypogene vs. supergene — for the origin of the ore in the following way:

> No distrito da Serra do Navio duas hipóteses principais foram aventadas para explicação da origem. Uma delas, a hipótese do

> gondito, propõe que os depósitos derivaram de silicatos e/ou carbonatos de manganês. Êstes minerais teriam sido atacados pelo intemperismo com remoção de alumina e sílica. Os óxidos de manganês remanescentes representariam uma concentração de minério residual.
>
> A outra hipótese é a de que o manganês se encontrava sob a forma de camadas sedimentares com alto teor de óxidos de manganês, os quais sofreram uma ação de metamorfismo. O metamorfismo pode ter produzido as pequenas quantidades de granada espessartita através da união química de pequenas porções de sílica com alumina, presentes como impurezas no sedimento original.

Though stating very well the problem of the genesis of the ore, Nagell and Seara do not manifest themselves in favor of one or another of the two hypotheses.

Martin (9), in 1959, expressed his opinion on the origin of the ore as follows:

> On T-4, in the middle portion of the main face, a remnant of the orebody is interbedded and interfolded with the schistose country rock. A system of small veins, filled with white kaolinic material, passes from the ore into the adjacent schists. The kaolinic filling and the general appearance make it probable that these veins are decomposed pegmatite or granitic veins. These veins have not been disturbed at the boundary between ore and country rock, neither do they show any sign of alteration in the orebody. This observation makes it probable that the ore is older than the folding and the matamorphism of the surrounding rock. Regarding the origin of the ore, it strongly favors the second hypothesis mentioned in the report "Trabalhos Geológicos no Distrito Manganífero" by R. H. Nagell and A. C. Seara. It suggests that the ore is of sedimentary origin with a high original content of manganese oxides, whilst the accompanying gondites would be derived from transitional, more siliceous beds, with a lower manganese content.

Coelho (1), in 1960, does not agree with Martin's conclusions. He thinks that the Serra do Navio mineralization has essentially the same origin than the Morro da Mina ores, and that Horen's hypothesis for the genesis of the Morro da Mina ores fits well to the mineralization at Amapá.

Syngenetic vs. Epigenetic — The crucial problem in the discussion of the origin of all gondite-type manganese deposits has been whether the manganese oxides are syngenetic or not. The economic implications of the problem are obvious. However, because in all manganese oxide deposits associated with manganese silicate protores some manganese oxides have undoubtedly been formed by weathering of other manganese minerals, the question should be put in more restricted terms: whether *some* manganese oxide is syngenetic or not.

In the particular case of the Serra do Navio manganese deposits, none of the ore-minerals identified in samples from the area can be considered as being critical evidence of the presence of some syngenetic oxide.

Hausmannite, determined with doubt by Lee (13), has not been confirmed by other investigators, and is not reported in any of the X-ray diffraction analyses. But even if the mineral is present, it does not constitute critical evidence since supergene hausmannite has been reported.

Ramsdellite, identified by X-ray diffraction in the Cleveland Laboratory (7) but not confirmed by any other analysis, is a mineral considered by Hewett and Fleisher (6) as being supergene in most cases, although it may be hypogene.

Also, neither manganite nor psilomelane, if present at all, would constitute critical evidence, for psilomelane is a supergene mineral and manganite may be supergene or hypogene.

Pyrolusite and cryptomelane, which are important ore minerals in the Serra do Navio district, are considered by Hewett and Fleisher as being both supergene and hypogene. Lithiophorite is a typical supergene mineral, and its presence in cores 75 meters below the surface indicates how deep weathering has reached in the area.

Therefore, the study of the mineralogy of the ore is not conclusive. It indicates that some ore is certainly supergene, but that hypogene ore may also be present.

Evidence from deposits in Minas Gerais of similar mineralogy to the Amapá deposits, makes it seem improbable that the manganese oxides are syngenetic. Due to the presence of graphite in the protore (up to 3 pct), and assuming a sedimentary origin, Dorr et al. (4) concluded that the material was deposited in an euxinic environment, where the pH is generally around 7 and the Eh around — 0.3. According to Krumbeir and Garrel's work (1952) in an environment with a pH of 7, manganese oxides cannot be deposited with a negative Eh. Instead of oxides, carbonates and sulfides are more likely to be formed, and this is in agreement with the presence of rhodochrosite and alabandite in the ore in the Merid Mine.

Now, since considerable amount of graphite also occurs in the Amapá ores, the same reasoning could be applied leading to similar conclusion. Alabandite constitutes the major difference between the two cases, for it has not yet been found in the Serra do Navio ores. Nevertheless, most authorities think that the mineral is very likely present; alabandite was not known to occur in the Merid Mine until a few years ago.

SOURCE-MINERALS

Rhodochrosite — The percentage of rhodochrosite in the protore is not known to the writer, but it probably was one of the more important source-minerals. As has been indicated by Park et al. (12), rhodochrosite is not only a source of ore but also a mineral that gives off CO_2 during weathering, which helps attack the other manganese minerals.

Tephroite — The author has found no reference to the actual response of the mineral tephroite to weathering. As it belongs to the olivine-group, it might happen that it is readily broken down during weathering, as most olivines are. Also, the inclusions of calcite along crystalographic direction (Fig. 13) almost certainly make the whole grain readily accessible to percolating solutions and promote, therefore, an easy breakdown. Nevertheless, the sample at hand (drill hole core, 148 ft) is fresh, and shows no sign of weathering. Only field work and a restudy of all drill hole cores of the area can show exactly how important was the part played by tephroite in the formation of ore. For the time being, the only possible statement is that the mineral tephroite might have been a significant source of ore.

Spessartite — Some manganese oxide has certainly been derived from spessartite but, to the writer, the significance of this mineral as a source of ore is rather doubtful. It withstands weathering for a long time and remains comparatively fresh after other source-minerals have been broken down. This is why, very often, spessartite crystals are found immersed in manganese oxide, thus lowering the grade of the ore.

An even when weathering is strong enough to break it down (with the consequent formation of some manganese oxide) an alumina-rich residue is left behind as an impurity and, if the percentage of spessartite in the protore is greater than a certain limit, the weathered material may be too high in alumina to be classified as ore. This is the case of sample IPR 2064 (Fig. 17 and Fig. 18) taken from a portion of Terezinha ore body which was been stripped away as too low-grade, high-alumina material.

Therefore, it is suggested that spessartite should be considered as an undesirable constituent of the protore rather than as a significant source of ore.

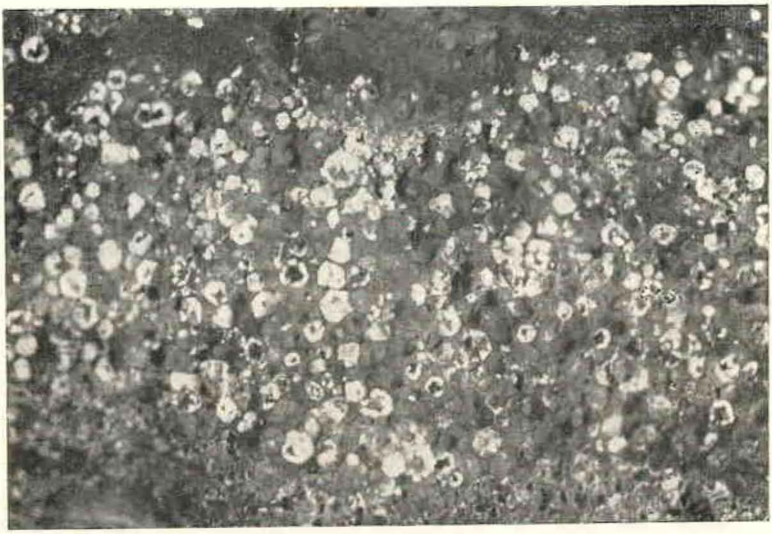

Fig. 17 — Microphotograph of hand-specimen IPR 2064. Altered spessartite grains (white) immersed in a mass of manganese and iron oxides. Black spots within white grains are remnants of unaltered spessartite crystals. X 10, IPR 2064, Terezinha T-2.

It is also the author's opinion that rhodonite and alabandite are likely to be found in future investigation.

Considering, therefore, the field information and the mineralogy and textures of the ores, the conclusion is that weathering was responsible for the formation of most, if not all, of the ore, and that permeability and susceptibility to chemical weathering of the rocks below the outcrops were important factors in controlling the formation and distribution of the ore at depth.

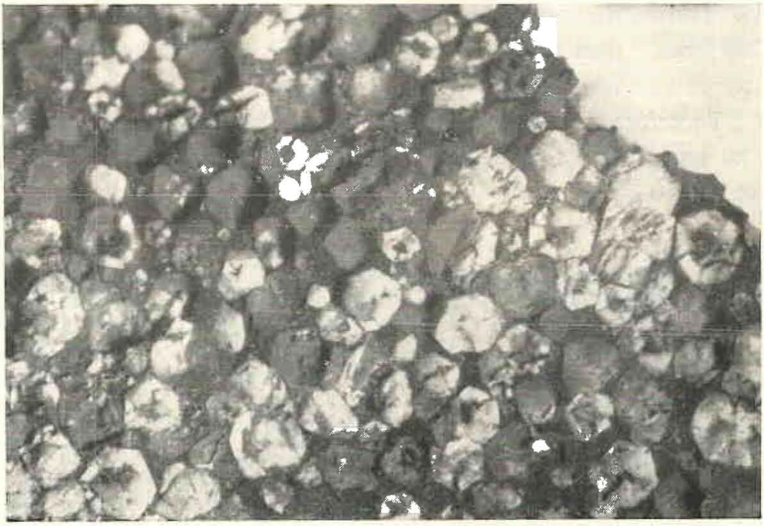

Fig. 18 — Another view of hand-specimen 2064 with higher magnification showing the well preserved dodecahedral shape of the garnet grains. X 30, IPR 2064, Terezinha, T-2.

ORIGIN OF THE PROTORE

Little or practically no evidence was found in the laboratory study that could give information on the origin of the protore. However, a stratigraphic control has been continuously reported for the ore, and deposits of similar nature in other parts of the world are generally thought to have a sedimentary origin. In their discussion of the origin of the Morro da Mina type protore, Dorr et al. (4) state:

> The sedimentary origin of the manganese of the silicate-carbonate protore is evident. In the Lafaiete district, for 60 km along

> strike the protore zone in interbedded with amphibolite, which may have been derived from an extrusive rock, and with graphitic schist or phyllite. The association of the manganese with a particular stratigraphic zone for 60 km can hardly be accidental.

Also, according to Service (15) and Fermor (5), who have written about very similar manganese deposits in Ghana and India respectively, those deposits present a stratigraphic control and are generally considered of sedimentary origin.

The author favors the idea that the Serra do Navio manganese protore also originated of sedimentary processes.

Metamorphic History — Judging from the present composition of the rocks of the area, the original sediments were probably argillaceous and calcareous rocks, manganese-rich sandstones, sandstones and tuffaceous sediments.

These rocks were subjected to a high grade metamorphism, probably regional metamorphism, by which they were changed to mica schists, amphibolites, dolomitic limestones, queluzites, gondites, quartzites, and metavolcanics.

Though not conclusive, there are some indications that these metamorphic rocks passed through a stage of igneous metamorphism. These indications are:

1 — the presence of tourmaline suggests the action of volatile-bearing solutions;

2 — tephroite is generally thought of as an igneous contact mineral;

3 — some drill hole cores have a distinct hornfelsic texture.

Finally, there is evidence of the existence of a hydrothermal stage in the history of the area. This evidence is the presence in veins of minerals such as pyrite, arsenopyrite, adularia, zeolites, calcite, and hematite, and the chloritization, silicification and sericitization of some rocks.

The effect of this hydrothermal stage on the protore and on the development of the ore cannot be easily evaluated. However, the fact that the tephroite-rock and the country rocks in general are cut by veinlets of calcite make it possible that the protore was cut by similar veins. If this was the case calcite certainly played the same role as rhodochrosite during the weathering of the protore: both were broken down releasing CO_2, which helped attack the manganese silicate minerals. The effect of calcite and rhodochrosite were additive and the net tendency was the formation of greater amounts of ore.

Note: Two other papers have been published on the manganese deposits of Serra do Navio after this one was written. They are:

"O Carbonato de Manganês como Protominério do Distrito de Serra do Navio", Nagell R. H. and Silva, A. R.; Bol. da Soc. Bras. Geol., vol. 10, N.° 2, November 1961, pg. 53-59.

"Geology of the Serra do Navio District", Brazil, Nagell, R. H., Econ. Geol., vol. 57, N.° 4, pg. 481-498, 1962.

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