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NICKEL-SILICATE AND ASSOCIATED NICKEL-COBALT-MANGANESE-OXIDE DEPOSITS NEAR SÃO JOSÉ DO TOCANTINS, GOIAZ, BRAZIL

BY

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By William T. Pecora

ABSTRACT

The nickel-silicate deposits and associated nickel-cobalt-manganese-oxide deposits on the summit area of the Serra da Mantiqueira, north of São José do Tocantins, State of Goiaz, Brazil, rest on unserpentinized pyroxenite, which is interlayered with serpentinized peridotite. The layers of intrusive igneous rock have a northerly trend and a steep westerly dip. All the known deposits are at high altitudes, from 950 meters to 1,130 meters, which is that of the summit, and are related to an ancient uplifted and dissected erosion surface. Serpentinized rocks have weathered to a yellow-brown ferruginous-siliceous clay and to residual blocks of jasperoidal chalcedony, which cap most of the high ridges.

The nickel district has an area of 36 square kilometers (13.7 sq. miles), and the forty-five deposits that have been prospected and sampled have a total measured surface area of about 74,400 square meters. The measured ore reserve, calculated to a depth of 1 meter and with the cut-off grade placed at 2 percent, is at least 184,000 metric tons having an average tenor of 4 percent of nickel. With a 4-percent cut-off grade, the measured reserve would be about 85,000 metric tons averaging 5.5 percent of nickel, and with a cut-off of 6 percent it would be about 25,000 metric tons containing 6.5 percent of nickel.

The indicated reserve would be much greater. With a 2-percent cut-off grade it would be at least 4 million tons containing between 2 and 4 percent of nickel; with a 4-percent cut-off, about 1,220,000 metric tons having an average tenor of 4.5 percent of nickel; and with a 6-percent cut-off, 305,000 tons having a tenor of from 6 to 8 percent of nickel.

Prospecting in other geologically and topographically favorable areas is expected to yield additional tonnage. The inferred maximum reserve in the district is estimated to be between 9 and 16 million tons averaging between 1 and 3 percent of nickel.

Between 20,000 and 75,000 metric tons of black, concretionary "pebbles" embedded in the near-surface soil in two accessible deposits can be recovered mechanically by screening. The pebbles are expected to contain between 1 and 2 percent of cobalt, small but appreciable quantities of nickel, copper, and barium, and much larger quantities of manganese and iron.

The central part of the deposits is 22 kilometers north of São José do Tocantins, and 340 kilometers north of Anapolis, a

railhead 1,221 kilometers by rail north of the port of Santos on the Atlantic Ocean.

INTRODUCTION

In 1942, at the invitation of the Brazilian Government, the Geological Survey, in extension of its strategic minerals investigations, and the Department of State, in pursuance of its program in cooperation with the American Republics, jointly sponsored a special investigation of the nickel deposits near São Jose do Tocantins, State of Goiaz,[1] Brazil. W. T. Pecora and C. W. Buckey were assigned to this project by the Geological Survey as geologist and topographer respectively, and A. L. de M. Barbosa, engineer of the Divisão de Fomento, was assigned by the Departamento Nacional da Produção Mineral. E. R. Swoboda, a United States citizen residing in Rio de Janeiro, served as technical field assistant. Many Brazilians of the region assisted the field party, among them Joaquim Godoi, guide, João da Costa and Antonio Gomes, rodmen, and Isidoro Duarte and Lindolfo Gomes, sample preparators.

The field party worked in the district from March 16 to July 10, 1942. Mr. Buckey established control and made a plane-table topographic map of an area of about 35 square kilometers (13.3 sq. miles), which includes all the prospected nickel deposits, and he also began a plane-table topographic sketch map of the surrounding region. The writer and Mr. Swoboda later extended this map by means of compass and barometer, and both men reconnoitered regional geologic features, which were sketched on the final topographic map. They also made large-scale topographic maps of several especially promising deposits, and the writer used these maps as bases for detailed geologic mapping. Mr. Barbosa assisted in mapping the geology of the Mantiqueira Mountains, and, with Mr.

1/ Accepted by the Departamento Nacional da Produção Mineral in preference to older spellings Goyas, or Goyaz.

Swoboda, helped to collect more than 50 simple and composite samples. The reserves were calculated by the writer.

During the field season the party was visited by Dr. W. D. Johnston, Jr., of the U. S. Board of Economic Warfare, and by Dr. M. da S. Pinto and Captain Leandro Costa of the Nickel Commission of the Board of Foreign Trade of Brazil, all of whom enthusiastically entered into discussions of the geology that were highly stimulating and helpful.

The Geological Survey is especially indebted to the Departamento Nacional da Produção Mineral for many chemical analyses, for twenty-five thin sections of rock specimens, and for expediting shipment of field equipment. The writer is personally grateful for the many courtesies extended him by both Dr. Luciano Jacques de Moraes and Dr. Antonio José Alves de Souza, former and present directors of the Departamento, and to their colleague, Dr. A. Licinio de M. Barbosa, for his aid in translating several pertinent Brazilian publications.

The directors of the Emprêsa Comercial de Goiaz generously placed at the disposal of the Geological Survey much unpublished information, including a report on the sampling program supervised in 1938-39 by the company engineers F. W. Schmitt and F. Von Ameln.

Talks with C. W. Wright, F. G. Pardee, L. J. de Moraes, O. H. Leonardos, H. A. Kursell, and W. J. Donnelley, prior to the writer's departure for Goiaz, materially aided him in planning his field work.

T. P. Thayer, F. C. Calkins, J. V. N. Dorr, 2d, and E. B. Eckel critically read and improved the manuscript of this report.

History of prospecting and development

The nickel-silicate deposits on the Serra da Mantiqueira are said to have been first recognized in 1908, and in 1932 the properties containing them were acquired by the Emprêsa Comerical de Goiaz, formed by Brazilians of German ancestry. This company subsequently sponsored an active prospecting and exploration program, the bulk of which was carried out in 1938-39. In the period 1932-39, nine shafts and more than 350 pits and trenches were dug. The shafts are from 4.5 to 12 meters in depth. The longest trench is 53 meters long, and more than 100 of the trenches are over 10 meters long. About 290 samples were collected and assayed for nickel by the company during this period.

In the fall of 1941 the American Smelting & Refining Co. obtained an option from the Emprêsa Comercial, but they relinquished it in the spring of 1942. During the option period, the American Smelting & Refining Co. further explored three deposits by means of diamond drilling and prospect workings. The cores of the drill holes were left at Jacuba and examined by the writer. The same company also did extensive auger-hole drilling, the results of which were not available when this report was written. In the summer of 1942 the Emprêsa Comercial was reorganized as the Companhia de Niquel do Tocantins, with which, late in 1942, the American Smelting & Refining Co. formed a partnership.

The Emprêsa in 1934 shipped about 170 metric tons of selected ore, containing 12 to 14 percent of nickel, to Rotterdam and thence to Germany. De Moraes[2/] reports that this shipment, for transportation alone, involved a cost per ton of ore of about 601$500 (about $30.00 in United States currency) on board at the port of Santos, or about 700$000 ($35.00) to European ports. The sale price at Rotterdam was computed to be about 902$400 ($45.00) per ton of ore containing 12 percent of nickel.

2/ De Moraes, L. J., and others, Niquel no Brasil: Fom. Prod. Min., Bol. No. 9, 168 pp., 1935.

The Emprêsa installed in 1934 a silica-lined reverberatory furnace with a daily capacity of 25 to 30 tons of silicate ore, intending, with charcoal for fuel and gypsum or pyrite and limestone as fluxes, to produce daily about 3 tons of matte containing 40 to 60 percent of nickel. The cost of the furnace, including transportation from Germany and installation, is estimated to have been 500 contos of reis ($25,000 in United States currency). The furnace was never used, even for experimentation, because, although an abundant source of limestone was discovered near the main truck road about 25 kilometers (18 miles) southwest of the furnace and an abundance of charcoal was assured from local timber, a search for a local source of pyrite or gypsum was unsuccessful.

Leonardos 3/ reports that the German firm of Krüff, Groppel, & Humboldt experimented with nickel-silicate ore from Goiaz averaging 4.4 percent of nickel, and that in these tests they produced by flotation a concentrate containing 10 percent of nickel and made an 80-percent recovery of nickel.

It is evident from these experiences that the cost either of local furnacing or of shipping selected nickel-silicate ore from the Serra da Mantiqueira would be excessively high. Either some special method of treatment other than furnacing, or some satisfactory process of concentration, would have to be devised before these deposits could be exploited profitably on a large scale.

Geography

Location and accessibility

The nickel deposits lie on the summit of the Serra da Mantiqueira, a few kilometers north of the village of São José do Tocantins, State of Goiaz (fig. 12). The deposits are

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3/ Leonardos, O. H., Os depositos niqueliferos de Goiaz: Mineração e Met., vol. 4, no. 19, pp. 37-44, 1939.

discontinuous and are contained in an area about 2 kilometers from east to west and 19 kilometers from north to south (see

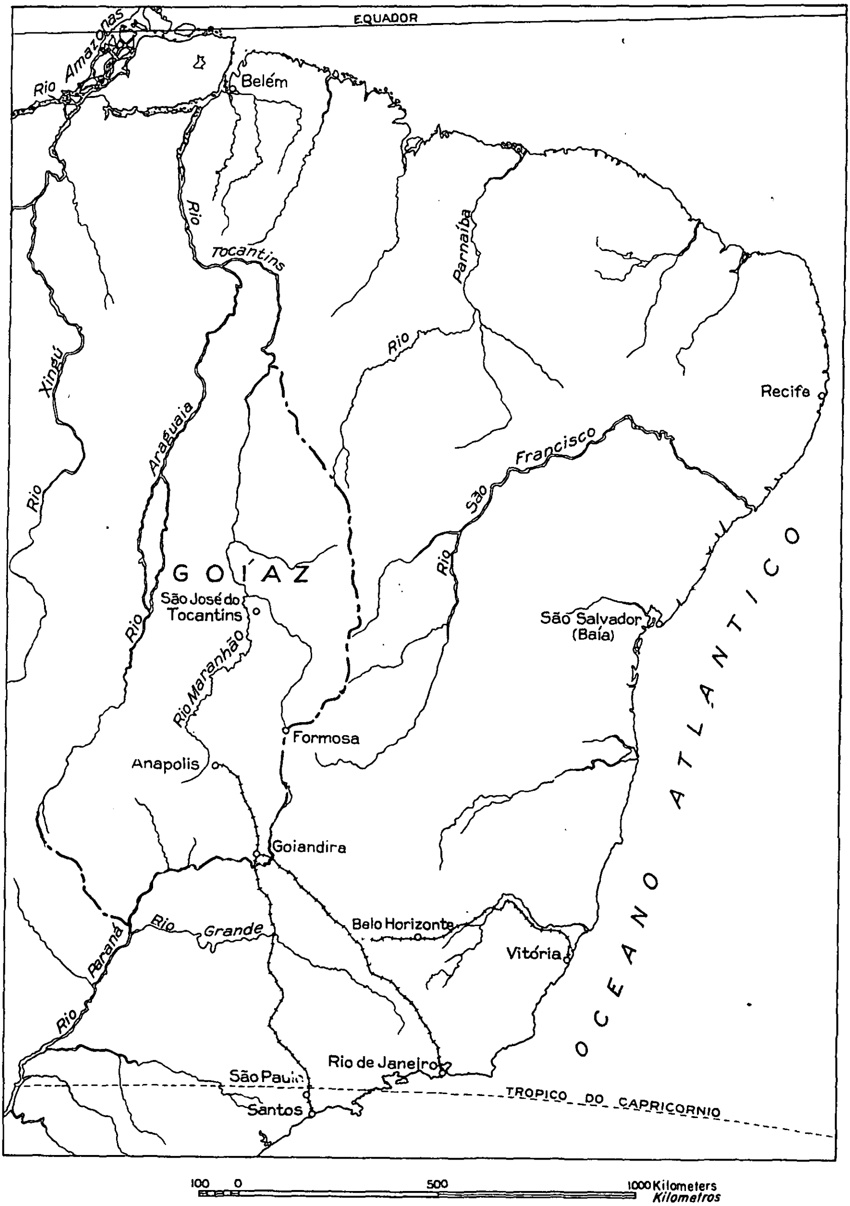

Figure 12.--Index map of eastern Brazil showing location of São José do Tocantins.

pl. 45). The central part of the mineral district is, by truck road, about 22 kilometers north of São José do Tocantins, and about 340 kilometers north of the city of Anapolis, the nearest point on a railway. The road to Anapolis is an unimproved dirt road, difficult to traverse in wet weather, without bridges that are safe for heavy trucks, and with only a cable ferry across the Maranhão River. To make it suitable for motor transportation during inclement weather, this road would have to be improved and maintained, and a bridge 30 to 50 meters long across the Maranhão River would have to be constructed. Additional truck roads can easily be constructed to the less accessible deposits within the mineral district.

A railway of about 1,221 kilometers runs southward from Anapolis to the port of Santos on the Atlantic Ocean.

An airfield site a few kilometers from São José do Tocantins, large enough to contain a landing field more than 1 square kilometer in area, has been cleared of vegetation. Its approximate airline distance from Anapolis is 225 kilometers, from São Paulo 860 kilometers, and from Rio de Janeiro 960 kilometers.

Living conditions

Rain rarely falls in the central part of the State of Goiaz between May and September, whereas at least 60 inches usually falls during the other months, mostly between November and March. Water is plentiful in the streams of the region even in the arid season.

Rainfall and temperature data for São José do Tocantins have not been recorded; but on the following page are given mean values and variations as computed from data furnished by the U. S. Weather Bureau for six stations in central Goiaz, lying within a radius of a few hundred kilometers from São José do Tocantins.

Table 8 gives the monthly variations of temperature and rainfall for the city of Formosa, which has an altitude of 912 meters (2,992 feet) and is located in the mountainous country about 200 kilometers southeast of São José do Tocantins.

	Metric	English
Mean annual rainfall........	1755 mm ± 209	69.1 in. ± 8.2
Mean annual temperature.....	23.2° C. ± 2.0	73.3° F. ± 3.1
Highest mean maximum temperature...............	32.8° C.	91.0° F.
Lowest mean minimum temperature...............	14.9° C.	58.8° F.

The summit of the Serra da Mantiqueira is open grassland, with many springs and wooded areas near the heads of the canyons that drain the mountains. The mountain slopes are moderately wooded, and dense woods and thorny bush follow along the lower watercourses. Malarial fever is said to attack the inhabitants of nearby regions but not the inhabitants of the mountains. External parasites are everywhere abundant, especially ticks and flying insects, and venomous snakes have been observed in the mineral district.

Table 8.--Rainfall and temperature data of Formosa, Goiaz, Brazil, for a period of 7 years

	Average rainfall		Mean temperature	
	Millimeters	Inches	Degrees C.	Degrees F.
January..........	360	14.17	21.2	70.2
February.........	222	8.74	22.0	71.6
March............	164	6.46	22.0	71.6
April............	135	5.32	21.3	70.3
May..............	19	.75	20.0	68.0
June.............	3	.12	18.8	65.8
July.............	4	.16	19.0	66.2
August...........	29	1.14	20.6	69.1
September........	56	2.21	22.7	72.9
October..........	135	5.32	23.2	73.8
November.........	213	8.39	22.2	71.6
December.........	376	14.80	21.4	70.5
Annual.......	1,716	67.58	21.2	70.2

The inhabitants of central Goiaz gain their livelihood mainly by ranching and farming, by mining alluvial placers for gold, diamonds, and rutile, and by mining in weathered rock for quartz and mica. Labor is for the most part transient, and the average laborer's daily wage is from 5 to 10 cruzeiros (25 to 50 cents in United States currency). São José do Tocantins, which is the seat of the municipio (county) of the same name, has a few thousand inhabitants. It does not have electricity or gas, but it has telegraphic service and almost weekly truck-freight and postal service to Anapolis.

Drainage and topography

The mountainous part of central Goiaz is drained by headwaters of the Araguaia and Tocantins Rivers, and the region immediately north of São José do Tocantins is drained by streams that flow into the Maranhão River, the principal headwater tributary of the Tocantins River. Numerous cascades and waterfalls along the course of the upper Tocantins River may possibly serve as sites for hydroelectric power.

As will be shown in a later section of this report, the physiographic history of the region is regarded as of equal significance with lithology in the formation of the nickel-silicate deposits, for the deposits are correlated with remnants of older, uplifted erosion surfaces on the Serra da Mantiqueira.

Three northward-trending mountains north of the village (see pl. 44)—the Serra da Mantiqueira, Serra do Barbosa, and the Serra do Borges—rise to altitudes of 1,000 to 1,100 meters above sea level. Their summits are roughly accordant with those of several neighboring mountains in the region, and since these mountains are underlain by rocks of different hardness, their summits probably represent an old erosion surface tnat has been uplifted and deeply dissected. For such a surface, if its existence is established elsewhere in Goiaz, the name Goiaz Upland Surface would seem appropriate. In many places the mountain slopes are rather steep and have a nearly uniform gradient; but in some places, for example on the western slope of the Serra da Mantiqueira, the continuity of the slope is sharply interrupted by a prominent bench. This bench, together with some terraces in the high valleys on the summit proper which grade into it, may represent a stillstand of erosion more recent than that represented by the Goiaz Upland Surface. Irregular, dissected benches are visible elsewhere in the region, and reconnaissance observations indicate that in the southern part of Goiaz these benches probably grade into a prominent dissected plateau of low relief, drained by part of the Paraná River system, that is known as the Planalto Central do Brasil. If such a correlation is warranted, the remnants of the Goiaz Upland Surface were preserved as monadnocks above the surface represented by the Planalto Central when it was the base level for the region.

The sharply incised canyons of the mountainous region are drained by streams of high gradient, which flow into northward-draining streams of lower gradient, bordered by flood plains. Near São José do Tocantins the Trairas and Bacalhao Rivers flow through northward-sloping plains with altitudes of 400 to 500 meters.

GEOLOGY

Regional geology

Central Goiaz is for the most part underlain by igneous and metamorphic rocks believed to be of pre-Cambrian age.[4/] Except along walls of steep canyons, a deep mantle formed by weathering covers much of the bedrock. On the summit of the Serra da Mantiqueira, the remnants of a once more extensive nickel-bearing lateritic mantle overlying peridotite have been further decomposed by ground water, to produce locally the nickel-silicate and nickel-cobalt-manganese-oxide deposits described in this report.

4/ De Oliveira, A. I., and Leonardos, O. H., Geologia do Brasil: 472 pp., 1 pl., Rio de Janeiro, 1940.

Tocantins intrusive complex

North of São José do Tocantins lies a composite mass of intrusive rocks which may be called the Tocantins complex. The complex has an area of about 740 square kilometers (281 sq. miles). Its width from east to west averages about 18.5 kilometers (11.5 miles) and attains a maximum of 24 kilometers (15 miles); its maximum length from north to south is 40 kilometers (25 miles). It is in fault contact on the south side with schist of the Minas series, of Algonkian age; on the other three sides it is probably in intrusive contact with the same series.

The Tocantins complex is made up of a great variety of igneous rocks, which have an orderly distribution in five belts, as listed in table 9 and shown in plate 44. The maximum thickness of the complex, measured across the layered structure, is about 22 kilometers (13.6 miles), about 16 percent of which is in the peridotitic belt, about 12 percent in the anorthositic belt, and the remaining 72 in the gabbroic belts.

The conspicuous northerly trend of the belts is reflected in detail by layering within each belt. The dip of the layered structure is predominantly steep and westward. In the gabbroic belts there is an interlayering of pyroxene and plagioclase so fine as to resemble a gneissoid structure. In the peridotitic belt, lenslike layers of coarse hypersthenite more than 30 meters wide are interlayered with even wider lenses of websterite and serpentinized dunite. The contacts between different igneous rocks within each belt are well-defined, whereas the contact of one belt with another is ill-defined because of the extensive interlaying of rocks.

The writer interprets the exposed part of the intrusive complex to be an edgewise section of an extensive stratiform lens of igneous rocks, derived from a subsilicic magma having

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a chemical composition near that of an olivine gabbro, which was differentiated during or after emplacement.

Peridotitic belt

The bedrock of the peridotitic belt consists essentially of interlayered varieties of peridotite, which are partly and irregularly serpentinized, with subordinate lenses of gabbro. "Peridotite" is used in this report as a general name for rocks consisting of olivine and pyroxene mixed in any proportion. The nickel-silicate deposits are all associated with unserpentinized peridotite, chiefly pyroxenite. As computed from plate 45, about 62 percent of the geologically mapped area of 24.6 square kilometers (9.3 sq. miles) is underlain by serpentinized peridotite, 34 percent by unserpentinized peridotite, and 4 percent by gabbro. There is about the same proportion of serpentinized rock in the area south of the district, and a much higher proportion in the area north of the district.

The contacts between serpentinized peridotite (serpentinite group in pl. 45) and other rocks are well defined, and in a few places they have been planes of shearing. Many springs flow from contacts between pyroxenite and serpentinized peridotite.

The unserpentinized peridotite (pyroxenite group in pl. 45) consists predominantly of a dark-colored, coarse-grained, hard, sparsely jointed pyroxenite (websterite and coarser hypersthenite) associated with subordinate layers of saxonite and plagioclase-bearing pyroxenite. In the nickel deposits, the ore richest in nickel is most commonly a weathered pyroxenite.

The partly to completely serpentinized peridotite, derived chiefly from the olivine-rich rocks dunite and saxonite, is a black, fine-grained, closely jointed rock that is tan-colored

Table 9.--Rock belts of the Tocantins intrusive complex (see pl. 44)

Name	Width along A-A' in plate 44 (kilometers)	Principal rocks 1/ and essential mineral composition
Western gabbroic belt...........	3.5	Norite (hypersthene and plagioclase) Gabbro (augite and plagioclase)
Anorthositic belt...............	3	Anorthosite (plagioclase and garnet) Hornblendite (hornblende) Hornblende gabbro, with magnetite
Central gabbroic belt...........	11.5	Gabbro and norite Hornblende gabbro on western margin Norite and peridotite on eastern margin Inclusions of altered quartzite and schist
Peridotitic belt 2/	3.7	Dunite (olivine and chromite) Saxonite (olivine and pyroxene) Pyroxenite, variety hypersthenite (hypersthene) Pyroxenite, variety websterite (hypersthene and augite) Troctolite (plagioclase and olivine) Serpentinized varieties of above rocks Gabbro, olivine norite, and norite
Eastern gabbroic belt...........	1.6	Norite and gabbro

1/ Pegmatite (feldspar, quartz, and mica) in each belt.
2/ Nickel and cobalt deposits only within peridotitic belt.

on weathered surfaces. At altitudes lower than 1,000 meters, the serpentinized and unserpentinized peridotite can easily be distinguished by their appearance in the outcrop, and at higher altitudes they can be distinguished by the residual products of weathering that overlie them, as described in a later section.

Partly serpentinized peridotite contains scattered grains of olivine and pyroxene embedded in fibrous serpentine. Some peridotite is completely changed to a rock that might properly be called serpentinite. Serpentinized troctolite (plagioclase and serpentine) has been noted throughout the belt and is common in the northern part. The serpentinization was a deep-seated process, which probably occurred late in the magmatic history of the intrusive complex.

Pegmatite and veins

Pegmatite, consisting essentially of quartz and feldspar, with subordinate amounts of tourmaline and mica, is found in both the igneous and metamorphic rocks of the region but is most abundant in the gabbroic rocks. In a few places numerous outcrops of pegmatite occur along well-defined shear zones in gabbro or between gabbro and serpentinized peridotite. Marketable clear mica has been recovered from a few large pegmatite deposits in this region, and it is reported that large, clear sheets of mica were once used as window panes in many homes in São José do Tocantins.

Veins rich in quartz are especially common along shear zones, faults, and fractures. In the peridotitic rocks, well-defined veins of random attitude, consisting essentially of anthophyllite, chlorite, vermiculite, quartz, and feldspar, grade into pegmatite having cores of quartz and feldspar in coarse graphic intergrowths.

Geologic sequence

The sequence of the principal geologic events, as interpreted by the writer, may be summarized as follows:

1. Regional diastrophism resulting in metamorphism of the Minas series (Lower Algonkian?).
2. Intrusion and differentiation of the igneous rocks north of São Jose do Tocantins, and selective serpentinization of the olivine-rich peridotitic rocks.
3. Regional faulting, and some shearing in rocks of the nickel district along contacts of serpentinized peridotite with pyroxenite and gabbro.
4. Intrusion of granitic pegmatite and related veins, and alteration and silicification along faults and fracture zones.

The geologic age of the rocks in the district is not known with certainty. On the basis of lithologic similarity to rocks elsewhere in Brazil, both De Moraes[5/] and Leonardos[6/] believe that the metamorphic rocks near São José do Tocantins belong to the Minas series (Lower Algonkian). Barbosa[7/] believes that the igneous rocks of the Tocantins intrusive complex are probably related to the third diastrophism of the Brazilian Algonkian (Upper Algonkian).

Geology of the nickel district

The nickel district, which locally contains deposits of cobalt-bearing manganese oxide, occupies the irregular summit area of the Serra da Mantiqueira, which, as shown in plate 45, has a maximum extension from north to south of about 18.5 kilometers and an average extension from east to west of about 2 kilometers. The deposits rest on pyroxenite, commonly at

5/ De Moraes, L. J., op. cit., p. 30.
6/ Leonardos, O. H., op. cit., p. 38.
7/ Barbosa, Octavio, Estudos petrographicos, in Niquel no Brasil, by de Moraes and others, op. cit. (2), pp. 108-113.

altitudes above 950 meters in the southern part of the district and above 1,000 meters in the northern part. Forty-five nickel deposits are known, and others will probably be found in the district. North of the district, in a dissected region of lower altitude underlain principally by serpentinized peridotitic rocks, a few occurrences of nickel-silicate are known, but these are of mineralogical rather than economic interest.

Cobalt-bearing manganese-oxide deposits are associated directly with the nickel deposits.

Relation of topography, weathering, and bedrock

The district is characterized by a succession of northerly trending subparallel ridges and valleys that reflect differences of bedrock. Deep canyons eroding headward into the mountain in an irregular transverse pattern and into the summit area along a more regular longitudinal pattern have been incised through weathered mantle to expose bedrock.

Most of the ridge summits of the district are at altitudes between 1,100 and 1,130 meters and are capped by prominent blocks of a spongelike chalcedonic rock embedded in unconsolidated ferruginous-siliceous material. This material overlies serpentinized peridotite. The lowest altitude at which the chalcedonic rock occurs is about 900 meters, and on most spur ridges no chalcedonic blocks that are embedded in weathered material are observed below 1,000 meters.

At altitudes above 950 or 1,000 meters, most of the longitudinal valleys that are underlain by pyroxenite contain an irregularly distributed mantle of soil-covered clay and decomposed rock, both of which form part of the nickel-silicate deposits. Many of the deposits can be correlated with well-defined topographic features herein referred to as "saddle valleys," "perched valleys," "hanging valleys," and "valley terraces." (See pl. 45.) Some high valley remnants as much as 500 meters wide form broad topographic saddles from which gulleys drain both north and south. Two of these "saddle valleys" are above 1,100 meters in altitude, and most of the others are above 1,000 meters. Other longitudinal valleys, such as that from Cachimbo East to Cachimbo North, are perched at high altitudes between bordering ridges and are poorly drained. Some of these valleys—on the Forquilha II and Jacuba I properties for example—are well drained at one end and hence are hanging valleys in a topographic sense. Well-defined terraces along the borders of wide longitudinal valleys, as for example Cachimbo West and Mosquito, are remnants of older broad valleys now being dissected by the canyon drainage. Encroachment of headward-eroding canyons, such as Ponte Alta, Jacuba, Mosquito, and many others, has evidently resulted in more rapid drainage of the larger longitudinal valleys and more rapid removal of the products of weathering.

Longitudinal valleys formed in serpentinized rocks have a mantle of tan clay on bedrock at high altitudes, but they do not contain any nickel-silicate or manganese-oxide deposits.

The chalcedonic material, which is the final weathering product of serpentinized peridotite, strongly resists erosion and caps all the dominant heights in the district. At lower altitudes, however, the serpentinized bedrock is less resistant to erosion than unserpentinized peridotite.

NICKEL-SILICATE DEPOSITS

Distribution and nomenclature

Forty-five individual nickel-silicate deposits are indicated by prospect workings in the district, and each of these is shown, with an identifying number, in plate 45. An attempt by the Emprêsa Comercial de Goiaz to name every deposit met with great difficulty, because of the great number of disconnected deposits encountered over so large an area. The principal deposits, however, have retained their names in local usage and also in publications earlier than this report. It is convenient to consider the deposits in six groups, based on distribution and named after the principal deposit of each group. These groups (see pl. 45 and table 14), from north to south, are the Forquilha (9 deposits), the Cachimbo (12 deposits), the Fazenda (8 deposits), the Jacuba (5 deposits), the Ponte Alta (1 deposit), and the Vendinha (10 deposits). Only the deposits of the Jacuba and Ponte Alta groups and a few of the Cachimbo group are immediately accessible by truck road.

Form and size

The surface area of any single nickel-silicate deposit in the district is commonly elongated from north to south, but the form and extent of each deposit have been determined by a combination of (1) linear continuity and width of the particular layer of unserpentinized peridotite on which the deposit rests, (2) altitude, and (3) topographic relief. The width of a deposit is rarely as much as that of the underlying rock layer, and its length depends on the persistence of favorable topography. Cachimbo Southeast is the longest of all the known deposits (1.2 km.), and Jacuba II the widest (150 m.).

A contact between pyroxenite and serpentinized peridotite may limit a nickel-silicate deposit sharply on one or both sides; limits determined by topographic relief, on the other hand, are irregular and ill-defined.

The relief in any one exposed deposit, where measured along a continuous group of prospect workings, has been found to range from a few meters to as much as 65 meters. In "hanging-valley" and most "saddle-valley" deposits, the material at higher altitudes is richer, on the average, in nickel, and extends to a greater depth below the surface, than the material at lower altitudes. The surface relief of a deposit is no reliable measure of the depth to which the weathered rock extends, although in some deposits it may determine the maximum depth of weathering. In "saddle valleys" and in the upper parts of "hanging valleys" the weathering extends much deeper than it does at lower altitudes. In Jacuba II, for example, which has a relief of 25 meters, the maximum depth of weathering is about 20 meters (see pl. 47), but the average depth of weathering below the "saddle" is about 12 meters. In Jacuba I (see pl. 47) the measured surface relief is about 30 meters, the maximum depth of weathering about 28 meters, and the average depth of weathering about 10 meters. In Cachimbo Southeast the surface relief is about 30 meters, the maximum depth of weathering about 30 meters (see pl. 47), and the average depth of weathering in the deposit less than 20 meters. In Cachimbo North the measured surface relief is about 30 meters, and an adit intersects the nickel deposit about 20 meters below its surface exposure (see pls. 45 and 47). In Forquilha II the measured surface relief is about 65 meters, and 12 drill holes in the "perched" section indicate that the ore extends from a few meters to 18 meters below the surface.

The nickel deposits are thus very irregular in form. Their depth is uneven and generally shallow, and their maximum relief is about 65 meters. Their surface dimensions can easily be defined by prospecting. They directly overlie pyroxenitic peridotite, and most of the deposits are deepest and richest near the contacts with clay derived from serpentinized peridotite.

Materials containing nickel

Nickel is contained in each of the materials listed below: (1) garnierite and garnieritized weathered pyroxenite; (2) several varieties of near-surface colored clays with a wide range of chemical composition; (3) black nickel-cobalt-

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manganese oxide; (4) soft, leafy, greenish vermiculite and white clay contained in weathered veins and pegmatites within the deposit; and (5) unweathered pyroxenite and serpentinized peridotite.

Garnierite and garnieritized weathered pyroxenite

Garnierite, the greenish-colored ore mineral in nickel-silicate deposits, is a hydrated nickel-magnesium silicate containing from a few percent to about 40 percent of nickel. The physical properties of the mineral vary in an orderly manner with its chemical composition. The varieties richer in nickel, which are those poorer in magnesium, are darker green in color, have higher specific gravity and refractive index, and are harder, than the varieties containing less nickel and more magnesium.

Nickel-rich garnierite has formed along joint cracks or in the interstices of weathered pyroxenite at or very near the surface. Tiny veinlets of dark-colored garnierite cut across garnierite of lighter hue. The veinlets are rarely free from very thin veinlets of flaky white quartz or opal, and they commonly are coated with manganese oxide and with soft, reddish, ferruginous clay. This association is especially evident where the garnierite veinlets follow cracks in greenish clay or joint cracks in partly weathered pyroxenite. In many surface exposures, garnierite has been entirely leached or partly replaced by opaline quartz or chrysoprase (greenish opal).

At one locality only, an open cut in the Sucuriú deposit, malachite is associated with garnierite and opaline quartz that make up irregular veinlike masses in a ferruginous clay. Tiny tufts of acicular malachite crystals form veinlets in the clay and line small cavities in the veins.

Garnieritized pyroxenite is exposed in most prospect workings. Websterite, the variety of pyroxenite that is commonest in the district, rarely contains as much nickel as the less common, coarser variety known as hypersthenite, which is particularly well exposed in the large open cut between drill holes Nos. 46 and 47 in Cachimbo Southeast and in the third open cut from the north in Jacuba I. Besides being thoroughly distributed in the interstices of the hypersthenite and in joint veinlets, garnierite forms tiny veinlets that either follow or cut across cleavage cracks in the altered hypersthene. Websterite appears to have been weathered to a greater depth than hypersthenite.

Some analyses of garnierite and garnieritized weathered pyroxenite are given in table 10.

Nickel-bearing clays

Much of the clay exposed at the higher altitudes contains from a fraction of 1 percent to as much as 4 percent of nickel. The color of clay derived from pyroxenite ranges from white to greenish, reddish, or purplish. The green clay is richest in nickel. The brown to yellow-brown clay, derived from serpentinized peridotite, contains less than 1 percent of nickel. The chemical and mineralogical composition of these clays have not been investigated, but partial chemical analyses of a few representative samples are shown in table 11.

Clays derived from pyroxenite.--Reddish, purplish, and greenish clays are exposed in many surface prospect workings, shafts, and drill cores. The reddish clay is a near-surface ferruginous material; the purplish clay, which underlies it, is a streaked or speckled magnesian-ferruginous material; and the greenish clay, which lies next to bedrock, is a streaked or spotted magnesian material containing appreciable amounts of nickel. As shown in an idealized vertical section (fig. 13)

Table 10.--Nickel content of garnierite and garnieritized weathered pyroxenite in samples collected from Cachimbo Southeast, Forquilha II, and Jacuba I

	A	B	C	D	E	F
Percent of Ni (air-dry state).	16.73	3.63	7.76	7.45	9.10	3.49
Percent loss in weight at 1,000° C.	15.44	8.04	8.46	14.62	9.75	8.73

A. Garnierite from Jacuba I; sample of 18 veinlets (aggregate thickness 96 mm.) of green to blue-green garnierite in cracks and joints of weathered pyroxenite, crossed by a vertical channel cut on west face of fourth open cut from north. Analysis by Cyrus Feldman, Geological Survey.

B. Weathered pyroxenite with interstitial garnierite, Jacuba I; sample of 2,438 mm. of material between veinlets in same channel cut as above. Analysis by Cyrus Feldman, Geological Survey.

C. Garnieritized weathered pyroxenite (hypersthenite), Cachimbo Southeast; numerous channel cuts in 40 square meters of exposed ore, in prospect workings between drill holes Nos. 46 and 47. Analysis by W. W. Brannock, Geological Survey.

D. Garnieritized weathered pyroxenite (hypersthenite), Cachimbo Southeast; numerous channel cuts in 13 meters of ore exposed in trench east of drill hole No. 43. Analysis by M. D. Foster, Geological Survey.

E. Garnieritized weathered pyroxenite, Forquilha II; numerous chips collected at random from exposed ore in many workings north of stake 45 (see pl. 50). Analysis by W. W. Brannock, Geological Survey.

F. Garnieritized weathered pyroxenite (websterite) with enclosed masses of unweathered pyroxenite, Jacuba I; numerous channel samples of 73 square meters exposed in second open cut from the north. Analysis by Cyrus Feldman, Geological Survey.

and in plate 47, greenish clay overlies pyroxenite, into which it grades with respect to compactness, texture, and chemical composition. The nickel content increases gradually in the downward succession from reddish through purplish and greenish clays, but it decreases markedly in the deeper-seated partly weathered rock. In the near-surface reddish clay, there is residual enrichment in iron and alumina, with a corresponding impoverishment in magnesia and silica. The reddish and purplish clay represents a downward encroachment on green clay, brought about by the chemical action of ground water.

Partial chemical analyses of representative samples of clay are listed in table 11. It seems most likely that the reddish, ferruginous clay is essentially a hydrated oxide, that the purplish, streaked or speckled clay is a mixture of hydrated oxides and hydrated silicates, and that the greenish clay is essentially a hydrated silicate. Long-continued chemical action by ground water has affected the character and composition of these clays, and has resulted in the rough vertical zoning illustrated in figure 13. Such supergene activity is perhaps responsible for enrichment in nickel of the deeper clays by some process of chemical exchange of nickel for magnesia, with subsequent leaching out of magnesia.

Where erosion has exposed the greenish clays in an area of low relief, either by removing the overlying purplish and reddish clays or reducing their thickness, well-defined veinlets of garnierite have formed along cracks. Some greenish clay, as exposed in the northernmost open cut of Jacuba I, has retained in part the original texture and jointing of the pyroxenite from which it was derived, but in large measure there has been superimposed upon it a haphazard set of cracks due to shrinkage and slumping of the mass. Such material, having undergone near-surface secondary enrichment, contains more nickel than deeper-seated greenish clay. The writer believes that further telescoping and nickel enrichment by ground water results in the formation of the well-garnieritized pyroxenite described in the preceding section.

Clay derived from serpentinized peridotite.--A brown ferruginous-siliceous clay, yellowish-brown to tan at the surface when dry, is a weathered product of serpentinized peridotite. In places it is associated with blocks or veinlike masses of hard, spongelike, jasperoidal chalcedony. One large sample of tan-colored surface material, collected from the trench adjacent to drill hole No. 45 in Cachimbo Southeast (No. 6, table 11), contained in its air-dry state 0.7 percent of nickel. Contacts with clays of the varieties previously described are well defined and in some places slickensided.

For a few meters below the surface, as may be seen in many open cuts, the clay has an indistinctly layered structure,

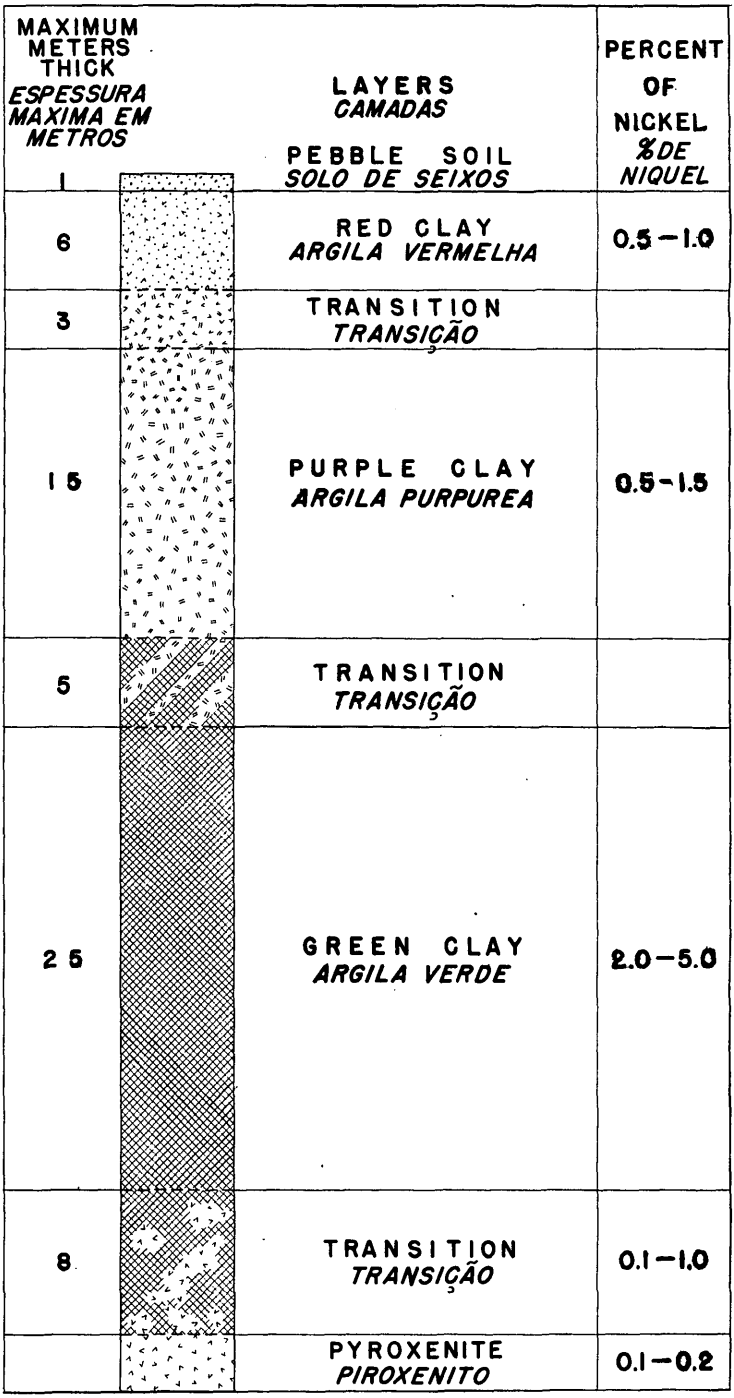

Figure 13.--Idealized vertical section showing zoning of the colored clays overlying coarse-grained unserpentinized pyroxenite in the Serra da Mantiqueira.

Table 11.--Partial chemical analyses of nickel-bearing clays collected from Jacuba I, Jacuba II, and Cachimbo Southeast deposits

[Analyses by Laboratorio da Produção Mineral, Rio de Janeiro]

	Percent (air-dry sample)	
	Ni	Fe
1. Reddish clay (ferruginous), Jacuba II; core from diamond-drill hole 9, at 6.1 m.	0.7	42.1
2. Purple, speckled clay (magnesian-ferruginous), Jacuba II; core from diamond-drill hole 9, at 7.9 m.	1.0	9.8
3. Greenish clay, Jacuba II; core from diamond-drill hole 9, at 9.7 m.	1.8	10.8
4. Purple, speckled clay (magnesian-ferruginous), Jacuba I; adjacent to greenish clay in fourth open cut from north.	.5	....
5. Greenish clay, Jacuba I; in fourth open cut, between garnieritized weathered rock and purple clay.	2.6	....
6. Tan-brown clay (ferruginous-siliceous), Cachimbo Southeast; weathered mantle overlying serpentinized peridotite; from trenches southwest of shaft.	.7	....

brought out by irregular, discontinuous streaks of powdery, siliceous material in the porous tan-colored clay. The clay at depths greater than 5 meters appears to be less siliceous than that above it. The tan-colored clay is well shown on the walls of the adit in Cachimbo North, in many cores from drill holes in Jacuba I and Cachimbo Southeast, and in many deep surface cuts.

On the surface, blocks of hard jasperoidal chalcedony up to a few meters across are embedded in brown, ferruginous-siliceous clay. Veinlike masses have formed for short distances along slips in brown clay, or along contacts of brown clay with other clays. On spur ridges at altitudes of about 1,000 meters, where the layer of clay is thin, a lattice of thin siliceous veins projects downward for a few meters into fractures in partly weathered serpentinized rock. Lower on the ridges such material is absent. On the hills in the eastern part of the nickel district and on knobs north of the district, siliceous material is rare and is found only on serpentinized peridotite above altitudes of 900 meters.

Tiny well-terminated crystals of quartz have been deposited on the walls of some cavities in spongy chalcedony, on fracture surfaces, and even in some porous brown clay. Barbosa,[8] Leonardos,[9] and Wright and Pardee [10] have considered the chalcedony to be of hydrothermal origin. The present writer believes that it was formed by chemical decomposition by ground water of ferruginous clay that was originally derived from the weathering of serpentinized peridotite.

Nickel-cobalt-manganese oxide

Nickel-cobalt-manganese oxide is intimately associated with the nickel silicate deposits and was likewise formed by long-continued weathering of pyroxenitic peridotite. It occurs in three ways: (1) as a massive capping on near-surface garnieritized weathered pyroxenite; (2) as thin, soft, discontinuous veinlets in near-surface purplish and greenish clays; and (3) as concretionary "pebbles" embedded in loose, reddish, ferruginous soil within a meter of the surface. The second variety, as shown by analyses in table 12, is richest in both nickel and cobalt.

Cappings.--A compact, black, manganese-oxide capping on garnieritized pyroxenite is widely distributed in the nickel district, but it is associated most abundantly with garnieritized, weathered, coarse-grained hypersthenite rich in nickel.

8/ Barbosa, Octavio, op. cit.
9/ Leonardos, O. H., op. cit.
10/ Wright, C. W., and Pardee, F. T., Nickel in Brazil: U. S. Bureau of Mines, Min. Trade Notes, pp. 10-14, Oct. 20, 1941.

The capping extends downward from the surface for a fraction of a meter, but interconnecting veinlets extend downward from the main capping for 1 or 2 meters. The capping is thickest over garnieritized rocks that have a thin overburden. Hand specimens of blocky veinlike masses as much as 10 centimeters wide can be obtained in many places. A partial analysis of a representative sample of about a ton of fragments broken from several outcrops in Jacuba II is given in column A, table 12. An X-ray powder picture taken by J. M. Axelrod of the Geological Survey shows a pattern identical with that of hollandite, a barium-rich variety of manganese oxide. This correlation is substantiated by the appreciable quantity of BaO in the analyzed material.

Thin veinlets in clay.--Discontinuous, thin veinlets of blue-black, soft manganese oxide are common in reddish and purplish clays and in near-surface streaked, greenish clays. The veinlets ordinarily extend for only a few meters below the surface, but they are found at depths up to about 10 meters in some drill cores.

A sample was made up of several pieces selected at random from purple clay exposed on walls of pits and trenches in Jacuba II and of numerous pits in Jacuba III. A partial analysis of this sample, given in column B, table 12, shows that this material likewise contains an appreciable quantity of BaO, and an X-ray powder picture has a pattern suggesting a mixture of hollandite and some other manganese oxide.

A second sample (column C, table 12) of blue-black manganese oxide was collected from the thin veinlets exposed in the greenish garnieritic clay of the northernmost open cut of Jacuba I. It shows less BaO than the other, but it also appears to contain hollandite, together with another manganese oxide.

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Table 12.--Partial chemical analyses of nickel-cobalt-manganese oxide from the Jacuba deposits

	A	B	C	D	E	F	G	H
SiO_2........	.....	5.2	.....	12.9	11.6	5.2	5.2	....
Mn..........	.....	34.2	22.3	10.2	11.4	25.9	34.2	....
Ni..........	.....	2.8	.....	1.0	1.0	.7	2.8	....
Co..........	3.4	4.3	4.3	(1.11)	(1.41)	(1.68)	(1.59)	0.6
Fe..........	.....	9.3	6.1	24.3	23.5	17.1	9.3	....
Cu..........	(1.9)	(1.8)	(2.5)	.4	.5	.6	1.0	....
BaO.........	(7.9)	(5.2)	(2.8)	......	......	......	......	....
H_2O at 110° C.	1.7	2.9	5.8	(1.05)	(1.17)	(.97)	(1.13)	1.6
H_2O+........	6.1	8.3	8.3	10.7	11.2	10.4	......	11.9

Analyses by the chemical laboratories of the Geological Survey (in parentheses) and by the Departamento da Produção Mineral.

Geological Survey: A, B, C; Michael Fleischer
D, E, F, G; W. W. Brannock
D. N. P. M.: A. C. N. de Oliveira

A. Massive, veinlike capping of manganese oxide, on garnieritized pyroxenite, Jacuba II; hand-selected fragments.

B. Veinlets of manganese oxide from purple clay, Jacuba II; hand-selected fragments from exposures below "pebble" layer.

C. Veinlets of manganese oxide, not entirely free from garnierite, Jacuba I; hand-selected from northernmost open cut.

D-G. Representative samples of "pebbles" recovered on 16-mesh screen; channel samples from walls of pits in Jacuba II and Jacuba III.

H. Hand-picked rounded "pebbles," from pebble layer in trench east of drill hole No. 12, Jacuba II.

Concretionary "pebbles."--A layer of "pebbles" of manganese oxide extending from the grass roots to a maximum depth of 1 meter has been noted in the upper parts of some "saddle valleys," and is particularly well exposed by prospect workings in Jacuba II and Jacuba III. The "pebbles" are commonly smooth, ellipsoidal, and hard and are dark brown on the surface. The maximum concentration of "pebbles" in loose ferruginous soil is exposed in the long trench east of drill hole No. 12 in Jacuba II. Here the "pebble" layer has a measured average thickness of 25 centimeters (10 in.), and the "pebbles," which have an average diameter of about 1.5 centimeters, make up 50 percent of the layer by volume.

Four composite samples of concentrates, representing more than 300 vertical channel samples of the exposed "pebble" layer in Jacuba II and Jacuba III, were collected on a 16-mesh

($\frac{1}{4}$ in.) screen. Partial analyses of these samples are given in columns D to G, table 12.

The layer contains "pebbles" of two kinds: some are flat, smooth-edged, and blue-black in color, and consist of material like that in the thin veinlets of manganese oxide already described; others, which are more rounded, are not homogeneous, being composed of irregular mixtures of porous limonite, hard jasperoidal chalcedony, and fine-grained manganese oxide. A hand-selected sample of the latter variety contained 0.6 percent of cobalt (see column H, table 12) and an X-ray powder picture showed a strong resemblance to goethite (limonite).

Manganese-oxide stain is widespread on the surfaces of the chalcedony blocks in the district, and rarely it forms crusts and "black hats" on brown, ferruginous clay in "saddle valleys" underlain by serpentinized peridotite. Nowhere is there any such concentration of manganese-oxide minerals over the serpentinized rocks as there is over pyroxenite. It seems most likely, therefore, that the manganese-oxide deposits as well as the garnierite deposits were formed by long-continued selective weathering.

Nickel-bearing vermiculite and white clay

Nickel-bearing vermiculite is exposed in some prospect workings of Jacuba II and Cachimbo Southeast, either in pegmatite, where it is associated with weathered fibrous anthophyllite, white clay derived from feldspar, and glassy quartz, or in well-defined veins consisting essentially of weathered anthophyllite and chlorite. The vermiculite is greenish, soft, and leafy, is interlayered in books with yellowish clay, and exfoliates when placed in a hot flame. One hand-selected specimen, dried and cleaned of mud, gave a positive qualitative test for nickel. This association of nickel-bearing vermiculite is similar to that near Webster, North Carolina, described by Ross, Shannon, and Gonyer.[11/]

In Jacuba II, on the walls of the long trench south of drill holes Nos. 1 to 6, white clay locally tinged with green forms part of a thin, veinlike mass of weathered pegmatite in weathered pyroxenite. This clay gave a positive test for nickel. It may be kaolinized feldspar containing some nickel compound, adsorbed or added by chemical replacement of some element in the clay.

Both the nickel-bearing vermiculite and the greenish-white clay are rare in these deposits.

Composition of unweathered rocks

Chemical analyses of unweathered pyroxenite and serpentinized dunite from the nickel district are given in columns A and B, table 13. Completely unweathered or unserpentinized saxonite and dunite, analyses of which would have been of interest, could not be found by the writer during his field investigations. Much of the gabbro in the district is unweathered, but that rock does not have any known genetic relationship to the nickel-silicate deposits.

The hypersthenite variety of pyroxenite, readily identifiable by its uniformly coarse grain, contains more manganese and cobalt but less nickel than the serpentinized dunite. Websterite, distinguished from hypersthenite by its mixed coarse and medium grain, is intermediate between hypersthenite and serpentinized dunite in its content of cobalt.

Vertical zoning

An idealized composite vertical section of the clays derived from pyroxenite is shown in figure 13. The vertical

11/ Ross, C. S., Shannon, E. V., and Gonyer, F. A., The origin of nickel silicates at Webster, N. C.: Econ. Geology, vol. 23, no. 5, pp. 528-552, 1928.

Table 13.--Chemical analyses of unweathered peridotitic rocks of the nickel district

	A	B	C	D	E
SiO_2	52.30	33.04	.....	.....	.....
Al_2O_3	3.02	1.61	.....	.....	.....
Fe_2O_3	1.87	4.74	.....	.....	.....
FeO	8.28	3.56	.....	.....	.....
MgO	29.93	40.39	.....	.....	.....
CaO	3.20	Trace	.....	.....	.....
K_2O	.30	.15	.....	.....	.....
Na_2O	Trace	.19	.....	.....	.....
TiO_2	.32	.24	.....	.....	.....
MnO	.33	.15	.....	.....	.....
BaO	Nil	Nil	.....	.....	.....
Cr_2O_3	.48	1.16	.....	.....	.....
H_2O+	......	14.64	.....	.....	.....
Ni	.08	.31	0.09	0.12	0.21
Co	Trace	Trace	.005	.010	.002
Total	100.10	100.18	.....	.....	.....

Specimens A and B collected by L. J. de Moraes and analyzed by M. L. Fontoura, D. N. P. M.

Specimens C, D, and E collected by W. T. Pecora and analyzed by W. W. Brannock, Geological Survey

A. Pyroxenite; Jacuba.
B. Serpentinized dunite; Jacuba.
C. Pyroxenite (websterite); Jacuba I; drill hole No. 19.
D. Pyroxenite (hypersthenite); Jacuba I; drill hole No. 19.
E. Serpentinized dunite; Vendinha.

zoning in the clays is attended by a general leaching of magnesia and silica, a downward enrichment in nickel, and a residual surface enrichment in iron, manganese, cobalt, and alumina. At the base of the clays, there is an abrupt chemical change to unweathered pyroxenite, which is rich in magnesia and contains only a small fraction of a percent of nickel, cobalt, manganese, and aluminum.

A surficial enrichment in nickel occurs only in thinner, telescoped sections, where garnierite has been deposited along joint cracks or in the interstices of weathered pyroxenite and in shrinkage or slumping cracks of green clay.

Origin and geologic history of the deposits

Chemical relationships

Appraisal of the potential ore reserves of the district depends directly upon whether the deposits were formed by magmatic water or by surficial ground water. According to the present writer's interpretation, the nickel-silicate and nickel-cobalt-manganese-oxide deposits are residual products of long-continued weathering of pyroxenitic rocks that occurred during a complex physiographic history. Ground water of surface origin has gradually decomposed the irregularly distributed mantle of nickel-bearing magnesian-ferruginous clay, derived from such rocks, producing nickel-rich magnesian clay, nickel-rich garnierite, nickel-cobalt-manganese oxide, and free silica. Serpentinized peridotite, also, gave rise to a mantle of nickel-bearing ferruginous clay, but when this clay was decomposed the characteristic end product was chalcedony instead of garnierite. The different behavior of these two varieties of bedrock under the same physiographic conditions is strikingly apparent on upland surfaces, where strips of garnieritized weathered pyroxenite are bordered by massive blocks of jasperoidal chalcedony, which overlies weathered serpentinized peridotite.

The reasons for such differential weathering are not clear, but the most reasonable explanation would seem to lie in the chief mineralogical and chemical differences of the two rocks in their unweathered state. In serpentinized peridotite an appreciable amount of combined water (see table 13) is contained in the serpentine minerals which are so abundant in the rock, whereas unweathered pyroxenite contains neither water nor serpentine. During their contemporaneous weathering, therefore, the two rocks reacted differently with ground water. The clays formed by supergene hydration of the silicate minerals, dominantly pyroxene, in the pyroxenite were more amenable to later supergene nickel enrichment than the clay derived from already hydrosilicated serpentine minerals and subordinate residual olivine in the serpentinized peridotite. Weathering generally went deeper, however, in the serpentinized rocks, probably because of greater fracturing and shearing, closer spacing of joints, the less massive character of the rock, and the greater susceptibility of serpentinized rock to weathering.

Although there is no direct evidence that nickel was transported from weathered serpentinized peridotite and eventually added to the enriched clay derived from pyroxenite, the writer believes that such a process accounts for a part of the nickel in the ore deposits. However, he considers that a much larger amount of the nickel was lost from the district during the long-continued weathering, by action of either ground water or surface water. The general idea is illustrated in figure 14. The magnitude of such loss or addition is, of course, purely speculative and can be envisioned only as a result of four variable factors:

1. Addition of nickel in weathered rocks as a result of downward enrichment.
2. Addition of nickel in weathered pyroxenite as a result of migration from weathered serpentinized peridotite.
3. Loss of nickel from weathered rocks as a result of mechanical transportation of surface material.
4. Loss of nickel from weathered rocks as a result of leaching by ground water.

On the assumption that no nickel is lost, and that none is added except by downward enrichment, an estimate of the quantity of rocks weathered to produce the ore deposits may be calculated from the nickel content of unweathered rocks and the quantity and grade of the nickel-silicate ore. For example, a layer of weathered material averaging 10 meters in

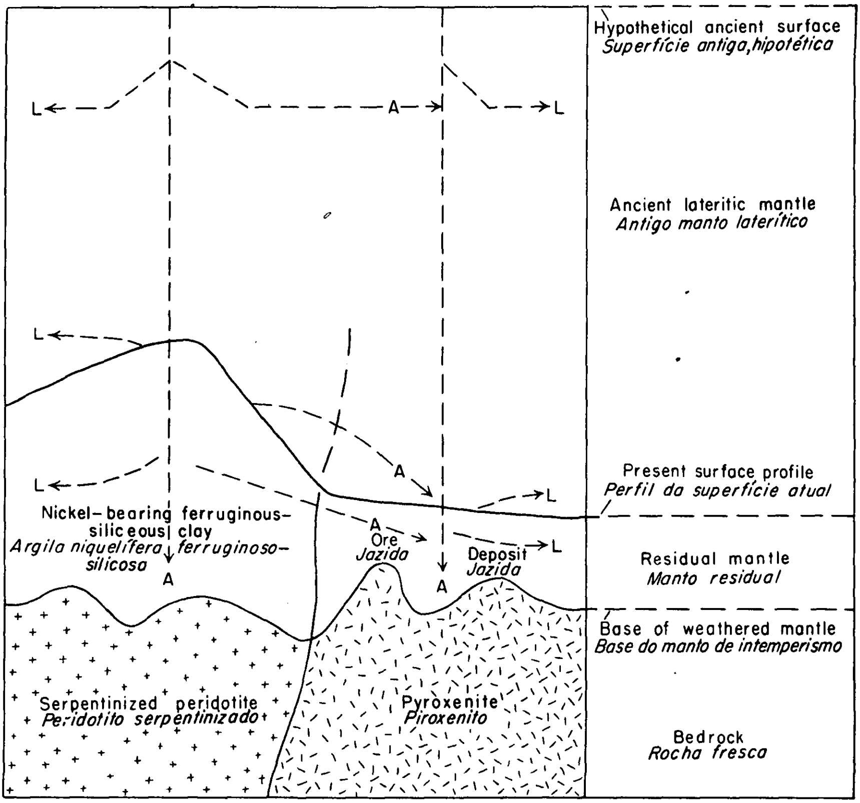

Figure 14.--Schematic diagram showing the loss (L) and addition (A) of nickel, by chemical or mechanical action of water, that occurred during the weathering history of the nickel-silicate deposits in the Serra da Mantiqueira.

thickness and 2 percent in nickel content would require the decomposition of at least 165 meters of overlying pyroxenite. On the basis of the two assumptions stated above, this figure is thought, indeed, to be but a small fraction of the total column of peridotitic rocks that must have been decomposed during the formation of these deposits, for a tremendous quantity of material has been removed from the district by chemical and mechanical processes. At high altitudes, erosion and through-moving ground water derived from plentiful rain are removing the nickel-bearing clays faster than they are being formed. It is improbable that much clay is now forming, for adjacent to weathered rock and clay, even in depressions well protected from erosion, there are exposures of hard almost unweathered rock.

Relation between origin and physiographic history

The regional physiographic events that, according to the writer's interpretation, bear directly on the formation of these deposits are summarized below:

1. Development, by weathering, of a thick mantle of magnesian-ferruginous clay on a surface of low relief (the Goiaz Upland), which was nearer base level or ground-water level than the present summit surface of the Serra da Mantiqueira.
2. Regional uplift of a few hundred meters, which allowed this surface to be dissected for a long period by southward-flowing streams of the Planalto Central do Brasil, with a probable continuance of deep weathering.
3. A new regional uplift of a few hundred meters, followed by canyon cutting throughout the region, development of a transverse and longitudinal valley pattern in the nickel district, formation of benches and terraces, and supergene alteration of the weathered material in the nickel district to produce the nickel-silicate and manganese-oxide deposits.

The writer believes, in short, that the garnierite deposits have been formed by a now-active supergene alteration and enrichment of already weathered material, which was derived chiefly from pyroxenite in an earlier physiographic setting.

Analogies with other deposits

In the nickel-silicate deposit near Riddle, Oregon,[12/] unserpentinized peridotite was found to be a more favorable country rock than serpentinized peridotite. Pyroxenite is not known to occur in that locality. Serpentinized ultrabasic rocks both in Cuba and in the Philippine Islands are known to have yielded ferruginous deposits containing 1 percent or more of nickel, but garnierite deposits have not been reported from these regions. The nickel-silicate deposits of the islands of New Caledonia and Celebes have not been described as being selectively associated with either unserpentinized or serpentinized peridotite, but this point may not have been considered by the geologists who investigated those deposits.

Three of the four earlier writers consider the garnierite of the nickel-silicate deposits north of São José do Tocantins to be associated in origin with the chalcedony so prevalent in the district. Barbosa [13/] believed that late magmatic, long-continued, serpentinizing solutions of Algonkian age caused an adsorption of nickel hydrosilicate and nickel hydroxide by serpentine. Leonardos [14/] was of the opinion that serpentinizing solutions of hydrothermal origin partly leached the silicate rocks, deposited chalcedony, and redeposited nickel in the form of garnierite veins. Wright and Pardee [15/] state their view as follows: "The deposits are part of an ore body formed by deep-seated ascending mineral solutions and are not locally enriched by weathering and precipitation. * * * The

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12/ Pecora, W. T., and Hobbs, S. W., Nickel deposit near Riddle, Douglas County, Oreg.: U. S. Geol. Survey Bull. 931-I, pp. 205-225, 1942.
13/ Barbosa, Octavio, op. cit., pp. 113-115.
14/ Leonardos, O. H., op. cit.
15/ Wright, C. W., and Pardee, F. T., op. cit., p. 12.

chalcedony or quartz lodes appear to follow the main fractures, along which the mineral solutions rose, filling cracks and impregnating the adjoining rock."

De Moraes, on the other hand, though he does not discuss the origin of the nickel-silicate deposits near São José do Tocantins, believes that a garnierite deposit elsewhere in Brazil, described in his report,16/ was formed as a result of weathering. He bases his view on the similarity of this deposit to those of New Caledonia, whose origin by weathering is generally accepted.

RESERVES OF NICKEL-SILICATE ORE

The minimum tenor required to class any part of the nickel-silicate deposits north of São José do Tocantins as ore—frequently denoted as the cut-off grade—cannot be intelligently judged without fully considering all the diverse factors that govern exploitation, marketing, and recovery. For nickel-silicate ore that is to be smelted into a matte, as is done in New Caledonia, the cut-off grade is approximately 4 percent of nickel; for reduction in carbon electrode furnaces to a ferro-nickel pig, which is the method used at Liberdade, Minas Gerais, Brazil, the cut-off grade is 2 percent; and for some process involving selective leaching, the cut-off grade might conceivably be placed lower than 2 percent. An efficient method of concentrating the ore to a product that could be transported without undue expense, or that could be treated locally, would likewise lower the cut-off grade for this nickel-silicate ore.

Classes of ore

In this report three classes of ore reserves are considered: (1) measured ore, (2) indicated ore, and (3) inferred

16/ De Moraes, L. J., op. cit., p. 30.

ore. This terminology is now accepted by the Geological Survey in preference to the one, better known to the mining industry, in which ore is estimated as proved, probable, and possible.

Measured ore in these nickel-silicate deposits is ore whose tonnage has been computed from careful measurements on outcrops and in surface prospect workings and whose grade is computed from the results of detailed sampling. A depth of 1 meter is assigned to the ore blocks whose area has been measured, because this is the average measured depth of most surface workings. The sites for inspection, measurement, and sampling are so closely spaced, and the geological character of the deposits is so well defined, that the calculated tonnage is fairly well assured. The margin of error in computing tonnage and grade is judged to be less than 20 percent.

Indicated ore, in these deposits, is ore whose tonnage and grade have been roughly computed, in part from specific measurements and in part from projection for a reasonable distance on geological evidence. A certain depth is assumed for each block of ore, on the basis of evidence afforded by diamond drilling, auger drilling, shafts, or observed geologic relations. The margin of error for estimates of tonnage and of average grade is not believed to exceed 50 percent, and for a part of the estimates it may be less than 25 percent.

Inferred ore, in these deposits, is ore whose tonnage has been estimated largely on the basis of a broad knowledge of the geology. In making the estimates, it was assumed that some already prospected deposits are more extensive than has yet been proved, and that similar deposits will be discovered in geologically favorable situations. Estimates of inferred ore have a wider margin of error than those for indicated ore, but they should give a useful idea of the potential yield of the district.

The measured specific gravity of the ore ranges between 2.0 and 2.9, and for calculations in this report a specific gravity of 2.5 has been assumed. Because of the variability in grade over short distances, estimates of tenor will probably have a larger margin of error than estimates of tonnage.

Area underlain by ore

In the 45 prospected deposits of the nickel district, the plane-table mapping, measurements, and calculations of the Geological Survey party indicate a total measured area of 74,400 square meters. The length of each deposit as given in table 14 is the linear distance between the northernmost and southernmost prospect workings in the same ore strip, and the width of each deposit is taken as the mathematical average of the linear distance for which all the crosswise prospect workings are in ore. In all the deposits, some ore presumably extends beyond the limits of the prospect workings, but since this extension cannot be considered as measured, it is classed as indicated or inferred ore. The maximum productive area possible for any of these deposits is rigidly controlled by geologic and topographic conditions. By extending the area of each deposit listed in table 14 to the limits of favorable ground, the maximum inferred total area underlain by ore is computed to be 357,000 square meters. This includes all the blocked-out area of 74,400 square meters but is nearly 5 times as large. The indicated productive area lies somewhere between the two figures.

In addition to the 45 prospected deposits, there may be others that overlie pyroxenite at favorable altitudes but that have not been prospected. The writer estimates, on the basis of map and field interpretation of topography and geology (see pl. 45), that there are more than 30 of these unprospected deposits, with a productive area of 300,000 square meters.

In round numbers, the total inferred productive area (657,000 sq. meters) in the district is 8½ times as large as the measured area blocked out by prospecting and about 7½ percent of the total area of the "pyroxenite group" as mapped in plate 45. It is, however, only 2½ percent of the total area of the mapped peridotitic rocks in the district and about 0.6 percent of the estimated area of the peridotitic belt shown in the regional reconnaissance map (pl. 44). The existing deposits are but meager remnants of a sheet of nickel-bearing material whose original area probably amounted to several square kilometers.

Tonnage and tenor

Methods of sampling

In 1938 and 1939, the engineers of the Emprêsa Comercial carried out a comprehensive sampling program. They numbered each of the prospect workings they sampled, and for each sample, weighed air-dry, they determined by analysis the percentage of nickel and the percentage loss of weight of the air-dry sample induced by calcining—at what temperature is not known. C. W. Wright and F. T. Pardee, of the Federal Bureau of Mines, collected six samples from the deposits in 1941 for purposes of comparison. The nickel content of these samples, as determined by Victor North of the Geological Survey, is shown on the following page in column A. The assays, it will be seen, agree fairly well with those in column B, which represent samples collected earlier at the same localities by the Emprêsa Comercial.

The Geological Survey field party of 1942 collected a great number of both geological and engineering samples. The geological samples, collected largely for the purpose of determining the distribution of nickel in various materials, represent many distinct varieties of garnierite, of clays, and of weathered and unweathered rocks. Some of these samples were analyzed for one or more elements; some were studied petrographically, either in thin section or as powders in oil immersions. The engineering samples, all of which were gathered for assay, were of two kinds: (1) simple samples, each made up of material from one or more regular channel cuts or of numerous chips from equally spaced points on a face of ore; and (2) composite samples, made up by mixing two or more simple samples in proportion to the lengths of the channels or the areas of ore faces that they represented. Before being assayed, all the samples were dried in the sunshine, crushed to pass through a 20-mesh screen, halved or quartered with a multicompartment sample splitter, crushed again to pass through a 40-mesh screen, and split again into four portions. One set of samples was first analyzed by the chemical laboratory of the Departamento da Produção Mineral, as a control check on later analyses by the Geological Survey of a duplicate set of samples.

Nickel content is given throughout as determined from air-dry material.

	A		B	
Prospect trench number of Emprêsa Comercial	Length sampled (meters)	Percent nickel	Length sampled (meters)	Percent nickel
Fazenda (No. 169)...........	10	5.45	10	5.8
Forquilha II (No. 264)......	10	9.76	11.8	9.3
Forquilha II (No. 261)......	13	7.56	13.8	6.2
Forquilha I (No. 294).......	8	14.35	8.0	12.7
Alegre I (No. 279)..........	8	10.96	5.0	10.8
Vendinha (Nos. 4, 5, 6).....	37	6.05	37.0	4.8

Measured ore reserves

The measured ore reserve is computed for 1 meter of depth in the areas blocked out by prospecting and sampling, as shown in table 14. About 184,000 metric tons of nickel-silicate ore composed of nickel-bearing clays and garnieritized weathered pyroxenite may be considered as reasonably assured. With the aid of information given by the Emprêsa Comercial de Goiaz regarding samples that had been collected and analyzed by engineers of that company, the writer calculated a weighted average of 4.0 percent of nickel for this tonnage. Using cut-off grades of 2, 4, and 6 percent of nickel, this reserve can be broken down as shown below:

	Metric tons	Percent nickel
Weathered material	184,000	4.0
Cut-off grade of 2 percent	183,883	4.04
Cut-off grade of 4 percent	85,468	5.41
Cut-off grade of 6 percent	25,526	6.56

These figures should be regarded as representing only the minimum reserves, assured in view of present information. Less conservative treatment would have resulted in transfer of part of the "indicated" ore to the "measured" class.

Indicated and inferred ore reserves

Some information is available regarding thickness of overburden and of ore layer, and regarding tenor of the ore below the surface, for the deposits of Jacuba I, Jacuba II, and Cachimbo Southeast, and in part also for those of Forquilha II and Cachimbo North. These are five of the nine largest deposits of the district, and together they include almost half of the geologically favorable area of the known deposits. More subsurface exploration is warranted for these and other large deposits, including the Vendinha, Cachimbo West, Alegre I, and Jacuba III. In all, the large deposits comprise two-thirds of the maximum favorable area in the 45 deposits already prospected, and more than 80 percent of the prospected ground that has been proved to be underlain by ore.

In the pages that immediately follow, those deposits are described first that have been explored below the surface.

Sampling information is given in table 15, estimates of the maximum area favorable for extended prospecting in the known deposits are given in table 14, and the indicated reserves are summarized in table 16.

Jacuba I.--Jacuba I contains what is perhaps the most thoroughly prospected of all the large known deposits. About 60 percent of the surface area is traversed by six lines of drill holes, the profiles of which are shown in plate 47. The area north of the drilled block, about 10 percent of the total area, includes the nickel-rich clay exposed in the large open cut; the area south of the drilled block, about 30 percent of the total area, is mostly underlain by partly weathered rock.

The drilled block has a measured average depth, from surface to unweathered bedrock, of approximately 9 meters, a surface length of 500 meters, and an average width of 47 meters. The block to the north has a surface area of about 3,250 square meters and has a depth in one place of at least 9 meters (see pl. 48). The block to the south has a surface area of about 10,500 square meters and an average depth of possibly 3 meters. Assuming an average specific gravity of 2.5, the writer has computed the following tonnages:

	Area (sq. meters)	Depth (meters)	Specific gravity	Metric tons
Drilled block..	23,500	9	2.5	528,750
North block....	3,250	9	2.5	73,125
South block....	10,500	3	2.5	78,750
Total indicated ore..........................				680,625

This over-all tonnage consists of such varied materials that its average nickel content cannot be closely determined; this content is estimated, however, to be between 2 and 4 percent.

Excluding the red, purple, and tan clay in the drilled block as overburden—and thus establishing a cut-off grade of about 1 or 2 percent—the writer estimates that the drilled

Table 15.--Analyses of composite samples of green clay, of garnieritized weathered pyroxenite, and of both, collected in 1942 by the Geological Survey and used in calculating reserves

No.	Field sample number	Sample	Percent Ni in sample as received	Percent loss of weight at 1,000° C.	Percent Ni at 1,000° C.
1	(14)	Jacuba I, first open cut from north; chip sample of about 500 square meters of green clay with garnierite veinlets.	6.03	17.23	7.28
2	(22)	Jacuba I, second open cut from north and 5 meters of eastward connecting trench; channel cut of about 73 square meters, mostly in hard pyroxenite with garnierite veinlets along joint cracks.	3.49	8.73	3.83
3	(27)	Jacuba I, three trenches immediately south of drill hole 20 (see pl. 46); channel cuts of 10 linear meters of garnieritized weathered pyroxenite.	5.15	12.62	5.90
4	(23)	Jacuba I, third open cut from north including 3 pits and trench; chip samples of about 50 square meters of garnieritized weathered pyroxenite.	4.89	16.47	5.86
5	(24)	Jacuba I, fourth open cut from north, and adjacent trench on south; channel cuts of 27 linear meters of green clay and garnieritized, partly to completely weathered pyroxenite.	5.98	14.51	7.00
6	(25)	Jacuba I, 20 prospect workings between fourth open cut and trench south of drill hole 23; composite sample of six chip samples representing 60 square meters of mixed varieties of ore.	6.70	14.55	7.85
7	(26)	Jacuba I, three trenches near drill hole 27; channel cuts of 25 meters of green clay and weathered rock.	2.38	17.35	2.88

8	......	Jacuba I, calculated weighted average of surface samples of green clay and garnieritized weathered pyroxenite exposed in surface workings on the drilled block.	5.62	....	....
9	(35)	Jacuba I, drill holes 29, 30, 31, and 32; total of 13.1 meters of green clay in drill cores.	3.25	12.52	3.72
10	(16)	Jacuba II, trench at sites of drill holes 1 to 6; 35 meters of mixed ore varieties.	4.89	8.38	5.34
11	(28)	Jacuba II, 3 trenches, including one at site of drill hole 16 and two immediately to the north; channel cuts of 35 meters of garnieritized weathered pyroxenite.	3.12	11.13	3.51
12	(17)	Jacuba II, chip sample of garnieritized weathered pyroxenite exclusive of green clay, in pits south of road.	5.63	9.98	6.25
13	(8)	Cachimbo Southeast, open cut and two trenches between drill holes 46 and 47; channel cuts of 40 square meters of garnieritized pyroxenite.	7.76	8.46	8.48
14	(9)	Cachimbo Southeast, 54 square meters of soft, green, weathered rock on west ends of two trenches mentioned in note on sample 13.	5.32	12.62	6.09
15	(10)	Cachimbo Southeast, chip sample of 76 square meters of both soft and hard garnieritized pyroxenite in three trenches northeast of drill hole 47.	3.89	11.86	4.36
16	(29)	Cachimbo Southeast, trench east of drill hole 43, west end; channel cuts of 13 meters of garnieritized weathered pyroxenite.	7.45	14.62	8.74

Table 15.--Analyses of composite samples--Continued

No.	Field sample number	Sample	Percent Ni in sample as received	Percent loss of weight at 1,000° C.	Percent Ni at 1,000° C.
17	(34)	Cachimbo Southeast, drill hole 44, chip sample representing 25 meters of core in green clay below purple clay.	4.15	18.93	5.12
18	(33)	Cachimbo Southeast, drill hole 47, chip sample of 6.5 meters of green clay from drill core.	2.85	20.84	3.60
19	(32)	Cachimbo Southeast, drill holes 42, 44, 45, 46, 47; composite sample of 65 meters of green clay from drill cores.	4.13	19.21	5.12
20	(43)	Forquilha II, chip sample of green clay and garnieritized weathered pyroxenite in prospect workings above 1,050 meters.	9.10	9.75	10.08
21	(44)	Forquilha II, chip sample from workings below 1,050 meters.	5.78	14.49	6.76
22	(30)	Cachimbo North, adit, channel cuts of 10 meters of green clay at 40 to 50 meters from portal.	2.92	21.25	3.71
23	(39)	Vendinha, chip sample of all but four of the workings on both sides of the Vendinha "saddle."	6.34	12.70	7.27
24	(40)	Iodoformio, chip sample of ore in ten workings.	4.14	14.64	4.85
25	(41)	Ponte Alta, chip sample of ore in four trenches on hillside.	3.63	12.17	4.13
26	(42)	Alegre I, chip sample of ore from all but two workings.	5.42	9.77	6.00

block has an overburden about 2 meters in average thickness, and an irregular ore layer with an average thickness of about 7 meters, which will probably yield more than 375,000 metric tons containing between 3 and 4 percent of nickel. Other special calculations of "selected ore," based on cut-off grades higher than 2 percent of nickel, are indicated in plate 46 and also listed in table 16.

Jacuba II.--The deposit of Jacuba II has a larger surface area than that of Jacuba I, but its ore layer is not so thick and its tenor of nickel not so high. As computed from plate 46, its maximum surface area is approximately 65,000 square meters.

For convenience in computation, the deposit is divided into a saddle block, a north block, and a south block. The saddle block, which comprises 50 percent of the total area and is the thickest of the three blocks, contains much clay, and also a deposit of "pebble" cobalt ore. In the north and south blocks, the rock is partly weathered to a shallow depth and has a relatively low nickel content.

The western part of the saddle block has been drilled along four transverse lines, the drill holes having an average depth of 12 meters from the surface to unweathered rock (see pl. 47). Very little is known about the eastern part of this block, but by reason of its location it should contain a greater average thickness of ore than the north and south blocks. The indicated metric tonnage, computed on the basis of over-all recovery and a specific gravity of 2.5, is given below:

	Area (sq. meters)	Depth (meters)	Specific gravity	Metric tons
Saddle block.....	33,000	12	2.5	990,000
North block......	18,000	3	2.5	135,000
South block......	14,000	3	2.5	105,000
Total indicated ore........................				1,230,000

The average nickel content of this tonnage is certainly below 3 percent and probably between 1 and 2 percent. The tenor could be markedly increased, though with a decrease in recoverable tonnage, by discarding as waste or overburden all the dark-colored clay and crystalline rock.

Special calculations are possible for the drilled block, which has a measured surface area of about 11,000 square meters. The measured average thickness of its overburden is about 4.5 meters and that of its ore layer about 7.5 meters. On the basis of these measurements the following calculations are made:

	Area (sq. meters)	Depth (meters)	Specific gravity	Metric tons
Total..........	11,000	12	2.5	330,000
Overburden.....	11,000	4.5	2.5	124,000
Ore layer......	11,000	7.5	2.5	206,000

This selection is based on a cut-off grade of about 1 to 2 percent, so that the above-computed 206,000 metric tons of ore probably contains between 2 and 3 percent of nickel. If the same proportion of overburden to ore layer were assured for the entire saddle block, it is estimated that 600,000 tons of ore, containing from 2 to 3 percent of nickel, might be obtained from the saddle block alone, and about 800,000 tons of the same grade from the deposit as a whole.

The critical cut-off grade for the deposit is about 2 percent of nickel; the amount of ore containing more than 3 percent of nickel is relatively small, probably less than 100,000 metric tons.

Cachimbo Southeast.--The Cachimbo Southeast deposit has not been so extensively drilled as Jacuba I and Jacuba II, but fairly reliable indications of the depth of weathering on it have been obtained from scattered drill holes. The deposit, as shown in plate 49, has an area of about 30,000 square meters. It comprises a central drilled block, a north block, and a south block. The drilled block has an area of about 10,500 square meters, with a depth from the surface to unweathered pyroxenite of 15 to 20 meters and an average width of about 21 meters. The north block has an area of about 14,000 square meters, and its average depth is estimated to be only a few meters. The south block has an area of 6,000 square meters and an average depth of perhaps as much as 10 meters.

The calculations below serve to indicate the probable over-all tonnage yield of weathered material from this deposit:

	Area (sq. meters)	Depth (meters)	Specific gravity	Metric tons
Drilled block..	10,500	17	2.5	446,250
North block....	14,000	4	2.5	140,000
South block....	6,000	10	2.5	150,000
Total indicated metric tonnage..................				736,250

The estimated average tenor of this total tonnage is between 2 and 4 percent of nickel.

As shown in the composite longitudinal profile in plate 47, the drilled block may be divided into an upper layer, consisting of low-grade red and purple clay, the thickness of which is irregular but averages about 8 meters, and a lower layer, consisting of higher-grade green clay, of about the same average thickness. Composite analyses of drill cores of the lower, green clay layer (see table 15) indicate a nickel content of about 4 percent. Thus the drilled block, at a cut-off grade of about 2 percent, has an indicated reserve of about 210,000 metric tons of ore containing nearly 4 percent of nickel. The north and south blocks may yield 90,000 metric tons of ore having the same or a lower tenor.

Forquilha II.--Forquilha II is a "hanging-valley" deposit. The yield of ore per square meter of area is expected to be greater in its higher part than in the lower. The total area (see pl. 50) of the deposit is about 18,000 square meters, 5,000 square meters of which has an altitude of over 1,050 meters. Garnieritized weathered pyroxenite and green clay make up about 75 percent of the material exposed by all the surface workings in the deposit, and red and purple clay makes up 25 percent. A composite chip sample of the garnieritized material exposed above 1,050 meters is found to contain about 9.1 percent of nickel, and another from the area below 1,050 meters contains about 5.8 percent of nickel.

Auger drill holes and shafts made by the Emprêsa Comercial show ore to depths of 3 to 18 meters, with an average of about 5 meters. Assuming that 5 meters is the average depth to the base of the weathered material, the total area is underlain by about 235,000 metric tons of such material, of which about 176,000 may have a weighted average nickel content as high as 6.5 percent. The material below 5 meters of depth probably contains only a few percent of nickel. The Forquilha II deposit may thus be regarded as containing a few hundred thousand tons of ore with an average nickel content of 4 or 5 percent. Available information indicates, moreover, that it may contain an appreciable tonnage of high-grade ore, which can be outlined by additional prospecting.

Cachimbo North.--The depth of the exposed ore in the higher part of the Cachimbo North deposit is indicated in part by a cross-cutting adit (see pl. 47), which intersects the deposit at a depth of about 18.4 meters below the collar of the shaft shown in plate 49. The ore in the adit is a greenish gumbo clay, totaling about 13 meters in width, whereas the corresponding width exposed by a trench on the surface is only 10 meters. It is reasonable to assume that the Cachimbo North deposit, with its surface area of 10,000 square meters, may contain more than 460,000 metric tons of weathered material. A composite sample of 10 meters of clay in the adit contained 2.9 percent of nickel (see table 15). The tenor of the Cachimbo North deposit will probably be between this figure and the 6 percent calculated by the writer as a weighted average of 14 analyses of surface samples furnished the Emprêsa Comercial. A much larger tonnage is inferred in view of the probable extension of the ore strip to the north and south.

Jacuba III.--On the northwest side of the valley between Jacuba I and Jacuba II, numerous prospect pits, distributed through an area of more than 50,000 square meters, expose nickel-bearing clay and garnieritized weathered pyroxenite to a depth of at least 2 meters. The nickel content of samples from these pits ranges from 1 to 6 percent, and the average is estimated to be between 1 and 3 percent. A yield of more than 250,000 metric tons is indicated, with a tenor of more than 1 but less than 3 percent of nickel.

Other large deposits.--A few other deposits may contain large additional reserves, but little or no information is available as to their thickness. All that the writer can attempt, therefore, is to make estimates that seem reasonable in view of the geological environment of each deposit. These deposits are the Vendinha, the Iodoformio, the Ponte Alta, the Cachimbo West, the Alegre I, and the Forquilha I.

At the Vendinha deposit, prospect workings on the hillside are mostly in garnieritized weathered rock, but the ore may not extend for more than a few meters in depth. At the foot of the slope, however, the workings show a higher proportion of clay. One shaft reveals ore to a depth of at least 6 meters under an overburden of 3 meters. On the assumption that the average depth of weathered material is 4 meters, the deposits in the Vendinha "saddle area" (see pl. 50), for an area of 39,000 square meters, may have about 390,000 metric tons of such material, whose nickel content is not known but is believed to be less than 4 percent. A composite grab sample consisting of the garnieritized material only, and estimated to represent about a fourth of the quantity of material exposed in all the prospect workings, contained 6.3 percent of nickel. Reserves of indicated ore may be fairly estimated as 100,000 tons with a tenor of about 6 percent of nickel.

In the Iodoformio deposits, an assumed average thickness of 4 meters for the ore layer, over a total area of 2,300 square meters, would result in a yield of 23,000 tons. This material probably contains less than 4 percent of nickel. A composite grab sample of garnieritized weathered rock, estimated to represent about 50 percent of the material exposed in the workings, had a nickel content of 4.1 percent.

At the Ponte Alta deposit, the material exposed in the few prospect workings is about half clay. By reason of its topographic position, the deposit may possibly be more than 4 meters thick, and it may yield more than 35,000 metric tons containing between 3 and 4 percent of nickel.

At the Cachimbo West deposit (pl. 49), a depth of at least 2 meters of weathered material is assured in one cut, and an average depth of 4 meters is not too much to hope for. The deposit may comprise, in an area of 15,000 square meters, as much as 150,000 tons of material containing between 2 and 3 percent of nickel.

At the Alegre I deposit, the amount of exposed clay is about equal to that of the weathered rock. On the assumption that the average depth of the deposit is 4 meters, the total area of about 10,000 square meters may yield 190,000 tons, which would probably contain less than 4 percent of nickel. A composite grab sample representing both the green clay and the yellowish-green garnieritized weathered pyroxenite contained about 5 percent of nickel. This sample is assumed to be representative of an indicated reserve of about 3,000 metric tons (see pl. 50), and a much larger tonnage of the same grade is inferred.

The Forquilha I deposit may perhaps yield as much as 10,000 tons of rich ore, with a nickel content certainly less than 8 percent but probably greater than 4 percent. The depth of the deposit is not known but can easily be determined by sinking a few well-placed shafts.

Summary of reserves

Enough is known about the prospected deposits to assure a yield of about 184,000 metric tons containing about 4 percent of nickel and to indicate a yield in excess of 4 million tons with an average nickel content between 2 and 4 percent (see table 16).

In the opinion of the writer, the inferred reserve for the 45 prospected deposits would not exceed 9 million tons and would average from 1 to 3 percent of nickel; and for the district as a whole it would not exceed 16 million tons averaging 1 to 3 percent of nickel. The district may possibly yield as much as 5 million tons averaging about 4 percent of nickel, or as much as a million tons averaging 6 percent of nickel.

The writer's computation of measured and indicated reserves in the 45 prospected deposits is summarized in the table on page 301. For each class, further development and additional prospecting can possibly increase both the reserves and tenor; the figures tabulated in the table are based solely on the information available at this time.

The writer's estimate of maximum potential reserves is much smaller than those published by Wright and Pardee [17/] and by Leonardos.[18/]

The range in percentage of metals other than nickel for 21 composite samples, 11 of which were analyzed by the Emprêsa Comercial, is shown on page 302.

17/ Wright, C. W., and Pardee, F. T., op. cit., p. 12. "Twenty to 100 million tons of 5% average."

18/ Leonardos, O. H., op. cit., p. 39. "Dozens of millions of tons of 4 percent or better."

Table 16.--Indicated reserves of principal prospected deposits with various cut-off grades

	A Metric tons with cut-off about 2 percent nickel (Includes B and C)	B Metric tons with cut-off about 4 percent nickel (Includes C)	C Metric tons with cut-off about 6 percent nickel
Jacuba I	700,000 (2 to 3%)	300,000 (4±%)	10,000+ (6+%)
Jacuba II	800,000 (2±%)	7,000 (4±%)	None
Cachimbo Southeast	736,000 (2±%)	300,000 (4±%)	3,000 (6%)
Forquilha II	235,000 (4 to 5%)	176,000 (6±%)	176,000 (6%)
Cachimbo North	460,000 (3 to 4%)	300,000 (4±%)	6,000 (6+%)
Jacuba III	100,000 (2 to 3%)	?	?
Vendinha	390,000 (2 to 4%)	100,000 (6±%)	100,000 (6±%)
Iodoformio	23,000 (3±%)	6,000 (4±%)	?
Ponte Alta	35,000 (3 to 4%)	20,000 (4%)	?
Cachimbo West	150,000 (2±%)	?	?
Alegre I	190,000 (3±%)	3,000 (5±%)	?

Forquilha I................	10,000 (6±%)	10,000 (6±%)	10,000 (6+%)
Miscellaneous..............	200,000± (2 to 3%)	?	?
Totals.................	4,000,000 (2 to 4%)	1,222,000 (4 to 5%)	305,000+ (6 to 7%)

Measured and indicated reserves in 45 prospected deposits

	Measured (assured) tonnage			Indicated tonnage (Includes assured)		
	Metric tons	Percent nickel	Pounds nickel	Metric tons	Percent nickel	Pounds nickel
A. Reserves containing over 2 percent Ni. Includes B and C.	184,000	4.0	16,500,000	4,000,000	2-4	220,500,000
B. Reserves containing over 4 percent Ni. Includes C.	85,500	5.5	10,200,000	1,220,000	4.5	121,000,000
C. Reserves containing over 6 percent Ni.......	25,500	6.5	3,600,000	305,000	6.0	41,000,000

	Eleven analyses by Emprêsa Comercial (percent)	Eight analyses by Geological Survey (percent)
Fe	6.2 to 10.7	6.9 to 12.3
Cu	.3 to 1.4	.2 to 1.7
Co	Not determined	.4 to .28
Mn	.2 to .8	Not determined
Al_2O_3	1.1 to 8.7	Not determined
MgO	2.0 to 2.8	Not determined

RESERVES OF NICKEL-COBALT-MANGANESE-OXIDE DEPOSITS

Adequate information is at hand from which to estimate the indicated reserves and tenor of concretionary "pebbles" loosely cemented in the ferruginous soil in the "saddle" of Jacuba II and Jacuba III. It is reported by the Emprêsa Comercial that about 750 metric tons of material containing 3 to 5 percent of cobalt was recovered by a Japanese-controlled company during 1939-1941, of which about 450 tons was shipped to Japan. Of the remainder, in 1942, about 200 tons was stored on the company property at Jacuba ready for transportation and about 100 tons was stored at the port of Santos. The product was obtained by screening the "pebbles" from earthy material, followed by hand sorting.

Calculations of reserves are based on the quantity of "pebbles" that can be recovered on a 16-mesh screen in four well-prospected areas. A great number of channel samples were picked from the walls of prospect workings that exposed "pebbles" in soil and veinlets of manganese oxide in underlying purple clay. The samples were screened and washed, and a small quantity of "fines" was lost in the process. The dried "pebbles" were then powdered in a small ball-mill, and the powdered sample split and analyzed. The results of the analyses are shown in table 12, D to G, and estimates of reserves are given in table 17.

The borders of the "saddles" in the principal longitudinal valleys may contain additional deposits. Prospecting in the

Table 17.--Reserves of concretionary "pebbles" of nickel-cobalt-manganese oxide from Jacuba II and Jacuba III

	I	II	III	IV
Number of vertical channel samples..............	108	74	60	108
Average thickness of layer (meters)............	.80	.40	.36	.80
Calculated tonnage (metric tons) per square meter of surface area.	.65	.31	.35	.40
Developed area (sq. meters)....................	17,850	6,000	7,500	5,800
Developed reserve (metric tons)................	11,600 at 1.1% Co (280,000 lbs. of cobalt)	1,860 at 1.4% Co (57,000 lbs. of cobalt)	2,625 at 1.7% Co (98,000 lbs. of cobalt)	2,320 at 1.6% Co (82,000 lbs. of cobalt)
Total indicated reserve (metric tons).......	25,000	50,000		
	75,000 metric tons containing at least 1% cobalt (1,650,000 lbs. of cobalt)			

flat area north of Jacuba I has shown indications of a "pebble" layer.

The district will yield, in the writer's opinion, at least 18,000 metric tons and possibly more than 75,000 metric tons of "pebbles" recoverable by screening. This material would contain, without hand sorting, more than 1 percent and less than 2 percent of cobalt, with appreciable quantities of nickel, copper, manganese, iron, and barium.

Addition of manganese oxide selected from the soft, thin veinlets might serve to increase the cobalt and nickel tenor of the "pebble" product, but to do this would in most cases require too much hand sorting.

CONCLUSIONS AND RECOMMENDATIONS

The nickel-silicate deposits near São José do Tocantins, Goiaz, Brazil, are the most promising nickel-silicate deposits that have thus far been reported in the Western Hemisphere. Most of the earlier published estimates, however, of potential reserves and tenor appear too optimistic. They are based on geological conclusions different from those of the writer, whose views are more nearly in accord with those of de Moraes than with those of other predecessors.

Decisions as to metallurgical process and product to be marketed will have to be made before the cut-off grade can be established and the potential value of the deposits determined. Roads and bridges must be repaired and constructed, sources of hydroelectric power on the upper Tocantins River must be investigated, supplies of flux and fuel must be assured, and additional prospecting must be done before a local industry can be established. The ore reserves, in the opinion of the writer, do warrant the establishment of a local industry. During the critical years of the war, high-grade ore can easily be selected for shipment, and meanwhile additional development can outline new deposits of high-grade ore. Surface mining of nickel-silicate and cobalt "pebble" ore could be begun immediately, by local laborers using hand tools; and trucks could set out a day later for the railhead at Anapolis, loaded with "pebbles" of nickel-cobalt-manganese oxide or with high-grade nickel-silicate ore.

APPENDIX

Conversion table

Metric	English
1 meter (m)	3.28 feet
1 square meter (m^2)	10.76 square feet
1 cubic meter (m^3)	35.31 cubic feet
1 kilometer (km) = 1/6 league	0.62 miles
1 square kilometer (km^2) = 100 hectares	0.38 square miles (247 acres)
1 hectare (ha) = 10,000 m^2	2.47 acres
1 metric ton	2,204.62 avoirdupois pounds or 1.10 short tons

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