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MANGANESE AND IRON DEPOSITS OF MORRO DO URUCUM, MATO GROSSO, BRAZIL

BY

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MANGANESE AND IRON DEPOSITS OF MORRO DO URUCUM, MATO GROSSO, BRAZIL

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ABSTRACT

The manganese and iron deposits of the Morro do Urucum are located in the vicinity of 19°20' S., 57°40' W., or about 25 kilometers south of the city of Corumbá, Mato Grosso, Brazil. They were investigated in 1941 by the Departamento Nacional da Produção Mineral of the Brazilian Government, and by the Geological Survey, United States Department of the Interior, under the auspices of the United States Department of State and of the Interdepartmental Committee for Cooperation with the American Republics. The main purpose of the work was to establish with some accuracy the magnitude and grade of the manganese reserves. These were found to aggregate about 4,420,000 metric tons of measured ore, 11,750,000 metric tons of indicated ore, and 17,500,000 metric tons of inferred ore, with an average content of about 45.6 percent manganese and 11.1 percent iron.

Morro do Urucum also contains some 1,310,000,000 metric tons of banded hematitic material which averages about 55 percent iron and 20 percent silica. Detrital ore has accumulated on the slopes of the mountain; in the one area prospected there is about 450,000 metric tons per meter of depth of indicated ore and between 500,000 and 800,000 tons per meter of depth of inferred ore that would average, after screening, perhaps 64 percent iron and 4 percent silica.

The deposits of both manganese and iron occur in the Jacadigo series, of unknown but probably late pre-Cambrian or early Paleozoic age. This has been subdivided into the Urucum, the Corrego das Pedras, and the Band' Alta formations. The Urucum formation, between 400 and 500 meters thick, consists of continental deposits of arkose and conglomerate. It grades upward into the Corrego das Pedras formation, about 95 meters thick, in which ferruginous arkose at the base grades upward into ferruginous sandstone and ferruginous jasper. Above the Corrego das Pedras formation is the Band' Alta formation, at least 300 meters in thickness, which contains the deposits of manganese and iron. At the base of the Band' Alta is a widespread bed of the manganese oxide cryptomelane. This is overlain by banded siliceous hematite, which makes up the greater part of the formation but is interbedded, about 40 meters or more above the base, with other lenticular beds of cryptomelane, and, higher in the section, with lenticular beds of clastic rocks, including siltstone, sandstone, and, rarely, conglomerate. The formation is cut off at the top by an erosion surface.

All the evidence now available indicates that the rocks of the Jacadigo series are primary sediments deposited in a marine or epicontinental basin. The mode of deposition of the banded hematites and manganese oxide of the Band' Alta formation is not fully understood. There is no unequivocal evidence of vulcanism or igneous activity in the region except for the basement granite, which is much older than the ore deposits. No evidence is known to indicate that the iron was originally deposited as carbonate or silicate.

Morro do Urucum is one of a number of mesas composed of rocks of the Jacadigo series that are scattered over an area of 800 square kilometers in western Brazil and eastern Bolivia. Large faults cut the region into blocks, and at least one of the faults is a high-angle thrust fault with a vertical displacement of about 600 meters. In Morro do Urucum the rocks form an irregular basinlike syncline, in which the dips are not steep enough to cause much difficulty in exploiting the manganiferous beds.

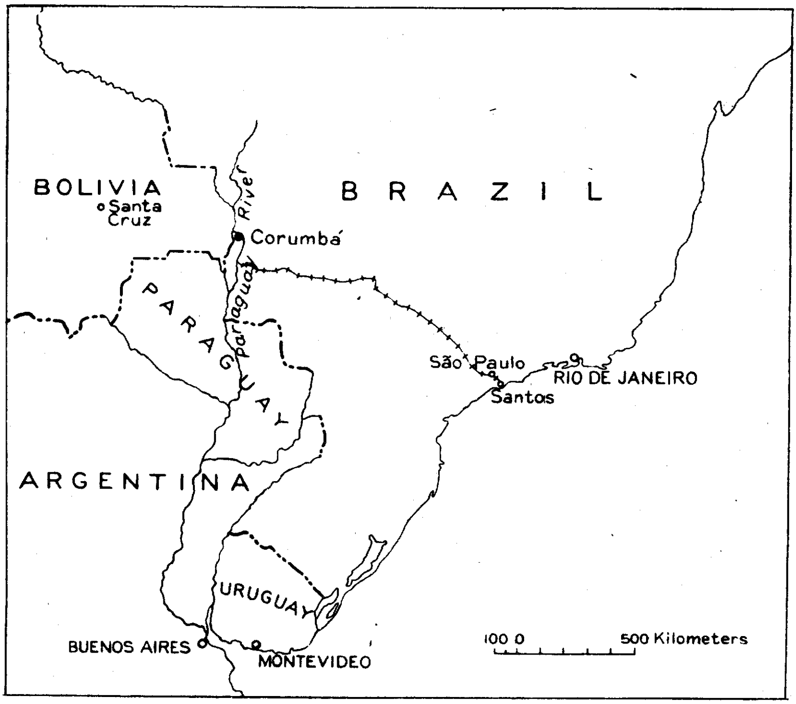

Figure 1.—Index map showing location of Corumbá, Brazil.

INTRODUCTION

The manganese and iron deposits of Morro do Urucum lie about 25 kilometers south of the city of Corumbá, Mato Grosso, Brazil, or in the vicinity of latitude 19°20' S., longitude 57°40' W. (fig. 1).

Transportation

Corumbá (population about 20,000) is now the mercantile center for a large part of southern Mato Grosso and will be the supply point in any development of the mineral resources to be discussed. The city is on the west bank of the Paraguay River, some 1,700 river miles above the Plate Estuary, and in 1941 two steamship lines made regularly scheduled trips from tidewater to Corumbá. Biweekly flights through Corumbá were also being made by the transcontinental air line on its trips between La Paz and São Paulo. The city is not yet directly linked by a railway to ports on the eastern coast. The Noroeste railroad joins the town of Porto Esperança, about 90 kilometers south of Corumbá, with the eastern part of Brazil, but in 1943 a railway from Corumbá to Porto Esperança was reported to be under construction. When this railway is completed, it will pass within less than 3 kilometers of the Morro do Urucum manganese deposits. A railroad was being constructed in 1941 from Corumbá westward into Bolivia toward Santa Cruz de la Sierra, of which about 120 kilometers was said to have been finished.

In 1941, ore from these deposits was transported from the mines to Ladario (pl. 1), in 4-ton trucks, over what was then a third-class unsurfaced road, though it was passable in all but the hardest rains. About 5 hours was required for the 64-kilometer round trip. That portion of the road which is on Morro do Urucum was extremely steep and would have to be in part relocated and widened before any large tonnage could be trucked over it. Ballasting, grading, and scraping would put most of the road in condition to bear heavy traffic. Road metal is not abundant except near the mines and might have to be hauled considerable distances.

River freight is transported by barges, with an average capacity of possibly 650 tons, and by steamers of up to 1,200 tons burthen. One steamer commonly tows several barges. Shipping costs for ore to Buenos Aires from Corumbá ranged from 150$ to 300$ ($7.58-$15.14 U. S.) per ton in 1943. River traffic is unrestricted for ships up to 1,200 tons capacity for 8 months of the year; for about 4 months, in most years, low water makes it impossible to carry full loads. In the dry season the minimum controlling depth is said to be about 4 feet.

Surface features

Three great physiographic features condition the life of the region adjacent to Corumbá, and would likewise condition any development of the mineral deposits. These are the Paraguay River, with its notable fluctuations in level and its great flood plain, which is known as the Pantanal; the low plateau stretching westward from the river for many kilometers; and the high mesas in which the iron and manganese deposits are found. The tops of the mesas, the plateau, and the flood plain respectively represent three distinct and unrelated erosion surfaces.

The highest erosion surface is cut on the beds of the Jacadigo series. Although this surface has been removed completely from most of the area, remnants of it may be seen in the mesa known as Tromba de Macacos (pl. 1); in Serra do Rabicho, some 5 to 10 kilometers northeast of the area shown in plate 1; in Serra de Albuquerque, about 10 kilometers southeast by south of the southern part of the area shown by that plate; and in Serrania de Mutun, some 30 kilometers west of Tromba de Macacos, as well as in Morro do Urucum and Serra da Santa Cruz. Valleys of steep gradient are being cut into all these mesas. The maximum elevation of the mesas, attained in Serra da Santa Cruz, is slightly more than 1,100 meters, and the average elevation of the ridge tops in Serra da Santa Cruz and Morro do Urucum is about 1,000 meters.

An intermediate erosion stage at an elevation about 150 meters above the general plateau level is represented by several extensive benches on several of the mesas mentioned above.

A gently rolling plateau 20 to 200 meters above the level of the river lies west of the Paraguay River and extends westward at least some tens of kilometers beyond the Bolivian border. This plateau is broken by steep buttes and ridges and by a few sink holes. The structure truncated by this erosion surface is rather complex between the Morro do Urucum and Corumbá, but farther to the north, in the vicinity of Puerto Suarez in Bolivia, it is simpler. The bedrocks of the plateau are dolomite, limestone, shale, granite, schist, and probably sandstone. Except in road cuts and on buttes, outcrops are rare. All-weather roads can be built on this plateau at moderate cost.

The third notable erosion surface is the flood plain of the Paraguay River. Although evidence is very incomplete, a few drill holes suggest that the alluvial fill in the valley is a relatively thin veneer over the bedrock, which, according to de Paiva,1/ consists largely of pre-Cambrian metamorphic rocks. Thus, because the extent of the feature in question is measured in thousands of square kilometers, de Paiva's reference to the Pantanal as a peneplain is fully justified.

Because the rainfall in the area is highly seasonal, at the end of the rainy season the Paraguay, which during the dry season is about 300 meters wide at Corumbá, overflows its banks and spreads over an area tens of kilometers wide. The main drainage then crosses the low divides between the fantastically intricate meanders of the sloughs and streams which drain the flood plain during the dry season. During the dry season the Pantanal is dotted with many oxbow, oval, and circular lakes and with fixed dunes, relics of an earlier drier cycle. In that season the Pantanal is grassy, and it is then a fine grazing ground for a large number of cattle.

The Paraguay River is the main traffic artery of the region. At Corumbá, 1,700 river miles from the sea, its elevation is only about 80 meters, so that its average gradient is only 0.14 foot per mile.

Climate, vegetation, and water supply

The climate of the area around Corumbá has wide seasonal variations. According to records obtained from the U. S. Weather Bureau for an 11-year period, the total precipitation for the 3 driest months, June, July, and August, averages $2\frac{1}{2}$ inches, whereas during November, December, and January the average precipitation totals 21 inches, equally distributed among the 3 months.

1/ Paiva, Glycon de, and Leinz, Viktor, Contribuição para a geologia do petróleo no sudoeste de Mato Grosso: Departamento Nacional da Produção Mineral, Boletim 37, p. 13 ff., Rio de Janeiro, 1939.

The average annual precipitation at Corumbá is 49 inches. During the dry winter months, south winds occasionally depress the temperature to about 40° F., and frosts have been reported by the ranchers near Urucum. During the summer months the temperatures and humidity are often high, but the periods of extreme heat are usually of no great duration. In general the climate is healthful, especially on Morro do Urucum, where the altitude tempers the heat. Malaria and other tropical diseases are said to be rare.

The characteristic vegetation of the widespread plateau below the higher mesas (see pl. 1) consists of thorny trees, many of which drop their leaves during the dry season; cactus is abundant, and there is little grass. The prevailing vegetation is thus characteristic of semiarid tropical country. Where water is relatively abundant, however, and on the slopes above this rather barren plateau, trees and vines grow luxuriantly, forming, in some places, a nearly impenetrable jungle. The summits of the mesas support only grass and a few low xerophytic shrubs except in certain sharply defined areas which, for some reason not readily apparent, are covered with a nearly impenetrable growth of stunted spiny trees and vines. The vegetation is primarily controlled by water supply, which in turn is controlled by the underlying bedrock and by altitude.

The lower slopes of Serra da Santa Cruz, Morro do Urucum, and Tromba de Macacos support many square kilometers of trees suitable for charcoal, and enough charcoal to feed a small charcoal blast furnace could probably be obtained within the region.

The water supply in the region, except on the Pantanal, is restricted. Several small permanent streams cross the low plateau, but on the higher slopes of the mesas, at the elevation of the manganese and iron deposits, an abundant water supply is available only at the spring which feeds the stream which passes through Fazenda do Urucum. The south end of Santa Cruz Valley contains many small springs which coalesce at an elevation of about 500 meters to form a small stream. Water would have to be piped from one or the other of these sources for any large development of the mineral deposits on Morro do Urucum.

Acknowledgments

The investigation resulting in this report was made by the Geological Survey, United States Department of the Interior, and the Departamento Nacional da Produção Mineral, Ministerio da Agricultura, of the Brazilian Government, in the months of August through December, 1941. It formed a part of the program of cooperation between the American Republics sponsored by the United States Department of State. The work would have been impossible without the whole-hearted and thoughtful cooperation of Dr. Luciano Jaques de Moraes, then Director of the Departamento Nacional da Produção Mineral, and of Dr. Glycon de Paiva, then Director of the Divisão de Fomento da Produção Mineral. Many other officers of the Departamento were helpful in various ways, among them Dr. Alves de Souza, Dr. Mario Pinta, and Dr. Evaristo Scorza. Dr. Licinio Barbosa rendered invaluable assistance in the field; he not only supervised most of the sampling, but did much to make the work pleasant. Dr. Eudes Prado Lopez contributed much during his short stay, but he unfortunately became ill and had to return to Rio de Janeiro.

The cooperation extended to the members of the party by the Sociedade Brasiliera da Mineração, which was exploiting the deposits, is deeply appreciated. The individuals who were thus helpful are too numerous to mention, but special thanks are to Dr. Selim Chamma, to Dr. Nelson Chamma, to Dr. Paulo Bohomoletz, to Geronimo Barbosa, and to Antonio Velho and Antonio Pequeno, the last two being laborers who served faithfully, well, and with great tolerance in work that was usually arduous and sometimes dangerous.

Among the Brazilian geologists to whom the writer is sincerely grateful for having given him the benefit of their regional knowledge, and of advice and counsel on the ground, are Drs. Avelino de Oliveira, Octavio Barbosa, Pedro de Moura, and Gabriel Mauro de Aranjo Oliveira. Their knowledge, freely shared, lightened the work, and their visits were highly stimulating.

To Mr. Charles R. Buckey, topographic engineer of the United States Geological Survey, belongs the credit for the excellent topographic base map and for the regional sketch map. His unfailing good humor and quiet efficiency were a great asset to the work. The visit of Dr. Charles F. Park, Jr., of the United States Geological Survey, was a distinct contribution, for his keen eye picked out several significant features which had previously been overlooked. His wise counsel has been of great assistance in preparing this report. The assistance of Mary Elizabeth Dorr in the field and in the office was invaluable and is deeply appreciated.

Dr. Charles Milton, of the Section of Chemistry and Physics of the Geological Survey, has been of great assistance in the petrographic work connected with the report; he studied many thin and polished sections and helped to interpret their significance.

The manuscript of this report was greatly improved by the critical editorial work of Mr. Frank C. Calkins and Dr. D. F. Hewett.

Mr. Buckey and the writer received unfailing and cordial cooperation from the Brazilian-Bolivian Mixed Railroad Commission, which is building the transcontinental railroad west from Corumbá. Coordinates on the geologic and topographic map (pl. 2) are tied in to those used by the Commission, with point of origin at Corumbá. The common point between coordinates on the map of Morro do Urucum and those of the railroad commission is about 10 meters southwest of the spring at Fazenda do Urucum (pl. 1). The azimuth used by the Railroad Commission surveyors differed from that determined by Mr. Buckey from solar observation, which agreed closely with that determined from astral observation by Dr. Seabra, surveyor for the Sociedade Brasiliera da Mineração. It was therefore decided to use Mr. Buckey's azimuth. The map made by Mr. Buckey can be brought into true relation with the coordinates of the Railroad Commission, by rotating it on the above-mentioned common point.

Elevations are based upon the Railroad Commission's figures for the common point. Control is based upon a triangulation net built up from a base line laid out along the ridge above the mines. The ends of the base line are marked by permanent concrete monuments with standard Geological Survey brass tablets affixed (pl. 2). Other triangulation points were not permanently marked. The topographic map was made according to the plane-table and alidade methods generally employed by the Geological Survey.

GENERAL GEOLOGY

Introductory statement

The immediate purpose of the field work on which this report is based was to establish with some accuracy the size and grade of the manganese deposits of Morro do Urucum. The fulfillment of this purpose necessitated a detailed local study of the stratigraphy of the rocks immediately related to the deposits. This study revealed the importance of the hematite deposits, which had hitherto been relatively unknown. Time was not available, however, to undertake regional studies, and until such studies are made many questions as to ultimate origin of the manganese and iron deposits must remain unsolved. Geological information is presented more fully in the following pages than is usual in economic reports because no thorough study of the rocks and structures of this remote part of South America had been made before. For the same reason, the writer has not hesitated to indulge in geological speculations, even though some are based upon admittedly inadequate evidence. The reader should have no difficulty in differentiating between established facts and speculative conclusions.

Previous work

D'Orbigny 2/ was the first geologist to record his observations in this region. He was followed in 1897 by J. W. Evans, 3/ and later by Arrojado Lisboa, 4/ whose work in this area has been standard for many years. Recently de Paiva and Leinz 5/ and Oliveira and Leonardos 6/ have contributed basic information on the area.

Oliveira and de Moura have carried on basic reconnaissance studies of the Corumbá formation, mentioned below, and Oliveira and Leonardos 7/ have described it in some detail. Very little is known, however, about the other sedimentary formations in the area, and less, to the best of the author's knowledge, about the areal distribution of the granite and schist exposed near Fazenda do Urucum (pl. 1). These three formations are source rocks for part of the Jacadigo series, which contains the ore beds, and their areal distribution and origin deserve careful study.

Very little is known of the geologic structure of eastern Bolivia and western Brazil, and detailed reconnaissance in the region will probably reveal a hitherto unsuspected structural complexity. The remoteness of the area, its general reduction to local base levels and the consequent scarcity of exposures, and the lack of adequate maps have discouraged such work, but with modern techniques and equipment, much basic information could be obtained.

2/ D'Orbigny, Alcide, Voyage dans l'Amérique Méridionale exécuté pendant les années 1826-33, vol. III, 3me partie (Géologie), p. 19, Paris, 1842.

3/ Evans, J. W., The Geology of Matto Grosso: Geol. Soc. London, Quart. Jour., vol. 50, pp. 85-104, 1894.

4/ Lisboa, Miguel Arrojado Ribeiro, Oeste de São Paulo, Sul do Mato Grosso. Estrada de Ferro Noroeste do Brasil, Rio de Janeiro, 1909.

5/ Paiva, Glycon de, and Leinz, Viktor, op. cit.

6/ Oliveira, Avelino Ignacio de, and Leonardos, Othon Henry, Geologia do Brasil, Série Didática, No. 2, Serviço de Informação Agricola, 2a Edição, Rio de Janeiro, 1943.

7/ Oliveira, A. I., and Leonardos, O. H., op. cit., pp. 210-218.

Crystalline rocks

No crystalline rocks crop out in the area studied in detail, and although several published and unpublished geologic sections of Morro do Urucum show an area of schist in the valley immediately east of that mountain, painstaking search of this valley revealed no outcrops or float of crystalline rocks. Three kinds of crystalline rock occur, however, in the immediate vicinity. In a pasture about 200 meters north of the main buildings of Fazenda do Urucum, a very small quarry has been opened in chlorite gneiss and schist. These rocks are composed of microcline, sodic feldspar, quartz, muscovite, and chlorite. All these minerals, except for late quartz in small veinlets, are crushed and distorted. The rocks represent a high stage of dynamic metamorphism and are undoubtedly among the oldest in the region.

Unmetamorphosed pink microcline granite crops out at several places in the region, notably about 1 kilometer up the stream that flows through Fazenda do Urucum, and also about a kilometer south of Puerto Suarez, Bolivia. Heavy cover of talus, alluvium, and colluvium makes it impossible to determine the relation between this granite and other bed rocks, but since the mineral constituents are uncrushed, it must be intrusive into the gneiss and schist mentioned above.

Several diorite dikes cut the granite along the road between Corumbá and Fazenda do Urucum.

Sedimentary rocks

Corumbá formation

The Corumbá formation consists of calcareous shales and argillites, sandy shales, black, well-bedded limestone, gray limestone and dolomite, and white dolomite. It underlies a considerable part of the plateau mentioned above and, according to Oliveira and de Moraes,8/ extends at least 200 kilometers westward from Corumbá into Bolivia, 100 kilometers to the south, more than 100 kilometers to the north, and an unknown distance to the east. The age of the Corumbá formation has been variously given as Algonkian to upper Silurian. The formation was correlated by Arrojado Lisboa 9/ with the Bodoquena limestone, probably of Cambrian age, and this correlation, though not unanimously accepted, is regarded by most Brazilian geologists as valid. A search for fossils produced no results.

In many localities the Corumbá formation has been marmorized. Although this recrystallization has been attributed to metamorphic effects of the intrusive granite which crops out near Fazenda do Urucum, it is more probably the result of dynamic stresses induced during the complex deformation of the area. There is no known evidence to prove or even strongly indicate that the granite is intrusive into the Corumbá formation.

8/ Personal communication.
9/ Lisboa, M. A. R., op. cit., pp. 55, 58.

Jacadigo series

The Jacadigo series, named and described by Arrojado Lisboa 10/ in the fascinating report on his exploration of the route of the Noreste railway in 1907, contains iron and manganese deposits of great magnitude. Lisboa defined the Jacadigo series as "the succession of sedimentary rocks of Urucum which lie directly upon the granite or the igneous mica schist." He further says:

> At Urucum I distinguished two formations in the series. The lower, composed principally of a brecciform sandstone, which I called the Urucum sandstone, contains, in addition to granitic elements, pieces of limestone, and passes (upward) into a finer breccia which also has a calcareous cement. The upper sandstone does not react with hydrochloric acid, but is arkosic throughout; it is distinguished from the lower by being eminently ferruginous. 11/

The writer accepts the term Jacadigo series as defined by Arrojado Lisboa, but he proposes to divide the series into three formations, the lower consisting of arkose, the middle one of ferruginous and arkosic jasper, and the upper of banded hematite and manganese oxides, together with lenticular beds of jasper, siltstone, and sandstone. It is proposed to restrict the term "Urucum formation" to the lower division (essentially in accordance with Arrojado Lisboa's usage), to name the middle division the Corrego das Pedras formation, and to name the upper division the Band' Alta formation. Although these divisions intergrade, tney are sufficiently distinct in composition to justify regarding them as separate formations. 12/

Arrojado Lisboa 13/ believed the Jacadigo series to overlie the Corumbá limestone unconformably. This belief was founded upon the presence of boulders of limestone similar in appearance to the Corumbá in the Jacadigo series, which is strong evidence but not proof, since it is conceivable that two similar limestones of dissimilar age may be present in the area, and that the Corumbá may not have contributed debris to the Jacadigo. These questions cannot be settled until the regional stratigraphy has been worked out in detail.

The Jacadigo series must originally have been of greater lateral extent than was observed in the present investigation. The writer has seen outcrops in an area extending for 40 kilometers from east to west and 35 kilometers from north to south. Fragments of hematite similar to that in Morro do Urucum have been found by A. I. Oliveira 14/ near El Carmen, 110 kilometers west of Corumbá, and near Forte Coimbra, 100 kilometers south of Corumbá. The series has not been reported north or east of Corumbá.

10/ Lisboa, M. A. R., op. cit., p. 59.

11/ Lisboa, M. A. R., op. cit., p. 59. Free translation by M. E. Dorr and the writer.

12/ Paiva, Glycon de: Código de Taxonomie-Ministério da Agricultura, Divisão de Geologia y Mineralogia, Notas Preliminares e Estudos Número 20, p. 6, Rio de Janeiro, Julho 1940.

13/ Lisboa, M. A. R., op. cit., p. 59.

14/ Personal communication.

The size of the area in which outcrops have been seen indicates that the series originally covered at least 800 square kilometers; but as no decrease in thickness is apparent at or near the boundaries of the present area of outcrop, it is probable that the series originally covered a much larger area. Its outcrop is limited on the west by a fault, and in its easternmost exposure, which is in the Serra do Rabicho, the Jacadigo series dips under the Tertiary and Recent deposits of the Pantanal.

No reliable data are available concerning the age of the Jacadigo series. Arrojado Lisboa 15/ classed the series as "pre-Devonian," while Oliveira and Leonardos 16/ classify it as Silurian. Paiva 17/ quotes Gerth as suggesting that the Jacadigo series might be correlated both with the Minas series (pre-Cambrian) and the iron-bearing Tocantins quartzite of the Amazon area, and seems to regard this correlation as not impossible. The writer, however, feels that there is as yet no adequate basis for a definite age assignment. More light may be shed on the question when the relations between the Jacadigo series and the El Carmen formation of Bolivia (Ordovician) have been established.

Urucum formation.—The Urucum formation, which is between 400 and 500 meters in total thickness, is composed of arkose and conglomerate. The dominant colors in its outcrops are buff to brown. These colors are probably in part the result of weathering, for the hue of fresh rock exposed in the road cut below the mines is dominantly greenish. Although its base has nowhere been seen, this formation probably rests unconformably upon the pink granite and the chlorite gneiss and schist. No satisfactory section of the formation could be measured, because a heavy cover of talus, colluvium, and vegetation makes the outcrops quite discontinuous. A composite section totaling approximately 340 meters was measured on the east side of Santa Cruz Valley, but the lowest beds in the section lie at least 50 meters above the base of the formation. This section is described on the opposite page.

The arkose consists of quartz, feldspar, and calcite with minor accessory minerals. Feldspar, generally including microcline and sodic plagioclase, constitutes between 20 and 30 percent of the rock. The plagioclase, which is usually crushed and sericitized, is more abundant in the lower part of the section, whereas the microcline which is relatively fresh is more abundant in the upper part. This change in composition may be due to a gradual change in source of material, the lower beds being derived mainly from the underlying gneiss and schist, and the higher beds from the younger, undeformed microcline granite exposed near Fazenda do Urucum. The quartz grains in the arkose are in general highly angular; they are not frosted, and they show no evidence of long transportation. Strain shadows are usually seen in them under crossed nichols. At least two of the beds of finer material contain carbonaceous matter. Calcite cements nearly all the rock and forms many veinlets, and the formation contains many fragments and cobbles of limestone.

Two notable cliff-forming sandstone beds crop out in the middle of the Urucum formation where it is exposed in the southern part of Santa Cruz Valley (pl. 2). In the northern portion of the valley, at about the same horizon, there is a corresponding cliff-forming bed, which does not outcrop so boldly because of the lower gradient of that part of the valley. These massive beds, thoroughly indurated by calcium carbonate, probably represent channel sandstone.

15/ Lisboa, M. A. R., op. cit., p. 55.
16/ Oliveira, A. I., and Leonardos, O. H., op. cit., p. 272.
17/ Paiva, G. de, op. cit., p. 69.

Partial section of Urucum formation, measured at south end of east side of Santa Cruz Valley

	Thickness (meters)
Red arkosic sandstone and fine conglomerate. Base of Corrego das Pedras.	
Covered	15
Coarse buff arkose	15
Covered	5
Coarse conglomerate; cobbles of granite, schist, and quartz	20
Covered	15
Cross-bedded conglomeratic arkose; buff	3
White shaly arkose	2
Covered	25
Well-bedded medium-grained arkose; buff	10
Covered	40
Cliff-forming cross-bedded channel sandstone; massive bedding	90
Gray sandy shale	1
Covered	19
Buff, well-bedded arkose	8
Gray and yellow medium-grained, well-bedded arkose; thin beds	2
Cross-bedded fine- and medium-grained arkose	6
Well-bedded medium-grained arkose	4
Banded black and gray fine shaly sandstone; organic matter	10
Covered	7
Gray well-bedded arkose, fine-grained	3
Thin-bedded yellow arkose, well-bedded, medium-grained.	5
Gray shaly sandstone, arkosic; some organic matter	5
Covered	37
Brown, friable, medium-grained arkose	3
Bottom of section at least 50 meters above bottom of formation.	
	350

The kind of conglomerate that is most abundant in the Urucum formation is composed of well-rounded cobbles, which are predominantly of granite but which include limestone, diorite, chlorite and muscovite gneiss and schist. Some of the conglomerate beds are typical pudding stones. Although some of the individual boulder beds are abruptly lenticular, there is a zone about 30 to 60 meters below the top of the Urucum formation in which these lenses are common. The thickness of the individual lenses ranges from a meter or less to more than 15 meters, but where the lenses are thin, one may be closely superposed upon another.

Conglomerates of a different type are found in the uppermost part of the formation. In these, pebbles, cobbles, or large boulders are scattered sparsely through beds of moderately well sorted clastic material having the texture of coarse sandstone or grit. An excellent example is to be seen in the first road cut south of the mine offices, where, in a coarse unaltered arkose, there is a well-rounded boulder of limestone at least 60 centimeters long. Boulders of this size and larger are not exceptional, and, since there is nothing in the structure or composition of the beds to suggest transportation by mud flows, and since the very slight cross-bedding at this particular horizon does not indicate torrential conditions, their presence suggests rafting. Such rafting might have been accomplished either by ice or by trees, but it seems possible that these boulders represent the remains of coarser sediments reworked by wave action before consolidation.

The material that constitutes the Urucum formation is in general poorly sorted, although there are many exceptions to this rule, notably the heavy channel sandstones and some of the fine-grained silts. Cross-bedding of the torrential type is not unusual, especially in the upper part of the formation. No systematic orientation of the foreset beds was observed. Ripple marks, both current and wave, are common on the bedding planes.

The characteristics of the Urucum formation are believed to indicate that it was deposited in a continental environment, partly in streams and rivers, partly in lakes and ponds. The terrain from which the material was derived must have been one of substantial relief to have provided boulders and cobbles of the size found in some of the conglomerate beds. The presence of limestone cobbles and the abundance of calcite in veinlets and cement suggest that the Corumbá limestone was being eroded over a considerable area when this part of the Jacadigo series was being deposited. The gradual coarsening of the sediments upward in the section indicates either that the relief increased somewhat during the deposition of the formation or that precipitation increased, or both.

Corrego das Pedras formation.—The Corrego das Pedras formation is defined as comprising the sedimentary beds between the arkosic Urucum formation and the bedded hematite and manganese of the Band' Alta formation. It is a transitional formation, the composition of which is variable throughout, both vertically and laterally. In Serra da Santa Cruz and Morro do Urucum it consists mainly of highly ferruginous sandstone and ferruginous jasper, but its basal beds are of ferruginous arkose. This formation is probably included in the unnamed "upper sandstone" of Arrojado Lisboa.18/

The bold cliffs which characterize the west and north sides of Morro do Urucum and Serra da Santa Cruz consist in large part of rocks belonging to the Corrego das Pedras formation, but they are unfortunately so steep that they cannot be examined in detail.

The section given below is a composite of partial sections measured below the mines and at the south end of Morro do Urucum. These have been checked by instrumental measurements of the formation as exposed in the cliffs of Serra da Santa Cruz and by partial sections examined there. No one continuous section would agree in detail with that which follows:

Composite section of Corrego das Pedras formation

	Thickness (meters)
Ferruginous jasper, distinctively banded in red, pink and white; some hematite; sand grains	5
Ferruginous jasper, specularite, and hematite; minor clastic material; well bedded	15
Ferruginous jasper; jasper in small nodules; much hematite and some specularite; sand grains in jasper and occasional beds of ferruginous sandstone	25
Ferruginous sandstone, jasper nodules, hematite cement and some hematite replacing jasper. Well bedded	20
Ferruginous arkose and sandstone, with hematite as cement; a little jasper. Well bedded; minor cross-bedding	20
Ferruginous arkose, occasional granite and quartz cobbles; largely cross-bedded	10
	95

18/ Lisboa, M. A. R., op. cit., p. 59.

As the upper and lower contacts of this formation are both gradational, their location is somewhat arbitrary. The gradational zone at the bottom, between the Corrego das Pedras and the Urucum formation is about 10 meters thick. Both the uppermost beds of the Urucum formation and the lowermost beds of the Corrego das Pedras formation may be cross-bedded, but the lowermost beds of the Corrego das Pedras formation as here defined are characterized here and there by aeolian cross-bedding. This criterion, however, can be applied only to a very limited extent. Of wider application as aids to drawing the boundary between the two formations are: (a) weathering aspects, (b) color, (c) cementing material, (d) joint patterns.

(a) The Urucum formation weathers to rounded granitoid forms, the Corrego das Pedras to craggy, blocky, angular forms. There is usually an overhang where the contact crops out in cliffs.

(b) The Urucum formation is buff on weathered faces and green on fresh faces; the Corrego das Pedras formation is red. Staining, however, usually masks the transition zone.

(c) In the Urucum formation the cementing material is calcite; in the Corrego das Pedras it is mainly hematite, though the beds at the very bottom of this formation may also contain calcite.

(d) The Urucum formation is only obscurely jointed, strains probably having been absorbed by shearing and recrystallization of the calcite cement. The hematitic jasper of the Corrego das Pedras formation is brittle, and as a result the rocks are closely and regularly jointed.

The rocks of the Corrego das Pedras formation grade rather regularly upward from ferruginous arkose at the base to hematitic jasper with scattered clastic quartz grains at about the middle of the formation. From there to the top there are relatively slight changes except for the presence of occasional beds in which clastic quartz is relatively abundant. The upper limit of the formation—its contact with the Band' Alta—should probably be placed, for maximum clarity of definition, at the bottom of the lowest bed of banded hematite or manganese oxide, whichever of these two is the lower. In the mapping for this report, however, the contact was drawn at the bottom of the lowermost manganese oxide, because that material forms a persistent bed, everywhere present in the area mapped, and because, in the few localities where banded hematite cropped out below the lowermost manganiferous bed, its base was so close to that bed that it mattered little which horizon was taken as the base of the Band' Alta.

Since this formation is closely related in genesis to the iron and manganese deposits, its rocks will be described in some detail.

Several common characteristics stand out in most of the thin sections of rocks from the jaspery beds in this formation. The jasper occurs in ovoid nodules or lenticules up to 7 millimeters in length and 2 to 3 millimeters in width, alined with their long axes parallel to the bedding. Many of the lenticules are concentrically banded, and many are asymmetrical, as if they had adapted themselves to the irregular surface of deposition caused by pre-existing similar nodules. Clastic fragments occur between the nodules, but are generally rare in those beds in which the nodules are well formed and abundant.

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Cryptocrystalline silica and fibrous chalcedony are common in some thin sections of the rocks. Where these forms of silica are abundant, iron oxide is also abundant and widely disseminated, but the jasper nodules are generally imperfectly formed and leached. Usually it is impossible to be certain what material the cryptocrystalline silica has replaced; in some cases it may have replaced feldspar grains; in other cases it has clearly replaced nodules of jasper and grains of quartz. Sericite is not uncommon in some of the slides, but little of it is clearly associated with residual feldspar. It coats the peripheries of some jasper nodules and fills crosscutting fractures in jasper, hematite, and quartz.

Hematite is present in all the rocks of the Corrego das Pedras formation. In some beds the proportion of hematite is as high as 70 percent, though in most beds it is less than 50 percent, and in some it is less than 30 percent. In the lower, clastic part of the formation it occurs as a cement. Jasper has been replaced by hematite, which is concentrated around the edges of the nodules and also is disseminated within them in shreds and patches. These may gradually decrease in abundance toward the center of the nodules, or they may form linear groups that cross the nodules. In the process of replacement, the nodules generally change from homogeneous brown, yellow, or pink jasper to pale cryptocrystalline silica.

Carbonate is absent from the greater part of the Corrego das Pedras formation, but minute rhombs of what may be dolomite are found at a few horizons in the middle and near the top of the formation. These are in a few cases replaced in part by hematite or cryptocrystalline silica, but one carbonate rhomb was seen in the middle of a jasper nodule, where it appeared to have replaced silica.

The whole aspect of the upper part of the Corrego das Pedras formation is that of a series of chemical sediments in which considerable rearrangement of the constituent materials has taken place since they were deposited.

In the absence of other evidence, the writer does not regard the presence of sericite in the Corrego das Pedras formation as evidence of hydrothermal activity. It seems probable that the rearrangement of silica and iron oxide largely occurred during the consolidation of the rock and that the sericite was formed during the late stages of this process.

Had either supergene or hydrothermal solutions been largely responsible for the introduction, recrystallization, or movement of the iron in the Corrego das Pedras formation, they would have been likely to penetrate the more permeable beds of the underlying Urucum formation, and to react with the calcite cement, as they did at the base of the Corrego das Pedras, depositing hematite. But if the ferruginous part of the Jacadigo series had been formed by such a process, its base would presumably be irregular, whereas in fact it is remarkably even. This evenness points to a sedimentary origin for the jasper probably under marine, estuarine, or closed-basin conditions. The environment in which the Corrego das Pedras formation was deposited evidently shifted during deposition, continental conditions being indicated by the aeolian and fluviatile cross-bedding at the base. The sources of the silica and iron will be discussed below in connection with the Band' Alta formation.

Impure manganese oxide is found in small quantity near the base of the Corrego das Pedras formation at three localities: (1) just under the highest cliff in Serra da Santa Cruz, (2) at the base of the cliff just north of the mines, and (3) on the trail at the base of the first cliff south of the mines. The manganese oxide appears to have replaced the calcite cement, and possibly some other minerals. These occurrences, which are of no commercial importance, probably illustrate supergene replacement. Thin sections of rocks from the localities named show no evidence of hydrothermal alteration.

Band' Alta formation.—The Band' Alta formation contains the only manganese deposits in the region that are of economic interest. The formation, which is a part of Arrojado Lisboa's 19/ "ferruginous arkose", is here defined as the series of banded hematite beds, associated with subordinate beds of manganese oxide, siltstone, sandstone, and jasper, that overlies the jasper and the ferruginous arkose of the Corrego das Pedras formation. In Morro do Urucum the bottom of the Band' Alta formation is marked by a bed of manganese oxide, but in some parts of Serra da Santa Cruz this bed is underlain by a few meters of banded hematite, and in Tromba de Macacos no manganese oxide was found at the base, which was there transitional between typical banded hematite and the jasper characteristic of the Corrego das Pedras. The Band' Alta formation is stratigraphically the highest in the region, and is cut off by an erosion surface. Its greatest measured thickness in the Morro do Urucum is slightly over 300 meters, but a greater thickness may be present in the Serrania de Mutun in Bolivia.

A detailed section of the formation in Morro do Urucum was measured above the road from the mines to the mine office. It is presented in graphic form, with analyses of continuous chip samples, in plate 3.

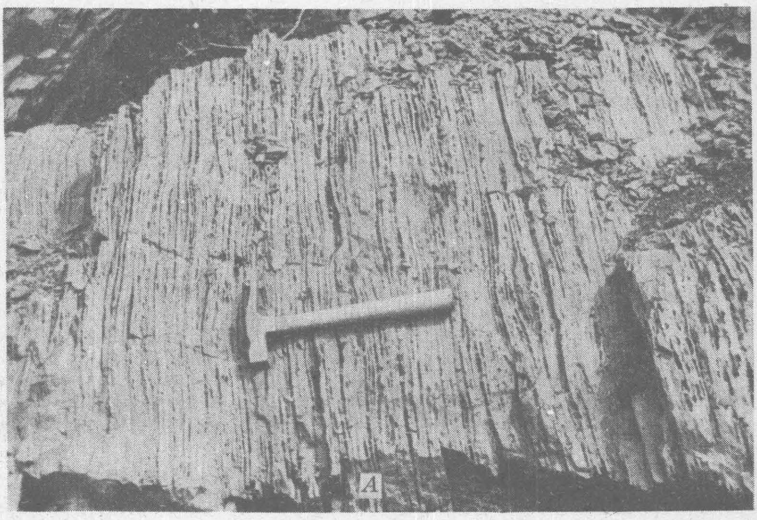
The Band' Alta rocks occur in massive beds averaging about 1½ meters in thickness and ranging up to 6 meters or more. Most of the beds consist of hematitic rock, about 70 or 80 percent of which, by weight, consists of the mineral hematite.

Each hematitic bed shows alternating bands of hematite and silica, the hematite bands ranging in width from half a centimeter to 10 centimeters, and those of silica usually averaging about 1 centimeter. This banding is due to intercalation of small lenses of silica in the hematite. These lenses vary considerably in shape and size, but might average a meter or two in breadth and 1 centimeter in thickness. At some horizons they resemble thin beds, while at other horizons they consist of round or oval nodules. Where deformation has been strong, the lenses are broken into individual nodules which assume blocky and twisted forms. The undeformed lenses have smooth upper and lower surfaces, generally broken in one or two places by rounded or mushroom-shaped apophyses and pendants that project as much as a centimeter into the surrounding hematite. The structures in the hematite bend around the lenses (figs. 2, 3, and 4).

In addition to the banding caused by the silica lenses, the hematite usually shows a fine lamination, measurable in millimeters or fractions of a millimeter. This lamination is caused by variation in grain size of the hematite and, to a minor extent, by concentration of sparse, extremely fine fragments of angular detrital quartz along bedding planes in the hematite.

19/ Lisboa, M. A. R., op. cit., p. 59.

Many of the bedding surfaces in the hematite are characterized by peculiar interlacing shallow grooves, usually much less than a meter in length and 1 to 3 millimeters deep (fig. 6). These grooves may represent the imprints of seaweed. They are too irregular to be shrinkage cracks developed during dessication, and too shallow, being confined to thin layers.



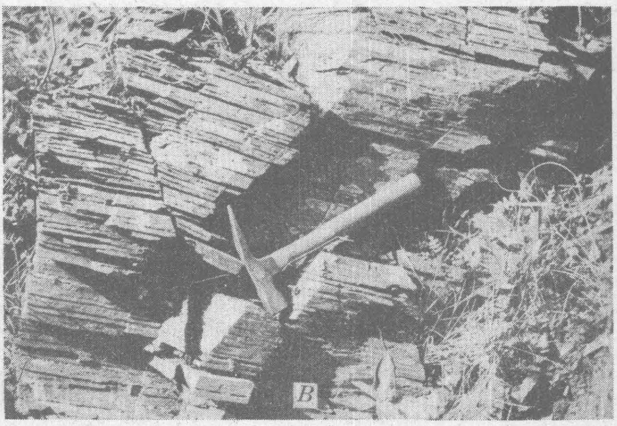


Figure 2.--Interbedded hematite and jasper, Band' Alta formation. Silica leached out on outcrop. B courtesy of Dr. Octavio Barbosa.

Near major faults in the area, the fine-grained hematite has been metamorphosed to oriented micaceous hematite, and the silica has been comminuted and distributed throughout the rock. Less intense or less localized stress, which must locally have raised the temperature of the rocks as they were deformed, has resulted in the formation of magnetite, often in euhedral crystals, which causes marked local magnetic deviation.

Figure 3.—Hematite and nodular jasper in Band' Alta formation. Part of silica leached out in A, almost all leached out in B, which is crushed and distorted.

At or near the base of the Band' Alta formation in Morro do Urucum and in Serra da Santa Cruz is a persistent bed of the manganese oxide cryptomelane,20/ which varies in thickness from 20 centimeters to nearly 6 meters. From 30 to 45 meters higher

Figure 4, A.—Hematite and nodular jasper, Band' Alta formation. Silica leached out. Supergene (?) quartz at right.

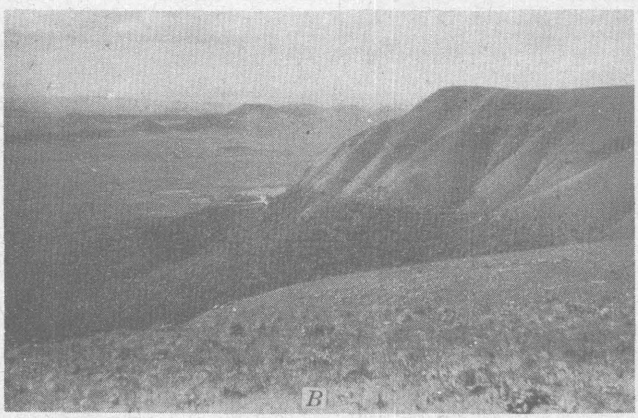


Figure 4, B.—Northwest corner of Morro do Urucum. Picture shows loading platform (black line at edge of trees), road to mines, and administration buildings (on spur). Distance to loading platform 1.5 kilometers. Courtesy of Dr. Octavio Barbosa.

is a second, less widespread bed of the same material ranging up to 2.2 meters in thickness. Smaller lenses of manganese oxide were found at several places in the area mapped in detail. The

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20/ Richmond, W. E., and Fleischer, Michael, Cryptomelane, a new name for the commonest of the "psilomelane" minerals: Am. Mineralogist, vol. 27, pp. 607-610, 1942.

distribution of these beds will be described in the section on ore deposits. The two major beds are hereinafter called bed No. 1 and bed No. 2, respectively.

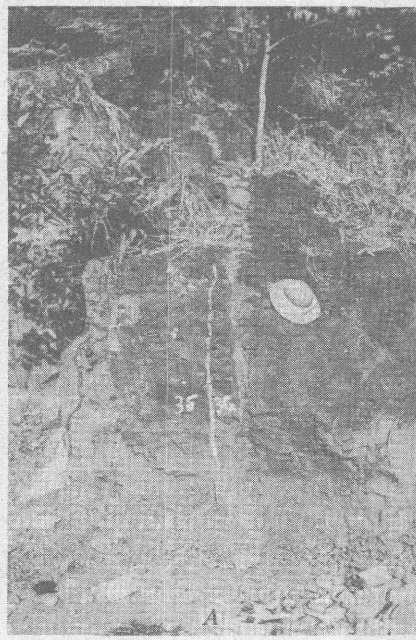

Figure 5, A.—Natural outcrop of bed 1, showing semi-channel sample. Courtesy of Dr. Octavio Barbosa.

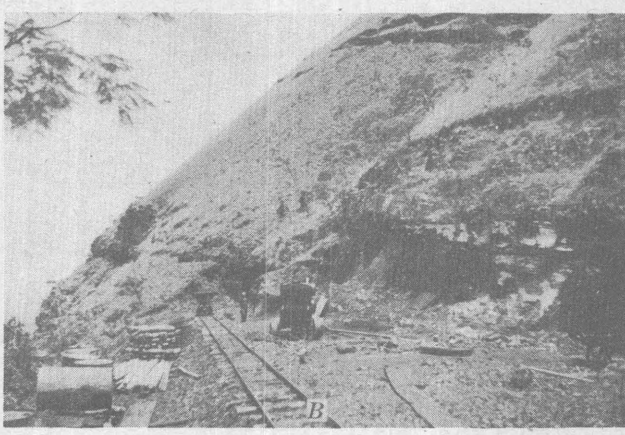

Figure 5, B.—Loading platform, showing portals of mines 1 (left) and 3 on bed 1. Typical overhanging outcrop of bed 1 on steep slope, left. Bed 2 exposed in top center.

The manganese oxide beds are characteristically dull-black to dark-gray on the outcrop, but on fresh exposures they range from dull-black through blue-black to steely gray. Banding is obscure on fresh exposures and is generally a gross lamination rather than true bedding. In the upper beds even this lamination is obscure. On weathered outcrops of the lower bed, however, differential solubility in the layers has produced an appearance of bedding. In a few localities the outcrop of this bed has somewhat the appearance of a weathered outcrop of black fissile shale. The bedding or lamination surfaces are commonly somewhat undulatory, and the top and bottom of the beds, in some localities, have forms similar to interference ripple marks. What appeared to be obscure cross-bedding was noted at one locality.

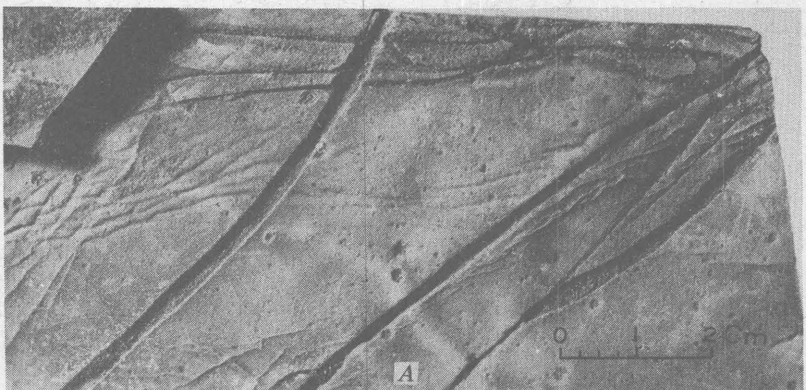

Figure 6, A.--Bedding surface of hematite, showing grooves of possible organic origin. Scale in centimeters.

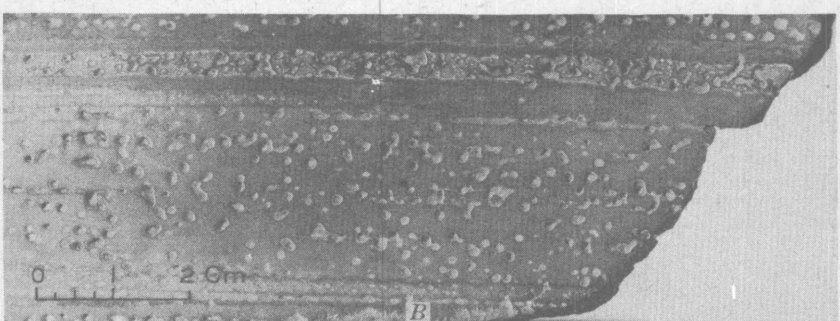

Figure 6, B.—Polished surface of typical specimen of "graphic" type manganese ore from bed 1. Scale in centimeters.

All the manganiferous beds contain nodules of material apparently similar to the surrounding material. Although on fresh exposures these nodules appear to be identical in composition with the enclosing rock, they become extremely porous on exposed faces and weather out from the matrix. This suggests that they are composed of a mixture of cryptomelane and some less stable manganese oxide. The nodules average from 3 to 5 centimeters long and from 2 to 3 centimeters thick, and have a very regular ovoid shape. Laminations in the matrix curve around them. As there are large numbers of these nodules in the second bed, in some cases forming 15 percent of the rock, and as the material in bed No. 2 is generally darker in color and shows smoother fracture, it is possible to distinguish between material from the two major beds.

The material making up the various manganiferous beds is remarkably uniform in appearance and its grade cannot easily be estimated by eye. Four general types of material were recognized in the field: "dense"; "dull" or "granular"; "steely"; and "graphic." In the lowest bed, the steely type is hard, has a very marked conchoidal fracture with extremely smooth faces, and is light steel gray in color. The dull or granular type is black in color, is sometimes slightly friable, and has rough and irregular fracture faces. The dense type is blue-gray to dark-gray, is not friable, and has a slightly conchoidal to splintery fracture. The steely type grades into the dense and the dense into dull. The graphic type will be described below. Of the four types, the dense and steely are the most widespread, and graphic the least so. The upper beds consist almost entirely of the steely and dense types, but are distinctly blacker in color than the lower beds and will not be confused with them.

Microscopic and chemical examination has shown that this distinction into types is of little practical value, for the first three types are not widely different in composition. The chief difference and the one that causes the difference in appearance is in pore space, the steely being only very slightly porous and the dull or granular being the most porous. The pores are so fine that they can be seen only under the microscope. As the steely type tends to be the lowest in grade and the dull the highest, and as these types are superposed in the bed, in many cases in alternating thin bands, they probably indicate differences in the primary sediments. It has been observed that if hand specimens of the rock soil the hands, the manganese content of the rock is probably over 48 percent. The dull type is the only one which attains this richness.

The graphic type (fig. 6) is so named because it is characterized by rounded tubules which sometimes resemble cuneiform writing. These holes, as much as 3 millimeters across and 5 or 10 millimeters long, are generally parallel to bedding and are confined to layers 1 to 5 centimeters thick. Some holes make abrupt turns, but they do not seem to be interconnected. They make up not more than 10 percent of the volume of the rock, in most cases less. They are lined by a coating of black dust, probably manganese oxide. The graphic type grades laterally and vertically into the other types over a few centimeters. The genetic significance of the graphic type is not known; it seems quite improbable that the holes represent worm borings.

The graphic type of material is almost entirely confined to the lower bed; the upper beds show a far greater homogeneity in rock type than the lowest bed and are composed almost entirely of the steely and dense types. No other systematic variation in the distribution of these various types, either laterally or vertically, in the beds, was noted.

The lowest 10 to 20 centimeters of the main manganiferous bed (bed No. 1) is less pure than the rest of the bed. In many localities it contains scattered clastic grains, especially at

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the bottom, and appears to contain a higher proportion of clay than the rest of the bed. Figure 5, A, illustrates a typical outcrop of the lowest bed.

Three typical sections of bed No. 1 are given below, listed in order beginning with the top of each section:

Sample 6:

		Thickness (meters)
	Manganiferous arkose; top of manganese bed irregular.	
	Granular type ore	0.12
Bedding obscure	Steely type ore with some fine granular type	.62
	Fine graphic type ore	.09
	Granular type ore	.28
	Steely type ore with conchoidal fracture	.65
	Sandy and low-grade ore	.09
	Ferruginous arkose.	
		1.85

Sample 10:

	Thickness (meters)
Ferruginous jasper.	
Graphic type ore	0.06
Dense, dark-gray ore, with obscure bedding	1.33
Alternating 1- to 2-cm. bands of dense, steely and granular type ore; well laminated	1.04
Granular type ore	.89
Ferruginous arkose.	
	3.32

Sample 20:

	Thickness (meters)
Arkose.	
Dense, nodular type ore	0.68
Graphic type ore	.28
Dense and dull, low-grade ore, with obscure bedding	1.14
Ferruginous arkose.	
	2.10

In the upper third of the Band' Alta formation in Morro do Urucum, lenticular clastic beds which consist of siltstone, jasper, conglomeratic jasper, sandstone, conglomeratic sandstone, and conglomeratic unbanded hematite are relatively common. These lenses are rarely more than 200 meters in length and are locally as much as 10 meters thick. The sandstone and siltstone beds are usually brown, often cross-bedded, and largely composed of quartz fragments. The conglomeratic jaspery beds, which are red and generally coarse-grained, are made up of highly altered rock fragments, red and white clay, and red jasper. All the material in these clastic lenses appears to be waterlaid.

Various minor structures of genetic significance are present in the Band' Alta formation. Local angular disconformities in the upper part of the slope above the mines and in the vicinity of coordinates 20,500 S. and 5,375 E. indicate slumping, and possibly local intraformational erosion, before consolidation of the beds below the disconformities. These disconformities can be traced laterally into fully conformable contacts between beds that show no evidence of this intraformational erosion. Minor intraformational conglomerates, including some edgewise conglomerate, in the section above the mine administration buildings further indicate that sedimentation was not continuous. It also seems possible that the widespread bed of oolitic jasper, about 4 centimeters thick, some 40 meters above bed 2 may represent a period of non-deposition.

Being composed of essentially brittle rocks, the Band' Alta formation is cut by many regular joints. These openings are in some places filled with vuggy white quartz. The only other mineral identified in these veins is specularite, which forms plates up to 8 millimeters across. All this material is probably supergene in origin, having been leached from the jasper and iron oxides which make up the body of the formation. Although three equally well-developed joint sets are usually present, in some localities the quartz veins are confined to only one of these sets. The significance of this fact is not known. In a few places, this supergene quartz replaces on a small scale both hematite and jasper, obliterating all structural features.

Microscopic examination of the hematite and jasper of the Band' Alta formation shows that changes, which the writer interprets as being the result of diagenetic processes, have been notable. Part of the hematite occurs in lenses several millimeters long, which are distinctly coarser grained than their matrix. This matrix is also hematite and shows a lamination that is due to slightly varying grain size. The hematite of the matrix is very finely crystalline, generally in anhedral crystals, rarely in minute bladed crystals.

Many small jasper nodules or lenticules, generally not more than 5 millimeters long, occur in the hematite bands. These are in various stages of replacement by hematite; all have corroded edges and many have been almost entirely replaced. Replacement is generally much more complete in those with a flat ellipsoidal outline than in those with more nearly circular outline.

It is believed that the iron and silica were deposited as primary sediments, probably as colloidal gels which at the time of original precipitation contained several times their own weight in water. As laminae in the hematite bend around the included lenticules of silica, the gelatinous silica assumed structural strength before the gel of ferric hydroxide. The relation between the shape of these lenticules and the degree of their replacement by iron oxide may be interpreted as a measure of the rapidity of consolidation, for, if a lenticule rapidly lost its original water content and thereby assumed structural strength, it would neither flatten when buried by later sediments nor be subject to the action of infiltrating iron-rich water released during dehydration of the ferric hydroxide gel. Another fact indicating that the silica consolidated more rapidly than the iron oxide is that silica is usually replaced by iron oxide, rarely the converse. If the silica nodules lost their contained water rapidly, the expelled water could disperse through the thin overlying sediment, whereas the water expelled from the ferric hydroxide gel, slowly dehydrating after more thorough burial, would be held in contact with silica far longer before it escaped, and would therefore have more opportunity to attack and replace the silica. Further replacement of silica would occur when the ferric hydroxide lost its water of crystallization and changed to hematite. This final dehydration may have taken place after the accumulation of several hundred meters or more of overburden, in which case the normal thermal gradient would facilitate reaction of the iron-rich solution with the silica.

In one thin section, pseudomorphs of silica after what appear to be crystals of the evaporite, such as glauberite, are present. The significance of this isolated example is difficult to evaluate. In the Band' Alta formation, carbonate is rather rare. Several thin sections of the hematite bands show small square areas of cryptocrystalline silica and jasper, which appear to be pseudomorphs after pyrite. In two thin sections, both hematite and jasper are cut by veinlets of quartz, which contain very small quantities of tourmaline. This latter mineral is interpreted by the writer and by Dr. Milton, who first identified it, as authigenic, that is, as not being of hydrothermal origin.

High in the section, lenses of relatively coarse clastic material occur. At several localities in the part of Morro do Urucum known as the Band' Alta, these lenses contain clastic fragments 2 or more centimeters across, embedded in unbanded argillaceous hematite. In the field it was believed that these fragments were tuffaceous; microscopic examination, however, showed them to be so completely replaced by cryptocrystalline silica, accompanied in some fragments by abundant kaolin, that their origin remains uncertain.

These lenses are thickest, coarsest, and most abundant at the north and northwest ends of Morro do Urucum. At the south end of that mountain at about the same horizon they are absent. In Serra de Santa Cruz, Tromba de Macacos, and Serrania de Mutun no evidence of such lenses was seen, but in the first two of these mountains the horizon has probably been removed by erosion. These facts suggest that the detrital material may have been introduced into the basin from the north and northwest.

Unconsolidated rocks

Blanketing parts of the slopes of Morro do Urucum and the other mountains of the vicinity are patches of unconsolidated detrital material derived from the iron-rich Band' Alta formation above. These patches are found below the cliffs and steep slopes which ring the mountains. Being largely overgrown with timber, vines, and thorny shrubs, they could not be mapped in detail in the time available; certain observations relating to them, however, seem worth recording.

In the process of weathering of the Band' Alta formation and transportation of the detrital material derived therefrom, the silica nodules and lenticules are broken down more rapidly than the harder, less soluble hematite, and the relative iron content of the resulting material is thus increased. This process of natural beneficiation is most effective, and the grade of the resulting material highest, below steep slopes, where fragmentation is more complete and transportation slower than it is below cliffs.

In some localities this hematitic colluvium has been recemented by limonite deposited by the evaporation of iron-rich waters, forming deposits of canga. Both the hematitic colluvium and the canga deposits are discussed in more detail in the section on mineral deposits.

At the head of the north portion of Santa Cruz Valley there is a large area covered by the remains of an ancient landslide, but the other unconsolidated rocks of the area are neither of geologic nor economic interest.

Origin of the manganese and iron deposits

Although manganiferous iron ore is common throughout the world, the Morro do Urucum deposit is the only one known to the writer in which high-grade beds of manganese oxide are interlayered with beds of medium-grade banded hematite to form deposits of each mineral of the first order of magnitude. No final explanation of the ultimate origin or mode of deposition of the oxides of manganese and iron will be attempted in this paper; such an attempt would be as presumptuous as proposing to explain the origin of the Mesabi Iron Range after studying 10 square miles for a few months. Certain hypotheses may, however, be discussed in the light of the facts now available.

Alternative theories of origin

The writer is convinced that the Band' Alta formation and at least the upper two-thirds of the Corrego das Pedras formation are the result of sedimentary accumulation under marine, estuarine, or lacustrine conditions. The presence of clastic lenses in these formations, and of clastic fragments in all the rocks, the cross-bedding which occurs in the lenses and to a minor extent in the ferruginous and manganiferous beds, the presence of intraformational conglomerates in the ferruginous beds, the local intraformational disconformities, the magnificently even and regular banding in the Band' Alta, the even bedding in the Band' Alta and the upper part of the Corrego das Pedras, the essential uniformity in chemical and physical nature of the Band' Alta formation over distances measured in tens of kilometers, all in sum lead to the conclusion that the Band' Alta formation, in so far as it is now preserved, consists essentially of primary sediments.

An outline of the salient facts and strong probabilities that must be considered in any hypothesis of origin is briefly as follows:

1. The stratigraphic column shows that the deposition of more than 430 meters of coarse clastic sediment, probably continental in origin, was followed by the deposition of more than 350 meters of dominantly chemical sediment. The transition between the two types of sedimentation was gradual. The most impressive fact about the chemical sediments is their uniformity, even though their succession is broken by the intercalation of coarse clastic lenses, including pebble conglomerate. The dominant product, interbedded hematite and cryptocrystalline silica, is essentially identical throughout the whole section and therefore the environment that caused this chemical sedimentation must have been extremely stable. In short, during Band' Alta time there was a norm of deposition which was periodically disturbed in such a manner that various beds of manganese oxide (also a chemical sediment) and of clastic sediments were deposited instead of hematite and silica.

2. The deposition of manganese oxide was in most cases immediately preceded and followed by the deposition of minor clastic beds.

3. Salient figures on the composition of the manganiferous beds and the banded hematite beds of the Band' Alta are as follows:

	Manganiferous beds (percent)	Banded hematite (percent)
Fe	8-16; Av. 11.1	48.7-62.1; Av. 56.9
Mn	39.4-50.7; Av. 45.6	0.005-0.60; Av. 0.08
SiO_2	Av. 1.25	Av. 17.3
Al_2O_3	Av. 1.74	Av. .65
MgO	Av. .13	Av. .06
CaO	Av. .20	Av. .06
K_2O	Av. 3.52	Av. .20
Iron-silica ratio	8.8:1	3.29:1
Iron-manganese ratio	0.24:1	710:1

4. Microscopic features of the rocks, discussed on page 22, strongly corroborate field evidence in pointing to the conclusion that the silica in the banded hematite beds was deposited as a colloidal gel in relatively quiescent water. There is no specific field evidence as to the state of the iron at the time of deposition, but it may well have been deposited as limonite and changed to hematite in the process of induration. There is evidence that hematite replaced some of the silica under both Corrego das Pedras and Band' Alta conditions or at some later time.

5. There is now no known unequivocal evidence, field or petrographic, of volcanic or igneous activity in this region during or subsequent to the deposition of the Jacadigo series.

6. The existing remnant of the Band' Alta formation represents only an unknown part of its original extent and thickness. Calculations based upon present known outcrops give a minimum original area of 800 square kilometers. The iron ore originally present in this area must have totaled not less than 500 billion metric tons, assuming an original average thickness of 150 meters. Since float has been reported from distances 100 kilometers to the south and west, it seems quite possible that the original tonnage in the formation was at least several times as great. The original tonnage of manganese ore may well have been as much as 200,000,000 tons, including that in Serra da Santa Cruz.

Although, as stated before, the writer believes that the Band' Alta formation as now preserved is sedimentary in immediate origin, it is conceivable that a series of limestones and shales might have been replaced by ferruginous and manganiferous hydrothermal solutions. It hardly seems probable that this could have been accomplished on the scale required without leaving definite evidence of hydrothermal action, however, especially in the rather porous clastic lenses. To find a source for the replacing solutions would be difficult, in view of the fact that there is no evidence of contemporaneous igneous activity in the region. It is difficult, also, to imagine how, under hydrothermal conditions, silica and iron actively replace beds above and below the present manganiferous beds but not those beds themselves, or why the iron-manganese ratio of the bedded hematite should be more than three thousand times that of the manganiferous beds.

The absence of unequivocal evidence of contemporaneous igneous activity in the area is of considerable significance, for many of the larger manganese and iron deposits of the world have been shown to have some genetic relation to such activity, even though the exact nature of that relation cannot in all cases be demonstrated. It is possible that future work in the areas surrounding Morro do Urucum may discover evidence that contemporaneous igneous activity did exist.

If it be granted that the materials constituting the Band' Alta and Corrego das Pedras formations were deposited as sediments, there remain the problems of source, transportation, and mechanism of deposition of the silica, iron, and manganese.

Source.—The basic work of Gruner, 21/ of Moore and Maynard, 22/ and of others has demonstrated that all the constituents of the rocks under discussion might have been supplied through leaching of the rocks of a large drainage basin by the ordinary atmospheric agents. On a purely volumetric basis, this agency seems more likely to have supplied the iron than hydrothermal leaching of more restricted areas, for in order to supply the iron in the Band' Alta formation, not less than 1,800 cubic kilometers 23/ of the average igneous rock would have to be completely leached of its iron content. There is no evidence for the former presence of any rocks abnormally high in iron in the vicinity.

Transportation.—Gruner's 24/ work and that of Moore and Maynard 25/ have shown that iron and silica can be transported by surface waters and ground water as ferric and silica hydrosols. Given sufficient time, this method of transportation seems adequate to introduce into a depositional basin such quantities of iron oxide as are found in the Band' Alta formation. Should hydrothermal leaching be called upon to supply the iron and silica, the problem of transportation is complicated by the likelihood that the solutions, presumably acidic to begin with, would have been rapidly neutralized on reaching the surface, and hence 26/ would not have been able to transport silica and iron as ionized salts for any long distance. As the basement rocks now exposed in the vicinity of the iron deposits have not been leached, any hydrothermal source must have been fairly distant.

Precipitation.—Moore and Maynard 27/ have also demonstrated that ferric and silica hydrosols are precipitated, at different rates, by mixture with electrolytes such as those which exist in closed basins, barred lagoons, or the sea. Little specific information is available concerning possible causes of deposition should the material forming the beds have been derived by hydrothermal leaching, unless the acid waters can be assumed to have been neutralized at the site of deposition.

21/ Gruner, J. W., The origin of sedimentary iron formations: The Biwabik formation of the Mesabi Range: Econ. Geology, vol. 17, no. 6, pp. 407-460, 1922.

22/ Moore, E. S., and Maynard, J. E., Solution, transportation, and precipitation of iron and silica: Econ. Geology, vol. 24, pp. 272-304, 365-403, 506-528, 1929.

23/ Fe content × M^3 in 1 km^3 × sp. gr. = tons/km^3
0.05 × 1,000,000,000 × 2.8 = 140 million tons Fe/km^3
Tonnage of Band' Alta × assumed Fe content = tons Fe in Band' Alta
500,000,000,000 × 0.50 = 250,000 million tons

$$\frac{250,000}{140} = 1,785\ km^3$$

24/ Gruner, J. W., op. cit.

25/ Moore, E. S., and Maynard, J. E., op. cit.

26/ Gruner, J. W., op. cit., p. 445.

27/ Moore, E. S., and Maynard, J. E., op. cit.

It seems possible that these formations were deposited in a gradually sinking basin, in which, during Corrego das Pedras time, waters derived from large drainage areas were concentrated, always remaining shallow, and in which constant circulation prevented the formation of thin laminae. During most of Band' Alta time, the waters must have been deeper and more quiescent. The great homogeneity of the Band' Alta formation and its tendency to return to a norm of deposition indicate that the environment must have been very stable during much of the period. Discharge by the electrolytes in sea water of colloids transported by a large river to an epicontinental or marine basin represents as stable a dynamic equilibrium as is conceivable, and the possibility of such action is well supported by chemical theory.

Unexplained facts

Although the classic theories on the origin of many of the banded hematite formations of the world might seem to explain satisfactorily the major problems of origin of the iron and silica of the Band' Alta and Corrego das Pedras formations, certain problems posed by the nature of the stratigraphic section remain unsolved. Some of these problems are:

1. What caused the deposition of the manganese in a few well defined beds, each contiguous to detrital layers, rather than throughout the section? And why are only relatively few of the clastic layers associated with manganese oxides?

2. Why is there no shale and very little argillaceous material anywhere in the section? Clay, rather than pebbles and angular sand grains, is the sediment to be expected from a large river such as that postulated above. If the electrolytes of salt water discharged the colloidal silica and ferric hydrosols carried by the river water, they should also be effective in precipitating the charged clay particles normally present in river water. The alumina content of the Band' Alta is extremely low, averaging only 0.65 percent.

3. If iron, silica, and manganese can be deposited under these conditions, why are not similar deposits encountered more frequently, for surely such conditions have been duplicated many times during the earth's history.

The absence of clay in the iron and manganese deposits is believed to be significant. It might indicate that the waters containing the manganese, silica, and iron in solution had dropped the clay before reaching the basin of deposition or at the margin of the basin of deposition. In the former case, a compound basin seems to be indicated; in the latter, facies changes would be expected. Regional stratigraphic studies would throw much light on this question. The absence of clay might also be explained if a subsurface source for the solutions were found. The solutions could have been either igneous in origin or could have been mineralized ground waters introduced into the basin by normal subsurface flow. The only evidence bearing on these questions is that the analyses of the material now present do not indicate strongly an igneous origin; the breccia pipe mentioned on page 33 is too obscure to be cited as strong evidence of the presence of major springs.

Woolnough 28/ suggests, in a stimulating paper, that peneplanation of a drainage basin or region of interior drainage is often an important factor in the formation of banded hematite deposits. In the present instance, however, the presence of pebbles and coarse clastic sediments in the section would seem to indicate that the immediate vicinity of the drainage basin can hardly have been peneplaned.

Special problems relating to manganese

The major problems to be met in considering the precipitation of the iron, silica, and manganese minerals are the sharp division between banded hematite and manganese oxide, the association of the manganese beds with detrital layers, and the great chemical difference of these beds. The iron-silica ratio of the manganese beds is about 9:1 and that of the banded hematite about 3.3:1. The average alumina content of the manganiferous beds, however, is twice as high as that of the banded hematites, and if, as may reasonably be assumed, all of the silica present in the manganiferous beds is in clay minerals, there is very little free silica in those beds. Some mechanism whereby the precipitation of silica was completely inhibited during deposition of the manganese oxide must be found, since there is no evidence that silica has been removed from them. The small extent of some of the lenses of manganese oxide indicates, however, that this mechanism could not have been operative throughout the basin. Differential precipitation of the manganese by bacterial agencies therefore seems unlikely, because it is difficult to conceive how the organisms could be confined to a limited area in the depositional basin except by incomplete drainage of the basin. Field evidence clearly shows that the horizon occupied by the manganese beds is not represented by an erosion surface where those beds are not present.

A similar objection might be raised against chemical precipitation by the discharge of colloids, if silica and oxides of manganese and iron were all present in the original solution. In that case exotic, temporary, and quite localized conditions would have to be called into play to explain the clean separation. It is not impossible that the intimate association of detrital beds with manganese oxide beds may represent a record of such conditions. Although the chemistry of the system is imperfectly understood, it seems possible that a radical temporary change in the pH of the waters or the presence of protective ions might precipitate manganese oxide and inhibit the precipitation of silica and iron. Again, however, the limited extent of some of the manganese oxide beds makes this mode of origin appear improbable, for, judging from the concentrations of manganese in naturally occurring surface waters of today, these beds could have been thus deposited only if many cubic kilometers of water had dropped their manganese content in rather limited areas. It is difficult to imagine how this could happen except under deltaic conditions, for which there is now no field evidence.

The possibility remains that the manganese may have been introduced into the depositional basin from some source other than that of the iron and that the interaction of the solutions, while inhibiting the precipitation of silica and to some extent the precipitation of iron, may have caused the precipitation of

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28/ Woolnough, W. G., Origin of banded iron deposits, a suggestion: Econ. Geology, vol. 34, pp. 465-490, 1941.

manganese. If the manganese had been introduced by thermal springs—and such has been the origin of many manganese deposits, including the bedded deposits of Cuba 29/—the pH of the waters of the basin might have been locally changed so as to inhibit precipitation of silica and promote the precipitation of manganese oxide. But this hypothesis fails to explain why the manganiferous beds are associated with detrital beds; and indeed, apart from the breccia pipe mentioned on page 33, no field evidence can be adduced in its support other than the fact that the beds are generally richest in their thickest parts, which might be supposed to be near the sources of the manganese. It will be remembered, however, that de la Sauce 30/ suggested submarine volcanic emanations as a possible source for the sedimentary manganese deposits of the Caucasus.

General conclusions

In summary, present evidence is believed to indicate that the banded hematites and manganese oxide beds of the Band' Alta formation are primary sediments which have undergone relatively little change since diagenesis. The iron and silica were probably deposited as hydrogels, and the manganese oxide may well have been precipitated in colloidal form as a hydrous oxide. The cause of the deposition of these chemical sediments is unknown. They may have been deposited in an epicontinental or marine basin; the writer tentatively suggests that they were deposited in a large epicontinental basin from somewhat concentrated waters. The ultimate source of the manganese, of the iron, and of the silica may have been the same, but that has not been proved.

It is unlikely, however, that the problem of origin can be satisfactorily answered until detailed regional studies of the lateral variation of the Jacadigo series have been made. Such detailed stratigraphic study may show that the upper part of the Corrego das Pedras is a near-shore phase of the Band' Alta, and that the fossiliferous El Carmen sandstone of Bolivia is contemporaneous with a part of the Jacadigo series. Possibly the upper part of the section, missing in the Urucum area, may be found elsewhere and shed more light upon the depositional environment in which the iron and manganese were formed.

It is hoped that later work will determine definitely whether volcanic activity has occurred in the region. Although no clear evidence of it has been found, it may nevertheless have occurred in some part of the region that geologists have not yet examined. The area that was studied in detail for this report was relatively small, and previous work has been largely in the nature of reconnaissance.

Structure

Regional structure

As no accurate maps are available and regional study was outside the scope of this report, only general observations can be offered concerning the regional structure of the Corumbá area.

29/ Park, C. F., Jr., Manganese deposits of Cuba: U. S. Geol. Survey Bull. 935-B, p. 93, 1942.

30/ de la Sauce, Wilhelm, Beiträge zur Kenntnis des Manganez-lagerstätte von Tschiaturi im Kaukasus, p. 38, Verlag von Wilhelm Knapp, Halle, 1926.

The dominant structure in the region seems to be large-scale block faulting. Considerably more than 500 meters of beds are cut out by a long northeast-trending reverse fault on the northwest side of the area of outcrop of the Jacadigo series, in Bolivia. Judging from physiographic evidence, it seems probable that the eastern edge of the Serrania de Mutun in Bolivia and Brazil is a fault-line scarp subparallel to the fault on the west side of that range. If that is the case, the vertical component of the fault may amount to several hundred meters. It is possible that another large northeast-trending fault, with downthrow on the west, traverses the area between Morro do Urucum and Tromba de Macacos. There can be no doubt that a northeast-trending fault with a vertical displacement of about 600 meters lies between Morro do Urucum and Serra da Santa Cruz. The regular scarp on the west face of the latter mountain suggests strongly that this fault continues to the southwest for some kilometers, and a fault can be seen to have displaced the beds in Serra do Rabicho, 10 kilometers or more along the strike to the northeast. No information is available on the structure of the east side of Serra da Santa Cruz. Other low ranges, such as the Serra da Cristal, have an elongate shape and northeasterly trend that suggest a continuation of the same structural pattern for some distance to the southwest.

The above statements as to the direction of relative motion of the individual blocks is based upon the assumption that the Jacadigo series is younger than the Corumbá limestone.

The regional dips of the Jacadigo series suggest that the whole dissected mountain mass may be a downfaulted anticlinorium some 40 kilometers wide from east to west, for along the western margin of the known outcrops the dips are prevailingly to the west, while along the eastern margin they are prevailingly to the east. The major faults would be subparallel to the northeast-trending axis of this anticlinorium.

Structure of Morro do Urucum

Minor structural features of immediate economic importance will be discussed in detail in the section on mineral deposits. Some general remarks on the larger structural features of Morro do Urucum will be presented here.

The structure of Morro do Urucum and of that part of Serra da Santa Cruz which has been mapped in detail is relatively simple. These mountains are essentially mesas composed of gently warped strata, and are separated by a deep fault-line valley (pls. 2 and 4). The dominant structure of Morro do Urucum is a rather vaguely defined syncline. In the southern part of the mountain there is a general easterly dip, which increases southward from 12° to as much as 30° or 35°. In its main body there is a generally low westerly dip except in two areas, one extending from the extreme western corner of the mountain to the vicinity of the workers' dwellings, where the dip is to the northeast at angles of 4° to 15°, and the other along the outer slopes of the northwest side of the mountain, where it is also to the northeast and east at angles of 5° to 20°. Along the outer northeast slopes the dips are low and variable.

The strata underlying most of the valley between the two mountains and those which compose the portion of Serra da Santa Cruz considered here dip evenly to the east and southeast at 12° to 17° and are disturbed by no complicating structure.

The fault between the two mountains, hereafter called the Santa Cruz fault, has a vertical displacement of about 600 meters. It is everywhere covered with talus and soil, but rock outcrops indicate its location with an error of not more than 75 meters at the northeast end, of not more than 200 meters in the middle, and of not more than 400 meters at the southwest end.

The abrupt major fold on the northwest side of the Santa Cruz fault imposed dips opposite in direction to those which would normally result from drag. In proximity to this fault the hard, brittle beds of the Band' Alta formation are notably deformed; their dips steepen abruptly to as much as 80°, and they are locally overturned; sharp, almost isoclinal minor folds are developed in the evenly bedded rocks, and the jasper lenses and hematite beds are severely distorted. All these features constitute evidence of crumpling resulting from compression. In the Urucum formation, on the other hand, there has been no visible disturbance or distortion even in fairly close proximity to the fault. Even though these rocks are massive arkose, in which the cement was calcite and in which bedding is not easily discernible, it seems almost certain that if they had been markedly deformed, some evidence of the fact would be apparent.

In view of the evidence of compression in the Band' Alta, the anomalous fold west of the fault (pl. 2) might be explained on the hypothesis that, under compressive stress, a sharp monocline was formed with the southeast side the lower and the rocks on the northwest side somewhat tilted, resulting in the present low west dips in the main body of Morro do Urucum. Further compression, in conjunction with a vertical component caused by elastic rebound of the depressed eastern block, could have resulted in a steep reverse fault in which the eastern block rode up on the western block to approximately its present position.

The large reverse fault on the west flank of Serrania de Mutun shows a somewhat similar relation between folding and the vertical component of movement to that along the Santa Cruz fault. There, however, it is the eastern side of the fault that is downfolded against the direction of net vertical movement.

Another fault intersects the Santa Cruz fault at the north end of the Santa Cruz Valley. Bed 1 of the Band' Alta formation is abruptly cut out at the low spur near 19,650 S., 6,000 E. of plate 2. Both dip and strike change abruptly, and it is evident that the spur is in a downdropped and steeply tilted block. The fault can be seen at 20,090 S., 5,695 E. Beds in the eastern block are distorted along this fault, and to some extent recrystallized.

At the most northerly point of the mapped portion of Morro do Urucum, the Band' Alta formation is sharply folded. Bed 1 can there be traced northward down the slope to the site of sample 16, where it dips about 80° W. and is at least 6 meters thick. This exceptional thickness is believed to be the result of plastic flow of the manganiferous material away from the axis of the fold, for all internal structure in the bed is obliterated and the adjacent hematitic beds are severely distorted. There is probably a fault on the west side of the spur (pl. 2), for undeformed horizontal beds crop out 115 meters west of the steeply dipping bed 1, but a cover of talus and colluvium makes it impossible to locate the fault closely.

A minor but significant fault may be seen at 19,400 S., 3,970 E. (pl. 2). This fault, which is vertical and has good walls, cuts off the upper manganese bed, offsetting it some 15 meters, yet it does not offset the lower manganese bed, which crops out about 40 meters lower, at the bottom of the cliff. This fault was probably developed at a time when the lower bed had solidified but the upper material was still somewhat unconsolidated.

A zone of breccia, not less than 35 meters wide, in the Corrego das Pedras formation is exposed in the cliff face near 18,790 S., 5,430 E. It consists of plates and tabular fragments of jasper stained with manganese oxides. Unfortunately the cliff is so inaccessible that the relations between this breccia pipe and the manganese bed above cannot be observed, but the breccia is believed to have been formed by underwater channeling; it may conceivably have been a spring conduit.

The peculiar pattern of beds 1 and 2 at the extreme southern end of Morro do Urucum (pl. 2) is the result of the southeastward increase of dip discussed on page 31. Although no outcrops of these beds are found below the trail, an unusual linear concentration of boulders of manganese oxide is evident in the detritus mantling the small ridge at 23,125 S., 4,050 E. Scattered boulders of manganese oxide in the float farther to the northeast tend to confirm the opinion formed as to the position of bed 2.

There have been at least three periods of structural deformation in the area. The first is related to the dynamic metamorphism of the basement gneisses and schists and occurred in pre-Cambrian times. After the deposition of the Corumbá formation (Cambrian?) and before deposition of the Jacadigo series, the rocks were uplifted and probably deformed. After the deposition of that series, warping and block faulting took place.

The evidence concerning the time at which the Jacadigo series was deformed is extremely indefinite; the deformation is older than the Recent or late Tertiary deposits in the area, and of course younger than the Jacadigo series itself, which is generally regarded as pre-Devonian. Some estimates of the minimum age of the deformation can be based upon the amount of erosion that has since taken place. The deformation is obviously older than the erosion that has carved the present isolated buttes and mesas from what must have originally been an extensive massif. Although the Band' Alta formation is now the youngest formation recognized in the area (apart from the late Cenozoic deposits of the Paraguay Valley), it must be assumed that at least a moderate thickness of younger rocks was at one time present, for the brittle rocks of the Band' Alta would hardly have yielded plastically under stress unless there had been considerable confining pressure at the time of deformation. Since the latest deformation, therefore, erosion must have removed all of the Jacadigo series (at least 800 meters thick) from the areas between the present buttes and mesas, and also a thickness of younger rocks that may well have been even greater. Erosion must have been slow, not only because of the resistant nature of many of the rocks but also because much of the area is now and must have been for some time near base level. Thus it seems possible that the deformation occurred near the end of the Mesozoic era; it may well be considerably older.

MINERAL DEPOSITS

History of mining

According to Arrojado Lisboa,31/ the first attempt to develop the mineral resources of the region was made by Baron de Villa Maria. In 1870 the Baron went to the Imperial Court in Rio de Janeiro to discuss means of developing the iron deposits of the Fazenda da Piraputangas, and he then referred, also, to the occurrence of manganese ore in the same district; he died, however, shortly thereafter. During the next eleven years, the Imperial Government granted several concessions, but they led to no actual development. Interest then lapsed altogether until 1894, when a 20-year concession was granted by the Government of Mato Grosso to Francisco Couto da Silva, who induced a firm in Rio de Janeiro to attempt the development of the manganese deposits. An engineer, Publio Ribeiro, was thereupon sent to investigate the area. Actual development work did not start, however, until 1906, when the concession was acquired by the Compagnie de l'Urucum, a company formed by Belgian steel interests. This company drove many short adits in the main manganese bed on the north and west sides of Morro do Urucum, laid a narrow-gauge railroad to Corumbá from the base of the mountain, constructed an inclined plane to transport the ore to the railroad below, built several kilometers of road, and mined and stacked about 7,000 tons of manganese ore before the collapse of the market at the close of World War I put a stop to the venture. It is said that no ore was actually shipped.

The deposit then lay dormant until 1940, when the Sociedade Brasiliera da Mineração obtained a concession from the State of Mato Grosso, to which title had been transferred by the Federal Government. This company repaired the roads, and in 1941 it began to ship ore from the piles left by the Belgian company more than two decades before. Equipment was procured, loading facilities on the Paraguay River were arranged, and mining from the lower ore bed was undertaken. About 10,000 tons of ore, including all the old stock piles, was shipped in 1941; about 25,000 tons in 1942; and about 8,000 tons in 1943. These shipments contained, on the average, somewhat less than 48 percent of manganese and somewhat more than 10 percent of iron. Three shipments received in the United States during 1943 totaled 17,225 tons and averaged 47.2 percent Mn, 10.6 percent Fe, 2.13 percent alumina, 1.12 percent silica, and 0.14 percent phosphorus.

Reserves

Estimates are given below for the grade and tonnage of the manganese beds and of two types of ferruginous material. Appendix II tabulates the results of analyses of 71 samples of manganiferous material and of 47 samples of ferruginous material, and Appendix III gives complete analyses of 16 specimens and samples. Plates 5 and 6 show the location of the samples.

As the ores of both iron and manganese are dense, fine-grained, brittle, and very hard, drilling in them would be difficult, but on the other hand they would stand well in cuts or underground workings, and would not powder in handling or shipment. The only important gangue of the iron ore is silica, and

31/ Lisboa, Miguel Arrojado Ribeiro, Oeste de São Paulo, Sul do Mato Grosso, Estrada de Ferro Noroeste do Brasil, p. 72 f., Rio de Janeiro, 1909.

the only important gangue of the manganese ore is hematite; both gangue minerals are too intimately mixed with the ore minerals to permit beneficiation on a commercial scale under present economic conditions.

Sampling and basis for estimating manganese reserves

The manganese beds were sampled under the direction of the writer and of Drs. Barbosa and Prado. Sampling on the outcrop was done by breaking a fresh surface, then taking a semi-channel sample about 10 centimeters wide and 1 or 2 centimeters deep across the exposed face, on a line as nearly normal to the bedding planes as possible. Between 2 and 3 kilograms of material was saved per linear meter of the cut. This material was broken into small fragments and split into three parts, one of which was analyzed by the Instituto Paulista Technologica de São Paulo for the Sociedade Brasiliera da Mineração, one by the laboratories of the Departamento Nacional da Produção Mineral of the Ministerio da Agricultura, and one by the laboratories of the Geological Survey. Certain individual analyses reported by each laboratory were erratic and were not used in computing the average. The mines were sampled in the same way.

Certain samples were taken in thirds, in order to determine whether the grade of the material varied systematically with vertical position in the bed. It was found that the upper or middle third is usually the richest and the lower third the leanest, and that variation in grade within the bed is considerable. Where the bed is more than 2 meters in thickness, it might prove necessary, in order to meet rigid grade requirements, to mine only the upper two-thirds; the manganese content of the material extracted would thus be raised at least 2 percent, and the iron content correspondingly decreased. The careful sampling which must precede any large-scale operation should be directed to securing further information on this point, as the present work is only qualitative.

Samples from within the mines are generally somewhat higher in grade than those from the outcrops. The average manganese content of the ore thus far produced from the mines has been more than 47 percent. Two explanations for this difference are possible: either (1) the grade actually rises inward from the outcrop or, (2) because few of the mine workings expose the full thickness of the bed and are mostly in the better ore, only the higher-grade portions of the beds were sampled. Because of the system of extraction, most of the mines are in the upper part of the bed, which has been proved by sampling to be the richer. It is believed that this unconsciously selective mining, rather than any significant concentration of manganese back from the outcrops, explains the higher grade of the samples from the mines.

Reserves have been calculated on the assumption that bed 1 and bed 2 are continuous within the limits indicated on plate 5. The eastern limit to which overall tonnages were calculated is the line connecting the most easterly outcrops at the north and south ends of the mountain. Ore beds crop out east of this line, but the folding along the eastern side of the mountain probably has crushed and distorted the manganiferous beds to such an extent that extraction would be considerably more expensive than in the less disturbed beds. No estimate of reserves in Serra da Santa Cruz has been made, because the beds in that range are too inaccessible and too thin to be considered economic in competition with the thicker deposits. They averaged less than a meter in thicknes where inspected.

Three classifications of tonnage have been made, because the data established at the outcrop on grade and thickness of the manganiferous beds decrease in validity when projected back from the outcrop into the mountain. Calculations are therefore made for tonnage within 50 meters of the outcrop, between 50 and 200 meters of the outcrop, and between 200 and 500 meters of the outcrop. The first is considered as measured ore,32/ with a probable error of not more than 10 percent, and the second and third might be regarded as indicated and inferred ore. An estimate is given of the tonnage that might be expected if the total area were underlain by bed 1 and the area indicated in plate 5 underlain by bed 2, but in this case grade and thickness are projected so far without control that little weight can be attached to the result.

This classification has been subdivided further on the basis of thickness of beds, in order to permit consideration of individual blocks of ore. The areas underlain by bed 1 have been broken into blocks A to F, those underlain by bed 2 into blocks W to Z (pl. 5 33/). Individual tonnage estimates have been made for each block. These estimates are not additive; thus, to find the total tonnage in block A within 500 meters of the outcrop, the tonnage for 0-50 meters and 50-200 meters must be added to that for 200-500 meters.

Areas were calculated by means of a superimposed grid. Specific gravity of a typical specimen of the ore was found to be 4.23; a value of 4 was used in computations. Measured ore was calculated to the nearest 10,000 tons, inferred and indicated ore to the nearest 50,000 tons. Tonnages as calculated herein may be

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32/ The terms "measured," "indicated," and "inferred" are used in conformity with standard Geological Survey practice. Definitions of these terms are as follows:

"Measured ore is ore for which tonnage is computed from dimensions revealed in outcrops, trenches, workings, and drill holes and for which the grade is computed from the results of detailed sampling. The sites for inspection, sampling, and measurement are so closely spaced and the geologic character is so well defined that the size, shape, and mineral content are well established. The computed tonnage and grade are judged to be accurate within limits which are stated, and no such limit is judged to differ from the computed tonnage or grade by more than 20 percent.

"Indicated ore is ore for which tonnage and grade are computed partly from specific measurements, samples, or production data and partly from projection for a reasonable distance on geologic evidence. The sites available for inspection, measurement, and sampling are too widely spaced, or otherwise inappropriately spaced, to outline the ore completely or to establish its grade throughout.

"Inferred ore is ore for which quantitative estimates are based largely on broad knowledge of the geologic character of the deposit and for which there are few, if any, samples or measurements. The estimates are based on an assumed continuity or repetition for which there is geologic evidence; this evidence may include comparison with deposits of similar type. Bodies that are completely concealed may be included if there is specific geologic evidence of their presence. Estimates of inferred ore should include a statement of the special limits within which the inferred ore may lie."

33/ In plate 5 it will be noted that, although limits for indicated and inferred ore are shown, no limit is shown for measured ore, because it would fall in a part of the map that is over-crowded with other data.

considered as minima. Values given for average grade in the individual blocks are rounded to the nearest half percent of the arithmetical average of the samples in that block.

Reserve estimates

Table 1.—Reserves and grade of manganese ore, Morro do Urucum.

Bed 1

	Area M^2	Av. thickness	Sp. gr.	Metric tons	Av. grade (percent) Mn	Fe
Block A						
0- 50 m.	140,000	2	4	1,120,000		
50-200 m.	435,000	2	4	3,500,000		
200-500 m.	688,000	2	4	5,500,000		
				10,120,000	46.0	11.0
Block B						
0- 50 m.	37,500	3	4	450,000		
50-200 m.	66,500	3	4	800,000		
200-500 m.	109,000	3	4	1,300,000		
				2,550,000	47.0	10.5
Block C						
0- 50 m.	30,000	2	4	240,000		
50-200 m.	81,000	2	4	650,000		
200-500 m.	94,000	2	4	750,000		
				1,640,000	45.0	10.0
Block D						
0- 50 m.	30,500	1.5	4	200,000		
50-200 m.	84,500	1.5	4	500,000		
200-500 m.	175,000	1.5	4	1,050,000		
				1,750,000	42.0	13.0
Block E						
0- 50 m.	120,000	2	4	960,000		
50-200 m.	306,000	2	4	2,450,000		
200-500 m.	359,000	2	4	2,850,000		
				6,260,000	44.0	13.0
Block F						
0- 50 m.	38,500	1	4	150,000		
50-200 m.	119,500	1	4	500,000		
200-500 m.	301,000	1	4	1,200,000		
				1,850,000	42.0	12.0
Total area (geologically possible ore)	4,984,000	2	4	40,000,000	45.0	11.2

Table 1.—Reserves and grade of manganese ore, Morro do Urucum—Continued

Bed 2

	Area M^2	Av. thickness	Sp. gr.	Metric tons	Av. grade (percent) Mn	Fe
Block Z						
0- 50 m.	105,000	1	4	420,000		
50-200 m.	242,000	1	4	950,000		
200-500 m.	296,000	1	4	1,200,000		
				2,570,000	47.5	11.0
Block Y						
0- 50 m.	57,500	1.5	4	350,000		
50-200 m.	183,500	1.5	4	1,100,000		
200-500 m.	250,000	1.5	4	1,500,000		
				2,950,000	47.5	11.0
Block X						
0- 50 m.	80,000	1	4	320,000		
50-200 m.	183,000	1	4	750,000		
200-500 m.	214,000	1	4	850,000		
				1,920,000	46.5	11.0
Block W						
0- 50 m.	35,000	1.5	4	210,000		
50-200 m.	88,000	1.5	4	550,000		
200-500 m.	218,000	1.5	4	1,300,000		
				2,060,000	47.0	11.0
Total area (geologically possible ore).	3,294,000	1	4	13,200,000	47.2	11.0

TOTALS

	Metric tons	Weighted average grade (percent) Mn	Fe
Bed 1			
Measured ore	3,120,000		
Indicated ore	8,400,000		
Inferred ore	12,650,000		
	24,170,000	45.0	11.2
Bed 2			
Measured ore	1,300,000		
Indicated ore	3,350,000		
Inferred ore	4,850,000		
	9,500,000	47.2	11.0
Total measured ore	4,420,000		
Total indicated ore	11,750,000		
Total inferred ore	17,500,000		
	33,670,000	45.6	11.1

Description of manganiferous beds

There are at least three manganiferous beds in Morro do Urucum; two of them are of potential economic importance. There are at least three in Serra da Santa Cruz, but these, because of their inaccessibility and thinness, will not be of economic interest for many years.

Bed No. 1.—The principal and lowest manganese bed, known as bed No. 1, crops out from the south end of Morro do Urucum along the west, northwest, and north sides to coordinates 19,558 S. and 5,843 E. (pl. 2), where a fault carries the horizon at which this bed occurs below the talus. In this distance of approximately 7.5 kilometers, the outcrop is completely covered in two areas, one, about 900 meters long, between mine H and sample 16, the other, about 570 meters long, between sample 18 and sample 20. In the former area a pit was sunk many years ago in search of the bed, but at too high a stratigraphic horizon. No attempt has been made to prospect for the bed in the other area. As the bed is more than 2.5 meters thick at mine H and sample 16, it is presumably continuous between these two points, and there is no reason to suppose that it is not continuous under the talus in the other area. Near coordinates 19,420 S., 3,700 E., or just west of the spring feeding the stream flowing to the Fazenda do Urucum, the structure is complicated by faulting, the grade of the ore becomes lower, its thickness decreases abruptly, and the bed disappears under talus for 50 meters to the west. Here there may be an area of nondeposition or possibly even of intraformational erosion.

Under some structural conditions, bed No. 1 and the clastic bed overlying it evidently carry water. Large springs issue at and near their outcrop below the valleys draining the main portion of Morro do Urucum, and elsewhere several small springs were found. At 18,860 S., 4,790 E., and 18,875 S., 4,805 E., tubular channelways lead along the strike into the mountain for not less than 10 meters. These are well over a meter in diameter at the exit and may be about a meter wide and half a meter high further in, but, as they were inhabited by buzzards, they were not explored. Mine No. 11 contains much water, and it is evident from water marks that mine H also is flooded at certain seasons.

Water probably percolates down along the well developed joints in the overlying ferruginous beds until it meets the tightly jointed and relatively impervious but somewhat soluble manganese bed; it then moves along the top of this bed, and to an unknown extent within it, to a structurally favorable outcrop. In undertaking any large mining operation, the possibility that water may be met at depth must be recognized and planned for; it is improbable, however, that enough water to seriously hinder mining operations will be encountered.

Bed No. 1 normally varies in thickness from a few tens of centimeters—at the northeast corner of Morro do Urucum—to more than 3 meters. From the area above the mine offices to the south tip of Morro do Urucum, an outcrop distance of over 3.4 kilometers, it is nowhere less than 2 meters thick and is generally more. In many places the thickness is difficult to measure accurately, because the lower part of the bed erodes most rapidly, causing loosened blocks to slump on even slopes and making outcrops inaccessible on the steeper slopes and cliffs.

Below bed No. 1, in the mine area, is a bed of coarse-grained ferruginous and sandy jasper about 3 to 5 meters thick, which is marked by broad red, pink, and white bands. This bed, which crops out strongly, is an excellent horizon marker. Above bed No. 1 there are usually a few centimeters of sandstone, manganiferous at some localities, above which are a few centimeters to several meters of well-bedded coarse-grained, ferruginous jaspery sandstone. This material is often saturated with water, and, although it stands fairly well in narrow drifts, would not stand well without support in large rooms. Some timbering is necessary even now where the top of the manganese bed has been penetrated.

Bed No. 2.—This bed, which is generally 30 to 45 meters above bed 1, crops out with minor interruptions from 19,090 S., 4,260 E. to the south end of Morro do Urucum. It is not present at the north corner of the mountain nor on the northeast end. In Serra da Santa Cruz, a bed at the same stratigraphic horizon crops out, where it has not been removed by erosion, from 21,219 S., 7,050 E., to 23,580 S., 5,085 E., an airline distance of about 3 kilometers, and it may well continue farther in both directions. Although bed 2 is not everywhere exposed on the smooth talus-covered slopes, it can be found, within the limits indicated, by digging at the appropriate horizon.

This bed is 1 meter or more in thickness from its outcrop just above the Fazenda do Urucum spring, which is on the northwest side of the Morro do Urucum, to the south end of the mountain, with the exception of about 300 meters near sample 31 and a few hundred meters just north of the mine offices. From above mine 1 to a hundred meters southeast of sample 11, it is over 1.5 meters in thickness, being about 2 meters thick for much of this distance.

A bed of brown sandstone a meter or less in thickness is usually present immediately beneath bed 2. A few centimeters of brown or black sandstone, often saturated with water, lies immediately above this bed in most places. Above the upper sandstone are the normal jasper and hematitic beds of the Band' Alta formation, which should stand well in fairly extensive open workings. Water seems unlikely to give much trouble in exploiting bed 2.

Other beds.—Above mine H, on the northwest side of Morro do Urucum, a thin lens of manganiferous material crops out between beds 1 and 2 for a hundred meters or more, but as this lens is nowhere more than 30 centimeters thick it is of no potential economic importance.

In Serra da Santa Cruz, near coordinates 23,600 S., 5,100 E., another lenticular bed crops out for about 200 meters on a ridge top. This bed, which is about 40 meters stratigraphically higher than bed 2, attains a maximum thickness of only 0.5 meter, and because of its location as well as its relative thinness, it has but little potential economic value.

Sampling and basis for estimating iron reserves

Two types of ferruginous material that might become of economic interest at some future time occur in the region. These are, first, the banded hematite of the Band' Alta formation, and, second, the colluvial deposits on the slopes of Morro do Urucum and of other neighboring mountains that are capped by the Band' Alta formation.

Band' Alta.—Under the direction of C. F. Park, a continuous chip sample, broken at about 5-meter vertical intervals, was taken from the Band' Alta formation in the gully above the mine offices (pl. 5). As the outcrop is somewhat leached and as the silica powders in the process of sampling, it is probable that, despite all efforts to make the samples representative, they contain 2 to 5 percent too much iron. Other samples were taken in the part of the section that is so well exposed at the southwest end of the mountain; these were chip samples spaced at 25-meter intervals and were taken by the writer from selected freshly exposed faces. There is no reason to believe that they are not accurate, but they are of limited significance. Both sets of samples were taken for the purpose of obtaining adequate qualitative data; quantitative information on grade can only be secured by drilling or deep trenching, because the outcrops are all enriched except on some small cliff faces.

Tonnage estimates of the Band' Alta formation in the Morro do Urucum were made by determining the areas within 100-meter contours by a grid system. Only that part of the formation above the 800-meter contour was included in the estimates. The tonnage of the portion within the upper, or 1,000-meter, contour line, but lying between the 900 and 1,000-meter elevations, was determined by multiplying the area by the known thickness, 100 meters, to determine the volume, then by 4.4, which is theoretically the weighted average specific gravity of a mixture of 70 percent hematite and 30 percent silica. The tonnage of the annular portion between 100-meter contour lines was determined by multiplying that area by an assumed average thickness of 30 meters to determine the volume and then by 4.4, the assumed specific gravity. The tonnage estimates for the part of the formation between the 800 and 900-meter contours were obtained in the same way. The area above the 1,000-meter contour line was assumed to have an average thickness of 10 meters. Thirty percent was deducted from the total result for lenses of jasper, sandstone, etc. Since adequate data for the close determination of structure and grade are not available, a more accurate method of calculation seemed uncalled for.

The tonnage estimates for Tromba de Macacos and Serra da Santa Cruz are of a much lower order of accuracy; a thickness factor of 30 meters is used for the latter, and of 50 meters for the former. The whole area of the upper portion of Tromba de Macacos was included, because it had been found to consist entirely of the Band' Alta formation. All of the north, east, west, and central areas of Serra da Santa Cruz were included. The lower plateau at the southwest and south end of that mountain (pl. 1) was not included, because it was not seen. It is believed to be in large part covered with the Band' Alta formation, although the valley above Piraputangas is known to be cut into lower formations. The resulting figures represent order of magnitude only, and they lean to the side of conservatism. The Serra do Rabicho undoubtedly contains additional reserves of considerable magnitude, but as this mountain was not visited no estimate of its reserves has been made.

Colluvial deposits.—Tonnage estimates for the colluvial ore are given for areas specified below, but they can be considered only as representing order of magnitude, because of lack of data on thickness. Judging from inadequate information, it seems probable that the average thickness in these areas might lie between 1.5 and 2.5 meters.

The analyses given below are of material taken from cuts along the road to the loading bins below mine No. 3 (pl. 6). The first analysis represents a composite of 23 samples taken by Dr. Bohomoletz and analyzed by the Instituto Paulista Technologica de São Paulo; the second is of a channel sample taken by the writer from a road cut in the same general area. The latter sample was split on an 8-mesh Tyler screen into coarse and fine fractions, which were analyzed separately in the laboratories of the United States Geological Survey. The composite sample evidently was screened, but it is not known under what conditions. Although the coarse material consists largely of angular fragments of hematite between 2 and 6 centimeters long, 1 to 3 centimeters wide, and about a centimeter thick, there are a few larger fragments, up to 15 or 20 centimeters in length, which contain rather more silica than the smaller pieces. Fragments from the manganese beds are scattered at random through the material. The two analyses illustrate well the feasibility of mining high-grade material by simple dragline and screening operations.

Analyses of colluvial ore

	Composite sample (Bohomoletz)	Sample Fe 6 (Dorr)	
		Coarse (83 percent)	Fine (17 percent)
Fe	64.7	63.6	29.1
SiO_2	3.7	3.1	33.5
Mn	1.3	2.6	.5
P	.09	.12	.11
Ca	Tr.	Tr.	Tr.
Al_2O_3	1.0		
TiO_2	None		
MgO	Tr.		
S	Less than .02		
Ignition loss	1.03		

The area for which tonnage per meter of depth was calculated is that opened by switchbacks of the road winding up to the loading platform of mines 1 to 9, an area measuring about 250 meters by 200 meters. To this was added a strip extending 50 meters on either side of the road to mine 12 for a distance of 1 kilometer from the other area. The total area is 150,000 square meters; the specific gravity was assumed to be 3. Cuts along the road to mine 12 expose material similar in appearance to that in the cuts of the other road.

The reserves of this material, which might be classed as "indicated" ore in this particular area, are roughly 450,000 tons per meter of depth. The thickness exposed in the road cuts locally exceeds 3 meters, though in most places it is considerably less. The underlying bedrock is nowhere exposed. A more accurate estimate of ore that must now be regarded as "inferred" could be made after test-pitting the slopes above and below the road to mine 12 and south of the workers' dwellings. There may be, here, as much as 500,000 to 800,000 tons per meter of depth of ore similar in grade to that represented by the above analyses.

The area north of the even slope in the neighborhood of coordinates 19,000 S., 5,000 E. on plate 2 would be an excellent place to prospect for material similar to that discussed above.

There are also several areas covered with a considerable thickness of coarse talus derived from the Band' Alta formation around Morro do Urucum. The most extensive is on the east side of Santa Cruz Valley, where the blocks are sometimes as much as several meters across, and the next largest is on the long spur running a little east of north from the mine offices. The inclined plane built down the spur in the first attempt to exploit the manganese exposes a considerable thickness of this material—as much as 4 meters in some of the deeper cuts. Bedrock is nowhere exposed. Here, too, many of the blocks are large and the talus is in general much coarser than in the area immediately below the mines. The grade of this coarse material is not known, but, as relatively little of the silica has been removed, it probably would average between 55 and 61 percent Fe and between 9 percent and 15 percent SiO_2 after crushing and screening. Reserves cannot be estimated accurately, since the depth factor is unknown, but those in Santa Cruz Valley alone may be roughly 2,700,000 tons per meter of depth.34/ Other areas of similar character could undoubtedly be found if searched for.

If this material were removed, there can be no doubt that the water supply of the region would be seriously affected, since the talus acts as a reservoir which checks runoff and maintains a continuous flow of water throughout the dry season in several small streams. Furthermore, some of the best stands of timber in the area are on this talus.

Reserve estimates

Table 2.—Reserves of iron deposits in Urucum area

	Metric tons	Percent Fe	Percent SiO_2
Band' Alta formation:			
Morro do Urucum............	1,310,000,000	55-56	18-20
Tromba de Macacos..........	650,000,000	50- ?	25- ?
Serra da Santa Cruz........	2,600,000,000	50- ?	25- ?

	Metric tons per meter of depth	Percent Fe*	Percent SiO_2*
Colluvial ore: Area along road between mines and Administration Building.			
Indicated ore.............	450,000	64	4.0
Inferred ore..............	500,000-800,000	64	4.0

* After screening.

Canga

Canga is colluvium or talus, composed in large part of fragments of iron-rich rock, that has been recemented into a coherent mass by limonite. As canga is porous, it is easily smelted in charcoal blast furnaces and has been an important type of ore for small furnaces at other places in Brazil. The canga in the Urucum region is of two kinds, which differ in environment and probably in age and mode of origin.

The less abundant kind lies on the higher ground, especially in valleys on top of Morro do Urucum, and, to a lesser extent, on

34/ Length of belt, 3 kilometers; average width, 300 meters; assumed sp. gr. 3.

Serra da Santa Cruz. Several small areas of canga are exposed in the valleys of these mesas. These valleys have been truncated by the headward erosion of Santa Cruz Valley, and the canga (see pl. 2) undoubtedly represents re-cemented stream gravels of a former epoch. It seems possible that ground water moving slowly through the iron-rich beds to the valley bottom became saturated with iron, which was precipitated as hydroxide around alluvial fragments of hematite when the water came to the surface in those valley bottoms and evaporated. These deposits are not widespread, but in general they are relatively pure. An analysis of a typical sample follows:

Sample Fe 55

	Percent		Percent
Fe	61.3	CaO	None
SiO_2	4.8	TiO_2	0.17
Al_2O_3	4.2	P	.16
MgO	.2	H_2O	2.96

The more abundant kind, and the one more likely to be of economic interest, is found in extensive areas of lower ground, especially around the base of Morro do Urucum and along the road to Piraputangas and São Domingo. This lower-lying canga occurs typically in soil-less patches 20 to 100 meters broad and of a somewhat greater length, which support no vegetation whatsoever except a few sparse and struggling cacti. Undoubtedly other such patches have become covered with soil and lie a few feet below the surface. No general estimate can be made of the thickness of these patches, but in two places a meter and a half of canga is revealed in stream banks where the bottom of the canga is not exposed. This low-lying canga, which is extremely hard and dense, appears less pure than that on the hilltops and contains little recognizable hematite.

From the north end of Morro do Urucum some of these barren patches can be seen to have a linear distribution and it seems possible that they may mark the trace of a fault. Upward-moving iron-rich ground water along such a fault would evaporate on reaching the surface under climatic conditions similar to those now obtaining and leave a precipitate of limonite. On the west side of Serrania de Mutun similar relations between the distribution of canga and the presence of springs were observed and although no fault is demonstrable in the area under discussion because of the heavy cover and low topographic position, it is not unreasonable to assume a similar origin for this lower-lying canga. It would seem to require some continuing agency to keep the many patches free of soil.

No samples of this material were taken, but a published analysis of similar material collected in Bolivia by Ahlfeld 35/ is as follows:

	Percent		Percent
Fe_2O_3	83.25	MnO	0.86
Fe	57.71	P_2O_5	2.16
SiO_2	8.88	SO_3	3.36
CaO	.21	Al_2O_3	.96
MgO	.32		

The high phosphorus and sulfur content reported by Ahlfeld are possibly unusual.

35/ Ahlfeld, Federico, Yacimientos de Fierro de Puerto Suarez: Boletín Año 1, No. 3; Ministerio de Economía Nacional, Dirección General de Minas y Petróleo, p. 51, La Paz, Bolivia, 1940.

Mine workings

Late in 1941 manganese ore was being mined by methods essentially similar to those employed and planned by the Compagnie de l'Urucum during the earlier period of exploitation. Most of the adits have been driven normal to the outcrop, starting at the bottom of the manganese bed. As the bed dips into the slope, the workings penetrated the top of the ore bed 5 to 15 meters from the portal. In order to continue mining in the ore the adits turned nearly parallel to the outcrop (pl. 6) and as a consequence, there were only a few meters of ore between the adit and the outcrops that could be extracted with the aid of gravity. In several cases (mines 1, 3, 8, and 11) inclines had been driven down the dip, but, because the broken ore had to be wheeled up an 8° to 14° slope in wheelbarrows, this procedure evidently was not economical.

As a result of this method of attack, the ore bed had not been explored more than 40 meters normal to the outcrop, and only a very small tonnage had been developed for extraction. Some of the adits are so close to the surface that their floors are now covered with a network of roots from the vegetation above.

Although all the openings were mapped, no one of them will be described in detail, because all are nearly the same in character and none show many features of geologic interest.

In addition to the twelve mines shown on plate 6, four other openings have been made in beds 1 and 2 on the northeast and northwest slopes of Morro do Urucum. These range in length from about 5 to 20 meters and contain little of economic or geologic interest.

Utilization of structural features in mining

Although mining methods and costs are not within the scope of this report, it seems useful to draw attention to several minor structural features that can be taken advantage of to lower the cost of developing the manganese beds.

Mining can be facilitated by following joints, three sets of which are present in most places. One set is subparallel to the strike and dips steeply, making good walls for strike drifts. Other sets, generally with dips between 50° and 65°, cross the strike of the beds at angles of about 45°, and these can also be utilized in mining. Joints will probably become less prominent, however, at greater distances from the outcrop than had been reached in 1941.

Advantage can also be taken of certain variations in the dip of the beds. In considering how this may be done, it will be assumed that stopes will be raised up the dip from development drifts, so that all the ore that is extracted will move downhill and be hauled out on a level. Development from adits rather than inclines not only makes for economical handling of ore, but removes any necessity for pumping should water be encountered.

A minor syncline is imposed upon the general northeast dips in the mine area (pls. 2 and 6). The axis of the syncline strikes approximately N. 35° to 40° E. Were a haulage adit opened about 25 meters vertically below the outcrop of bed No. 1

near mine No. 4 and driven to that bed, and were lateral workings then driven along the strike of the bed, a considerable tonnage of ore could be extracted with the assistance of gravity rather than by working against gravity, as would have to be done if the bed were developed by an incline shaft down the dip. Furthermore, the hard jasper through which the haulage tunnel would be driven would require no timbering, whereas any large adit or incline on the ore bed would eventually have to be timbered. It would be advantageous for the haulage tunnel to follow the axis of the syncline. Both of the lateral development drifts on the ore bed would then swing gradually away from normal to the tunnel and become roughly parallel to the outcrop, thus developing a maximum amount of ore per meter of drift.

The beds probably flatten gradually inward from the outcrop, but, as the dips at the outcrop and in the mines are somewhat variable, no detailed prediction regarding the change of dip can be made; the consequences following from certain assumptions can however be considered. Assuming a constant dip of 12°, an adit 25 meters vertically below the outcrop would intersect bed 1 about 165 meters from the portal, and, with 100-meter lateral development drifts on the ore bed, about 240,000 tons of ore in bed 1 would be developed, together with 77,000 tons in bed 2, which could be reached by a 35-meter raise. If development should prove that the dip of bed 1 decreased regularly from 12° to about 4°, the intersection of the haulage adit with the ore bed would be about 260 meters from the portal. In that case, about 345,000 tons of ore would be developed in bed 1 and about 140,000 tons in bed 2 by 100-meter lateral drifts on the ore bed. Detailed surface mapping and some core drilling should be undertaken in order to determine conditions more precisely than is now possible.

An abrupt change in the strike and dip of bed No. 1 in the vicinity of mines 8 and 9 is indicated by direct measurements and by the trace of the outcrop of bed 1. The altitude of the outcrop rises from 779 meters at mine 8 to 818 meters at sample 6 and to 830 meters a short distance further to the southeast (pl. 2). In fact, the outcrop is lower at mine 8 than at any point to the south of that mine. Taking advantage of the relatively abrupt fold by driving a haulage adit along the strike of the bed would permit the development of about 163,000 square meters of the bed above that adit between mines 8 and 11. This area contains about 1,200,000 tons of ore averaging about 46 percent Mn. By developing bed 2 with raises from the haulage adit inclined 60° to the northeast, about 135,000 square meters, or 675,000 tons of ore, which might average 47 percent Mn, would be developed. No allowance is made for ore tied up in pillars in any of the above estimates.

Similarly, by starting an adit on the strike of bed No. 1 near sample 4 (elevation 803 meters), a considerable tonnage of material could be extracted with the aid of gravity from the south end of the Morro do Urucum.

It should be emphasized that before any large-scale development is attempted, the above conclusions should be checked by core drilling and large-scale mapping, since the maps on which the estimates are based were not of large enough scale to serve as a basis for detailed geologic prediction. The tonnage figures given merely show order of magnitude.

APPENDIX I

Conversion factors

Metric	English
1 millimeter (mm)	0.039 inch
1 centimeter (cm)	.394 inch
1 meter (m)	3.28 feet
1 kilometer (km)	3,281 feet or 0.62 mile
1 square meter (m^2)	1.19 square yards
1 cubic meter (m^3)	1.31 cubic yards
1 metric ton	2,205 pounds or 1.102 short tons