Geology and Ore Deposits of the Itabira District Minas Gerais, Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 341-C

Prepared in cooperation with the Departamento Nacional da Produção Mineral of Brazil under the auspices of the International Cooperation Administration of the United States

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By JOHN VAN N. DORR 2D *and* ALUIZIO LICINIO de MIRANDA BARBOSA

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GEOLOGY AND ORE DEPOSITS OF THE ITABIRA DISTRICT, MINAS GERAIS, BRAZIL

By JOHN VAN N. DORR 2d and ALUIZIO LICINIO de MIRANDA BARBOSA

ABSTRACT

The Itabira iron district is a part of the Quadrilátero Ferrífero or iron quadrangle of Minas Gerais, Brazil. It is located between the Rio de Peixe and Rio Tanque about 100 kilometers northeast of Belo Horizonte and about 360 kilometers almost due north of Rio de Janeiro.

The district is the most productive of the iron ore districts in Brazil. During 1955 production exceeded 2.7 million metric tons, more than two-thirds of which was lump hematite averaging 68.7 percent iron. The remainder or about 700,000 metric tons was minus one-half inch ore which was wasted or stockpiled near the mine.

The oldest rocks of the Itabira district are Precambrian. Subdivisions, lithologic character and the relation of subdivisions to each other are as follows:

Series	Group	Formation	Description
Minas	Piracicaba		Quartzite, phyllite, and conglomerate.
	Itabira	Gandarela	(Not of mappable thickness.)
		Cauê itabirite.	Host rock for the iron ore.
	Caraça		Conglomerate, quartzite, and phyllite.
	Unconformity.		
Rio das Velhas.			Schist, quartzite, and iron-formation.

A granitic gneiss is in contact with the Precambrian rocks. This gneiss has four intergradational phases: (a) an evenly foliated granitic gneiss of igneous aspect; (b) a rock apparently nearly identical in composition but characterized by ptygmatic folds and abundant pegmatites; (c) a quartz-muscovite gneiss apparently derived from quartzite; and (d) a richly biotitic gneiss grading into biotite schist which was almost certainly derived from the pre-Minas sedimentary rocks and perhaps also from rocks of the Minas series.

A group of ultramafic and mafic rocks now altered to steatites, serpentinites, amphibolites, and talc and actinolite schists, are intrusive into the Rio das Velhas sedimentary rocks, but not into the Minas series. These intrusive rocks are believed to be either contemporaneous with or slightly younger than the older sedimentary rocks and older than the Minas series. They are found in the granitic gneiss, but not necessarily in intrusive relation.

The Borrachudos granite, a new formation described herein, is intrusive into the granitic gneiss. It is an extremely coarse grained, faintly foliated biotite granite with characteristic accessory fluorite. The biotite blebs have a remarkably uniform lineation, generally within 5 degrees of east, over an extent of more than 20 kilometers. An age determination showed this rock to be 475 million years old.

Both the Borrachudos granite and the granitic gneisses are cut by diabase dikes, which seem to be the youngest intrusive rocks of the area and may be of Mesozoic age.

All rocks described above, except the diabase and related rocks, are foliated. The pre-Minas sedimentary rocks have probably been metamorphosed twice; they are generally at a higher level of metamorphism than the rocks of the Minas series, for they are generally in the biotite zone, whereas the pelites of the Minas are now low-grade phyllites except in areas of contact metamorphism. The granitic gneiss produced a metamorphic aureole in the rocks with which it was in proximity. Garnet, kyanite, and staurolite are found in this aureole in the older sedimentary rocks and garnet and kyanite in Minas series rocks as high stratigraphically as the Piracicaba group.

The relatively young sediments and sedimentary rocks are Tertiary and Quaternary clays, sands, and gravel, found principally in the valley bottoms and on stream terraces.

Folds dominate the structure in the Itabira district as they do in the rest of the Quadrilátero Ferrífero. The major structural feature in the Itabira district is the tight, probably deep, syncline which traverses the central part of the area and plunges in a northeasterly direction. Two subsidiary synclines and their connecting anticlines are imposed on the northwest limb of this syncline. These folds have a generally easterly plunge. Still smaller and tighter folds are imposed on these subsidiary folds and upon them still others on scales down to a few millimeters. Faults are a minor structural feature.

The major ore bodies, with the exception of those of the Conceição area, are generally localized on the subsidiary folds. The Conceição area is an exception which is relatively near the keel of the major syncline in an area where the syncline is isoclinal, in part overturned, and complicated by extremely tight minor folds. The crosscutting relationship, on both a small and large scale, of the pure hematite bodies makes it obvious that these bodies are of replacement rather than sedimentary origin. There is no evidence to indicate that simple supergene leaching of silica produced residually enriched bodies of high grade (+66 percent Fe) ore, al-

though this process enriched the itabirite to a great extent locally and softened it to notable depths.

It is believed that the high-grade hematite bodies were formed by metasomatic replacement of siliceous itabirite by hematite dissolved from the iron-formation elsewhere. These fluids were of hypogene origin, genetically related to the granitic gneiss. The replacement process occurred during the metamorphic epoch at elevated temperatures and pressures. The ore-forming process was governed by the changing solubility of quartz under rising temperature conditions up to 332°C, and its falling solubility from that temperature to the critical. Ore bodies are localized by zones of increased porosity in the iron-formation.

The ore is of three main types: (a) high grade (+66 percent Fe) hematite; (b) soft itabirite; and (c) surface ores of various origins. The high-grade hematite may be subdivided into three intergradational types of differing value. The most valuable is the hard hematite, which is used as charge ore in the open-hearth furnace and which commands premium prices. Soft hematite, on the other hand, although of nearly equal chemical purity, has no immediate value and was being stockpiled during 1954. Between these extremes is the intermediate type of ore, which yields some lump and some soft ores. The average analysis of 7.5 million tons of hematite ore exported from 1948 to 1954 is 68.66 percent Fe, 0.35 percent SiO_2, 0.67 percent Al_2O_3, 0.013 percent S, and 0.025 percent P.

Reserves in the Itabira district are classified as "reasonably assured ore," or ore that, except in localities where underground exploration made necessary greater extrapolation in depth, lies within 50 meters of the surface, and as "inferred ore," or ore that lies within 250 meters of the other ore. Total tonnage of "reasonably assured ore" in the Itabira district was calculated to be about 374 million metric tons containing an average 67 percent or more of Fe, and of which about one-third is lump ore. Total tonnage of "inferred ore" in the Itabira district was calculated to be 638 million metric tons with the same chemical and probably better physical characteristics than the near-surface ore. An extremely rough estimate of "geologically possible" ore gave a total of about 2.5 billion tons, although much of this is at depths which make it uneconomical to mine at present. This ore should have much better physical characteristics than the near-surface ore.

A rough estimate of the amount of soft and easily concentratable itabirite available at depths down to an average of about 100 meters gave a total of 1.74 billion metric tons that would average about 45 percent Fe before concentration. Concentrates ranging in grade up to 68 percent Fe have been made from such material with a Humphrey Spiral. Metallic iron contained in the soft itabirite and in the "reasonably assured" and "inferred" ores amounts to 1.45 billion metric tons. Many times this total is contained in the hard itabirite and in the "geologically possible" ore.

INTRODUCTION

The Itabira district is perhaps the best known of the famous iron-ore districts in the Quadrilátero Ferrífero of central Minas Gerais (fig. 1). It is located on the divide between the Rio de Peixe and the Rio Tanque drainage basins about 100 kilometers northeast of Belo Horizonte and about 360 kilometers almost due north of Rio de Janeiro. Itabira, formerly "Presidente Vargas" and even earlier "Itabira do Matto Dentro," is a town of about 7,000 inhabitants and is the only population center in the district. Its geographic coordinates are latitude 19°37′S. and longitude 43°13′W. This town was founded about 1720 as a gold-mining center and as such flourished until the middle of the nineteenth century, when gold mining gradually came to a standstill owing to the exhaustion of easily mineable reserves. It is possible that at the height of the gold mining boom the population was greater than at present.

The town is reached from Belo Horizonte by automobile in 3 hours, by train in 12 hours, or by taxi airplane in 20 minutes. It can also be reached by the meter gage Vitória á Minas railroad from the port of Vitória. A new railroad from Belo Horizonte was under construction in 1954.

Electric power enters the area from the Peti dam of the Companhia de Fôrça e Luz de Minas Gerais at 69,000 volts, and from the Salto Grande project near Guanhães at 161,000 volts. The city of Itabira has a municipal hydroelectric powerplant which is inadequate for the demand of the populace.

The Itabira area, outside the mineral zone, is moderately fertile but food is imported into the district and it is probable that the import of staple products exceeds the exports. Most farming is on a subsistence basis. Mining is the main industry at present, but

TABLE 1.—*Meteorological data, Itabira district, Minas Gerais, Brazil* [1]

	Average precipitation [1]		Monthly temperature [2] (in degrees centigrade)		
	Years of record	Precipitation (millimeters)	Maximum	Minimum	Mean
January	35	250.0	34.8	12.0	22.4
February	37	218.2	34.0	10.0	22.3
March	36	193.3	33.0	11.6	21.8
April	37	89.0	31.6	7.0	20.4
May	37	25.8	30.8	2.6	18.4
June	36	13.2	28.8	1.6	17.0
July	37	9.5	28.6	−0.4	16.0
August	37	14.8	32.4	2.0	17.5
September	35	46.3	33.6	4.2	19.3
October	35	136.1	35.2	7.8	20.6
November	36	232.6	34.4	9.0	21.3
December	36	350.6	34.6	11.0	21.8
		1,579.4			

[1] Precipitation data from Divisão de Aguas, Departamento Nacional da Produção Mineral. Temperature data from Seção de Meteorologia of the Ministério da Agricultura.

[2] Temperature data for years 1919–42; precipitation data from 1918–54.

The maximum rainfall in a 24-hr period 1918–54 was 90.1 mm. There were 10 months during these years in which the maximum 24-hr rainfall was between 70 and 80 mm, and 55 months in which the maximum rainfall in a 24-hr period was between 60 and 70 mm.

farming and woodcutting for fuel and charcoal are also important.

The Itabira district was formerly covered by dense forests. Because the wooded areas have all been cut over at least several times, only dense thickets and tangles of vines, taquara (a type of bamboo with thorns), bushes, ferns, and low trees remain. Except on paths, these woods are practically impenetrable. The soil cover is deep and outcrops are few. To the writers' knowledge, there are only three natural outcrops of the Minas series in the district aside from those of iron-bearing rocks.

Rainfall in the area is definitely seasonal, as shown by table 1.

The climate is generally pleasant and healthful. The mean monthly temperature shows no great variation, and extremely hot days are much rarer than days on which sweaters or jackets are welcome. Torrential rainfall occurs several times a year causing flash floods. Hail is not unknown but freezing temperatures are rare.

ACKNOWLEDGMENTS

This report is based on work that is part of a larger project for the geologic study and estimation of reserves of economic minerals in an area of about 7,000 square kilometers in central Minas Gerais, in which eight Brazilian and American geologists are now (1958) engaged. The project is part of a program of cooperative investigations of mineral resources in Brazil implemented by the Brazilian Ministério da Agricultura through the Departamento Nacional da Produção Mineral (hereafter referred to as DNPM), Divisão do Fomento Mineral, and the U.S. Geological Survey.

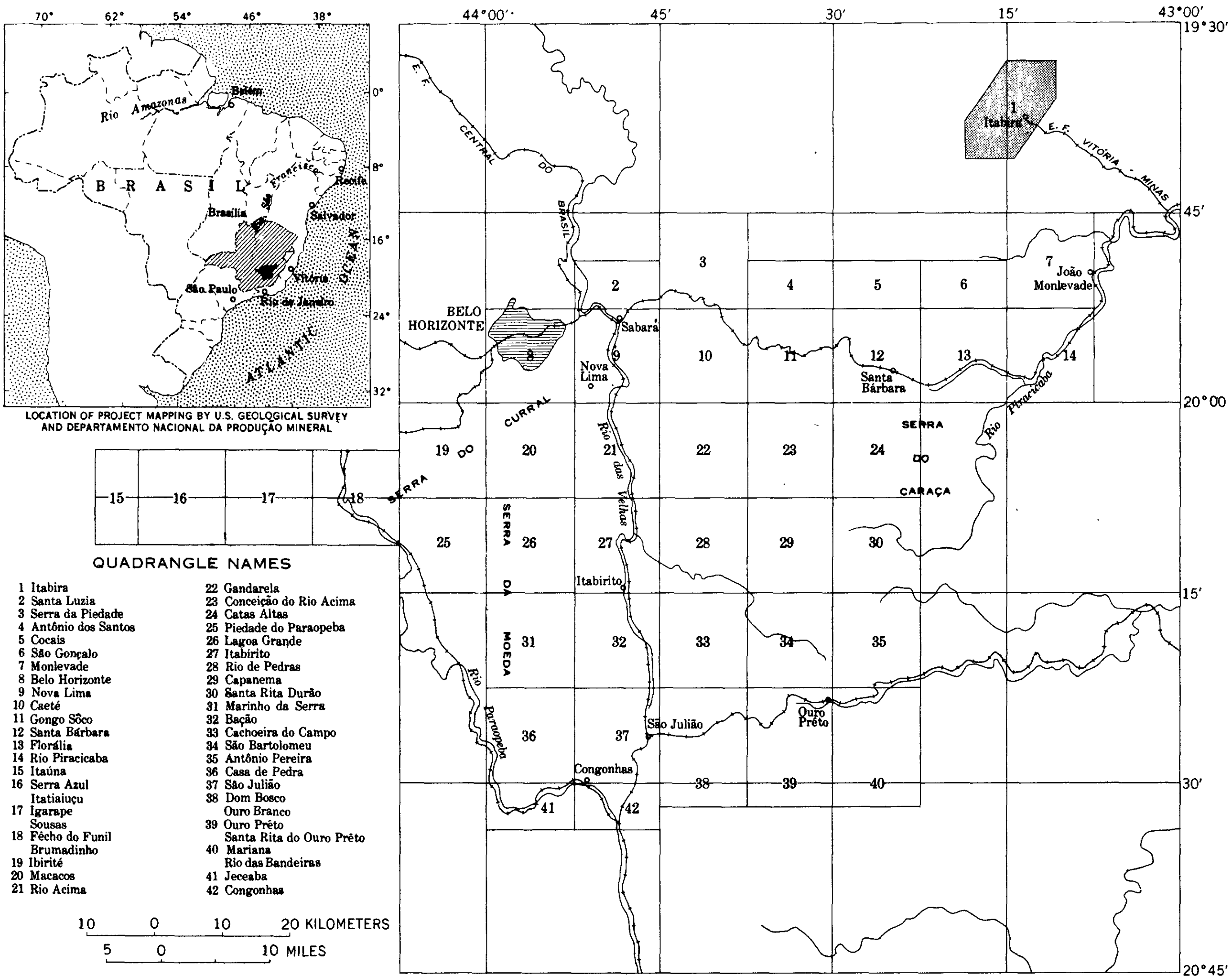


Figure 1.—Index map of Brazil and the Quadrilátero Ferrífero showing the location of Minas Gerais, the total area in the Quadrilátero Ferrífero to be mapped, and the location of the Itabira district in relation to the other quadrangles.

The work has been financed by the Ministério da Agricultura through the Departamento Nacional da Produção Mineral and by several United States agencies. The first of these was the Department of State, through the Inter-Departmental Committee for Cooperation with the American Republics. Later the financing on the American side was transferred to the Institute of Inter-American Affairs under the Technical Cooperation Administration of the Department of State. This in turn was followed by the Institute of Inter-American Affairs under the Foreign Operations Administration and by the International Cooperation Administration of the Department of State.

Particular acknowledgment should be made to Dr. Mario da Silva Pinto and Dr. Alberto Ildefonso Erichsen, respectively Directors of the Departamento Nacional da Produção Mineral and the Divisão do Fomento da Produção Mineral when the work was being started, for their interest and unflagging support. Dr. Avelino Ignacio de Oliveira, Director of the Departamento Nacional da Produção Mineral from 1950 to this writing, and Drs. Irnack Carvalho do Amaral and Eugenio Bourdot Dutra, successors of Dr. Erichsen, were an unfailing source of aid and support. Mr. Robert G. Groves, Deputy Director and Acting Director of the Institute of Inter-American Affairs in Rio de Janeiro for several years, was of signal assistance in securing support for the work and a special debt of gratitude is owed him.

In Itabira itself, numerous persons helped to stimulate and carry forward the work. Particularly helpful were Dr. Gilbert Whitehead, Superintendent of Mines of the Companhia Vale do Rio Doce until 1950, and the present Superintendent, Dr. Francisco Fonseca. Both men gave the work every support and had caved mines and pits opened so that more data could be secured. The Companhia Vale do Rio Doce S. A. kindly supplied housing and other courtesies to the writers for 7 years, and made many chemical analyses. The Companhia Aços Especiais de Itabira, S. A. extended many courtesies and much help to the writers and opened a vital adit, which had collapsed, so that the essential relations hidden therein could be observed.

The authors owe a debt of gratitude to their friend and colleague, Dr. Luciano Jacques de Morães, for much time and thought devoted to introducing them to the complexities of Brazilian geology in the Quadrilátero Ferrífero. Other colleagues, notably Drs. Wilson de Padua and Celso Velloso were of great assistance in the field. Dr. Benedito Alves worked hard and well.

Several stratigraphic concepts on which interpretations in this report are base were worked out elsewhere in the Quadrilátero Ferrífero by colleagues, notably Garn A. Rynearson, Joel B. Pomerene, and Joseph R. O'Rourke, who worked in areas where exposures of the Minas series and other rocks are better than in the Itabira district. The writers were unable to make reasonable interpretations of some features until these men had shown the way. Errors in interpretation in the Itabira district remain the responsibility of the authors.

When this work was originally planned, Professor C. K. Leith kindly made available to the project the complete files of the Brazilian Iron and Steel Co., and gave to the senior author copies of all material concerning the geology and ore reserves not only of the Itabira district but also of other areas in the Quadrilátero Ferrífero. These voluminous files, composed largely of unpublished reports by E. C. Harder, R. T. Chamberlin, Hugh Roberts, J. D. Conover, and others, were most helpful.

Mr. Charles Gauld very kindly supplied assay data from the files of the late Percival Farquhar concerning ores of Conceição Peak.

HISTORY

The Itabira district, like so many mining districts in the Quadrilátero Ferrífero, began as a gold-mining center. Undoubtedly the first production came from placer deposits; later adits and shafts were sunk in search of lode deposits. The first discoveries were made in 1720 by the bandeirantes (groups of early adventurers from São Paulo who roamed the interior of Brazil).

Records do not exist showing when the first iron foundries were established in the area, but, according to Pimenta (1950, p. 19), the first blast furnace in Brazil started to function at Morro do Pilar, north of Itabira, in 1814. According to the same source, Catalan forges were functioning in Itabira by 1830 and it is understood that the last of these forges was shut down in 1932. Details of the early history and reduction processes can be found in the cited paper by Pimenta and in a paper by E. C. Harder (1914, p. 2573–2585).

Interest in the iron-ore deposits as such began about 1908, when the Itabira Iron Ore Co. was formed and initiated steps to secure control of the Vitória á Minas railroad and to purchase ore properties. The first of these purchases was formalized in 1910 and by 1916 several of the choicest properties had been purchased by that company, which was formed with British capital.

At the International Geological Congress at Stockholm in 1910, Orville Derby presented a paper by Gonzaga de Campos in which the iron-ore reserves of Brazil were estimated at more than 5 billion tons of ore between 50 and 65 percent iron. Soon thereafter American, French, and German interests began to acquire properties in Minas Gerais.

The Brazilian Iron and Steel Co., with American capital and with the well known geologists Van Hise and Leith as officers, made a study of the whole Quadrilátero Ferrífero. The fieldwork was carried on mainly by R. T. Chamberlin and E. C. Harder, and many excellent deposits, including the central part of the Itabira district, were bought. An outstanding scientific paper on the geology of central Minas Gerais resulted from this work.

The writers wish to pay special tribute to the work done by Harder and Chamberlin and their assistants during this period. At present the geologist covers in a jeep in 4 hours the same ground that these pioneers spent 2 to 3 days to traverse on muleback, plagued by ticks and without satisfactory food or shelter. Today, extensive roadcuts and, in many localities, mine workings, give clear and unequivocal evidence as to relations which had to be guessed at 40 years ago. Although, as will be apparent in the following pages, the writers do not agree in all cases with the interpretations of these geologists, the basic groundwork of the stratigraphy and structure of the Quadrilátero Ferrífero was laid by them on the foundation previously laid by Derby and, fundamentally, the work of the present investigators is only a needed refinement and reinterpretation, in the light of the advancement of the science of geology in the last four decades, of the work done by these men. The writers hope, optimistically, that their work will stand the test of time as well as that of these outstanding geologists.

The Itabira Iron Ore Co. and the Brazilian Iron and Steel Co. fell into a protracted lawsuit over ownership of the major part of Cauê Peak, which was finally decided in favor of the former. This lawsuit and the advent of World War I, which dried up capital sources, prevented immediate development of the district.

Shortly after that war, a contract was signed between the Itabira Iron Ore Co. and the Brazilian Government whereby the railroad, which had not yet reached Itabira, would be completed and the company would be permitted to export ore from the port of Santa Cruz (today Ara Cruz). The company agreed to install a blast furnace and to reduce a minor percentage of its production to metallic iron for the local markets. This contract produced a political tempest, as state and national interests were thought to be conflicting, and it was never implemented. Efforts to consolidated the holdings of the Itabira Iron Ore Co. and the Brazilian Iron and Steel Co. in the Itabira district were made from time to time but the merger never materialized.

In 1942, because it appeared that the Spanish and North African sources of iron ore for Great Britain's steel industry might be cut off by an invasion of Spain by Germany during World War II, the "Washington Agreements" were signed by the Brazilian, American and British Governments.[1] These agreements provided in part that the British Government would buy the Itabira Iron Ore Co. and the Vitória á Minas railroad and hand over rights to these properties to a Brazilian company controlled by that Government. The American Government agreed to finance, on easy terms, dollar expenses for extending the railroad from Nova Era to Itabira and to finance the installation of the mine and reequipment of the railroad. The Brazilian Government agreed to establish a government-controlled company and to finance expenses on construction work in domestic currency. The British and American governments were each to have the right to buy up to 750,000 tons of iron ore per year for 3 years at world prices, and this right could be extended.

The Brazilian Government then created in 1942 the Companhia Vale do Rio Doce, S. A. (hereafter called CVRD), with mixed public (85 percent) and private (15 percent) capital, the President and Directors of which are now appointed by the President of Brazil, to own and to operate the mines in the Itabira district which originally belonged to the Itabira Iron Ore Co. as well as the Vitória á Minas railroad. The United States Export-Import Bank has made a series of loans to this company which in 1955 totalled about $27,500,000 at interest rates of about 4 percent.

In 1945, the Brazilian Iron and Steel Co. sold its holdings in the Itabira district to Companhia Aços Especiais de Itabira (Acesita), a company formed to construct and operate a small steel plant about 100 kilometers from Itabira down the Vitória to Minas railroad in the valley of the Rio Doce. This company originally was financed entirely by private capital, but it was undercapitalized and such large sums had to be borrowed from the Bank of Brazil that eventually that bank took over the management.

[1] Oral communication by Herbert Feis, then Economic Counselor to the U.S. Department of State.

FIELDWORK AND MAPS

The fieldwork on which this report is based was started in May 1947 and continued with minor interruptions until late in 1949, when it was interrupted for a year. From 1950 to 1954, other responsibilities prevented continuous work in the area, and less than one quarter of that period was spent in field or office work on the report.

In order to finish the report as soon as possible, and to take advantage of his specialized knowledge of petrography, J. E. Gair was requested late in 1954 to examine the 200 thin sections that had been cut from the specimens collected in the field. The results of this petrographic work, which was much more detailed and systematic than that done by the authors, and of interpretations therefrom have been incorporated into the body of the report. As a result of this work, several new ideas concerning certain rocks were developed. In essence, the petrographic work confirmed concepts arrived at from the fieldwork, as far as petrographic work can be diagnostic. Mr. Gair should not be blamed for errors in interpretation, responsibility for which remains with the authors.

When the present work was started in 1947, the only map of the Itabira district as a whole was a manuscript State planimetric map on a scale of 1:100,000. Cauê Peak was geologically mapped using as a base a CVRD 1:2,000 scale topographic map compiled by that company from old maps, with some original work added. While this geologic mapping was being done, Milton Denault, of the Geological Survey, made a topographic map of the central part of the district at a scale of 1:10,000, based on the CVRD datum, triangulation system, and coordinates. About two-thirds of this map was surveyed by planetable methods and the remainder was compiled from the excellent Brazilian Iron and Steel Co. map kindly supplied by Acesita, and from CVRD maps. John J. Collins, also of the Geological Survey, completed the small part of this map still unfinished when Denault returned to the United States. This map was photographically enlarged to a 1:5,000 scale and used in part as a base map for plate 2.

Several years later the Departamento Nacional da Produção Mineral secured aerial photographs of the area at an approximate scale of 1:10,000 and these were used as a base for geologic mapping outside the ore areas.

The DNPM then contracted with Serviços Aerofotogramétricos Cruzeiro do Sul, S. A. for aerial photographs, at a scale of 1:25,000, of the part of the Quadrilátero Ferrífero which drains into the Rio Doce. These photographs were the basis of the topographic map of the Itabira district prepared by the same company for the Geological Survey. The datum and geographic coordinates of this map were based on a line of first order triangulation and levels run about 35 kilometers south of the Itabira district by the Conselho Nacional de Geografia with equipment supplied in part by the Inter-American Geodetic Survey. Unfortunately, an error was made by the Cruzeiro do Sul Co. in running levels from the first order work of the Conselho Nacional de Geografia into the Itabira district and the datum of the 1:25,000 district map is 3.775 meters higher than mean sea level. For this reason and because of inherent differences between planetable and photogrammetric techniques, topography on the two maps is not the same. In case of doubt, the planetable sheet should be preferred, although the culture on the district map is more recent.

The planimetry of the underground maps of the major adits, plates 3, 4, and 7, was copied from maps left by the Itabira Iron Ore Co. These were not rigorously checked during the underground geologic mapping but, based on tape and goniometer surveys made during the present work, they seem to be adequate. The smaller and the new adits and shafts were surveyed by the writers with Brunton, tape, and goniometer, and are not rigorously correct. No effort was made to carry elevations during mine mapping. The average slope of the adits may be somewhat over 1 percent; it is quite variable, for the early miners were not very successful in making their underground mine connections in the vertical plane, although connections in the horizontal plane are excellent.

Mapping was hindered by the fact that the iron-bearing rocks are locally quite magnetic and it proved impossible to use a compass in large parts of the district. All planetable mapping had to be done by traverses, checked by intersecting on the numerous triangulation stations established by Mr. Denault.

GENERAL GEOLOGY OF THE QUADRILÁTERO FERRÍFERO

The Itabira district is not directly connected with the great sweeping curves of iron formation which characterize most of the Quadrilátero Ferrífero (fig. 2). It is rather an island of downfolded sediments in a sea of gneiss and granite, about 20 kilometers from the nearest continuous iron formation. The formations and structures which are well exposed in the major area to the southwest cannot be traced directly into the district. Nevertheless, most of the recognizable rocks in the central part of the Quadrilátero Ferrífero are present in the Itabira district. Hence

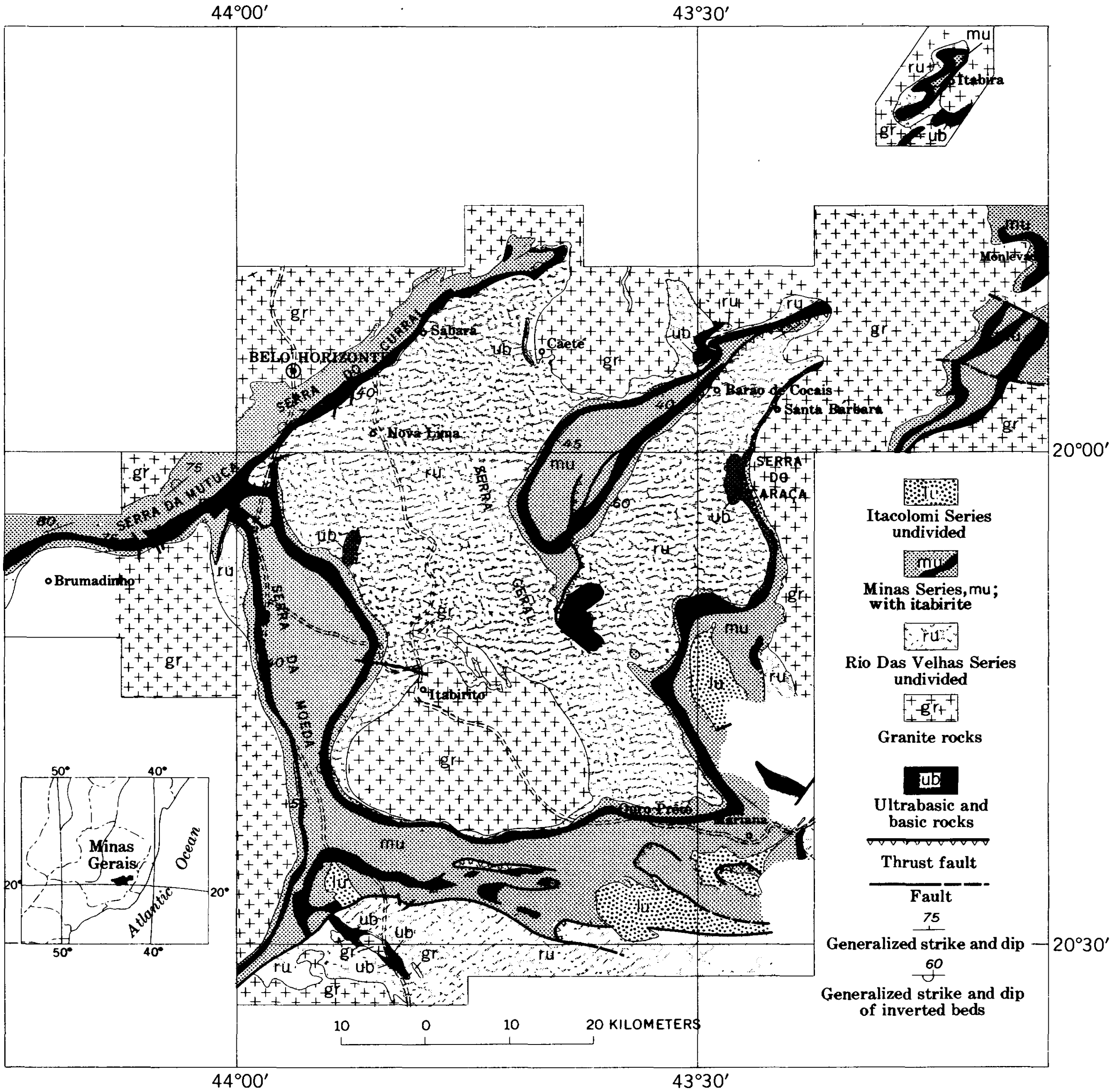


FIGURE 2.—Sketch map showing the distribution and outcrop pattern of the Itabira group, the principal source of iron in the Quadrilátero Ferrífero, Minas Gerais, Brazil.

a short summary of the geologic setting of the area as a whole will be of assistance in understanding the details of the Itabira district.

TOPOGRAPHY AND PHYSIOGRAPHY

The Quadrilátero Ferrífero is a generally mountainous area resulting from the erosion of an ancient peneplain. The peneplain may correlate with the Cretaceous peneplain of northern Minas Gerais and the northeast states of Brazil. Total relief is about 1,200 meters; local relief ranges from 300 to 600 meters. With few exceptions, streams are actively downcutting and there are few broad valleys or alluvial plains. Rock structure and resistance to erosion controls drainage, and the distribution of many rock types is rather faithfully reflected by topography.

Linear ranges, including the Serra do Curral, the Serra da Moeda, and the Serra de Ouro Preto, are generally caused by iron-formation. The crests of these ranges are considered to approximate the old-peneplain surface because of the general accordance of their summit levels. Other linear ranges, such as the Serra do Ouro Branco, are held up by quartzite. Individual peaks, such as Cauê, are caused by hematite, others by quartzite, and still others by hard siliceous iron-formation without canga.

Granitic and gneissic rocks form broad lowland areas of relatively subdued relief, whereas schists and phyllites form broad smooth steep slopes locally oversteepened by rapid erosion and corrugated by soil creep and small landslide scars. Dolomite locally forms bold crags on the lower slopes and sides of valleys, but generally does not crop out.

In the western part of the Quadrilátero Ferrífero at least three well-defined terraces mark periods of lateral erosion by the streams. In the eastern part of the district, several erosion levels also may be seen but observations in this zone are too spotty to permit generalizations.

The broad, rather flat, slopes on some of these terrace levels have given an opportunity for the accumulation of extensive deposits of canga and, locally, bauxitic rock and bauxite. In the Itabira district, only canga is of economic interest. The one bauxite deposit is too low grade to be of value. Others of these terraces, generally the lower ones, have been sites for gravel accumulation and many were worked for gold during the time of the Empire.

STRATIGRAPHY

The rocks of the Quadrilátero Ferrífero have been examined and studied for more than a hundred years by many geologists, resulting in an extensive literature. However, before the present cooperative project was undertaken, no regional studies based on adequate base maps had been made. As a result, the literature is conflicting, observations are scattered and unsystematic, and a number of basic disagreements exist. An elaborate critical examination of the evolution of ideas and nomenclature and of the stratigraphic concepts of earlier geologists is beyond the scope of a report that is focused on a limited area. Such an examination can best be made after the regional mapping now in progress has been substantially completed. Therefore, only enough detail about the regional stratigraphy to clarify problems in the Itabira district will be given.

Table 2 indicates the stratigraphic interpretations used in this report and is based on the general literature and on preliminary observations made during the current DNPM–USGS mapping project. These interpretations may be modified and probably will be elaborated by future fieldwork, although the main features are considered to have been well established in the region.

The rocks of the Rio das Velhas series (Dorr and others, 1957, p. 15–22) are possibly the oldest rocks in the Quadrilátero Ferrífero. Most of the rocks mapped as Archean by Harder and Chamberlin (1915) have proved to be post-Minas in age. Other intrusive gneissic rocks hitherto called Archean may be younger than the Rio das Velhas series, although older than the Minas series.

The Rio das Velhas series in its type locality consists of two stratigraphic groups separated by an unconformity. The lower, the Nova Lima group, is dominantly composed of metavolcanic and metasedimentary rocks now greenschist, mica schist, and quartz-mica schist, with subordinate and lenticular beds of graywacke, carbonate-facies iron-formation, and quartz-dolomite-ankerite rock. The upper group, the Maquiné, is composed of quartzite, conglomerate, quartzose phyllites and mica schists, and phyllite. In the type locality the combined thickness of these rocks is not less than 6,000 meters. The Rio das Velhas series is very widespread in the Quadrilátero Ferrífero.

After deposition of the rocks of the Rio das Velhas series, strong orogeny and great erosion occurred. In the Gandarela quadrangle, more than 1,000 meters of Rio das Velhas sediments were eroded before deposition of the overlying beds. Much greater thicknesses were probably eroded in other areas. The Rio das Velhas beds were strongly and complexly folded in pre-Minas time in part of the area. Other parts of the area apparently remained relatively undeformed.

The Rio das Velhas series was originally included in the Minas series as defined by Derby (1906). In 1954 O. Barbosa restricted the Minas series and separated from it rocks which probably correspond in part to the Rio das Velhas series. In 1957, Dorr and his colleagues restricted the Minas series still further on the basis of the unconformity first specifically described by Rynearson and others (1954).

The Minas series has been subdivided into three groups (Dorr and others, 1957, p. 22–29) from bottom to top the Caraça, the Itabira, and the Piracicaba. These correspond roughly to the original formations set up by Harder and Chamberlin (1915). These groups were subdivided into formations in a Symposium on the stratigraphy of the Minas series (Bol. Soc. Bras. Geol., 1958).

The Caraça group consists dominantly of clastic rocks. Quartzite, conglomerate, and grit are the dominant rock types, but phyllite and quartzose phyllite are also widespread. The Itabira group is dominantly composed of chemical sediments, with oxide-facies iron-formation and marble the prevailing rocks. The Piracicaba group, locally separated by an erosional but not structural unconformity from the Itabira group, is composed dominantly of clastic rocks, including quartzite, ferruginous quartzite, phyllite, graywacke, metavolcanic rocks, and local conglomerate and dolomite lenses.

The Itacolomi[2] series, which Harder and Chamberlin included with the Minas series, was shown by D. Guimarães (1931, p. 14) to unconformably overlie those rocks. The Itacolomi series is composed of quartzite, conglomeratic quartzite, conglomerate, and phyllite. Locally the conglomerates contain pebbles and cobbles of iron-formation. Where present, these serve to distinguish it from the otherwise lithologically similar basal quartzite of the Minas series, in which such material has not been found except very locally above Nova Lima group iron-formation. In many localities, however, these iron-formation cobbles are not found in the Itacolomi series, and great confusion has resulted owing to lithologic similarity of the two rocks. The Itacolomi series does not crop out in the Itabira district.

STRUCTURE

Folds are the dominant structural feature in most of the Quadrilátero Ferrífero. The Itacolomi and older rocks are strongly folded. Outcrops of the Minas series are disposed in great sweeping curves and lines giving evidence, in their pattern and in the stratigraphic succession, of great synclines and anticlines which in many places are overturned (fig. 2). The crests of the major anticlines have generally been deeply eroded, revealing the older sedimentary rocks, migmatites, and granitic rocks.

The major folds, with an amplitude of 1 to more than 10 kilometers, are accompanied by minor folds which range in amplitude down to millimeters. The larger minor folds generally follow the normal structural laws, and major structure can often be deduced therefrom. Most smaller folds are random and are probably the result of flowage. As is to be expected, the various rocks reacted differently under stress; the more brittle rocks fractured, producing fracture cleavage and breccia instead of folds.

A prominent lineation is one of the more important features in the region. This is caused by the intersection of fracture cleavages and by parallel orientation of elongate minerals and pebbles. Where folding and squeezing of the iron-formation has been intense, long rods of quartz have formed and locally these have been squeezed into boudins. The linear structure in an area of 7,000 square kilometers normally plunges between 15° and 30° in a general easterly direction. In restricted areas, measured in square kilometers, the directional consistency is very marked. This structure is apparently a major control in determining the place of origin of some of the iron-ore deposits.

It is difficult to generalize about faulting in the Quadrilátero Ferrífero. The most prominent faults are the cross faults, locally numerous, which offset major trends and structures. With some exceptions, the offsets are measured in tens of meters, and in some cases, in hundreds of meters. Generally it is impossible to date the faults more closely than post-Minas, but the Itacolomi series seems to be offset in some localities by cross faults, and it may well be that most of the faults are post-Itacolomi. Guild (1953, p. 649) and A. L. M. Barbosa (1958) have shown that some prominent thrust faults are post-Itacolomi in age and it seems probable that most of the major thrust faults are of this age and are closely related in time to the extreme folding.

Presumably the metamorphism of the Minas and post-Minas rocks was contemporaneous with or came shortly after the period of maximum deformation. Because Itacolomi rocks were involved in the metamorphism it is concluded that folding was post-Itacolomi. It is very probable that the metamorphism of these rocks is related to the formation of the granitic gneiss (500 million years).

Throughout the Quadrilátero Ferrífero, a prominent joint set nearly normal to the prevailing lineation is found almost universally in the more brittle rocks. Where the lineation is steep, these joints are nearly horizontal; where it is flat, they are nearly vertical. The joints are important physiographically, for they help control erosion patterns, and economically, for they control rock fracture in quarrying and mining operations.

METAMORPHISM AND THE GRANITIC-GNEISS PROBLEM

All the rocks of the region are to some degree foliated, except veins, certain intrusive gabbroic rocks, some steatitic and serpentinitic rocks, and Tertiary and younger sediments. This foliation is largely the result of planar orientation of the micaceous minerals in the gneisses and, particularly, in the schists but also reflects compositional differences in the various layers of the gneissic rocks and the orientation in planes of certain acicular minerals.

Within the Minas series, in most places bedding is easy to distinguish except in those localities where thermal or dynamic metamorphism was unusually intense. The foliation of these rocks is generally but

[2] Note correct spelling according to present Brazilian orthography. This has been spelled Itacolumi in earlier U.S.G.S. publications.

not invariably parallel to the bedding; it cuts across flowage folds and crenulations in the itabirite. In the Rio das Velhas series, bedding is much more difficult to distinguish unless outcrops are exceptionally good or the rocks less metamorphosed than normal.

In the maps of the Itabira district accompanying this report, the attitude of bedding is shown in the Minas series, but only foliation is indicated for the older rocks because the writers were unable to distinguish the bedding with certainty.

Metamorphism in the Quadrilátero Ferrífero has been dynamic and thermal. Dynamic metamorphism, transforming original argillaceous rocks into phyllites and muscovite and biotite schists, limestones and dolomitic limestones into marbles, tuffaceous rocks into greenstones, sandstones into quartzites, and iron-formation into itabirite, is the most widespread. The intensity of the metamorphism naturally differs from place to place; a comprehensive statement as to this difference will be possible only after completion of the whole mapping project. Thermal metamorphism is also widespread. It manifests itself largely by aureoles of characteristic minerals formed in sedimentary rocks around intrusive bodies. Such aureoles may be as much as a kilometer wide, and, in the case of large intrusive bodies, can be traced for many kilometers.

The Rio das Velhas series generally has the aspect of a higher metamorphic grade than the rocks of the Minas series. Primary sedimentary features have been largely destroyed in the nonquartzitic rocks and the metamorphic minerals seem in many places systematically coarser grained. The severe folding in pre-Minas time which affected these rocks, as shown by the angular unconformity along the contact with the Minas series in the western part of the Quadrilátero Ferrífero (Rynearson and others, 1954), may well have been accompanied by a regional metamorphism of slightly higher grade than that of post-Minas time.

Large areas underlain by granitic gneiss exist in the Quadrilátero Ferrífero. These have been mapped as "Basement complex" in the past, except by O. Barbosa (1954), who considered them pre-Minas in age and equivalent to the pre-Minas sedimentary rocks. As will be demonstrated in later pages, some, perhaps most, of these granitic gneisses are younger than the Minas series.

Coarse-grained granitic intrusive rocks which locally engulfed large blocks of Minas sediments are known in several places in the Quadrilátero Ferrífero. These seem to grade into the granitic gneisses mentioned above. As will be brought out in succeeding pages, certain rocks included in the gneiss in mapping are almost certainly metamorphosed quartzites.

OTHER IGNEOUS ROCKS

Besides the mixed rocks discussed in the foregoing section, a wide suite of intrusive rocks is to be found in the Quadrilátero Ferrífero. These are now represented by steatites, serpentinites, and related rocks; amphibolites; various mafic dike rocks, metamorphosed and unmetamorphosed; granodiorites; granite gneisses; gabbros; and others. Many of these occur in the Itabira district and will be described in some detail in later pages. It is here only necessary to point out that, in the Quadrilátero Ferrífero, the ultramafic suite of serpentinites and steatites is known to occur, with one exception, only in the Rio das Velhas series and in the granitic gneisses which have been in part derived therefrom and that most evidence points to a pre-Minas age for these rocks.

The only other rocks with age implications are the nonfoliated diabase dikes, correlated by several previous workers with the Mesozoic Paraná basalts which occur several hundred kilometers to the west. If this correlation is correct, it limits the age of the last metamorphism.

GEOLOGY OF THE ITABIRA DISTRICT

STRATIGRAPHY

The geologic column in the Itabira district is shown in table 2. The distribution of formations at the surface is indicated on plate 1.

RIO DAS VELHAS SERIES

The oldest rocks in the Itabira district are the schistose rocks believed to be the stratigraphic equivalent of the similar rocks of pre-Minas age that are well exposed in the Rio das Velhas valley, about 100 kilometers to the southwest. These rocks are known as the Rio das Velhas series (Dorr and others, 1957, p. 15). Direct correlation between the type locality of the Rio das Velhas series and the Itabira district is impossible because of intervening extensive areas of younger rocks, but lithologically the correlation is close and stratigraphically the position of the rocks is the same with relation to the unconformably overlying Minas series, which can be correlated with confidence. Because of the presence of iron-formation in the pre-Minas rocks and the general lithologic similarity, the pre-Minas rocks of the Itabira district are believed to correlate with the Nova Lima group rather than with the Maquiné group of the Rio das Velhas series at the type locality. The rocks will be considered as "Rio das Velhas series, undifferentiated," in this report.

LITHOLOGY

In the Itabira district, the Rio das Velhas series is composed of chlorite, muscovite, and biotite schists, with greater or smaller amounts of intermixed quartz; feldspathic quartzites and metaarkose(?); mafic metavolcanic rocks; dolomitic schists; and lean iron-formation. Here the rocks rarely crop out in natural exposures and are uniformly so weathered and rotten that specimens for petrographic study cannot be secured except from drill cores.

Two diamond-drill holes were sunk by the Departamento Nacional da Produção Mineral in the Rio das Velhas series along the main access road to Cauê Peak. The drill holes passed through an average of 50 meters of weathered material too soft for core recovery before reaching solid rock. About 75 meters of core were recovered from each hole and the holes were located so that there is little if any duplication of the strata intersected. The drill cores cannot be assumed to be typical of the Rio das Velhas series as a whole because they represent only a very small percentage of the total section which exists in the area, and because, in one drill hole, granitic gneiss alternated with the quartz-mica schist. It is evident that this hole was close to the contact between these rocks. Intrusive amphibolite was also found.

SCHISTS [3]

Schists are the most abundant rock types in the thin sections from the drill cores and are also by far the most abundant rocks in the natural and artificial exposures of the Rio das Velhas series. In the drill cores, the following kinds of schist were found: muscovite-quartz schist; biotite schist with abundant quartz, with carbonate and quartz, with quartz and epidote or muscovite and epidote; chlorite schist with much muscovite, with quartz and epidote, and with quartz and feldspar; and hornblende schists, some with much quartz.

The muscovite-quartz schist and the biotite schists are generally fine to medium grained and are well foliated. The micas are typically concentrated in layers between 0.1 and 1.0 mm thick, alternating with quartz layers of equal thickness intergrown with some feldspar and epidote to form a more or less equigranular granoblastic fabric. Decussate texture is developed in some biotite-rich layers but is not common. Porphyroblasts of carbonate that have grown across other grains are common and in places they are astride the boundaries between micaceous and quartzose layers. Some of these carbonate porphyroblasts have sieve structure caused by inclusions of quartz or biotite.

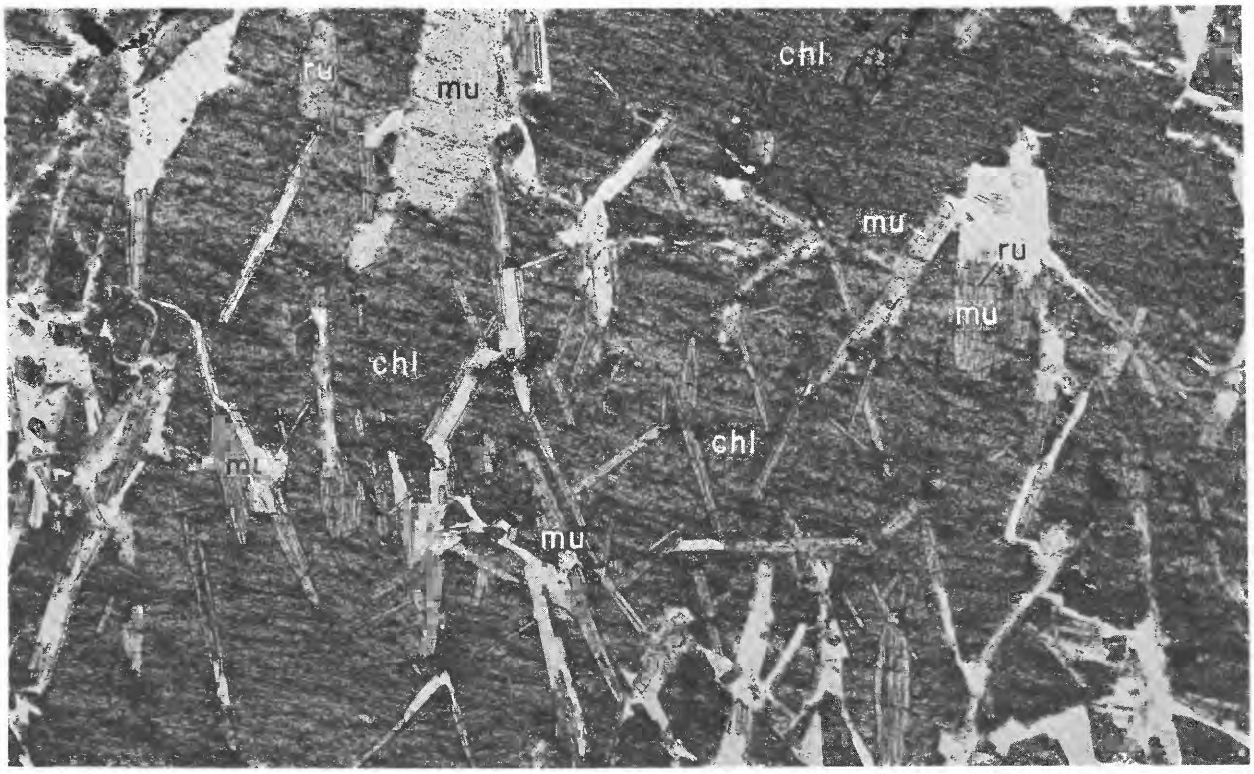
The relative scarcity of feldspar compared to quartz and mica indicates a sedimentary origin for these schists. However, several features in one thin section of muscovite-quartz schist suggest the action of later fluids and the probability of modification of the original rock by metasomatism. In this thin section both fine and medium-grained muscovite occur in separate areas. The medium-grained muscovite is oriented across the schistosity, and near the boundary of the two areas the coarser muscovite has grown into the finer. Relicts of the finely foliated quartz-muscovite can be seen in the coarser grained zone. The coarser grained layer contains most of the small quantities of tourmaline and rutile(?) found in the slide. Porphyroblasts of feldspar with ragged edges that are crossed by lines and thin layers of quartz and muscovite continuous with similar layers in the schistose groundmass are scattered throughout the fine-grained zone.

In contrast to the layered mica schists described, the chlorite in the chlorite schists appears to be relatively evenly distributed throughout that rock. Quartz, feldspar, muscovite, or epidote may also be relatively abundant in these rocks, with minor quantities of carbonate, garnet, pyrite, or magnetite present in some of the chlorite schists.

The chlorite schists were probably derived from fine-grained to glassy mafic volcanic rocks or, where relatively rich in quartz, from clastic sedimentary rocks derived in part from basic igneous rocks. Their present mineralogical composition is caused by regional metamorphism.

Alkali metasomatism is suggested by features in several thin sections of the chlorite schist. Thus, where muscovite or feldspar are abundant, they appear to be later than the surrounding minerals. In one section (fig. 3) containing 76 percent chlorite, the strong schistosity is cut by muscovite blades that form 22 percent of the material in the section and are as much as 1.0 mm long. Lines of fine rutile(?) extend across the muscovite parallel to the traces of schistosity. The muscovite is not only later than the schistosity, but must have received potash from outside the rock inasmuch as there is no evident source of potash within the rock. In another thin section of chlorite schist (fig. 4), irregular plagioclase (An_{16-38}) grows across the strong schistosity with saw-toothed projections of feldspar projecting out along the schis-

[3] Petrographic description and interpretation of the thin sections are closely paraphrased after the report submitted by J. E. Gair, with omission of detail. "Fine grained" means grains less than 0.1 mm in average diameter. "Coarse grained" means grains larger than 2.0 mm. "Medium grained" falls between the two. Stated percentages of minerals are volume percentages measured with a point counter.



3.—Photomicrograph of chlorite-muscovite schist. Chlorite (chl), muscovite (mu), rutile (ru). Shows chlorite groundmass with very minor quartz. Muscovite grows across foliation. Rutile crystals continue across muscovite parallel to foliation. Magnification × 25; plane light.

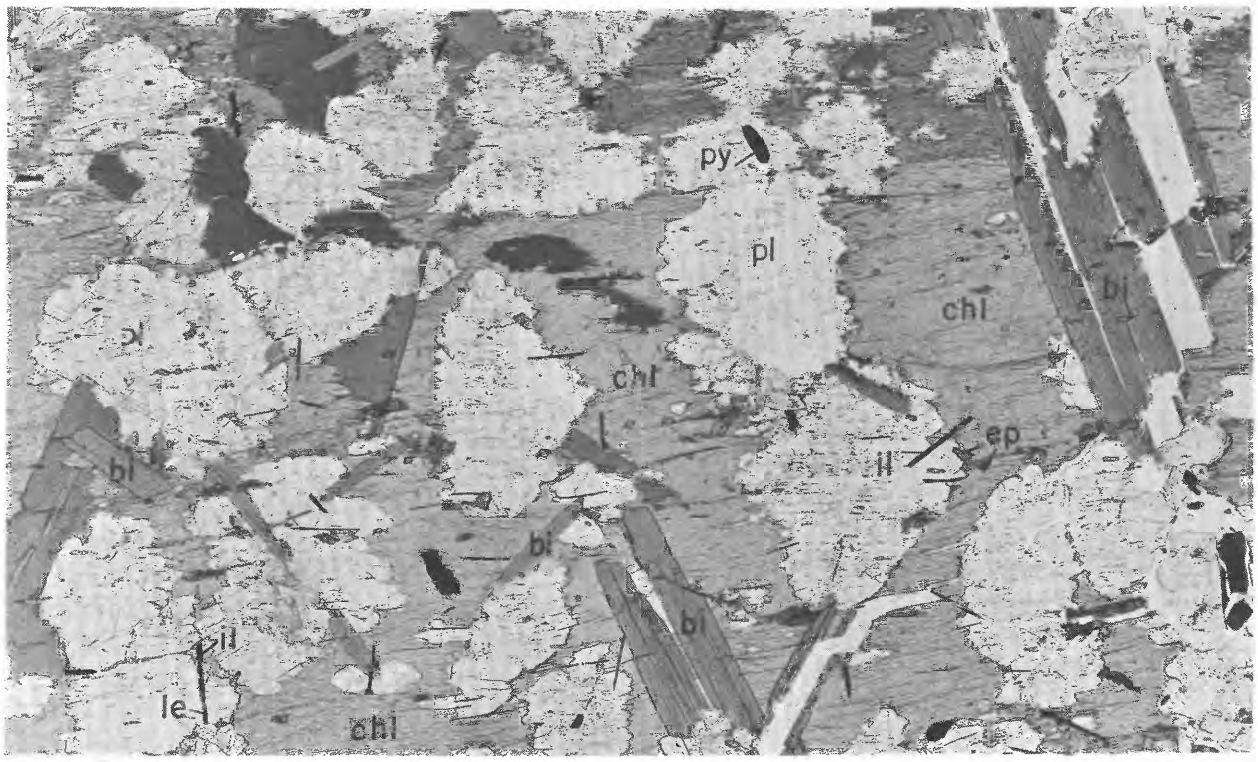


FIGURE 4.—Photomicrograph of chlorite-feldspar schist. Chlorite (chl), plagioclase (An_{16-38}) (pl), biotite (bi), epidote (ep), ilmenite (il), leucoxene (le), pyrite (py). Groundmass is pure chlorite schist. Feldspars strongly zoned under crossed nicols, grow into groundmass. Biotite plates grow across other minerals. Elsewhere in section, minor ilmenite is rimmed by leucoxene. Magnification × 20; plane light.

tosity planes and with lines of inclusions across the feldspar parallel to the schistosity regardless of the crystal orientation. It seems clear that the feldspar grew in the solid rock, replacing chlorite. This thin section also contains porphyroblasts of red-brown biotite that have grown across foliation in the groundmass and locally across the plagioclase porphyroblasts. The groundmass of this rock consists almost entirely of chlorite and thin layers of quartz, with minor epidote, carbonate, and opaque minerals. At least most of the alkalis of the biotite and plagioclase must have been introduced into the rock.

These and similar specific features in the chlorite schists are considered to be strong evidence for metasomatic alteration of the rocks.

A chlorite schist thought to be somewhat different in origin from those previously described was found in one part of the drill core. This rock is a fine-grained chlorite schist containing as much as 25 percent of medium-grained, rounded, and deeply embayed oligoclase feldspar, with small amounts of quartz, clinozoisite, epidote, carbonate, rutile, and opaque mineral (fig. 5). The mineralogy is suggestive of a mafic or intermediate igneous rock, whereas the size discrepancy between the feldspars and the groundmass minerals and the embayed form of the feldspars suggest that the original rock may have been a partly crystalline tuff.

QUARTZITE AND META-ARKOSE(?)

These rocks are moderately to weakly schistose. Although in thin section there is little separation of the platy minerals into lenses or layers, in the rocks themselves some separation of mica into thin seams separated by layers 0.5–4.0 cm thick of quartz-feldspar may be observed. These rock types are made up, in the thin sections examined, of quartz, 30–70 percent; oligoclase or andesine, 15–45 percent; muscovite or chlorite, traces to 25 percent; and small amounts of biotite, clinozoisite, epidote, leucoxene(?), and magnetite(?). One specimen contained 18 percent carbonate, another about 1 percent tourmaline which transgressed boundaries of the quartz grains and of ragged-edge porphyroblasts of feldspar containing inclusions of quartz.

The quartzitic rocks contain less than 25 percent feldspar. The feldspar is medium grained and generally larger than the surrounding quartz; it may or may not be elongate parallel to schistosity but commonly has borders anastamosing around quartz grains. Some feldspars contain abundant inclusions of quartz. In the quartzitic rocks, most of the feldspar is con-

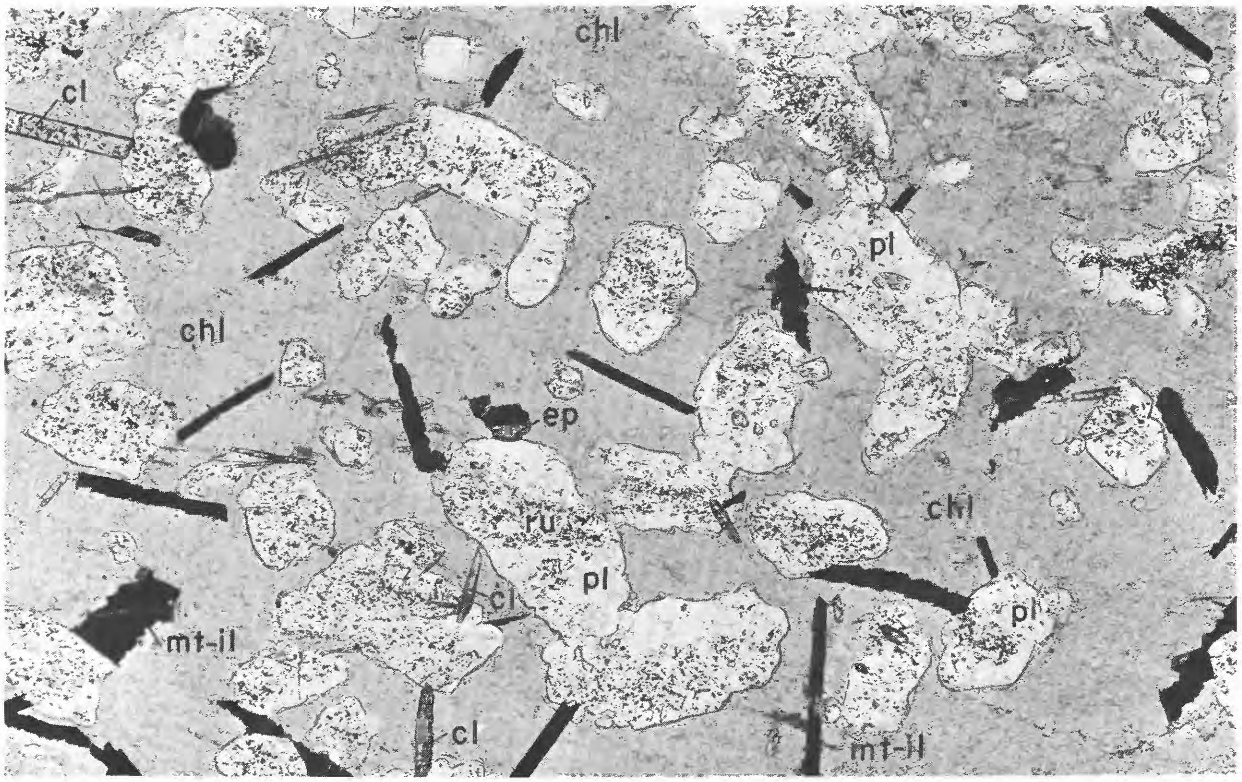


FIGURE 5.—Photomicrograph of mafic metatuff. Chlorite (chl), plagioclase (pl), epidote (ep), magnetite-ilmenite (mt-il), clinozoisite (cl), rutile (ru). Groundmass is chlorite, originally a glass. Plagioclase is between andesine and oligoclase. Magnification × 20; plane light.

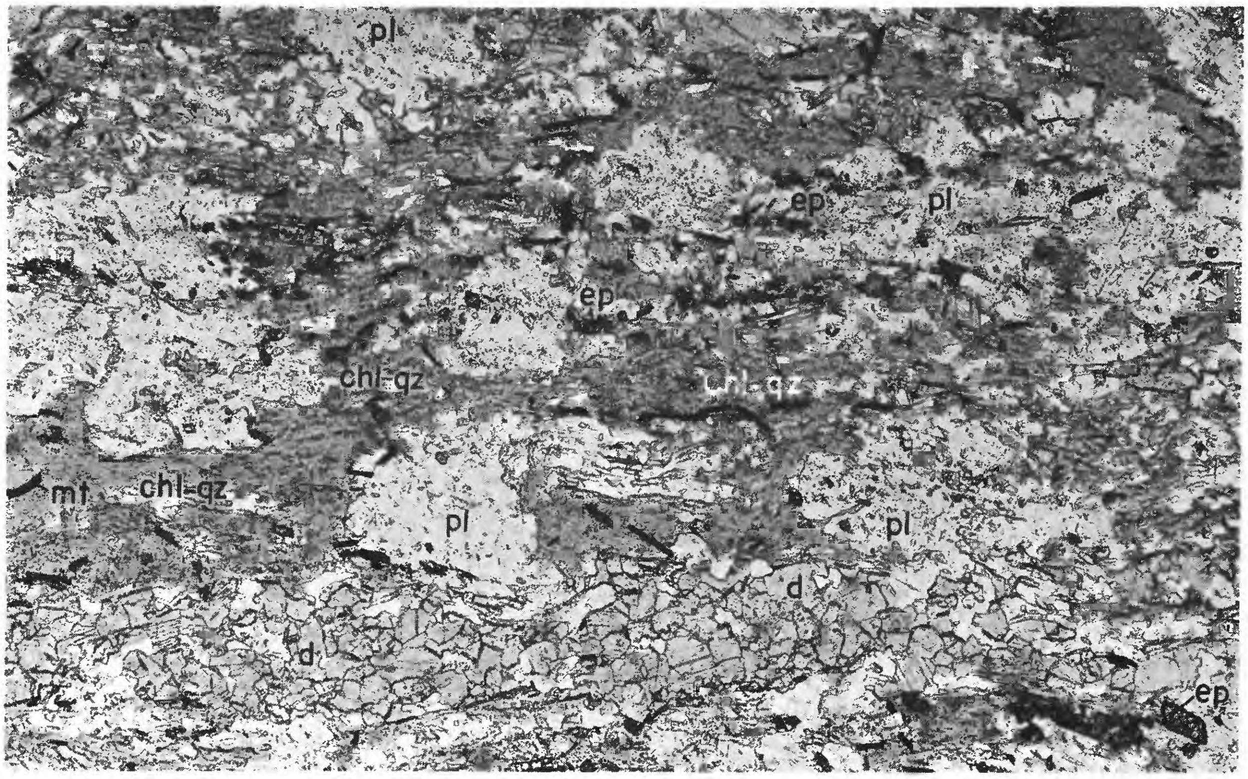


FIGURE 6.—Photomicrograph of dolomitic chlorite schist. Plagioclase (An_{25}) (pl), chlorite-quartz (chl-qz), epidote (ep), dolomite (d), magnetite (mt). Feldspar porphyroblasts, groundmass of quartz and chlorite, carbonate mineral in layers, foliation strong. Probably a metasediment, originally a quartzose dolomitic argillite. Magnification × 15; plane light.

sidered porphyroblastic and to have developed after deposition of the quartzose sediments, possibly by metasomatism during the emplacement of the granitic gneiss.

The meta-arkose(?) contains 35–45 percent of medium-grained feldspar, surrounded by medium- to fine-grained quartz. The feldspar typically is angular, appears to be fragmental, and has no preferred orientation. This rock could be igneous or sedimentary from a compositional viewpoint; the texture suggests a clastic origin.

DOLOMITIC SCHIST

Two thin sections from core taken at widely separated intervals in one of the drill holes are of dolomitic rock of some genetic interest. Both contain 45–55 percent carbonate, 20–25 percent plagioclase (An_{35-40}), 5 percent quartz in one specimen, 23 percent in the other, 5–10 percent chlorite, and less than 5 percent each of clinozoisite, epidote, muscovite, and biotite (fig. 6).

The dolomite and quartz are intergrown in medium-grained mosaics, with no evident shearing surfaces between the equant grains. Layers of mixed quartz and dolomite about 0.5 to 1.5 mm in thickness alternate with thinner zones that contain chlorite, muscovite, or plagioclase. The plagioclase is much elongated nearly at right angles to the albite twinning. In some of these thinner zones the entire thickness of 0.1–0.3 mm is represented by the width of single plagioclase crystals elongated end to end along the zone.

The large elongated plagioclase crystals are completely at variance with the fine-grained mosaic of the dolomite and quartz and with the fine chlorite and muscovite, and could hardly represent primary compositional layering as the other minerals probably do. Since the marginal parts of the feldspars in places anastomose around adjacent dolomite or quartz crystals, it seems probable that the material for the feldspars may have been introduced and the mineral formed by metasomatic action.

OTHER ROCKS

Systematic lithologic description of parts of the Rio das Velhas series, not cut by drill cores, is not possible because the deep weathering precludes petrographic investigation except by methods too laborious to be practical in work of this scope. Similarly, the generally poor exposures preclude close descriptions of the distribution of the various rock types. However, several features of these rocks as exposed in the Itabira district are worthy of description.

The most typical outcropping rock is a weathered red and purple quartz-mica schist with alternating bands of fine saccaroidal quartz and micaceous minerals. Any feldspar which may have been originally present is altered to clay on the outcrop, and it is impossible to know how much of this mineral may have originally been present. The micas are either altered biotite or muscovite, now stained red by iron-stained clay or iron oxide which has worked into the cleavage planes of the crystals. In some areas the muscovite occurs in relatively coarse plates, up to 5.0 mm across, which are twisted and stained, and have ragged edges.

Rocks thought to have been chlorite schist and quartz-chlorite schist are believed to be the next most abundant in the area. On the outcrop these rocks have a deeper purplish cast and are generally more finely foliated than those described in the preceding paragraph.

Along the main access road to Cauê Peak (hereafter called the Six-percent Road, in accordance with local usage), excellent outcrops of weathered schists reveal that tourmaline is a common accessory mineral at many horizons, particularly in red and purple chlorite schists (metavolcanics?). The tourmaline is usually oriented along foliation planes, generally with the long axis alined parallel to the regional linear structure. In some cases the crystals have been broken and healed with an obtuse angle at the point of healing. Few are longer than 2 mm. Prismatic garnets as much as 1.5 cm in longest dimension, the long axis normal to, and the crystals cutting, the schistosity, are found at one locality near the CVRD triangulation station of Americanos. Similar garnets have been found in other parts of the Quadrilátero Ferrífero in the Rio das Velhas series.

The iron-formation which characterizes the Nova Lima group of the Rio das Velhas series in parts of the Rio das Velhas valley, in the Congonhas region, and southwest of Santa Barbara is also found in the Itabira district. Two outcrops along the road to the "*C*" ore body on Conceição Peak show that the iron-formation here is perhaps 20 meters thick, and is dominantly composed of quartz and hydrated iron oxide. The iron content was estimated at 20–25 percent. It grades upward through several meters of slightly ferruginous fine quartzite, which may originally have been chert or jasper, into 2 meters of slightly manganiferous cherty rock from which the originally high dolomite content has been leached. The iron-formation is underlain by several meters of nonmanganiferous leached dolomitic rock, underlain in turn by impure quartzite and by the characteristic chlorite schist with garnet metacrysts. All the rocks are highly contorted and crenulated. Farther to the northeast along the strike, the iron-formation becomes very clayey and grades into a highly ferruginous schist. Locally this schist weathers to low-grade aluminous canga. This abrupt change in facies is characteristic of the iron-rich zones of the Rio das Velhas series. It is not known whether this iron-formation was carbonate-facies or oxide-facies because fresh specimens could not be secured for petrographic study. The weathering product is similar to that of the carbonate-facies iron-formation of the Rio das Velhas valley.

Included in the Rio das Velhas series are several zones of talc schist, locally garnetiferous. These may be genetically related to the ultramafic suite described in later pages, representing metamorphosed sills, but no evidence to prove this could be found, and it was not practical to separate them during the mapping.

Thus the Rio das Velhas series in the Itabira district seems to have been originally composed of mixed, poorly sorted argillaceous and arenaceous sediments, possibly dominantly siltstones, with beds and zones in which the chemical sediments chert, jasper, iron-formation, and dolomite were deposited. The sediments were probably contaminated by pyroclastic rocks and sedimentation was interrupted by mafic flows.

Along the contact between the Rio das Velhas series and the Minas series just north of Conceição Peak, the Rio das Velhas beds strike toward Minas beds at an angle of 90° to the younger rocks within about 30 meters of the probable location of the contact, which is hidden. The exposure is about 20 meters in maximum dimension. This apparent strong angular unconformity may actually be distortion caused by slump of the deeply weathered and plastic older rocks under the weight of the topographically higher and much heavier iron-formation. Three hundred meters east of this exposure, the rocks are roughly concordant, but still farther east there is again strong discordance.

Generally speaking, bedding in the schist has been destroyed by metamorphism to such an extent that it is impossible to demonstrate with confidence either angular or concordant relations. The fact that metamorphism in the immediately overlying Minas series has not progressed to the extent that such sedimentary structures have been obliterated is itself probably the best proof in this district of the time gap between the two series of rocks. Elsewhere in the Quadrilátero Ferrífero, the angular unconformity between these rocks is obvious.

THICKNESS AND CONTACTS

The stratigraphic thickness of the Rio das Velhas series in the Itabira district is not known. The maximum outcrop width, somewhat more than 1,000 meters, is found to the southwest of Conceição Peak. Poor exposures, complex structure, and the indefinite lower contact prevented calculation of the true thickness. In the Rio das Velhas valley, the Rio das Velhas series is at least 6 kilometers thick.

The lower contact of the Rio das Velhas series in the Itabira district is with the intrusive or highly metamorphic granitic gneiss and will be described in detail in the discussion of that formation (p. C41). It is sufficient to state here that the contact is to some extent gradational and that a zone of mixed rock is found in the contact zone.

The upper contact of the Rio das Velhas series is with the Minas series and is unconformable. In the Itabira district, the contact is exposed only in artificial openings through distances of a few meters. An angular unconformity is indicated by the apparent angular relations between bedding in the Minas series and what is believed to be bedding in the Rio das Velhas series near the contact in the valley called Abóboras (pl. 1). Similarly, the trace of the iron formation within the Rio das Velhas series southeast of Conceição Peak is taken to indicate slight angularity between bedding in the overlying Minas series and that in the older rocks. A basal conglomerate is known to exist in the Minas series which contains angular fragments of rock derived from the Rio das Velhas series, indicating at least an erosional unconformity.

MINAS SERIES

The Minas series contains all the ores of economic interest in the Itabira district and therefore has been exposed by mine workings and other excavations to a greater extent than any of the other rocks. A thick mantle of regolith, talus, canga, and in many places vegetation covers all the rocks other than the iron formation and iron ore, and the rocks are so deeply weathered that material suitable for petrographic study could be collected only from the more resistant iron-rich rocks.

The Minas series is the second oldest of the sedimentary series in the Itabira district and is commonly assigned in Brazilian literature to middle or late Proterozoic time. The series was recently divided (Dorr and others, 1957) into three groups, the Caraça, the Itabira, and the Piracicaba. Within the Itabira district, as within the Quadrilátero Ferrífero as a whole, the rocks comprising these groups have a certain genetic unity in that the lower is composed dominantly of clastic rocks, the middle of chemical or biochemical sediments, and the upper of clastic rocks. Elsewhere in the Quadrilátero Ferrífero, each group has been subdivided into two or more formations (Soc. Bras. Geol. Bol., 1958), but within the Itabira district, poor exposures make it impossible to map most of the individual rock types characteristic of the formations that have been described elsewhere in the region.

It should be emphasized that, with few exceptions, the rock types that have been mapped elsewhere as formations are present in the Itabira district. The heavy soil and canga cover make it impossible to trace them in detail without much subsurface exploration.

CARAÇA GROUP

LITHOLOGY

The Caraça group is composed of conglomerate, quartzite, metachert, phyllite and quartzose phyllite, and schists of low metamorphic grade. Although the exposures that can now be found in the field indicate a dominantly phyllitic composition for most of the stratigraphic section, old maps of several hundred meters of tunnels in Conceição Peak that cut these rocks indicate a dominantly quartzose composition. Most of these workings are now collapsed and cannot be reexamined.

The phyllite ranges from a rather silvery colored rock composed dominantly of sericite, through a light-greenish phyllite and red-stained quartzose phyllite to sericitic quartzite, commonly red on the weathered surface. The silvery fissile phyllite locally contains holes indicating that a long (10 mm) acicular mineral was once contained in it, oriented parallel to the planes of foliation but not strictly parallel to the regional linear structure. Actinolite crystals of size and shape similar to the holes have been seen in specimens of similar phyllite from the Ouro Preto district. Some slightly quartzose phyllite or schist of low metamorphic grade near the top of the group exposed in Cauê Peak is brownish to grayish and has a splintery fracture parallel to the regional linear structure. This fracture is entirely different from the planar fracture of the ordinary phyllite of the district and is probably the result of local deformation. The same type of material is also exposed in the same stratigraphic position near the Dois Córregos ore body.

In several localities phyllites containing appreciable percentages of clear light-green and blue-green tourmaline in needles up to several millimeters in length have been found near the top of the group. It seems probable that these are the result of metasomatic alteration. The crystals are commonly oriented parallel or subparallel to the regional lineation.

The quartzites are generally impure and grade through sericitic quartzite into the phyllites. They are normally fine grained, in contrast to much of the material from the corresponding stratigraphic interval farther west in the Quadrilátero Ferrífero. In the new adit in Conceição Peak (pl. 2), a fine white saccaroidal quartzite, apparently pure, is interpreted as having been derived from original chert. Such rock has been seen from this stratigraphic interval (corresponding to the Batatal formation) in six other localities in the Quadrilátero Ferrífero.

The basal conglomerate, which crops out only near 49,335 N, 47,650 E, (pl. 2) is at the contact between the Rio das Velhas series and the Caraça group. Schist float derived just below the outcrop indicates that the older rocks must occur not more than 3 meters and probably within 1 meter stratigraphically below the outcrop.

The conglomerate is composed of rounded pebbles of quartzite and vein quartz in a matrix of very clayey coarse quartzite containing smeared out sheets of phyllitic material which probably represent original phyllite pebbles and fragments. The material is most similar to the basal conglomerates exposed in the Serra da Moeda (120 km to the southwest) at the same horizon. The quartz pebbles are generally elongate (about 2×), oriented parallel to regional linear structure, and may average 3 cm in longest dimension with a maximum size of 6 cm. Thin sections show that the quartzite and vein quartz pebbles have been shattered and recrystallized.

This basal conglomerate was found at no other locality in the district. It is doubtful whether it occurs generally through the district, as some of the artificial exposures should have revealed it elsewhere or at least float should have been found. The authors assume that it is discontinuous and lenticular.

Judging from the lithology of the Caraça group, the original sediments seem to have been argillaceous and sandy, probably shales and impure sandstones with shale interbeds. As pointed out by Harder and Chamberlin (1915, p. 397), the basal quartzite of the Minas series farther to the west is a transgressive formation deposited by an advancing sea. It seems probable that in the Itabira area, the coarser sediments were swept along by the advancing sea with the only known coarse rocks, the local basal conglomerate, trapped in a local depression or channel on the old erosion surface. The other rocks of the Caraça group would thus represent finer sediments laid down offshore.

DISTRIBUTION, THICKNESS, AND CONTACTS

The distribution and thickness of the Caraça group in the Itabira district is apparently rather erratic. It is not known whether this is due to deposition of the sediments on an uneven erosion surface or whether these rocks have been so squeezed during the very tight folding that they thicken or thin abruptly for tectonic reasons. Exposures are at their worst on the axes of the major folds, precisely the critical areas to resolve the question.

The greatest apparent thickness, over 150 meters, is just to the south of Conceição Peak. The Caraça group is quite thin, in the order of 5–25 meters, where seen along the north side of the Conceição syncline. It is here composed largely of gray phyllite, locally graphitic. Near 45,728 N, 44,772 E, it is apparently as much as 100 meters thick, but again thins rapidly to the northwest and can be not more than a few meters at Córrego da Conceição.

On the flanks of the Piriquito anticline the Caraça group is apparently absent but reappears again at least 50 meters thick near the axis of the Dois Córregos syncline. There is no evidence as to the presence or absence of the Caraça group northeast from this syncline for 4.5 kilometers. At the outcrop of the basal conglomerate near the Chacrinha anticline, the group must be about 150 meters thick. However, it can only be a few meters thick on the axis of that anticline. On the south flank of the Cauê syncline the Caraça group evidently thickens toward the axis but never becomes more than a few tens of meters, at most 100 meters, thick. Northwest of the axis of the Cauê syncline there is very little evidence as to thickness or even the presence of the Caraça group.

The contacts of the Caraça group with the Rio das Velhas series have been described.

Locally the Caraça group is in contact with the granitic gneiss; these contacts will be described in the discussion of the granitic gneiss.

The contact of the Caraça group with the overlying Itabira group is exposed in a number of mine workings and roadcuts. In most cases the contact is between itabirite and soft weathered gray or brown phyllite, in some cases tourmaline-bearing. Elsewhere the contact is with quartzose phyllite or black or gray phyllite, locally ferruginous. The contact is invariably sharp and completely concordant. Where exposures permit, it can be located within a few centimeters. No sign of local erosion has been found at the contact.

ITABIRA GROUP—CAUÊ ITABIRITE

In this section the Itabira group will be considered as a lithologic unit; discussion of the ore and potential ore bodies which one of the units contains will be reserved for later pages.

The Itabira group (Dorr and others, 1957, p. 26) composed largely of iron-formation in the lower part and of dolomite in the upper, with an intergradational and interfingering contact, is partially the equivalent of Harder and Chamberlin's Itabira formation (Harder and Chamberlin, 1915, p. 358). That formation, and therefore the group, was named for the town of Itabira do Campo, now Itabirito, in the Rio das Velhas valley.

The Itabira group has been subdivided into two formations, the Cauê (Dorr, 1958, p. 61) and the Gandarela formation (Dorr, 1958, p. 63).

The part of the Itabira group dominantly composed of siliceous itabirite is herein named the Cauê. This formation is named for Cauê Peak, world famous for its riches of high-grade iron ore, the mining of which is now contributing to the building of Brazil's industrial strength. On Cauê Peak, the formation is well exposed by long adits, by working faces in the iron mines, by old gold workings, and by natural outcrops. Here the formation is almost entirely composed of siliceous itabirite or of high-grade hematite derived from the itabirite. As elsewhere in the Quadrilátero Ferrífero, it is impossible to be sure of the true stratigraphic thickness of the formation, because of tectonic disturbance, but the apparent thickness is about 200 meters.

In extensive areas of the Quadrilátero Ferrífero, the Cauê itabirite is overlain by the Gandarela formation. This latter formation is dominantly dolomite, but contains zones and beds of itabirite and other rocks. The contact between the two formations is interfingering and gradational.

Because both formations are dominantly chemical sediments and because the Cauê may contain dolomite and the Gandarela may contain itabirite, the exact placing of the contact between these formations may be difficult in practice. The contact is placed where the normal siliceous itabirite of the Cauê itabirite becomes subordinate to dolomitic itabirite or dolomite, considering the sedimentary section as a whole. Thus, the Cauê itabirite may contain minor dolomite beds, as is the case in the Itabira district, and the Gandarela formation may contain siliceous itabirite beds, as it does in the Gandarela quadrangle. In neither case, however, are the atypical beds dominant. Commonly, although not everywhere in the Quadrilátero Ferrífero, the transition from one formation to the other is marked by a variable thickness of dolomitic itabirite.

Because of its economic importance, it is desirable to subdivide the Itabira group whenever possible. However, in some areas exposures may be so poor and the itabirite generally so impure that it is necessary to map the group as a whole. In the Itabira district, the Gandarela formation is present only locally and is too thin to be mapped separately.

In the Itabira district, the Itabira group is conformably overlain by the quartzitic rocks of the Piracicaba group.

LITHOLOGY

In the Itabira district, the Cauê itabirite is composed almost entirely of the rock known as itabirite and of the ores derived therefrom. The word itabirite has been in use in Brazil for many years, has achieved some currency in the European and Russian literature, and has been used to some extent in American literature since 1914. In view of the recent work by James (1954) on sedimentary facies of iron-formation, which seems to the writers to be destined to become one of the keystones of iron literature, it might be well to redefine the term in the light of James' work. The term, if used with care, can be very useful to geology because the rock appears in many parts of the world under a confusing array of names.

The term itabirite denotes a laminated, metamorphosed, oxide-facies formation, in which the original chert or jasper bands have been recrystallized into granular quartz and in which the iron is present as hematite, magnetite, or martite. The quartz bands contain varied but generally minor quantities of iron oxide, the iron-oxide bands may contain varied but generally minor quantities of quartz. The term should not include quartzite of clastic origin with iron-oxide cement even though such rocks are sometimes grossly banded. It should include only rocks in which the quartz is megascopically recognizable as crystalline, in order to differentiate it from unmetamorphosed oxide-facies iron-formation. A certain amount of impurity in the form of dolomite or calcite, clay, and the metamorphic minerals derived from these materials may be included, but these may never be dominant constituents over any notable thickness. Where they are, the rock term must be qualified by the use of the appropriate mineral name as a qualifier (for example, dolomitic itabirite, a rock in which the dolomite largely takes the place of the quartz). Rarely itabirite grades into ferruginous chert which, when recrystallized, may look like low-grade itabirite, although commonly it is finer grained and whiter. To prevent confusion, a cutoff point of about 25 percent iron should be established. This figure is a practical one, as few itabirites are so lean in iron and most ferruginous cherts do not contain so much iron. Itabirite may grade into pure hematite through enrichment in iron or removal of quartz: the cutoff point might well be set at 66 percent iron because at and above this grade quartz is rarely concentrated in regular laminae.

Some definitions of itabirite [4] have included the masses of pure hematite ore without silica because it was considered that the pure hematite ore in the itabirite was an original sedimentary rock. Von Freyberg believed that it would be "unscientific" to make the practical distinction of separating the two rocks as proposed by Harder and Chamberlin. However, the shape of the curves representing the chemical analyses of various size fractions of soft hematite (fig. 7) ore and of itabirite (fig. 8) illustrate characteristic differences between soft ore and rich itabirite of practically the same chemical composition. This difference reflects a difference in origin. Because high grade hematite ore in oxide-facies iron-formation is generally a replacement or enrichment product rather than an original sediment, the practical separation of itabirite from pure hematite ore can be recognized as scientifically as well as practically valid.

High-grade regional metamorphism reconstitutes oxide-facies iron-formation into a coarse-grained quartz-magnetite and quartz-specularite rock with a gneissic texture. Itabirite of this type crops out some tens of kilometers northeast of the Itabira district.

The itabirite exposed by the adits and by artificial and natural exposures in the area is generally weathered and soft, but on Conceição Peak and in Grota de Esmeril fresh hard itabirite, from which thin sections can be cut, crops out. The more westerly adits on Conceição cut itabirite which, although not entirely unweathered, is quite hard.

The rock that composes the bulk of the Cauê itabirite in the Itabira district is composed of laminated specular hematite and granular quartz. The only megascopically visible impurity other than iron hydroxides is flaky tan and green talc, which is in great part concentrated on the contacts between the dominantly quartzose and dominantly ferruginous layers. The laminae or compositional layers in itabirite in the Itabira district range in thickness from about 0.1 centimeters to about 1 centimeter, the average thickness being perhaps 0.3–0.5 cm. A finer lamination, down to 0.1 mm, is visible in thin sections.

Laminae in the itabirite are composed of granular quartz with a varied percentage of hematite, generally low, and of hematite with a varied percentage of granular quartz, generally lower than the percentage of hematite in the quartz laminae.

Twenty-three thin sections of itabirite were examined by Gair, all of which were of specimens of the hard itabirite cropping out in Conceição Peak and in the Grota de Esmeril. Certain specimens were of material on the borderline between high grade hematite ore (+66 percent Fe) and itabirite.

In the Itabira district the specularite grains are commonly oriented parallel to the bedding and foliation. Individual specularite grains range from 0.01 to 0.1 mm in average diameter and are generally aggregated into clusters. The quartz, on the other hand, is in angular grains which form a granoblastic equigranular fabric with the grain size ranging from 0.04 to 0.4 mm.

Petrographic examination shows that the dominant iron mineral is hematite, with magnetite predominating in only one specimen. Magnetite is present as fine euhedral grains, in most cases in minor amounts. Some layers of iron oxide were devoid of quartz even on a microscopic scale, but most contain small quantities in ragged and extremely irregular grains. The iron oxide clearly transgresses contacts between adjoining quartz grains and the quartz within the iron-rich layers has the aspect of relicts eaten into and overgrown when the iron mineral crystallized or recrystallized.

Contacts between the iron-rich and quartz-rich layers are gradational on a microscopic scale with isolated grains of iron oxide on the quartzose side of the contact. Most of the quartz-rich layers contain only a few percent of iron oxide in small scattered grains. However, the central parts of most of the quartz grains contain very fine unidentified dusty inclusions which may well be particles of an iron oxide.

Thin section studies by Gair revealed the presence in a few of the sections of small quantities of a pale-green chloritic mineral and of a brownish micaceous mineral, possibly biotite or stilpnomelane.

Petrographic examination of the itabirite revealed no criteria as to clastic versus chemical origin of the rock, as the rock is so completely recrystallized that all original textural features have been destroyed. Replacement of quartz by hematite discussed above is evidence for the mobilization and movement of the iron oxide.

[4] Von Freyberg gives an excellent discussion of the development of the word itabirite. His definition does not agree with that proposed here.

See Freyberg, B. von, Ergebnisse geologischer forschungen in Minas Geraes (Brazilien): Neues Jahrb., Sonderband II, 1932, p. 39–60.

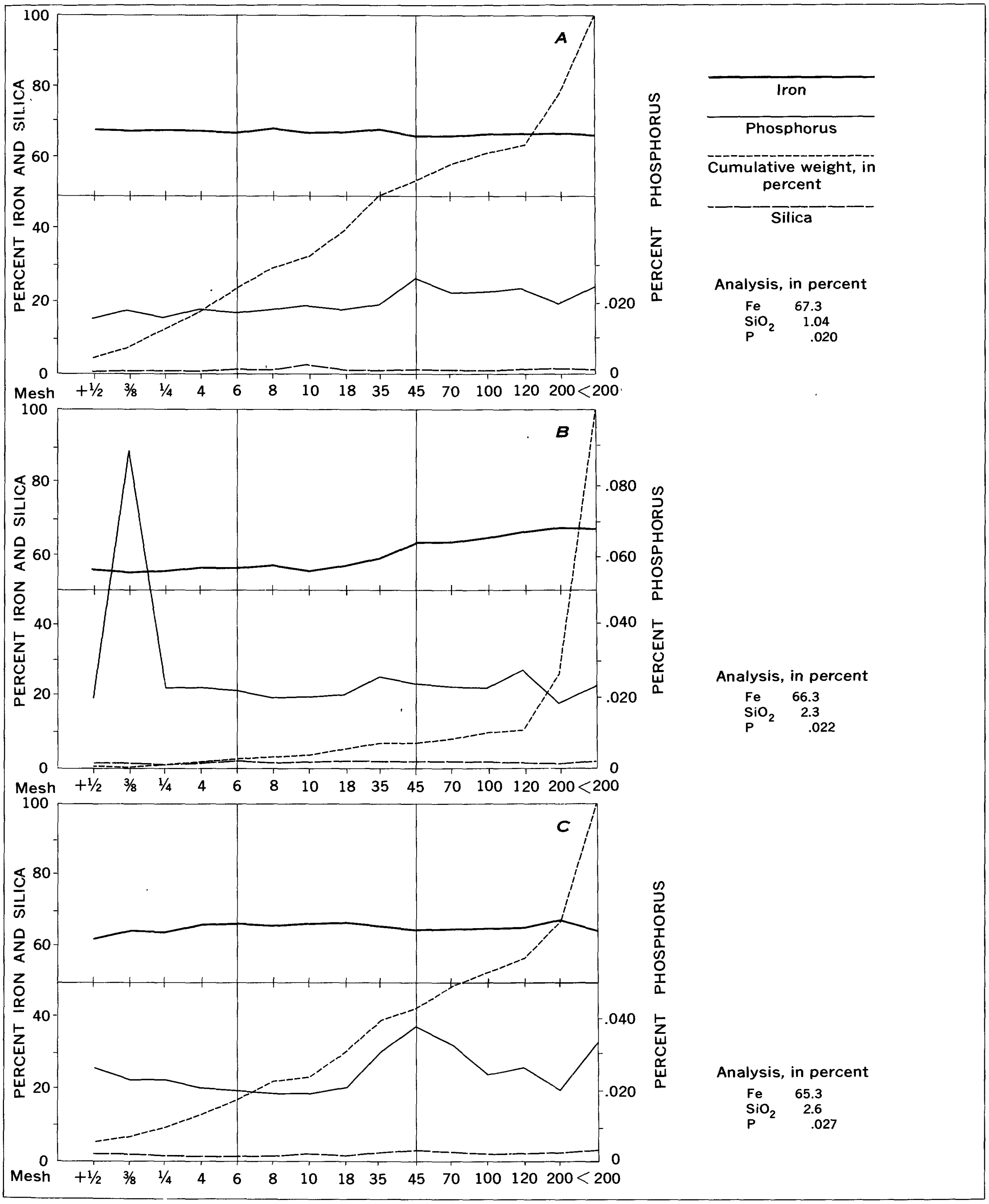


FIGURE 7.—Chemical analyses of soft hematite by screen fractions. (*A*) chip sample, main drift, Mine 7; (*B*) 2.6-meter channel sample, 1340 bench, Cauê; (*C*) chip sample, main drift, Mine 7.

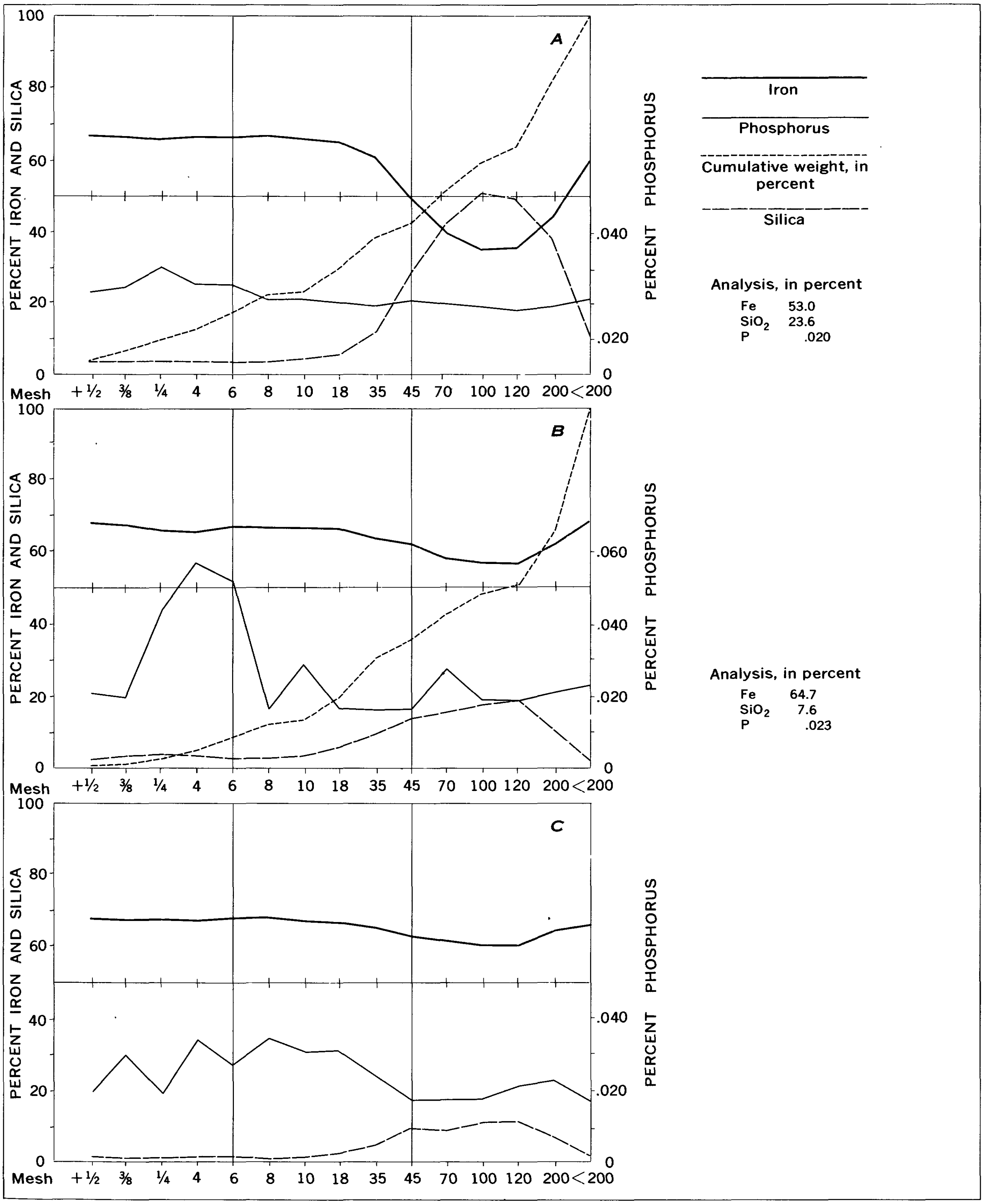


FIGURE 8.—Chemical analyses of itabirite by screen fractions. (*A*) Normal itabirite (an average of 5 samples), Cauê Peak 1,100-meter level; (*B*) rich itabirite, 4-meter channel sample, Cauê Peak; (*C*) rich itabirite, Cauê Peak.

The compact granoblastic fabric of the itabirite shows conclusively that the hard itabirite has not contained, since the present metamorphic rock was formed, significant amounts of soluble minerals such as dolomite or other carbonates.

No dolomite or dolomitic rock crops out or is exposed by adits in the district. However, there are several thin lenses and beds of material of a type which has been shown, elsewhere in the Quadrilátero Ferrífero, to have been derived from the weathering of dolomitic rock. This material is brown or black, finely cellular, is extremely porous on a microscopic scale, and, when saturated with water, squeezes between the fingers into a wet smooth paste which leaves the skin very rough and which is most difficult to remove. The brown variety is largely composed of limonite, the black of mixed manganese and iron oxides. This unusual rock was first described by Derby (1896) and has been described in more detail by Guild (1953, p. 42). In the Cauê itabirite in this district, the brown iron-rich variety predominates. This material has been seen in the new adit on Conceição Peak, in a zone less than a meter thick, and in two zones in the itabirite exposed in the railroad cut in Morro do Cruzeiro (see pl. 1), one of which is about a meter thick, the other several meters thick. All these occurrences are toward the base of the itabirite section. A thin exposure of the black material may be seen in the cut near the main church in Itabira.

The Cauê itabirite also contains several schist layers ranging up to a maximum thickness of about 2 meters which seem to be concordant with the general bedding and are therefore thought to be sills. These layers are lithologically similar to the dikes (now metamorphosed to schists).

Clastic quartzite is interbedded with the itabirite at one locality in mine 6 (pl. 3) and in mine 7 (pl. 4), Cauê Peak. Here a single lenticular bed of rather coarse clean quartzite about 2 meters in maximum thickness and several thinner beds of similar material are exposed in one of the drifts. No other clastic rocks are known in the Cauê itabirite in this district, but clastic interbeds are known in several other parts of the Quadrilátero Ferrífero, where they may attain a thickness of a few tens of meters.

The south limb of the major syncline in and near the town of Itabira contains itabirite which is somewhat different in aspect from the itabirite of the north limb. The regular and consistent lamination which is so common on the north limb and which is typical of the itabirite throughout the region as a whole is there subordinate to linear structure. On the south limb the quartz laminae are in many places rolled into cylindrical pipes of coarsely crystalline quartz. Locally the rock breaks out in loglike forms that reach 2 m in length and 30 cm in diameter.

There is more evidence of dolomite in the south limb. The canga derived from the itabirite on the south limb contains less fragmental ore and more chemically deposited limonitic material than that from the north limb. Some of the canga is very finely cellular with the pores containing loose quartz fragments rounded and etched by solution. It is believed that the original itabirite of the south limb was much the same as that of the north limb, possibly containing more dolomite, but that the effects of the much stronger directional stress evidenced by the locally intense linear structure have masked the original nature of the rocks by intense squeezing.

DISTRIBUTION, THICKNESS, AND CONTACTS

The distribution and apparent variations of thickness of the Cauê itabirite in this district are well documented by plate 2 and by the 66 structure sections of plate 8. The minimum known thickness is about 10 meters, on the south limb of the major syncline in the town of Itabira. The probable maximum is on Conceição Peak, where an incomplete section of the formation is more than 500 meters thick. Neither the minimum nor the maximum thickness represent true stratigraphic thickness because of structural complications. The true stratigraphic thickness may have been about 150 to 200 meters in other parts of the district, although, owing to the uncertain nature of the data, this can be little more than a guess.

The contact of the group with the underlying Caraça group has been described as being conformable.

At several localities, notably near the axis of the Cauê syncline and near the axis of the Conceição syncline, there is an unusually high concentration of magnetite and martite at the contact, which, in conjunction with the concentration of tourmaline in the underlying phyllite, may well indicate the passage of hydrothermal solutions.

The contact between the Itabira group and the overlying Piracicaba group is exposed at eight localities. One of these contacts is apparently gradational with the overlying formation; the others show a rather abrupt transition from itabirite to nonferruginous rocks. Interformational shearing and differential movement can be proved in one locality.

The gradational contact is exposed in the Santa Barbara mine, an old gold mine tunnel now filled with debris washed in from mine workings and dumps on Cauê Peak. Its portal is located at 51,108 N, 49,492 E. The Santa Barbara mine (fig. 9) starts in medium-grained tan quartzite of the Piracicaba group. A

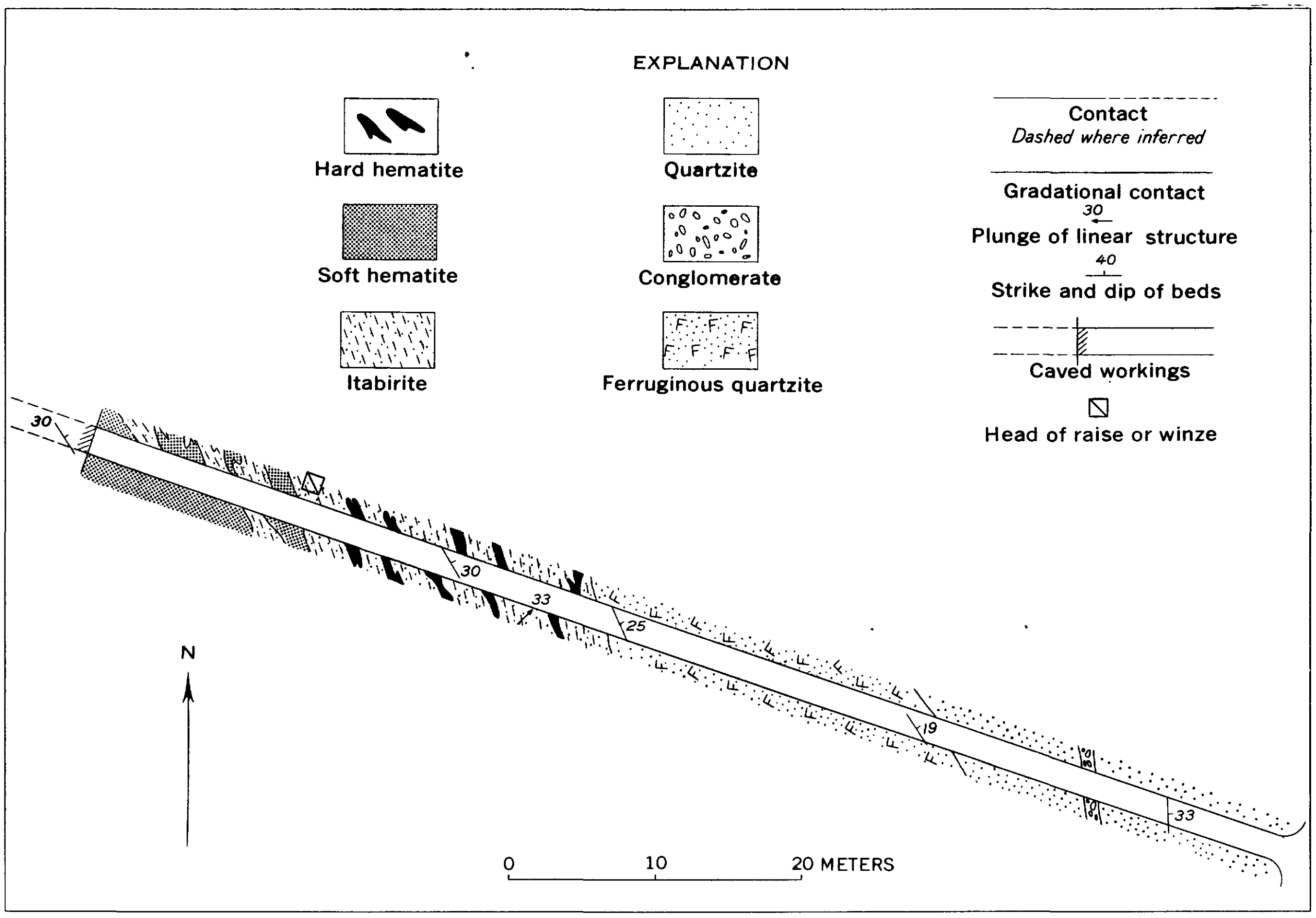


FIGURE 9.—Geologic map of the Santa Barbara mine 51,108 N, 49,492 E, Cauê area. The contact between itabirite and ferruginous quartzite is gradational.

one-meter bed of conglomerate is exposed. Stratigraphically below the quartzite is a ferruginous, nonbanded quartzite that may correspond to the Cercadinho formation (Pomerene, 1958, p. 64) of the western and central part of the Quadrilátero Ferrífero, there considered to be the basal member of the Piracicaba group. Down section, the material gradually becomes more banded and richer in hematite as it grades into lean itabirite. The stratigraphic thickness of the transition zone is about 10 meters.

A nearby exposure along the conveyor belt, however, shows an abrupt transition from high-grade itabirite in the Cauê itabirite to slightly ferruginous quartzite and silvery phyllite of the Piracicaba group. It should be emphasized that these localities are now close to each other because of deformation but originally they may have been as much as a kilometer apart.

Along the road from Campestre to Conceição, poor exposures of the upper contact may be observed. The overlying quartzose phyllite apparently is in abrupt contact with the Cauê itabirite.

In the new adit on Conceição Peak (pl. 5), the itabirite ends rather abruptly against banded, somewhat graphitic, phyllite that appears at first glance to be clayey itabirite but which contains no quartz and little hematite. Eight meters above the itabirite a thin conglomeratic zone of sparse but well-rounded quartz pebbles up to 4 centimeters in longest dimension occurs in quartzite which is in turn overlain by phyllite and quartzite.

In the railroad cut below Morro do Cruzeiro, there appears to be a slight angular discordance between the itabirite and the overlying quartzose mica schist (this area has been contact metamorphosed). It is believed that the discordance is due to slippage along the contact, for the area is one of strong deformation.

ORIGIN OF ITABIRITE

The itabirite of the Quadrilátero Ferrífero of Minas Gerais is merely another example of a type of rock which is very common in the Precambrian shield areas of the world. In different parts of the world similar rock has been given various names, including calico rock, zebra rock, jasper bars, banded hematite quartzite, banded ironstone, oxide-facies iron-formation, and others. The only thing that differentiates itabirite from some (not all) of the foregoing rock types is the degree of metamorphism, which is such in the itabirite that the silica is megascopically crystalline. Composition, structure, and mineralogical nature of all these rocks are essentially similar. Textures, however, vary with degree of metamorphism.

ORIGINAL COMPOSITION

The original composition of the iron-rich sediment merits more discussion because iron-formation entirely similar to these sediments has elsewhere been considered by some writers to be an alteration product of sediments originally sideritic. In the Quadrilátero Ferrífero there is no evidence that the original sediments were ever of essentially different mineralogical composition than they are now. Whether the iron minerals as originally deposited were hematite and magnetite or whether the iron was deposited as the hydroxide and changed to hematite and magnetite during diagenesis cannot be determined.

The unmetamorphosed oxide-facies iron-formation of Morro do Urucum, Mato Grosso, likewise shows no diagnostic evidence (Dorr, 1945) to resolve this question, although it does contain sparse rhombic voids which were probably originally a carbonate. The iron-formation in Singhbhum, India, observed by one of the authors (Dorr) to be typical oxide-facies iron-formation, has been described in detail by Spencer and Percival (1952). They too found no definite evidence as to the original sedimentary mineral but they consider it to be "little altered from its original condition." Because these and other relatively unmetamorphosed oxide-facies iron-formations apparently never had a high percentage of siderite and because there is no local evidence for the presence of siderite, there is no reason to postulate carbonate-facies iron-formation as the original type in Minas Gerais.

The basic work of Krumbein and Garrels (1952), of James (1954), and most recently of Huber (1955) have shown that hematite and magnetite both have specific stability fields dependent upon pH and Eh conditions within the sedimentary environment. It is entirely probable, considering the generally low percentage of magnetite in the Cauê itabirite, that the original sediment was either hematite or ferric hydroxide and that the expected lower Eh of the diagenetic environment reduced a part of the ferric iron to magnetite during diagenesis. In a dynamic equilibrium such as that under which chemical sediments are deposited, conditions would change locally and periodically. Stratigraphic zones in which magnetite is more abundant or less abundant would be expected and can now be found. Zones representing extreme conditions are rather thin.

The quartz in the itabirite has been considered by some authors (Harder and Chamberlin, 1915, p. 359; Freyberg, 1932, p. 39–60) to be clastic sediment. Tyler (1948) has presented evidence showing that the itabirite does not contain the heavy minerals to be expected in a clastic sediment and concluded that it was a chemical sediment. Heavy-mineral determination during the present program has produced the same results. Furthermore, the writers have observed in the Congonhas district crystalline quartz in dolomite in the same relations to the enclosing rock that chert nodules commonly have to dolomite in cherty dolomite. The quartz grains in such nodules are identical, except for the lack of iron dust in the individual crystals, with the quartz of the itabirite. In itabirite, no rounded quartz grains have been seen, nor have sedimentary structures which might be expected in clastic rocks, such as crossbedding, been observed. It is therefore concluded that the quartz now present in the itabirite was deposited as chert slightly contaminated by iron. The silica assumed its present crystalline form as a result of metamorphism.

SEDIMENTARY ENVIRONMENT

Krumbein and Garrels (1952) and James (1954) have discussed the probable sedimentary environment of iron-formation in the light of known Eh and pH requirements for the deposition of such sediments. James concluded that oxide facies iron-formation was deposited in the shallower parts of a barred basin (op. cit., p. 279–280). Iron and silica are thought to have been introduced by large volumes of fresh water from rivers, probably transported as colloids. In the outer parts of the barred basin, where the deeper water was less well aerated and the Eh was lower, carbonate- and sulfide-facies iron-formation were deposited. This conception is based upon the condition in the Lake Superior region, where four facies (the three facies mentioned above plus the silicate facies) are found and must be explained.

In the Cauê itabirite, as in many other of the great iron-formations in the world, no other facies than the oxide has yet been found. Therefore the generalized explanation advanced above to explain the existence of two or more facies in a single large area is more complex than needed here. A well aerated, brackish-water environment with no large-scale source of detrital sediments would satisfy the Eh and pH requirements of the environment without appealing to special conditions such as barred basins and island arcs, as suggested by James and, for Brazil, by Guild (1953, p. 655). In the case of Brazil, there is no evidence for the presence of an island arc which might have formed a barred basin. Either an epicontinental sea or a large area along the shores of an ocean near a large river in which the water is essentially brackish or fresh (the Amazon River technically extends more than a hundred miles northwest of its geographic mouth, for the "ocean" water is fresh) might furnish a suitable environment. It is suggested that the environment was that of an epicontinental sea.

As already discussed in detail by Harder and Chamberlin (1915, p. 397), the rocks herein called the Caraça group represent the sediments of a transgressing sea. They correctly believed that this sea advanced over a peneplaned surface of low relief. The advancing sea reworked the mantle of regolith, which was classified to a greater or lesser extent and deposited as the sediments called the Caraça group.

If it be assumed that this transgression was caused by gradual continental downwarping, a broad gently sloping platform would be created, on the shoreward edge of which coarse and fine clastic sedimentation might be taking place at the same time as chemical sedimentation under conditions promoting high Eh might be occurring farther seaword. Strong storms, local currents, or transitory oscillations of the sea would explain the minor clastic breaks in the dominantly chemical sedimentation of the Itabira group. A border zone in which iron-formation is contaminated by clay and other fine sediments would be expected. Considerable areas of impure iron-formation are known, irregularly grading into purer iron-formation.

The pH of the open ocean today ranges from 7.8 to 8.2. The pH of the waters from which carbonate-free oxide-facies iron-formation was precipitated was probably below 7.8, the "limestone fence" of Krumbein and Garrels (1952), for very little calcium or calcium-magnesium carbonate is associated with the iron-formation except locally. Thus the pH of the waters during deposition of the carbonate-free iron-formation need have been only a small amount lower than that of seawater under modern conditions. Were the pH radically lower, for example, about 6.5, the Eh would have had to be unusually high or siderite would have been precipitated instead of hematite. The presence of magnetite in the iron-formation indicates that the Eh was not abnormally high. Therefore it may be concluded that a slight lowering of what today is the normal pH of sea water would provide a suitable environment for the deposition of carbonate-free oxide-facies iron-formation.

Because oxide-facies banded iron-formation was a common and widespread sediment during Precambrian time, and has not been deposited in any quantity since (with the possible exception of the iron-formation of Morro do Urucum, Mato Grosso) it is perhaps natural to look for special conditions during Precambrian time to explain the prevalence of a form of sediment peculiar to it. Extensive literature exists on this subject.

The writers, although believing that the general environment probably was somewhat different than that in later eras, have no facts bearing on the problem. Their belief is based on a series of hypotheses.

(1) The volume of water in the oceans of the earth was less during Precambrian time, therefore any addition of juvenile acid waters would be more effective in changing pH than at present.

(2) The Precambrian is generally acknowledged to be an epoch of more active volcanism than later times. If this is correct, there may well have been a substantially greater contribution of juvenile acid waters.

(3) Some authorities believe that the percentage of CO_2 in the atmosphere (and therefore in the oceans) was higher. The writers can hardly see how the present balance of oxygen versus carbon dioxide, based as it is upon a generally luxuriant and world-wide cover of vegetation, can be the same as it was when vegetation is believed to have been in the first stages of its evolution and volcanism, a prolific source of CO_2, was more active. A higher percentage of CO_2 in the water would decrease its alkalinity.

The writers do not believe that local volcanism influenced the local environment. No evidence exists for local volcanism contemporaneous with formation of the Cauê itabirite. If there were volcanic influences, they must have been on a general, world-wide scale. The writers think that a somewhat higher percentage of CO_2 must have been present in the atmosphere; this would have promoted the leaching of iron from weathering rocks and its transportation by rivers to the sites of deposition of the great iron formations of the world.

The matter of Precambrian environment will be open to argument for a long time (see Rubey (1951), McGregor (1927), and Chilingar (1956)), and facts now available do not justify dogmatism. That some special, worldwide condition, which is no longer part of our environment, existed which promoted the deposition of banded iron-formation as a common sediment in Precambrian time seems apparent to the writers, however. The rock is too common and too widespread geographically for each occurrence to be dependent on special local conditions demanding unusual combinations of structural and chemical environments.

RELATIONS TO VOLCANISM

The iron-formation of the Cauê and that of the pre-Minas rocks and of the Piracicaba group should be considered separately in their relations to volcanism. The Cauê itabirite, in which all the high grade iron ore is found and which formed a sheet tens of thousands of square kilometers in extent, has no known direct relation to volcanic rocks, whereas the thin, discontinuous, lenticular, impure iron-formations in rocks disconformably overlying and unconformably underlying the Cauê itabirite occur in rocks which are believed to be in part of volcanic origin.

The Minas Gerais occurrence thus seems to fall into a world-wide pattern, in which iron-formations closely associated with volcanic rocks are, with exceptions, generally thinner, more lenticular, and more impure than those not so associated. Miles (1946) has shown that this relation obtains in Australia and Bruce (1945) suggests that the same relation may be true in Canada.

Bruce also points out in the same paper that in the Lake Superior region of the United States, iron-formation of Huronian age is in no case known to rest conformably on volcanic rocks. The great iron-formation of the Imataca series of Venezuela is also not associated with evidence of volcanic action, nor is that of Morro do Urucum (Dorr, 1945). Iron-formation in Labrador proves, however, that the presence of contemporaneous volcanic rocks and volcanism does not inhibit the deposition of major iron-formations. Thus a close association in time and space of major iron-formation and volcanic rocks must be fortuitous.

Recent papers (Guild, 1953; Guimarães, 1953) relating the iron-formation of Minas Gerais to volcanic activity did not distinguish between the minor iron-formations of the Rio das Velhas series and the major regional iron-formation of the Cauê itabirite. The paper by Guild has already been discussed (Dorr, 1954).

The paper by Guimarães cited the presence of amphibole asbestos in the Cauê itabirite as proof of volcanism during the deposition of these rocks. The work by Miles (1942) in Australia and by Hall (1930) and Peacock (1928) in South Africa indicates that the presence of asbestos in iron-formation need have no relation with volcanism. In the Minas Gerais area the occurrence seems to be very similar to that on the other continents mentioned, although the detailed study to prove this has not yet been completed. The available field evidence indicates that the Minas Gerais asbestos, like that on the other continents, is the result of the metamorphism of iron-formation contaminated by normal detrital sediments.

A secondary and indirect relation between volcanism and the Cauê itabirite is believed to exist, however. The pre-Minas sediments contain notable quantities of chlorite schist which probably was derived in part from volcanic rocks. The presence in these rocks of zones which probably were tuffaceous was discussed previously. O. Barbosa and Guimarães (1935, p. 38) have demonstrated the existence of rocks derived in part from mafic volcanic rocks in the pre-Minas terrain of Rio das Velhas valley. The deep weathering of such rocks might well have supplied the iron now in the Cauê itabirite. The pre-Minas rocks were extensively peneplaned and chemical, rather than mechanical, erosion must have been dominant in some areas during Cauê time.

DISAGGREGATED ITABIRITE

In the Itabira district, as elsewhere in the Quadrilátero Ferrífero, outcrops of hard fresh itabirite are a rarity. Adits cutting the itabirite more than 100 meters below outcrop in Cauê Peak do not encounter fresh hard itabirite. The itabirite as exposed near the surface is a soft rock disaggregated into separate grains and assemblages of grains, generally more than 75 percent minus 10 mesh, which can be dug out of walls by the fingernails or shovel. No explosives are needed in mining the rock except to break up parts cemented by secondary limonite. No crushing is needed to obtain material which is almost entirely less than three-fourths of an inch in maximum dimension. However, slump structures are rare except very near the surface and the rock usually presents the same appearance as the harder itabirite.

The disaggregated itabirite is generally residually enriched near the surface. Because the disaggregation of the itabirite is economically very important, it will be considered in some detail from a genetic viewpoint.

The cause of this disaggregation of the itabirite near the surface has been sought for many years and several explanations have been put forward. The earliest and most commonly suggested explanation is that the disaggregated itabirite originally contained small quantities of carbonate cement that, when the rock was close enough to the surface to be affected by descending meteoric solutions, dissolved, thus disaggregating the rock and disappearing in the process. This explanation is undoubtedly valid for some areas where the iron-formation is dolomitic, although dolomitic itabirite is known to be hard close to the surface in many localities, indicating that the mineralogy of the iron-formation may not be the major control even in such rock.

Guild (1953, p. 672) recently added a refinement to this theory. He believed that the major control was that mentioned above but added the idea that the carbonate going into solution made the leaching solutions alkaline so that silica was also dissolved to a limited extent. In order to explain the lack of field evidence for abundant dolomitic iron-formation, he suggested that the fresh hard unleached itabirite not containing dolomite or calcite is atypical, and implied that most of the typical soft itabirite originally contained carbonate.

The only evidence ever advanced to substantiate the theories of origin cited above is the fact that siliceous dolomitic itabirite, when leached with dilute acid, produces a material similar to much of the soft itabirite. The presence of such dolomitic itabirite in great quantity in the Cauê itabirite has never been proved. It is known, however, that such rock exists and, that in some parts of the Quadrilátero Ferrífero it forms a significant part of the itabirite. As far as is now known, however, in no locality does it form as much as half the iron-formation.

In contrast to the classical and generally accepted theory outlined above, the writers believe that the primary controls in the disaggregation of hard itabirite to form soft itabirite are not mineralogical but physiographic and textural. Softening is believed to be primarily due to the solution of silica. It is further believed that the specific problem of disaggregation of itabirite is intimately related to the more general problem of residual enrichment of oxide-facies iron-formation.

Some of the field and geochemical evidence on which this belief is based is as follows:

(1) Much of the hard itabirite which crops out in the Quadrilátero Ferrífero forms craggy mountain peaks, monadnocks which project above the ancient canga-capped peneplain mentioned on page C7 or other widespread canga-capped erosion surfaces. In these peaks, such as Conceição or Serra da Piedade, mechanical erosion is dominant. Such bodies of hard itabirite generally pass into the normal soft itabirite along strike as the outcrop of the itabirite formation passes under the canga cap marking the old erosion surfaces. Hard itabirite in these peaks contains no carbonate, and, according to the thin-section evidence that is available, has never contained carbonate since the present rock was formed.

(2) Hard itabirite also occurs at the bottom of canyons formed when the canga cap marking the old erosion surface was broken and the soft itabirite which underlies the cap was rapidly removed by mechanical erosion. The Grota de Esmeril in the Itabira district (pl. 1) is typical of such a setting. Here fresh hard itabirite containing no carbonate crops out in the bottom of the canyon, preventing further rapid erosion, and long irregular fingers of this material project upward into the overlying soft itabirite which in turn underlies a broad continuous canga sheet.

(3) In the Alegria deposit 60 kilometers southwest of the Itabira district, the Brazilian Iron and Steel Co. sank a vertical shaft in softened residually enriched itabirite dipping about 45° S. The outcrops of the beds which were cut by the shaft were carefully sampled and found to vary little from 66 percent Fe. The same beds where exposed in the shaft also were sampled and a decline in iron and increase in silica was found to occur with depth. No carbonate was noted at depth by the original workers; the shaft is now inaccessible.

(4) The 36 analyses of itabirite presented in table 5, page C79 are random samples with respect to stratigraphic horizon. These analyses represent all kinds of sampling, from grab samples and short channel samples taken by the writers, to channel samples representing as much as 40 meters of tunnel each taken by the Itabira Iron Ore Co. Although the samples cannot be considered to give a rigorously accurate picture of the grade of the itabirite of the district, because of the vast tonnages and small number of samples, a qualitative picture of variation in grade is assured. The differences in composition between hard and soft itabirite is as follows:

	Hard itabirite (15 samples) (percent)	*Soft itabirite (21 samples) (percent)*
Fe	44.96	53.81
Insoluble	35.24	21.69
Percent of material accounted for, calculating Fe as Fe_2O_3	99.48	98.57

Because the soft itabirite is usually hydrated to varying degrees, the calculation of all the iron as hematite in this material must be incorrect, thus accounting for at least part of the 1.4 percent of material unaccounted for. The hard itabirite is rarely and sparsely hydrated.

The above facts prove that residual enrichment of the itabirite takes place during the softening process. The varying degrees of residual enrichment in iron is clearly illustrated by the wide spread in tenor in the analyses given in table 5.

The 9 percent difference in iron content between soft and hard itabirite is believed to be a measure of the average amount of residual enrichment in the softening process and the 14 percent difference in insolubles between soft and hard itabirite a measure of the average amount of removal of silica in the softening process.

Because no carbonate has been found in the hard itabirite, it is impossible to attribute the softening of itabirite to removal of original carbonate in the itabirite on a district-wide scale. By the same token, fresh hard itabirite containing no carbonate cannot be considered to be an atypical type of itabirite in this district, nor, because the soft itabirite of the Itabira district is essentially similar to much of the soft itabirite exposed elsewhere in the Quadrilátero Ferrífero, atypical elsewhere.

(5) If the presence of carbonate in itabirite controlled the pH of meteoric solutions to such an extent that leaching of silica was made possible thereby, it would seem reasonable to suppose that there would be a spatial relation between softened itabirite and known carbonate beds in the itabirite, because aqueous circulation in the itabirite is much easier parallel to, rather than across, the foliation and bedding owing to the tabular nature of the iron-oxide minerals. The higher pH waters would be relatively concentrated near the dolomitic beds. No difference in the nature of the soft itabirite can be found adjacent to such carbonate beds in the Itabira district, and, other than normal sedimentary variations; none is known to the writers elsewhere in the Quadrilátero Ferrífero.

(6) Mason (1952, p. 142) reproduces a curve by Correns demonstrating that the solubility of silica in solutions with a pH of 6 is about 3.5 millimoles per liter, and that, at a pH of 8, the solubility of silica is about 5.0 millimoles per liter. Thus the difference in solubility between mildly acid and mildly alkaline solutions, such as are found in nature, is not significant. At a pH of 4, uncommon in naturally occurring supergene waters, the solubility of silica is 1 millimole per liter. Even this difference is hardly significant, when viewed in the light of geologic time . It would seem that pH control over solubility of silica under normal supergene conditions is unimportant.

The writers believe therefore that the important factor in the softening and residual enrichment of itabirite is primarily time (reflected in the physiographic setting) and secondarily texture and grain size.

The factor of time in the disaggregation and residual enrichment of itabirite is indicated by the relation of such material to the canga caps. The great canga chapadas and high-level slopes of the Quadrilátero Ferrífero, under which much of the soft itabirite lies, have not been definitely dated. In most cases they show a profound topographic unconformity with other rocks. Harder and Chamberlin (1915, p. 374) discuss evidence that indicates the higher chapadas in the Gandarela area must be pre-Miocene. They may be considerably older, and the oldest may correlate with the Cretaceous peneplane known to occur elsewhere in Minas Gerais. In any case, the older canga caps have existed at least 11 million years, and possibly many times this period.

Such canga caps effectively inhibit mechanical erosion of the underlying rocks. Thus the canga caps provided the essential time for the solution of silica by downward percolating meteoric waters, causing the disaggregation of the originally hard itabirite. The maximum depth of penetration of exploration under such canga caps in the Itabira district is 120 meters; at this depth the schistose, quartzose, and phyllitic rocks appeared to be as soft and weathered as they are on the surface.

In those parts of the Itabira group where carbonate minerals formed a part of the mineral assemblage of the itabirite, they too were removed, but the softening of itabirite is not believed to be dependent on the presence or absence of carbonate.

The silica in hard itabirite has a granoblastic texture (figs. 10–13). Solubility is increased by stress. Any stress either caused by differential unloading of the rocks through erosion or residual from tectonic movements will be concentrated at the interlocking parts of the silica grains. Therefore, it is exactly these parts of the individual grains that may be expected to be affected first by any leaching of the silica from the itabirite. Thus by relatively minor amounts of solution, the rock may be disaggregated.

Texture is also important because itabirite which is coarsely crystalline owing to high-grade metamorphism can be expected to be less rapidly soluble, whereas finer grained material will be relatively more rapidly soluble. (Rapidity of solution is governed by surface exposed to solution, which, in turn, is a cubic function of the grain size.)

Excellent examples of the difference in tendency of itabirite to disaggregate and to become residually enriched because of differences in grain size may be observed in Venezuela, where the grain size of the quartz and iron in the itabirite of the Imataca series increases radically to the east. Only in the central and western part of the area, where the grain size is small, is residually enriched itabirite important. In the Cerro Bolivar deposit, only minute quantities of carbonate are to be found in the fresh fine-grained itabirite. There too the disaggregated and residually enriched itabirite is found under a canga cap. Similar conditions have been observed in India. Because grain size of the quartz is finer in both these areas than in Itabira, residual enrichment is much more important. Because the grain size of the itabirite in the western part of the Quadrilátero Ferrífero of Brazil is smaller than in the east side, residual enrichment is more important there.

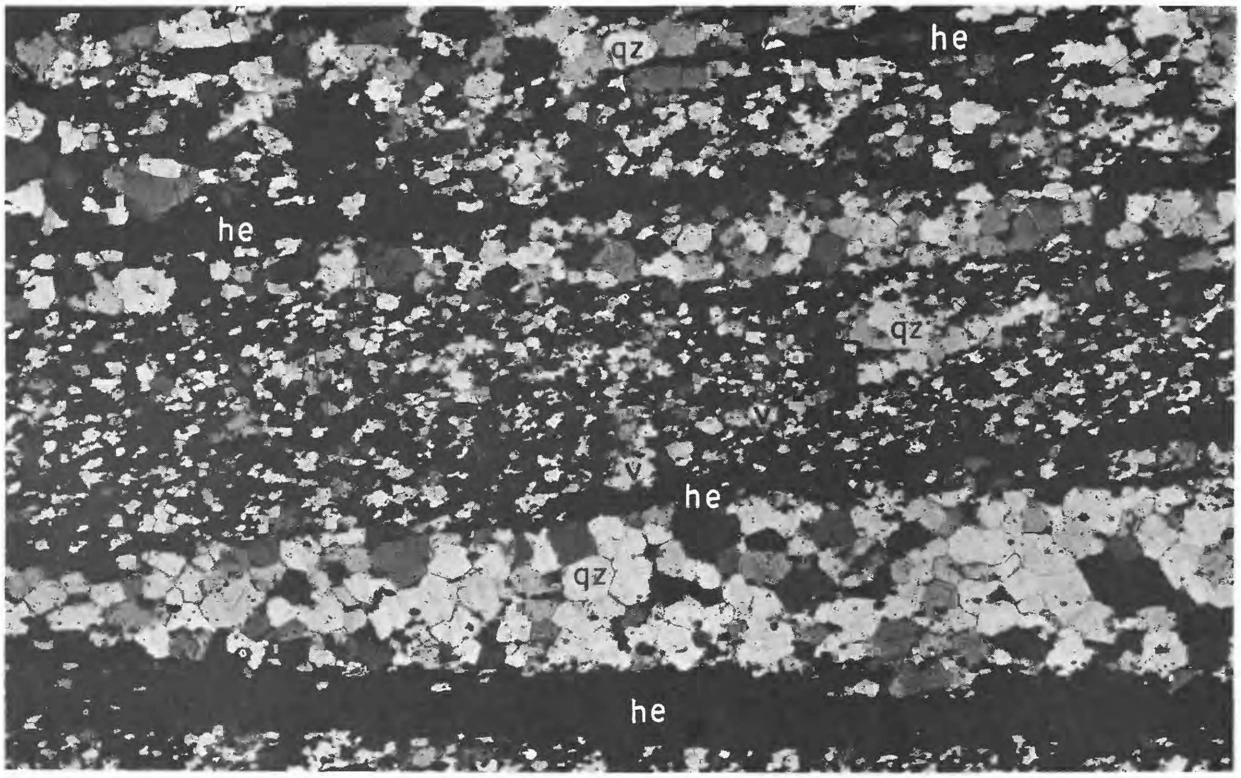


FIGURE 10.—Photomicrograph of Cauê itabirite showing typical distribution of quartz (qz) and hematite (he) in itabirite. Hematite replaces quartz. Late veinlet of quartz (v) cuts hematite. Magnification × 25; crossed nicols.

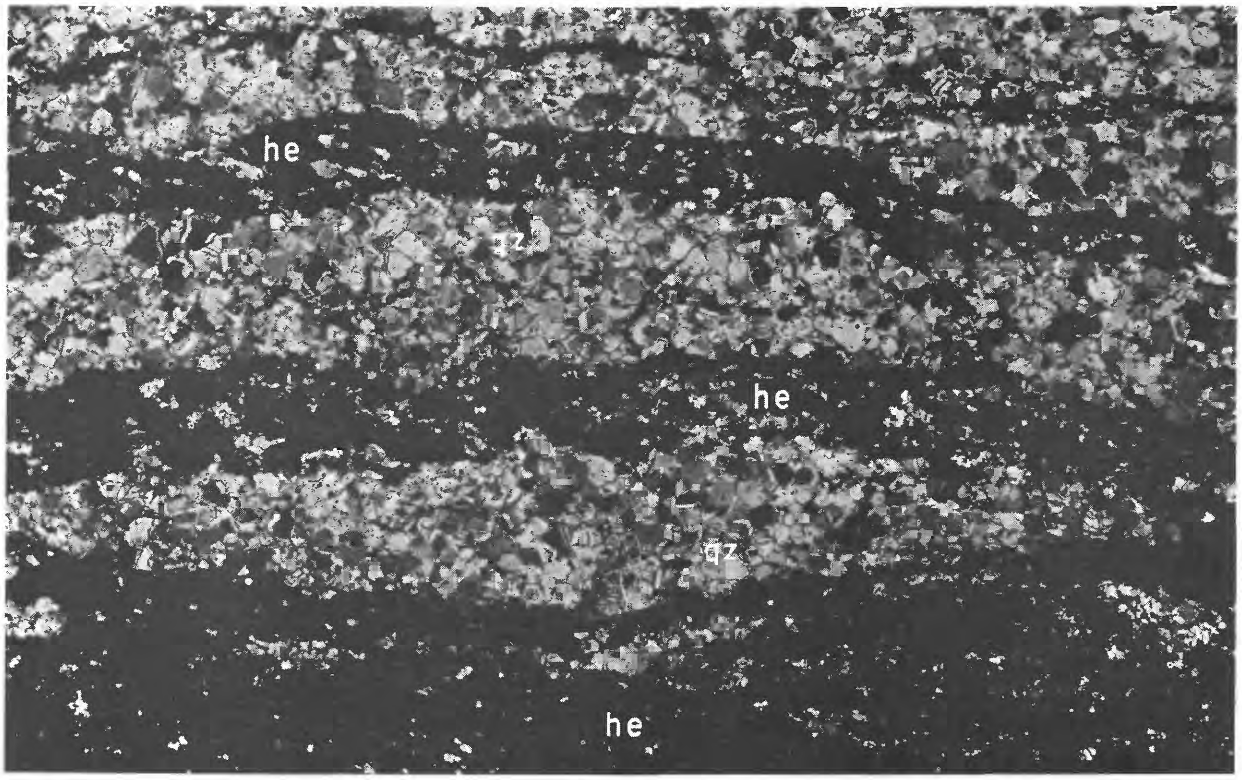


FIGURE 11.—Photomicrograph of Cauê itabirite illustrating normal distribution of quartz (qz) and hematite (he) in itabirite. Note lenticular nature, on microscopic scale, of bands. Magnification × 25; crossed nicols.

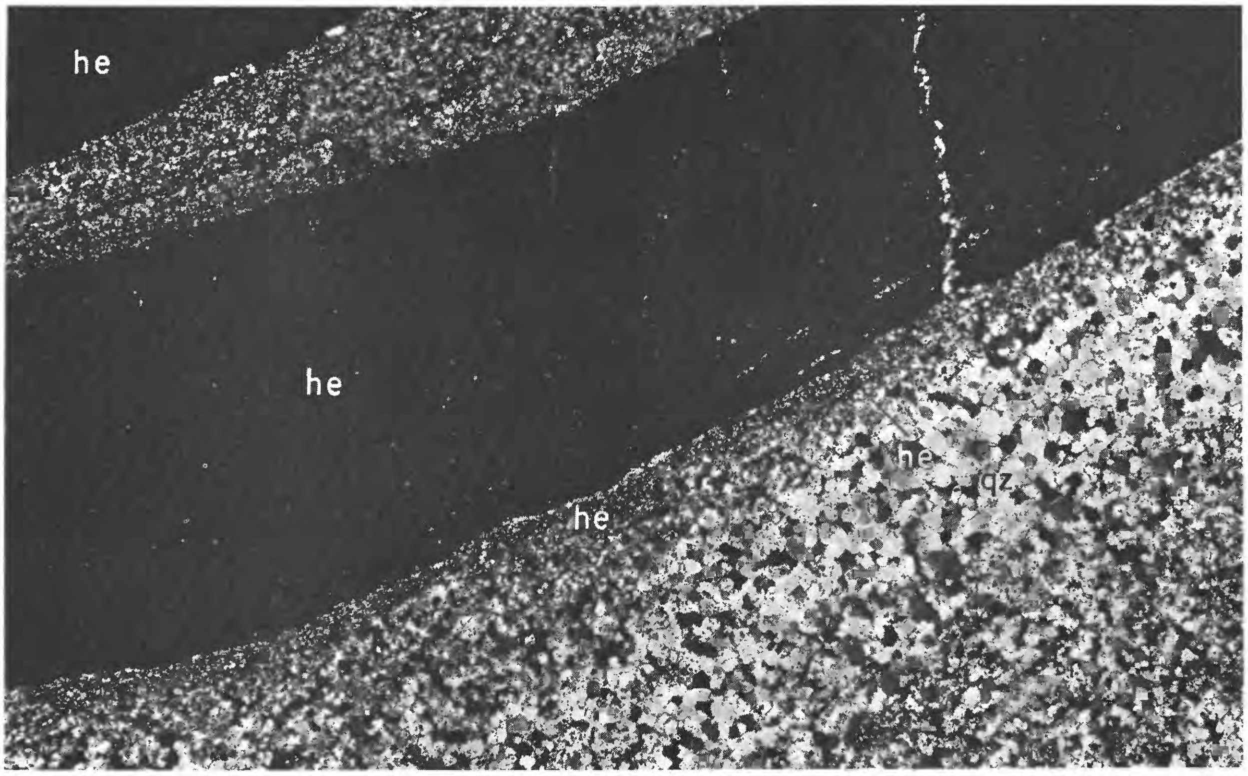


FIGURE 12.—Photomicrograph of Cauê itabirite showing irregular degree of recrystallization of the quartz (qz). Hematite (he). Note late quartz band. Magnification × 25; crossed nicols.

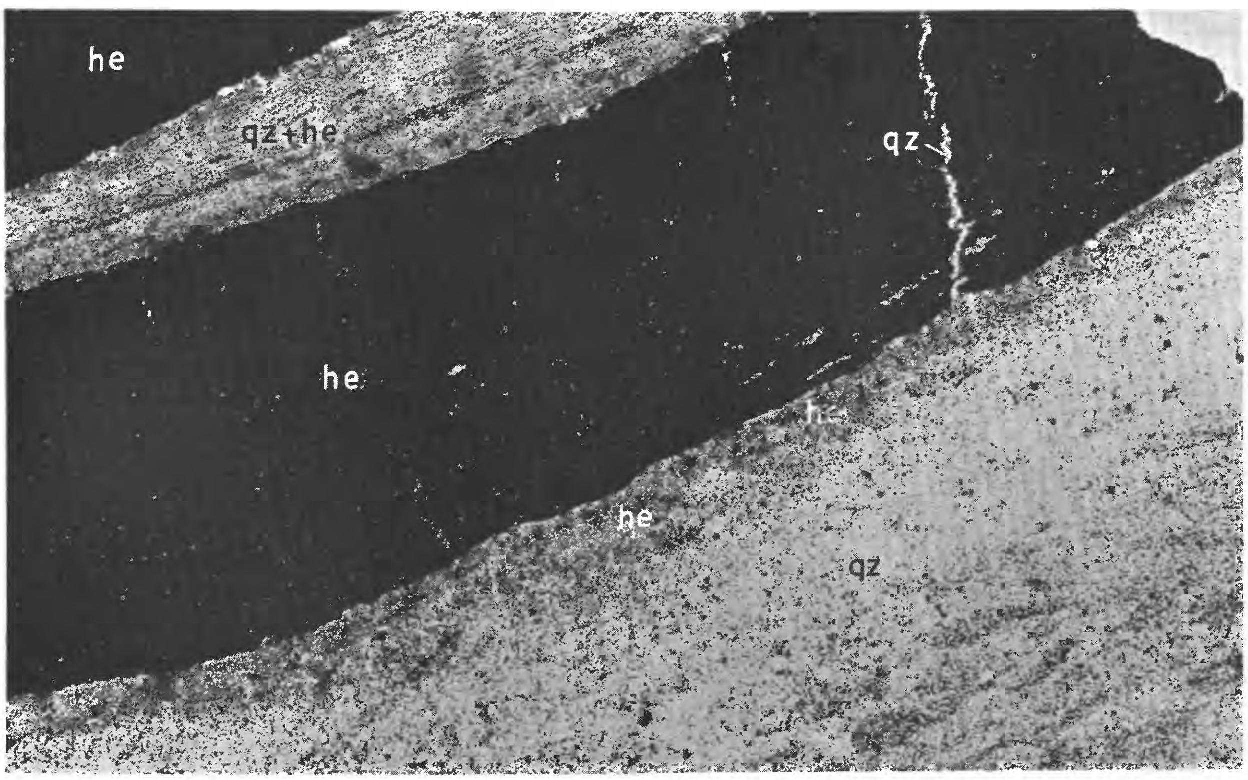


FIGURE 13.—Photomicrograph of Cauê itabirite showing fine hematite (he) dust in quartz (qz). Magnification × 25; plane light.

As a corollary of this theory of origin for the disaggregated itabirite it is to be expected that the deepest disaggregation will have occurred in areas which have been protected the longest time from mechanical erosion or which have physiographic and structural settings appropriate to facilitate ground-water circulation. The economic implications in mining activities and prospecting are evident.

PIRACICABA GROUP

Rocks of the Piracicaba group are equivalent to the Piracicaba formation of Harder and Chamberlin (1915, p. 362), which is well exposed along the Piracicaba river in the eastern part of the Quadrilátero Ferrífero. In the Itabira district, rocks belonging to this group are poorly exposed in natural outcrops, but numerous roadcuts and workings for gold and manganese give good but scattered exposures.

The Piracicaba group occurs within the core of the major syncline and is largely covered by canga or fairly deep soil. Because the syncline is tightly folded and the central rocks have been severely squeezed, an exact duplication of the section on either side of the synclinal axis is not to be expected. Enough similarity exists to permit some generalizations about the section.

LITHOLOGY

No thin-section studies have been made of rocks of the Piracicaba group in the Itabira district because the rocks are everywhere too decomposed to secure adequate specimens. Artificial exposures show the following rocks to be present: quartzite, ferruginous quartzite, kyanite quartzite, phyllite, graphitic phyllite, tuffaceous(?) phyllite, dolomitic quartzite and phyllite, and conglomerate.

The dominant rock type appears to be quartzite. Locally this quartzite is white, pure, and relatively fine grained, as in the scattered exposures near the Grota de Esmeril, but generally it appears as a tan evenly grained quartzite containing sericite and locally kyanite. At horizons a short distance above the Cauê itabirite, this quartzite may be ferruginous and conglomeratic, containing well rounded oval and disk-shaped pebbles as much as 4 cm long. The pebbles are dominantly vein quartz. The rock in some of the conglomeratic and other zones appears to be cross-bedded, but it is normally so sheared and weathered that it is not possible to ascertain whether the structures are sedimentary or tectonic in origin. These rocks probably correlate with the Cercadinho formation (Pomerene, 1958, p. 64) of the central and western parts of the Quadrilátero Ferrífero.

The kyanite quartzite is generally quite local in distribution. Poor exposures in this part of the section prevent generalizations about the occurrence of this rock.

The phyllitic rocks range from pure soft silky light gray to silvery phyllite, through quartzose phyllite to sericitic quartzite. In many places phyllite and quartzite are interbedded in thin bands; elsewhere a thickness of as much as 75 meters of nearly pure phyllite can be found. Along the railroad from Campestre to the Itabira station and in the valley of Agua Santa, 10–15 meters of highly graphitic phyllite is exposed immediately above the basal quartzite beds. This graphitic phyllite may correlate with similar rocks in a similar stratigraphic position which crop out in the western part of the Quadrilátero Ferrífero, there called the Barreiro formation (Pomerene, 1958, p. 67). The rock is dark gray to black.

Zones of weathered soft black manganiferous material which is believed to have been originally dolomitic are exposed in railroad cuts in the same vicinity. The material is similar to the weathered dolomitic beds in the Cauê itabirite. On one side of the syncline, one thin bed of this material is exposed; at the corresponding horizon on the other limb of the syncline, near 49,700 N., 48,575 E., two beds each about 5 meters thick separated by white highly sericitic quartzite are revealed by the cut. The manganiferous material is very soft and contains about 15–30 percent manganese. A drill hole put down by the DNPM to intersect the zones at about 100 meters depth recovered no core. These beds are stratigraphically 35–50 meters above the base of the Piracicaba group. They are probably to be correlated with the Fecho do Funil formation (Simmons, 1958, p. 65).

Another zone of manganiferous rock is exposed by old gold workings a short distance below the railroad and some 200–400 meters to the northeast of the locality cited above. This material is even lower grade in manganese than that just described. The host rock is now completely weathered to clay, but textures remain that are suggestive of a tuffaceous phyllite. The manganese oxide is both in thin stringers and disseminated in the rock.

Although the scattered exposures do not permit the stratigraphy of the Piracicaba group to be mapped in any detail, it seems probable that the lower part of this group is dominantly quartzitic rock mixed with varied quantities of sericite. Manganese is sporadically present in the lower quartzite. A dominantly phyllitic zone overlies the quartzitic zone, with interbeds of manganiferous dolomitic rock, of quartzite, and of graphitic phyllite. The rocks that are stratigraphically highest are again dominantly quartzitic and even locally conglomeratic. These rocks and their general stratigraphic succession are essentially the same as those found in the western part of the Quadrilátero Ferrífero, where the Piracicaba group has been divided into five formations.

DISTRIBUTION, THICKNESS, AND CONTACTS

The Piracicaba group in the Itabira district consists of strongly folded and squeezed remnants preserved in the centers of the larger synclines. Because these rocks do not resist erosion, outcrops are on the lower slopes and in the valleys. Plate 1 shows that they have been tightly infolded with the Cauê itabirite in the main syncline on Conceição Peak and also in the Dois Córregos syncline and in the main syncline. The distribution of these rocks as mapped on the Cauê syncline is largely hypothetical owing to the extremely sparse exposures.

The maximum stratigraphic thickness exposed in the Itabira district is possibly in the main syncline north of the town of Itabira, where 200–300 meters may be present. Greater thicknesses may be present elsewhere.

The Piracicaba group is the uppermost member of the Minas series and is now limited by an erosion surface. It is not surely known whether the younger Itacolomi series, which unconformably overlies the formation elsewhere in the Quadrilátero Ferrífero, was ever deposited in this area. The metamorphism and structural habit of the Minas series rocks of the district indicate strongly that the deformation and metamorphism took place under deepseated conditions, so it seems probable that younger rocks were once present and have since been eroded away.

The contact of the Piracicaba group with the underlying Itabira group has been described as conformable.

TALC VEINLETS

An interesting exposure of Piracicaba quartzite cut by numerous talc veinlets was made during excavation for the ore stocking facilities near Campestre. These features can no longer be observed, owing to later construction. Veinlets of pure green talc with minor quartz follow both bedding planes in the quartzite and joints nearly at right angles to those bedding planes, as illustrated in figure 14. The material showed the pencil structure so common in the region. It is believed that this talc was introduced by hot fluids, possibly those which introduced the talc into the Cauê itabirite.

FIGURE 14.—Talc veinlets on bedding planes and crosscutting disaggregated quartzite of the Piracicaba group. Excavation for ore and stocking facilities, Campestre.

TERTIARY AND QUATERNARY DEPOSITS

In the Itabira district, as in the rest of the Quadrilátero Ferrífero, there is no record of Paleozoic sedimentation. It is conceivable that the higher canga caps may represent late Mesozoic deposition, but the complete absence of a fossil record or of nearby fossiliferous formations place such correlations in the realm of speculation. The conventional assumption that all the superficial rocks are Tertiary or Quaternary will therefore be followed, even though there is no direct evidence for this assumption either.

Tertiary and Quaternary deposits in the district consist of canga, thick soils, locally strongly laterized, talus derived from the bold outcrops of hematite ore, gravel deposits, and minor alluvium. The economic aspects of the deposits, with the exception of the gravels, will be discussed in a separate section.

From a more general viewpoint, the major interest in these surficial deposits is the evidence they provide for drainage changes in the area, which seem to have been major. At least two main periods of soil formation occurred in the past, possibly during Pleistocene time, possibly earlier. Not enough regional information is yet known to draw broad conclusions from this fact, but the evidence in this district will be presented with the expectation that later work will enable such regional conclusions to be drawn, for it is known that similar ancient surficial deposits occur elsewhere.

A long linear zone of red lateritic soil can be traced from near the entrance of Grota de Esmeril almost continuously to the airport, about 5,500 meters to the northeast. This soil is brick-red, infertile, contains few fragments of quartz or other rock, and is shown by several deep cuts and an adit to be not less than

10 meters and as much as 25 meters thick. The material is quite porous. The scarcity of quartz fragments precludes formation in place, for all of the underlying rocks contain quartz veins. Hematite and, locally, itabirite boulders in localities thought to be some distance from the iron-formation and the ore deposits may be seen at the base of this soil in several deep cuts. Locally the brick-red soil is characterized by irregular white blotches.

An adit, the portal of which is located at N 50,994, E 50,692, was driven in this material (fig. 15). This adit traversed 25 meters of this red lateritic soil before encountering several meters of canga dipping toward the portal. The canga was largely composed of well rounded itabirite and hematite boulders up to several tens of centimeters in diameter which are in most cases so soft that they may be pulverized with the bare hand. Yellow and tan ocherous soil similar to that outcropping at the east end of the airport occurs below the canga. This soil appears to be more completely laterized than that overlying the canga. The adit is flooded 20 meters beyond the canga because it was driven with a downward slope. A variant was caved 25 meters beyond the canga. The dump gave no indication that bedrock had been reached. The present face of the adit is more than 25 meters underground.

The evidence provided by this adit proves that the yellow ocherous soil found at the northeast end of the airport is an older generation which was eroded and on which coarse debris, overlain in turn by another fossil soil, was deposited.

The younger brick-red soil that rests on the canga also belongs to an earlier drainage cycle, for its trace is nearly normal to present drainage patterns and it is being actively eroded. It may also be observed along the Itabira-Campestre railroad in an old valley cut in bedrock.

Unconsolidated stream gravels are found at several levels on terraces a few meters to perhaps 20 meters above present stream levels. None of the high-level gravels found elsewhere in the Quadrilátero Ferrífero are present in the Itabira district. The low-level gravel deposits are too small and too coarse to have economic value but yielded some gold during the gold-mining period of the district.

Commercial gravel might be extracted from the broad alluvial valley south of the Itabira substation of the Salto Grande power line. Possibly 500,000 cubic meters of material per meter of depth exist in this valley and cut banks show the deposit to be at least a meter thick. Other potentially commercial gravel deposits may be found in the main stream below the town of Itabira and in the headwaters of the Rio do Peixe.

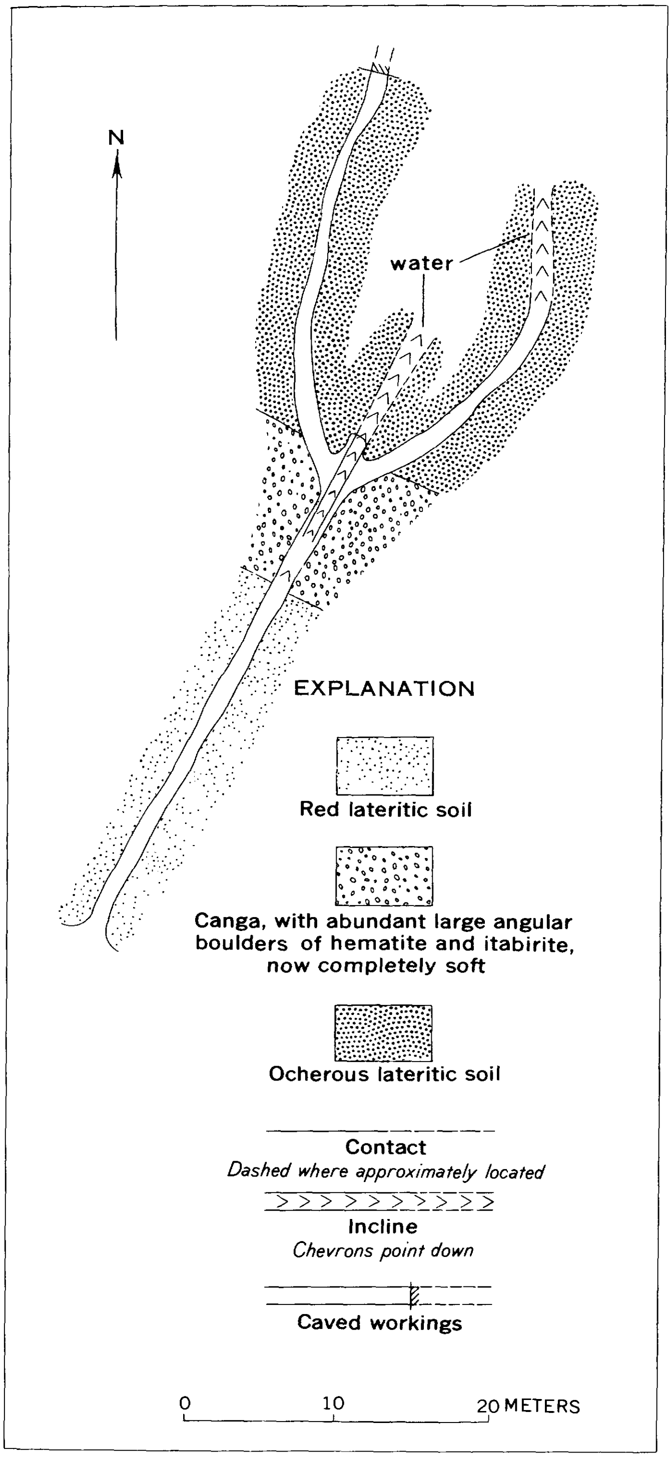


FIGURE 15.—Geologic map of adit at 50,994 N.–, 50,692 E., Cauê area.

A small deposit of very low grade bauxite occurs on the broad nose just to the southwest of the bridge by which the Itabira–Santa Barbarà road crosses Córrego de Conceição. The bauxite is the result of laterization of the phyllites and schists of the Rio das Velhas series. It is of no economic importance nor are the other smaller patches of this material derived from the same rocks that occur on the southwest flanks of Cauê Peak.

IGNEOUS AND GNEISSIC ROCKS

ALTERED ULTRAMAFIC AND MAFIC ROCKS

Altered ultramafic and mafic rocks are, with the exception of the metamorphosed pyroclastic rocks and the sills that form an integral part of the Rio das Velhas series, the oldest igneous rocks in the Itabira district. These rocks are now found in the form of soapstone and serpentinite, talc schists, amphibolite, talc-chlorite schist, talc-chlorite-tremolite schist, and actinolite schist. This diversity of rock type reflects not only the original variations in composition, which probably ranged from dunite to gabbro, but also variations in metamorphic history and in alteration.

The rocks are clearly intrusive into the Rio das Velhas series in other parts of the Quadrilátero Ferrífero. Relations between the two groups of rocks prove that the mafic and ultramafic rocks are also intrusive in the Itabira district. In outcrops along the Sixpercent road below mine 8 on Cauê Peak, amphibolite is intruded in lit-par-lit manner into schist of the Rio das Velhas series. Plate 1 shows that the main bodies of the ultramafic group are emplaced both concordantly and across the structure. The amphibolites commonly were more influenced in their emplacement by host rock structure than were the more mafic rocks.

In the Itabira district it cannot be definitely proved that the ultramafic and related rocks are older than the Minas series. This assumptions seems reasonable, however, because they have not been found intrusive into the Minas series in this district, whereas they are widely distributed in the older rocks.

Plate 1 shows that the soapstone occurs almost entirely in the part of the Itabira district southeast of the main syncline. Northwest of this syncline, only a few small scattered occurrences of the soapstone, mainly in the form of float, were found. Amphibolites, on the other hand, are abundant in this general area.

Southeast of the main syncline both soapstone and amphibolite are abundant and are often contiguous. In this area, an attempt was made to map separately these two rock types but it is known that areas represented as soapstone contain some small bodies of amphibolite and vice versa.

Although contacts between amphibolite and soapstone are exposed in some of the new railroad cuts along the Rio do Peixe, age relations between the two rock types are obscure. Locally the soapstone appears to be intrusive into the amphibolite, projecting into it in apophyses, but, because the amphibolite is a relatively competent rock and the soapstone is relatively plastic, the apparently intrusive relation may really be caused by later tectonic movement. Although the available evidence is equivocal, it is believed that the soapstone is the older.

SOAPSTONE AND SERPENTINITE

Fresh soapstone, a rarity, is found on the northeast side of the deep and steep valley carved by the Córrego de Conceição (pl. 1) on the slpoes of the 901 hill, about 600 meters below the crossing of that stream by the Itabira–Santa Barbara road.[5] The rock is a gray steatite, tough but soft, with some talc veinlets and no megascopically visible quartz or sulfide. The texture of the preexisting rock is faintly visible; it was medium grained and equigranular.

Elsewhere, the weathered rock as observed on the outcrop is generally tan or light gray, very soft, and unfoliated. In many localities it is pocked by holes roughly rhombic in section, ranging in size from 2 millimeters to 2 centimeters, that are lined by a dark-brown iron hydroxide mineral. Locally, these holes make up 25 percent of the rock. Crystals of magnesite, which originally filled these holes, were found in only two localities. Locally, the soapstone is formed in part of fibrous serpentine(?) cutting across the rock in well oriented cross-fiber veins.

Extreme weathering makes the rock so porous that dry pieces thrown in water will float. The completely weathered rock consists mainly of minute boxworks of limonitic material, all the silicates having been leached out.

The bulk of the larger bodies of the soapstone is composed of unfoliated and massive material, which, toward the borders, may grade into talc-rich schist. This talc is well foliated and is at least generally concordant with structures in the enclosing foliated rocks even in those places where the foliation is nearly perpendicular to the trend of the contact. This peripheral foliation is attributed to the plasticity of the talcose rock, which failed along the borders of the larger bodies and absorbed most of the stress imposed on the rocks along the margins of the bodies, permitting the central parts to remain massive and unfoliated. Smaller bodies were completely foliated to talc schist. It is probable that some of the talc schists in the Rio das Velhas series actually belong to the soapstone group but have been so sheared that their identity has been lost.

[5] An alternate road was constructed in 1957 but is not shown on plate 1. Fresh soapstone is found also a few tens of meters southwest of the crossing of Rio do Peixe by the new road.

It must be emphasized that the altered ultramafic rocks are generally so weathered on the outcrop that specimens suitable for microscopic or chemical investigation are almost impossible to secure. Only six such specimens were secured, a number entirely inadequate statistically for basing any conclusions concerning the exact composition of the rock or for indicating its possible economic value. As a generalization, the soapstones of the Itabira district appear to be less pure and more shattered than other deposits of the same material elsewhere in the Quadrilátero Ferrífero, and are therefore of less economic interest.

The rock is composed of medium-grained talc (about 99 percent) with small amounts of carbonate, opaque mineral, and yellow iron oxide. Talc in the massive rock commonly has unit extinction in medium-sized patchy or block areas, indicating that they are pseudomorphous after a primary igneous mineral, probably olivine. Carbonate in veinlets proved to be a member of the magnesite-siderite-rhodochrosite system containing 75–85 percent of the magnesite component ($n^o = 1.73$).

The soapstone is believed to have been derived by deuteric or hydrothermal alteration of preexisting olivine-rich ultramafic rocks as discussed by Turner (1948, p. 132). This will be discussed in some detail on pages C47–48 where an explanation of the related bull quartz bodies is discussed.

The body of ultramafic rock mapped just to the northwest of Conceição Peak is somewhat different from the average rock of this type in the district. It is composed of dark-green to black serpentinitic rock with locally abundant euhedral magnetite crystals as much as 0.5 cm across. Some of the rock is slightly foliated and lighter green, but also seems to be serpentinite rather than soapstone.

In thin section the serpentinite is seen to be dominantly antigorite (70 percent plus) occupying irregular or blocky areas surrounded by seams or zones of carbonate and talc. The antigorite forms small flakes and blades which are intergrown in the typical cross-hatched pattern of serpentinite. Talc forms 5–25 percent of the rock. Carbonate, which characteristically occurs as porphyroblasts (85–90 percent magnesite) which grew across the talc into the adjacent antigorite, forms less than 5 percent of the rock. Magnetite and pyrite are common accessory minerals. One thin section contained 45 percent chromite. Chromite has been reported from similar rock at Morro do Pilar, some 40 km to the north.

Megascopically, the serpentinite can be seen to have been derived from a medium-grained rock. The original minerals have all been altered but the dominant antigorite and its characteristic cross-hatched pattern are thought to indicate derivation of this mineral from olivine. The talc seams and zones, apparently localized along irregular fractures, may indicate alteration of antigorite to talc either at a later stage of the deuteric process or by later hydrothermal solutions. (See fig. 16.)

AMPHIBOLITE

Amphibolite is closely associated spatially in parts of the Itabira district with the more mafic rocks just described. The rock crops out in many other parts of the Quadrilátero Ferrífero and in adjoining areas, and is a major rock unit in this part of Minas Gerais.

The fresh rock has a schistose to finely gneissic structure and is very hard. It weathers to a characteristic porous, coherent, reddish-brown to yellow soil which is quite fertile. In this area two types of amphibolite can be identified. These types occur in the same intrusive bodies, and were not separated in the field; they probably represent slightly different phases of the same intrusive magma.

The first type contains 60–80 percent of fine- to medium-grained blue hornblende alined subparallel to the schistosity. The plagioclase (An_{15-40}), which comprises 10–30 percent of the rock, is untwinned and occurs in isolated equant crystals or as lensoid or irregular aggregates surrounded by hornblende. Epidote or clinozoisite are everywhere present and have formed simultaneously with the present plagioclase from a more calcic plagioclase during metamorphism. Other minor minerals are quartz, biotite, leucoxene, apatite, and magnetite. One thin section contained 17 percent biotite. Although no relict fabric can be distinguished in this rock, it has probably been derived from mafic igneous rocks by regional metamorphism.

The second and more common type of amphibolite retains relics of the original fabric and the schistosity is not so pronounced in thin section as in the first type, although megascopically it is prominent. The rock is composed of blue-green hornblende (40–60 percent), plagioclase with An_{12-40} (20–40 percent), and epidote, clinozoisite, biotite, quartz, chlorite, sericite, leucoxene, and magnetite. Primary ilmenite is commonly rimmed by leucoxene.

In most thin sections, original blocky or lath-shaped outlines, with or without albite twinning, are preserved by mottled or altered and replaced plagioclase. In a few specimens, dense aggregates of clinozoisite clearly pseudomorphous after plagioclase have the blocky outlines of the original feldspar. The hornblende has been completely recrystallized and has no

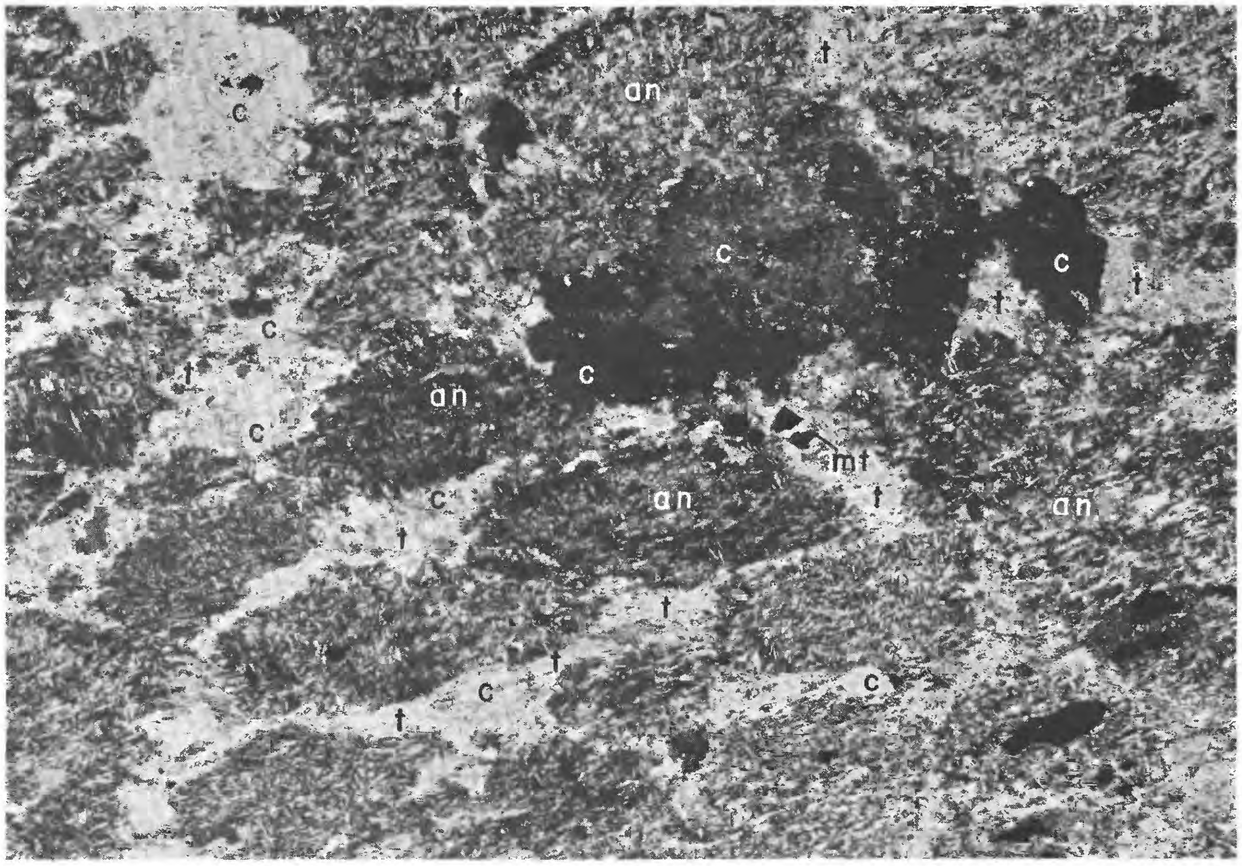


FIGURE 16.—Photomicrograph of serpentinite. Brecciated ultra mafic, serpentinized, with antigorite(an) replaced in part by talc(t) and a carbonate(c) (largely magnesite) accessory magnetite(mt). Magnification × 25; crossed nicols.

form suggesting the original mineral, presumably augite.

The following features show that these rocks were originally gabbros:

1. Relict gabbroic textures.
2. Abundant hornblende indicates original mafic rock.
3. Combination of present oligoclase and andesine with epidote-clinozoisite suggests original more calcic plagioclase.
4. The minor primary minerals are characteristic of gabbroic rocks.
5. The minor secondary minerals, particularly leucoxene, are characteristic of metagabbroic rocks.

In one locality, amphibolite has been altered to an apple-green mineral, similar to material from an identical environment from another locality that was identified as pinguite (a variety of chloropal) by Dr. Othon Leonardos. This material has been mistaken for a copper mineral by the unwary. The single known occurrence is on the 901 hill below the crossing of Córrego de Conceição by the Itabira–Santa Barbara road.

OTHER AMPHIBOLITIC ROCKS

Actinolite and tremolite schists, locally talcose and chloritic, were not mapped separately, because the exposures are small and discontinuous. Most of the examples found could not be related to mappable bodies.

The largest single area of these rocks is just south of the Itabira–Santa Barbara road along the west bank of Córrego de Conceição. Although on plate 1 the rock is mapped as amphibolite, about half or more of the area north of the quartz deposits is composed of tremolite-actinolite rock and a small area south of the mapped quartz body also contains this rock. Scattered pieces of float and small outcrops were found elsewhere, particularly at the east end of the major soapstone body along the Rio de Peixe.

As seen in the best exposures, some of this rock consists of long (as much as 2 cm) bladed crystals of actinolite and minor rosettes of pyrophyllite, locally without preferred orientation. Elsewhere the rock is quite schistose and the pyrophyllite is missing.

These amphibolitic rocks may have been derived from the metamorphism and hydrothermal alteration of pyroxenite, peridotite, or hornblendite material, localized either in separate intrusive bodies or as minor differentiates of the original mafic or ultramafic intrusive bodies. Solutions that formed the adjacent quartz deposits are probably responsible for the formation of this rock.

The soapstone-serpentinite group and the amphibolite group of rocks may have formed from different magmas at different times and their close spatial relation in the Itabira district may be purely fortuitous. Even within this district, amphibolite is found in many localities without ultramafic rocks. The soapstone and the related talc schists also occur locally without amphibolite. Because they are so closely associated in many localities, however, the two rocks may well represent differentiates from a common gabbroic magma. They are envisaged as being the typical mafic and ultramafic rocks that are so commonly emplaced in down-buckled geosynclines such as that in which the Rio das Velhas series seem to have been deposited. Such also was O. Barbosa's interpretation (1954, p. 21) of the talcose rocks that are common throughout and near the Quadrilátero Ferrífero.

GRANITIC GNEISS

The geologic map of the Itabira district shows that more than half of the area of the district is occupied by gneissic and schistose rocks collectively described as "granitic gneiss." This term is applied as a temporary convenience. Until the relations of this great and widespread formation, which crops out over tens of thousands of square kilometers in central Minas Gerais, have been better studied and the genesis and nature of the rocks better defined than is possible in the Itabira district, the formation can not be satisfactorily named or defined.

Hitherto the rocks have been called Archean gneiss with no formation name, except by O. Barbosa (1954, p. 20) who recognized that they were derived in part from the rocks described above as the Rio das Velhas series. Barbosa included both those schistose metasedimentary rocks and the granitic gneiss in his proposed pre-Minas Barbacena series, because he considered the gneissic rocks to be the equivalent of the schistose ones. He did not realize that at least some of the granitic gneiss is also younger than the Minas series, and therefore much younger than the Rio das Velhas series.

Samples of the granitic gneiss from the Itabira district and elsewhere in the Quadrilátero Ferrífero have been dated by the K^{40}/A^{40} method as being 500–550 million years old (Hurley, 1958, p. 81; Herz, 1958, p. 88). Other granitic rocks in the Quadrilátero Ferrífero are known to be 1,340 and 2,500 million years old (Herz, op. cit.). There is no reason to believe that granitic rocks older than 550 million years occur in the Itabira district, although enough sampling to prove this has not been done.

The formation as a whole is the least resistant to weathering of any of the major units in the Itabira district. It forms low, rolling, soil covered and wooded hills. Outcrops, with the exception of rare smooth black sidehill outcrops, occur mainly along the streams, where waterfalls and rapids are produced by more resistant ribs in the rock. Chemical weathering is dominant, particularly in the zones of biotite gneiss, where coherent rock may not be found in areas of several square kilometers. Northeast of Itabira and outside the district, kyanite-bearing quartz muscovite gneiss forms a series of northeast-trending hogbacks that dominate the topography for 10 kilometers or more. This rock was not located along the Rio do Peixe east of Itabira, but occurs with a more subdued topographic expression on trend south of Itabira.

LITHOLOGY

As exposed in the Itabira district, the granitic gneiss may be subdivided into four general types. Field separation of these types was attempted but proved impractical because of the poor and discontinuous exposures and the intergradational nature of the types. Although the individual types as they are described may seem very different from each other, this is an oversimplification of an intergradational series. Detailed petrographic mapping in an area of good exposures could undoubtedly set up more types and map separately those separated here.

The most common type, called herein granitic gneiss (figs. 17, 18) is a granitoid rock of igneous aspect which is faintly to moderately foliated. The foliation is even and regular and not strongly contorted. The rock is dominantly composed of quartz, feldspar, and sparse biotite, with gneissic texture. Petrographically, it ranges from tonalite to quartz-monzonite in composition, with the dominant plagioclase containing 10–20 percent of anorthite and with the varying quantities of microcline, orthoclase, and perthite determining the rock classification. Minor amounts of epidote or clinozoisite are present, probably derived from the alteration of more calcic feldspar. Micaceous minerals generally comprise less than 15 percent of the rock. Muscovite and green-brown biotite occur separately or interleaved; chlorite occurs replacing feldspar and in blades interleaved with biotite.

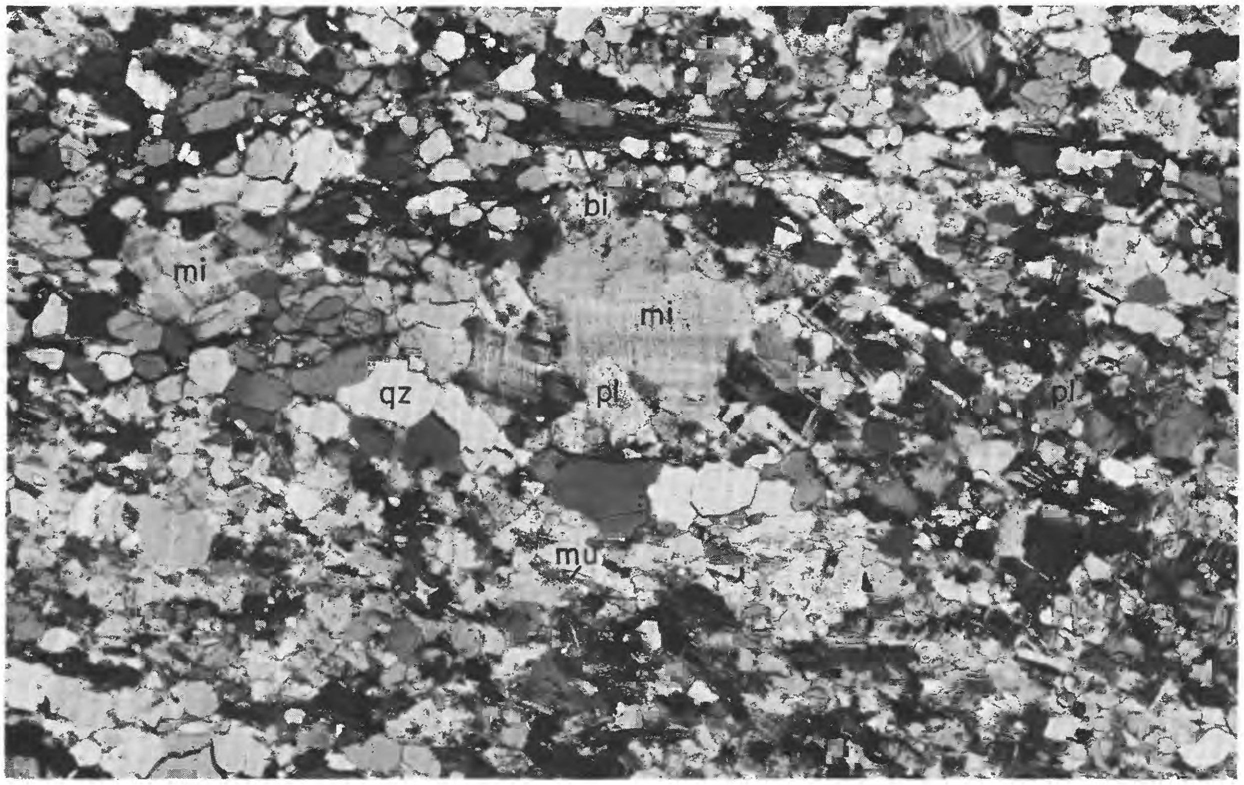


FIGURE 17.—Photomicrograph of quartz monzonite gneiss. Typical type 1 granitic gneiss, showing strong alinement of micas but generally subdued foliation. Microcline (mi), quartz (qz), plagioclase (An_{14-22}) (pl), muscovite (mu), biotite (bi). Magnification × 25; crossed nicols.

Textures of the feldspars and quartz are allotriomorphic granular to granoblastic. Individual grains are generally medium size; aggregates of fine-grained quartz and feldspar and coarse crystals of feldspar in a medium-grained groundmass are also found. Mosaic intergrowths of quartz and feldspar are common.

Individual grains of quartz and feldspar generally have sutured borders against each other or sharply angular fragmentation outlines. Shearing fragmentation is strongly indicated in some thin sections by aggregates of medium-grained microcline elongate parallel to foliation. The slight angular optical discordance between individual members of the aggregates indicates in such cases that an original large microcline crystal was fractured and sheared out during deformation.

There is no petrographic evidence for important metasomatic action during formation of the rock. If such action took place, it must have occurred before the final deformation of the rock, and the evidence for the metasomatism destroyed by recrystallization during the deformation.

Contorted granitic gneiss, the second type distinguished, is mineralogically indistinguishable from the uncontorted granitic gneiss. It is separated on the basis of the strong folding and contortion evidenced by the foliation. Ptygmatic folding is common in this rock. The rock is cut by two generations of pegmatitic veins, one of which seems contemporaneous with this sharp folding, the other later. The local lack of sharp walls observed in the field suggests that the earlier veins may be the result of anatexis.

A third type of the granitic gneiss is a quartz-muscovite gneiss. The rock is practically a quartzite, with minor, possibly clastic, feldspar, abundant muscovite in plates as much as 7 mm in diameter and a well-defined schistose to gneissic texture. This rock is commonly deeply weathered on the outcrop. As a result, the few thin sections which could be cut are not representative.

This rock contains 60 percent to 99 percent quartz in medium-grained granoblastic aggregates or as isolated angular grains separated by mica seams.

The micaceous minerals, which make up as much as 19 percent of those rocks are dominantly muscovite

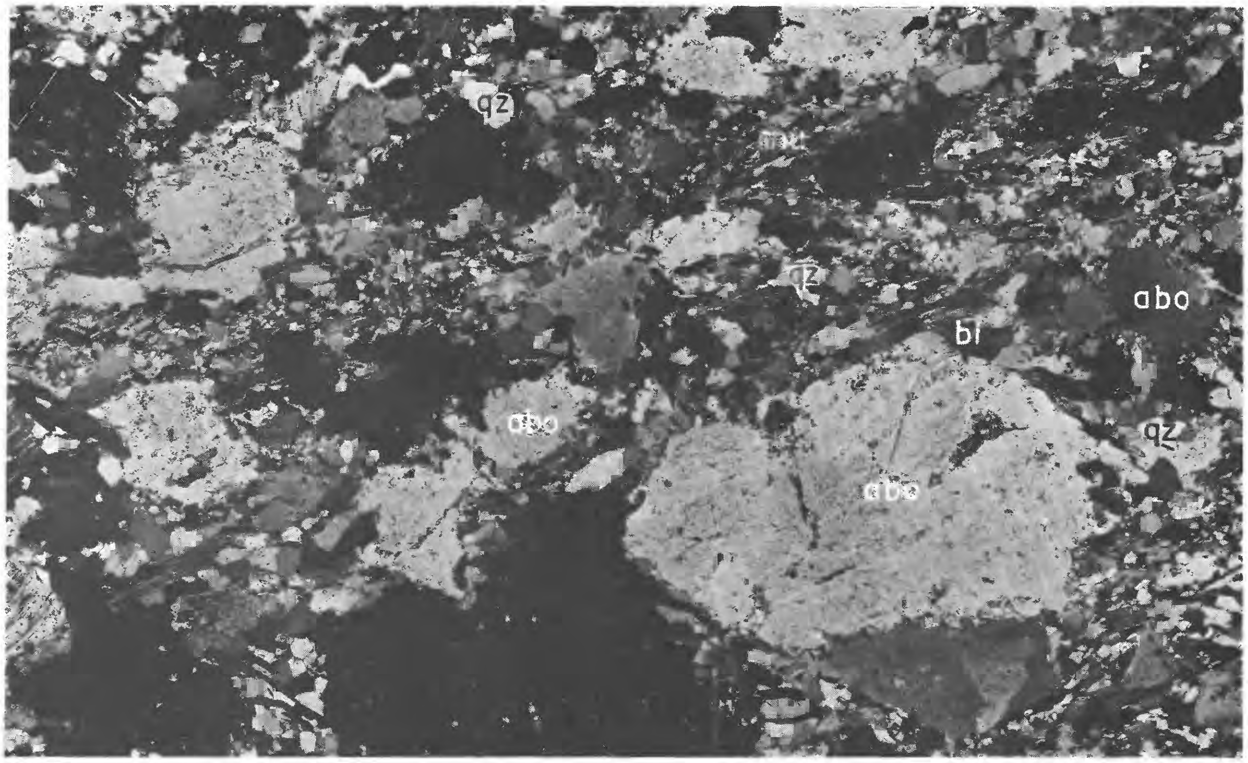


FIGURE 18.—Photomicrograph of tonalite gneiss. Typical type 1 granitic gneiss showing subdued foliation, relatively large feldspar, good alinement of micas. Albite-oligoclase (abo), quartz (qz), biotite (bi), muscovite (mu). Magnification × 15; crossed nicols.

FIGURE 19.—Photomicrograph of quartz-biotite-epidote schist. Typical of one aspect of type 4 granitic gneiss. Large crystals are of biotite, epidote very fine grained and interstitial. Biotite (bi), quartz (qz), quartz-epidote (qz-ep), carbonate (c). Magnification × 25; crossed nicols.

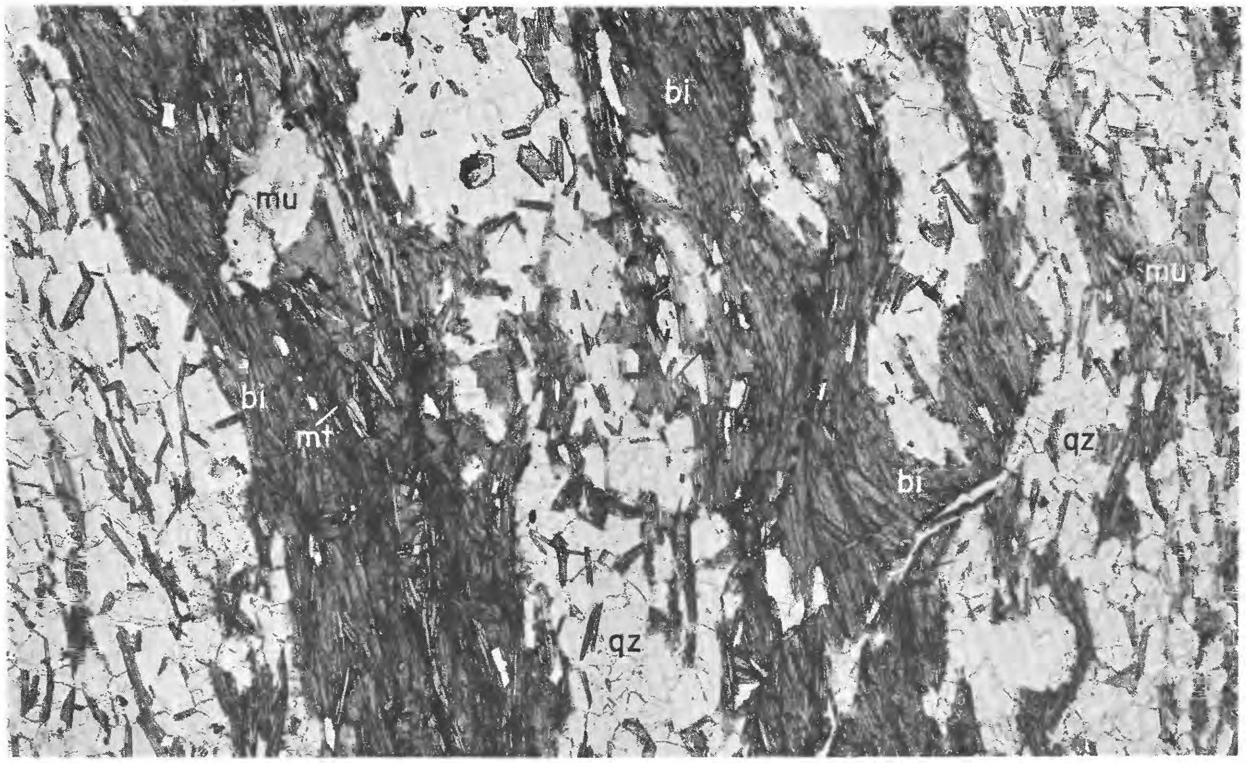


FIGURE 20.—Photomicrograph of quartz-mica gneiss. Typical of one aspect of type 4 granitic gneiss. Minor chlorite and kyanite present. Quartz (qz), biotite (bi), muscovite (mu), magnetite (mt). Magnification × 25; plane light.

in ragged plates and folia, with biotite and chlorite also present. Locally kyanite forms as much as 20 percent of the rock. This mineral is particularly abundant in localities to the northeast and south of the town of Itabira a short distance beyond the limits of the mapped area.

Feldspar is found in minor quantities in the typical quartz-muscovite gneiss, but some thin sections reveal more than 25 percent of this mineral. In such rock, the feldspars consist of plagioclase, microcline, and perthite, and occur in relatively large angular crystals isolated in a matrix of medium-grained to fine-grained mica. This rock is probably a metaarkose.

The fourth type of the granitic gneiss is dominantly a biotite-rich quartzose gneissic and schistose rock, with very pronounced foliation generally strongly crenulated. Petrographically, quartz-biotite gneiss and schist and quartz-biotite-chlorite gneiss and schist are the most abundant rocks, although quartz-biotite-hornblende schist, quartz-muscovite schist, and biotite-plagioclase schist also occur with the biotite-rich rocks.

In the thin sections examined, quartz ranges from 15 to 80 percent with the average in the rock as a whole perhaps 50–60 percent. It occurs in thin layers and lenses. The individual crystals are generally equidimensional, medium grained, and have been completely recrystallized. The quartz is interlayered with micaceous minerals. Biotite and chlorite are commonly interlaminated. (See figs. 19 and 20.)

Mixed rocks are formed at the contact of the granitic gneiss with other rocks. Generally these are too weathered to secure material suitable for thin sections, but two fresh specimens were secured near the contact of the gneiss with the large ultramafic body in the valley of the Rio do Peixe. This well foliated rock contains about 45 percent quartz, 38 percent hornblende, and 15 percent plagioclase (oligoclase). Garnet as porphyroblasts is a minor constituent.

The varied aspect of the granitic gneiss throughout the Itabira district is interpreted as reflecting two major factors: the original composition of the rocks and the varied intensity of their metamorphism. Thus, the quartz-muscovite gneiss is thought to have been originally a quartzite or arkose because of its composition and relict sedimentary structure. Whether the original quartzites were of Rio das Velhas series or of the Minas series cannot now be stated although the former seems more probable. It may be safely presumed that the large bodies of muscovite-quartz gneiss to the northeast and southeast were probably derived from the Rio das Velhas series because of their location and because of the apparently minor quantities of coarse basal quartzite of the Minas series in this part of the Quadrilátero Ferrífero. The quartz-biotite gneiss and schist was probably derived from the Rio das Velhas series which resemble them so much in certain phases and appear to grade into them along strike. These rocks were probably originally pelites and volcanic rocks.

The difference between the evenly but faintly foliated granitic rocks and those which show strong ptygmatic folding and abundant pegmatites seems to be merely a matter of degree, for the mineralogical composition is about the same and there is no evidence in the Itabira district for structural or stratigraphic unconformity between these two types. Trace element work to prove whether these rocks were igneous or metasedimentary in origin has not yet been attempted.

DISTRIBUTION

The distribution of the granitic gneiss may be observed on plate 1. The distribution of the four main rock types within the areas mapped as granitic gneiss is generally as follows:

The uncontorted granitoid gneiss may be encountered in most parts of the district where the unit crops out. Particularly good exposures are found in the quarries along the Rio do Peixe near Gabirobas, in the outcrops between Gabirobas and Itabira, along the Vitória á Minas railroad southeast of the Itabira railroad station, to the east of the Itabira substation on the Salto Grande powerline, and along the road from Campestre to the Borrachudos dam. Scattered exposures occur along the west edge of the district and in other localities. This type is the dominant rock of the granitic gneiss.

The contorted granitoid rock has a more restricted distribution and is found best exposed in and to the north of the larger of the two quarries northeast of Itabira and along the Itabira-Santa Maria de Itabira road.

The quartzitic gneiss and schist occurs from the Companhia Vale do Rio Doce S.A. farm (Chácara) in a widening band to the northeast. It also occurs in a restricted area south of the Rio do Peixe and just to the west of Conceição Peak.

The biotite-rich gneiss and schist is the second most abundant rock type. It is the most prevalent type to the south of the Itabira-Santa Barbara road west of Conceição and extends at least several kilometers to the south of the district. It is also found to the west of Conceição Peak mixed with the granitoid rocks.

Although the general distribution is as described above, the areas mentioned are not exclusively occupied by the dominant rock of that area, and examples of the other types and intermediate types between those described may be found.

CONTACTS AND AGE RELATIONS

Plate 1 shows that the granitic gneiss is in contact with all the other Precambrian rocks of the district. These contacts are believed to be intrusive ones. If this is correct, the granitic gneiss is the youngest Precambrian rock of the district except for the Borrachudos granite, which is intrusive into the gneiss.

In all known cases except three, only the granitoid granitic gneiss is present at the contact. The three known exceptions show quartz muscovite gneiss at the contact. However, exposures at the contact zone are generally so poor that it is possible that the other types of the granite gneiss may locally be present at the contact and not crop out. For example, south of Conceição Peak, no exposures of bedrock occur in some areas for more than 2 kilometers from the supposed location of the contact.

Over most of the border of the granitic gneiss body, the contact is with the Rio das Velhas series. Because the biotitic phase of that rock is most similar on weathered outcrop to the biotite schist phase of the granitic gneiss, which is believed to have been in part derived from the older rocks, considerable difficulty is encountered in differentiating the two rocks. The best criterion found by the writers was the presence of clear fresh muscovite of pegmatitic origin, which is commonly found in the soil covering the granitic gneiss and not in soil covering the Rio das Velhas series. The degree of feldspathization is another, less reliable, criterion.

The actual contact is exposed in few localities. A locality which is probably typical is that exposed in excavations for the new railroad about 200 meters north of the crossing of Dois Córregos by the old Itabira-Conceição road. Here the rocks are completely disaggregated and soft, and most of the minerals have been altered to clay. The exposure shows that the contact consists of a zone about 15 meters wide composed of mixed rock, with many remnants of red weathered biotite schist of the Rio das Velhas series in white and pink clayey material showing residual foliation, the common manifestation of weathered granitoid granitic gneiss. The two foliations are concordant. Many irregular white clay veins, shown by the coarse muscovite plates which they contain to be the remains of pegmatites, occur in the matrix. Toward the Rio das Velhas rocks, the white and pink clayey material gradually disappears, and toward the granitic gneiss, the red schist disappears. Pegmatites are found in the schistose rocks for only a few meters beyond the contact zone. It is not possible to state definitely whether a migmatization front exists here or whether it is strictly igneous contact; certainly there is a zone of mixed rock between the two major units. The Rio das Velhas series seems to strike into the granitic gneiss, if foliation is parallel to bedding. A hundred meters south of the contact, scattered outcrops of typical granitoid granitic gneiss occur. There is no evidence of faulting.

In a number of other localities, the pre-Minas metasedimentary rocks contain abundant high grade metamorphic minerals. This metamorphism is discussed on page C53.

Contacts between the granitic gneiss and the Minas series are more restricted and are very poorly exposed. The only exposure of the actual contact is along the road to the CVRD chácara. Here the contact is a fault contact, but it is believed that the fault is pre-granitic gneiss in age because the Minas series above the contact is altered by thermal metamorphism several tens of meters into the Piracicaba group and contains minor pegmatite veins. Quartz-muscovite gneiss, possibly representing the Caraça group, is against the Itabira group in this exposure.

In the railroad cut below the Morro do Cruzeiro similar and more pronounced contact metamorphic features are to be found in the Piracicaba group of the Minas series. Granitoid granitic gneiss is in contact with the Minas series at this locality. Thermal metamorphic minerals are common in the argillaceous rocks of the Minas series where that group of rocks is in juxtaposition with the granitic gneiss.

Along the road from Itabira to the larger of the two quarries northeast of Itabira, a few tens of meters beyond the turnoff from the Itabira-Santa Maria de Itabira road, a gneissic rock rich in hematite and magnetite occurs in contorted granitic gneiss. This rock resembles strongly metamorphosed itabirite. The occurrence is nearly on strike with the north limb of the Cauê syncline and is about 300 meters beyond the last known occurrence of the itabirite of this limb. It seems very probable that this hematitic and magnetitic gneiss was derived from Cauê itabirite by partial granitization or incomplete assimilation of the Minas series.

If this is the case (exposures are too sparse to permit certainty), it seems probable that the granitic gneiss is in intrusive and crosscutting contact with most of the Minas series and much of the Rio das Velhas series in this vicinity.

Elsewhere in the Quadrilátero Ferrífero, several cases are known in which foliated intrusive granitic rocks believed to be the equivalent of the granitic gneiss have engulfed blocks of Minas series rocks.

There is no doubt that some granitic gneisses in part of the Quadrilátero Ferrífero are younger than the Minas series. It is still an open question as to whether those granitic gneisses that are intrusive into the Minas elsewhere are contemporary with the gneissification which produced the "granitic gneiss" formation of the Itabira district. As a working hypothesis it seems more reasonable to assume a single post-Minas period of gneissification and intrusion, rather than two or more periods. No evidence has yet been found to indicate this hypothesis to be wrong. The seemingly gradational relations between the granitoid granitic gneiss, which is known to be post-Minas in the Itabira district and elsewhere, and the other types is the strongest positive evidence for the hypothesis.

BORRACHUDOS GRANITE

This name is proposed for the very coarse grained granitic rock that crops out in the falls and stream valley of Córrego de Borrachudos (pl. 1) on the northwest side of the major syncline dividing the Itabira district. This rock forms the entire northwest boundary of the district and continues for an unknown distance, but not less than 20 kilometers, to the northeast and about 10 kilometers to the southwest of the Itabira district. Northwest of the type locality, the Borrachudos measures about 5 kilometers across the long axis of the body.

A very similar rock crops out near the Peti dam of the Companhia Fôrça e Luz, between São Gonçalo de Rio Abaixo and Santa Barbara and it may occur elsewhere in the Quadrilátero Ferrífero.

The rock crops out boldly and over large areas. It is very massive and practically unjointed, so that chemical weathering can attack it only with difficulty. The granitic gneiss is generally much less resistant to weathering and the Borrachudos granite therefore locally forms imposing scarps and crags above the softer gneissic rock near the contacts.

LITHOLOGY

The Borrachudos granite is a light-gray, coarse-grained, faintly foliated rock with a strong linear structure imparted by the alinement of elongate biotite clusters and aggregates. In the Itabira district this lineation is everywhere within 5° of east, and it is known that this direction of lineation is maintained for many kilometers to the northeast outside the district. Foliation is too indistinct to be measured.

The dominant minerals in the rock are quartz, orthoclase, microcline, albite, oligoclase, and biotite. Accessory minerals are fluorite, muscovite, garnet, epidote, clinozoisite, tourmaline, ilmenite, leucoxene, chlorite, and possibly magnetite. Petrographically, the rock

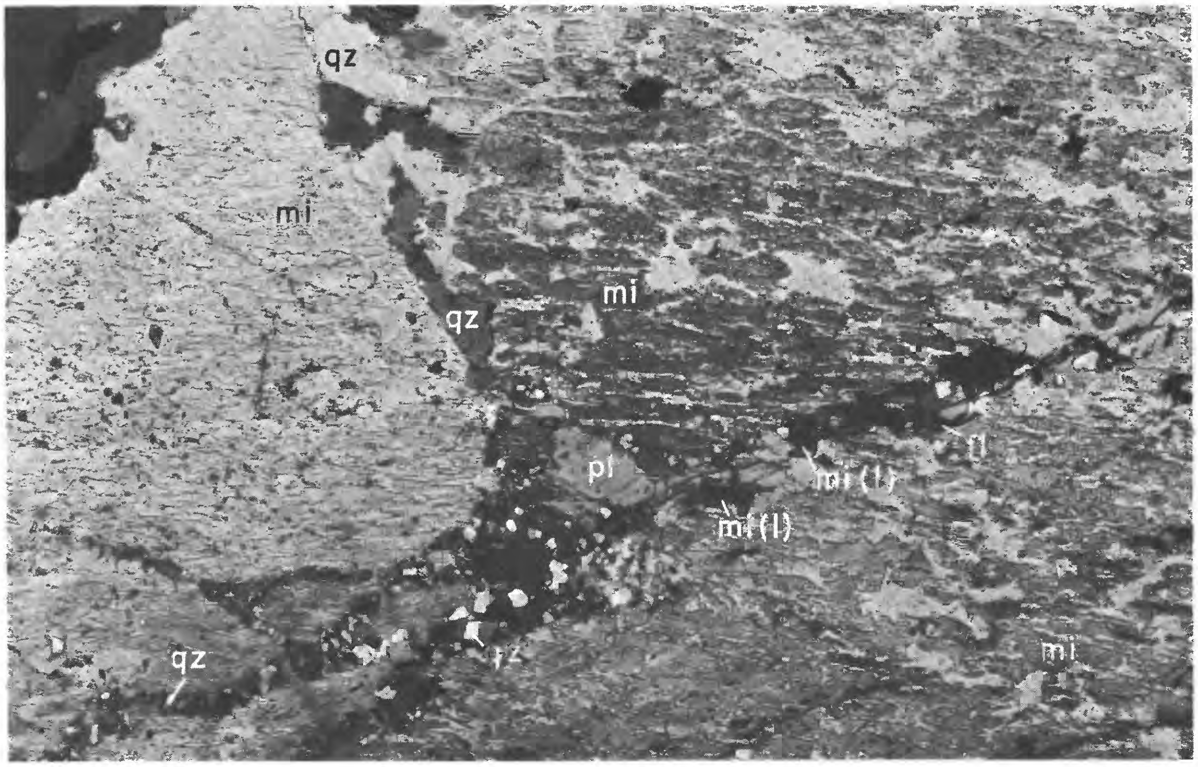


FIGURE 21.—Photomicrograph of the Borrachudos granite showing typical mottling of intergrown feldspars and veining by late quartz. Traces of epidote with the quartz and also fluorite with the quartz. An igneous rock? Microcline (mi), quartz (qz), plagioclase (pl), fluorite (fl), late microcline (mi(l)). Magnification × 50; crossed nicols.

varies between granite and quartz monzonite, depending on the relative percentage of potassium feldspar. Because of the coarse grain of the rock, thin sections make a poor sample. In the thin sections studied, feldspar ranged from 45 to 75 percent and quartz from 30 to 45 percent. Half or more of the feldspar is potassic. As much as 12 percent biotite was found but usually this mineral is much less abundant.

The grain size of the rock generally has relatively little variation. There are two phases of the rock, the dominant one characterized by microcline crystals that average perhaps a centimeter across and that range up to several centimeters in greatest diameter. A relatively finer phase contains microcline crystals that may average about half a centimeter across. This phase does not have the very large crystals of the coarser phase.

The two phases are rather intimately intermixed, but the finer seems to cut the coarser with dikelike relations. The intrusion, if such it was, of the finer into the coarser rock was before final consolidation of the rock, for contacts are sinuous and contorted and the finer masses are not tabular. Neither rock shows evidence of crushing. Compositionally, the two phases are indistinguishable.

The megascopic features which set the Borrachudos apart from other granitic rocks of the Quadrilátero Ferrífero with which the writers are familiar are the even coarse-grained porphyritic texture in the rock, the nearly ubiquitous fluorite, the strongly and uniformly oriented biotite clusters, without significant variation in direction, and the general gray cast with a pinkish undertone shown on fresh faces. Other rocks may have one or two of these features, but not all of them.

Certain microscopic features also set this rock apart. The feldspars are both vaguely and distinctly mottled and have perthitic or perthiticlike textures. The vaguely mottled feldspars are orthoclase with indistinct grid structures which may grade into patches of microcline with distinct grid structures (figs. 21, 22). The distinct mottling in part appears to be an ex-solution phenomenon, in part it is definitely the result of the replacement of oligoclase by orthoclase forming a true perthite in some cases, of oligoclase by albite in others.

The only completely unaltered feldspar in the Borrachudos granite is medium-grained microcline in groundmass seams between the larger feldspars. This appears to be microcline which crystallized late.

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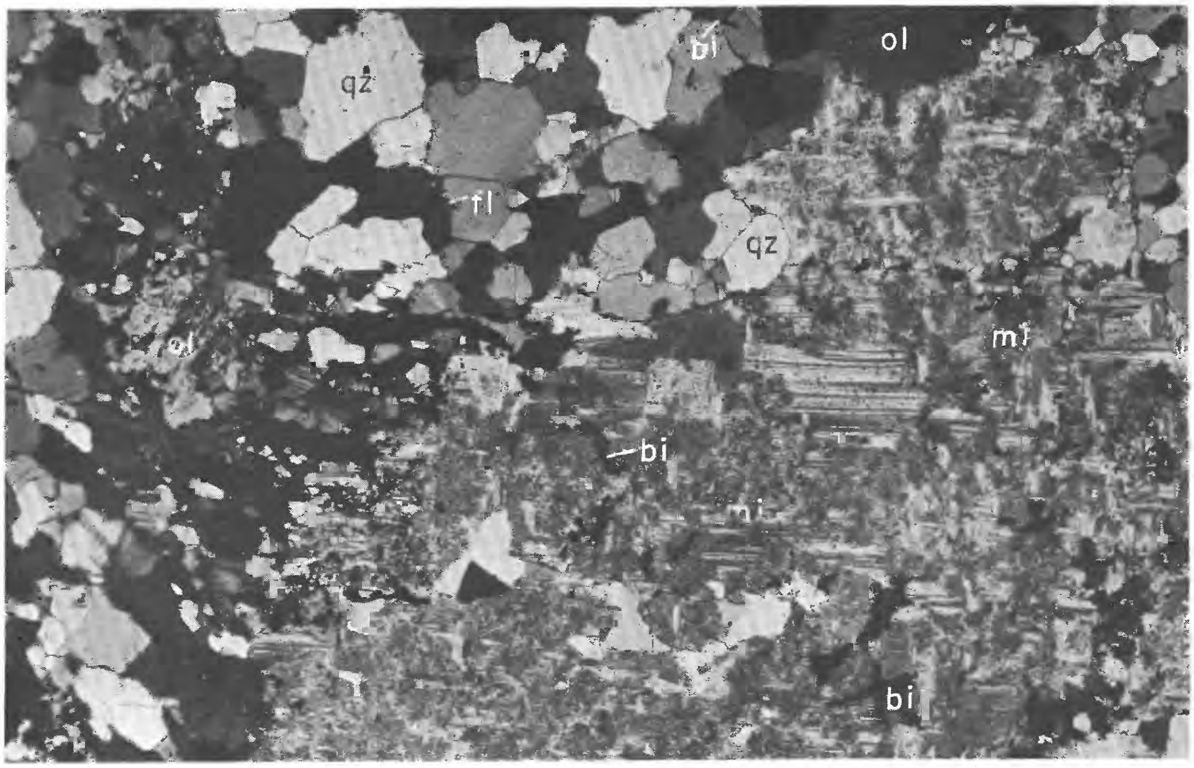

FIGURE 22.—Photomicrograph of Borrachudos granite showing small part of one large altered feldspar crystal, illustrating one phase of typical mottling and intergrowth of feldspars. Microline (mi), oligoclase (ol), quartz (qz), biotite (bi), fluorite (fl). Magnification × 25; crossed nicols.

The groundmass of the rock is composed of fine- to medium-grained quartz intergrown with small amounts of feldspar and mica. The groundmass forms irregular narrow seams and pockets between the large feldspar crystals and locally traverses fractures across them. Fluorite occurs along the edges of the groundmass and is not uncommon in ragged-edged blebs in the larger feldspar crystals.

The biotite aggregates, which in hand specimen may be observed to occur as elongate irregular masses as much as a centimeter or more in length, are seen in thin section to consist of blocky and podlike forms with unstrained quartz. Ilmenite with leucoxene rims occupies the central part of some of the biotite aggregates.

The alterations and replacements in the feldspars cited here cannot be the result of regional metamorphism, for the adjacent granitic gneiss shows no such features. These features are rather those to be expected from late-stage residual solutions rich in mineralizers, as indicated by the fluorite and by the contrast in grain size between the feldspars and the groundmass. The residual solutions must have been relatively enriched in potash and soda.

A puzzling fact, however, is the complete absence of pegmatites either in the Borrachudos granite or in the wallrocks. The lack of joints and the very coarse grain size of the rock may imply deepseated emplacement; possibly the fluids which could be expected to form pegmatites escaped upwards during the crystallization of the rock, or perhaps they stayed in the rock without becoming localized in fractures to form conventional pegmatites, as the very coarse grained rock is pegmatoid throughout.

AGE RELATIONS

The excellent exposures of the Borrachudos granite would certainly have revealed any intrusion of dike rock, amphibolite, or xenoliths of other rocks which might have been included in it. However, the only rock foreign to the formation which was found by thorough search was a thin diabase dike that was also found to cut the nearby granitic gneiss.

The contact of the Borrachudos granite with the granitic gneiss is nowhere exposed, although it can be localized within a few meters in some localities. With one exception, no diminution in grain size or other normal contact features of igneous rocks were found in either formation. In the one exception, which is near the contact, the Borrachudos was found to be much finer grained and better foliated than in most localities.

Just to the northeast of the north edge of the mapped area, the Borrachudos engulfs or surrounds a moderately large body of granitic gneiss; outcrops are sparse and relations in this area are not clearcut.

The Borrachudos granite is thought to be younger than the granitic gneiss on the basis of the tenuous evidence cited above and also because it is evidently younger than the latest metamorphism. There is no internal evidence for regional metamorphic stresses. The very faint foliation, too faint to be measured in the field, cannot result from stresses which were competent to impose strong foliation on all the other rocks of the district, but must come from movements during emplacement of the rock. Similarly, the constancy of direction of the linear structure in the late-crystallizing biotite cannot result from the folding which imposed foliation and linear structure which vary in direction in all the other rocks, but must come from mild directed stresses during crystallization of the rock.

Possibly the Borrachudos granite may represent a late stage, potassic, igneous granite of the type discussed by H. H. Read in his notable contribution entitled "Granite Series in Mobile Belts" (1955). The granitic gneiss may then represent the sodic type of granite resulting largely from granitization processes earlier in the granite cycle. Absolute age determinations by Hurley (1958) assign an age of 475 million years to a specimen of the Borrachudos granite and an age of 500–550 million years to the granitic gneiss, which seems to confirm Read's hypothesis and our interpretations of field relations.

DIKES

There are several types of dike rocks in the Itabira district but poor exposures conceal relations between the various types. Because the dike rocks weather easily, there are no natural exposures and continuity along strike cannot be proved except in those cases where artificial exposures fortuitously cut the same dike in several places. Undoubtedly, many more dikes exist than were found.

The dike rocks in the district have been divided into three categories, the metamorphosed mafic dikes, the pegmatites, and the unmetamorphosed mafic dikes.

The only criterion as to relative age of these different types of dike rocks is the rather uncertain one of metamorphic grade. On this basis, it is believed that the metamorphosed mafic dikes are probably the oldest, the pegmatite dikes the next, and the unmetamorphosed mafic dikes the youngest. For reasons which will be apparent below, it is believed that the metamorphosed mafic dikes were intruded during the metamorphic process, possibly in the middle or later stages. The pegmatites are thought to have been intruded after the granitic gneiss had been emplaced and cooled enough to maintain fractures with regular walls. Because the granitic gneiss is foliated, this must have occurred in the waning stages of metamorphism. The pegmatites are not foliated. The unmetamorphosed mafic dikes may be related to the Mesozoic volcanism which had its center to the west and thus would be much younger than the other types.

METAMORPHOSED MAFIC DIKES

The oldest set of dikes in the area are possibly those in the Itabira group which are exposed in the underground exploration, the mine faces, and the road cuts on Cauê, Dois Córregos, and Conceição peaks (pl. 2). It is probable that they occur in other rocks and were not distinguished during field mapping, owing to complete weathering.

These dikes are so badly altered that their original composition is conjectural. They are now largely composed of talc with local quartz pods and locally much hematite in grains and angular rock fragments. Tourmaline is a rare accessory mineral. The dikes range in color from green through tan to yellow, and were evidently once a medium-grained rock.

That the dikes are postore in age and therefore can have had no influence in ore formation is proved by the included hematite and by relations between the dikes and wallrocks. The best place to observe the included hematite fragments is in the sharp turn in the Sixpercent road just above the 1,100-level on Cauê Peak. Here the dike rock locally contains nearly 30 percent hematite in grains ranging from less than a millimeter to foliated angular fragments (orientation random) up to 2 centimeters across, apparently torn from the walls of the ore bodies traversed by the dike. In underground mines 6 (pl. 3) and 7 (pl. 4), the dike material can be observed injected into the hard hematite wallrock along joints and fractures, in a few places for several meters.

The dikes are everywhere somewhat foliated and schistose. In fact, they have been mistaken for schist interbeds in the iron-formation by some geologists. Once the relations have been mapped, however, it is obvious that they crosscut the sedimentary structure and are intrusive (see pl. 3). The schistosity of the dikes is parallel to that of the iron-formation, not to the trend of the dike itself, indication that the final deformation was imposed after the dikes had been emplaced. Because of the talcose composition of the rock, no great stress was needed to make the rock schistose. In mine 6, some of these dikes can be traced for 200 meters or so in the various drifts and crosscuts. The altered state of the dikes make them very dangerous in underground workings. Caving is frequent even when the timbering is new; the majority of inaccessible workings have caved at dikes.

It is probable that these dikes were originally mafic rocks and that they were completely altered by deuteric or other solutions of hypogene origin shortly after emplacement.

PEGMATITES

The second oldest dike rocks in the area are probably the pegmatite veins and pods which cut the Rio das Velhas series, the Minas series, and the granitic gneiss. These pegmatites are generally composed of quartz and feldspar, now altered to kaolin,[6] with minor muscovite. These dikes are generally only a few centimeters or less in thickness and seem to have little continuity along strike. Along the Campestre-Santa Barbara road near Dois Córregos, a pegmatite dike several meters thick composed of quartz and white clay is exposed in a roadcut in the Rio das Velhas series. This is the widest individual pegmatite dike found in the area. Another wide pegmatite dike with much muscovite occurs along the Sixpercent road just below the scarp of Cauê Peak on the northwest side.

These pegmatites are undoubtedly related to the formation of the granitic gneiss rather than to the emplacement of the Borrachudos granite because no pegmatites have been observed in the Borrachudos granite whereas they are abundant in the granitic gneiss. Moreover, pegmatites in the older metasedimentary rocks are much more plentiful close to the contact of those rocks with the granitic gneiss.

As exposed in the fresh rocks of the quarries in the granitic gneiss, the pegmatites can be observed to intersect each other and the host rock. Contorted granitoid gneiss generally has abundant pegmatites with no particular preferred orientation. They thicken and thin abruptly, to a considerable extent follow the contorted structure of the host rock, and locally have indefinite walls. Some pegmatites in this rock tend to be more tabular and veinlike and cut the other rocks, possibly indicating a later phase. These latter pegmatites are richer in quartz and poorer in feldspar than the concordant pegmatites. In uncontorted granitic gneiss, the pegmatites tend to follow the foliation of the rock. Here too there seem to be at least two ages of the pegmatites, the older concordant, feldspar-rich, and containing calcite and chalcopyrite in large but sparse blebs; the younger cutting the older rocks at low angles and richer in quartz. None of the pegmatites are rich in muscovite, but all contain small quantities of that mineral. These pegmatites are all less than a meter thick and average less than 10 centimeters. Rarely, the pegmatites are zoned on a minor scale and show quartz cores.

Pegmatites seem sparse and irregular in the other two facies of the granitic gneiss. However, the other two facies are rarely observed in fresh outcrop. The weathered outcrops of the granitoid granitic gneiss rarely reveal abundant pegmatite dikes, and so it is thought that the scarcity of such dikes in the other types may be more apparent than real.

The pegmatite dikes and pods found in the weathered metasedimentary rocks near the contact with the granitic gneiss are, with the two exceptions cited above, uniformly thin (less than 5 centimeters) and discontinuous. They are characteristically poor in muscovite, and only their texture and mineralogical composition proves that they are pegmatitic in origin. They are apparently identical with the clay-quartz veins which can be traced into pegmatite dikes in the fresh exposures of granitic gneiss.

The pegmatite dikes are of no economic interest and are of importance only in that they definitely prove post-Minas granitic activity.

POSTMETAMORPHIC MAFIC ROCKS

There are two types of unfoliated dikes in the Itabira district. The diabase dike which was mentioned above as cutting the Borrachudos granite is typical of one type. The other is of gabbroic composition and occurs in larger bodies with chilled walls. It is believed that these two rocks are comagmatic. Throughout the whole Quadrilátero Ferrífero these two types of rock are common, and there seem to be gradational phases between the diabasic texture and the gabbroic texture. As elsewhere, in the Itabira district the diabase dikes are generally thin (0.5 to 5 m), but where exposures permit, they can be traced for some distance. The diabase dike which is exposed in an outcrop on the main road near Dois Córregos can be found at widely separated intervals for about a kilometer to the south-southeast.

Petrographically, this rock is a diabase. The two specimens studied contain between 50 and 65 percent plagioclase (An_{58-70}) and about 20 percent pigeonitic pyroxene, with chlorite forming 5 to 15 percent and magnetite 5 to 10 percent of the rocks. The chlorite is believed to have formed from deuteric alteration of the plagioclase. The texture of the rock is typically diabasic. It is completely unfoliated.

The gabbroic bodies seem to be individually thicker but cannot be traced any great distance. The best

[6] Identity based on several X-ray determinations made by E. Tavora, Departmento Nacional de Produção Mineral.

example of this medium-grained rock is found a few tens of meters east of the east portal of the tunnel carrying the Companhia Vale do Rio Doce S.A. water supply under the pass from Borrachudos to Campestre.[7] The rock is in schists of the Rio das Velhas series and in granitic gneiss, has a chilled border phase, and must occupy an area not less than 75 meters wide. If, as is believed, the diabase dikes and this gabbroic rock are comagmatic, it would appear that there is a relation between the rock type and the size and shape of the intrusive bodies.

These rocks, being unfoliated, must be later than the last metamorphism. They may be late Paleozoic or, as has been suggested by several geologists, may well be related to the vast Mesozoic plateau basalt eruptions which resulted in the tremendous Paraná lava field, the present edge of which lies several hundred kilometers to the west.

QUARTZ VEINS

In the Itabira district, as in the Quadrilátero Ferrífero as a whole, quartz veins are very common and may have formed at several periods in the history of the rocks. In this section, quartz veins which are thought to have formed in four environments will be described. These are: (1) the quartz veins intimately related to the ultramafic rocks; (2) those thought to result from the regional metamorphism of the granitic gneiss and other rocks; (3) those formed during the emplacement of the Borrachudos granite; and (4) the gold-bearing hydrothermal quartz veins.

(1) Veins related to the ultramafic rocks:

The presence of a large body of massive vein quartz near the boundary of the steatite and amphibolite bodies described above can be noted in the valley of Córrego de Conceição (pl. 1). A similar body occurs just south of the mapped area and south of Conceição Peak. Many smaller bodies of similar material that were not mapped may be found along this contact.

This quartz is the variety known to miners as bull quartz. It is milky white, contains no euhedral quartz crystals, no feldspar, no sulfides, no carbonates, and no silicates. The bodies are evidently not tabular, but irregular and pod shaped. This type of quartz may occur in large masses. The largest mass in this district is as much as 100 meters across and single boulders of bull quartz in Córrego de Conceição measure 10 by 5 by 5 meters as exposed above ground.

[7] Considerable areas are underlain by similar gabbroic rocks, some much coarser grained, in an area lying about 20–30 kilometers to the northwest of the Itabira district. Reference to these rocks has not been seen in the literature. These rocks are apparently similar to the large gabbroic intrusions near Serro and to the northeast of Diamantina.

These quartz bodies are commonly not within the soapstone itself, but in the adjacent wallrocks. The nature of the wallrocks does not seem to be critical. The association between the bull-quartz bodies and the soapstone is so typical that the presence of large quartz boulders is in many cases the first indication that the field geologist has of the presence of soapstone. A close genetic connection between the two rock types is indicated by this association. Large massive bodies of bull quartz not associated with soapstone are not known, although of course, fairly large through-going tabular quartz veins entirely unrelated to soapstone do occur.

The following explanation of the genesis of this type of quartz follows to a considerable extent a theory by J. E. Gair and is an extension of the classical theories of soapstone formation discussed by Turner (1948).

It will be recalled that the altered ultramafic rocks were believed on petrographic grounds to have originally consisted of dunite or peridotite and that they are thought to have been altered to the present rocks, steatite and serpentinite, either by deuteric solutions or by hydrothermal solutions. It will be remembered also that considerable percentages of magnesite occur in the altered ultramafic rocks, locally as much as 25 percent, although the average is much less. Such a considerable percentage of magnesite in the rocks seems to demand either a high concentration of CO_2 in the residual solutions or the introduction of CO_2 on a large scale by later hydrothermal waters. Similarly, the formation of talc from serpentine (as was indicated by mutual relations between these two minerals in the thin sections) demands the introduction of SiO_2 or CO_2 or both. Turner (1948, p. 132) gives two hypothetical equations illustrating possible reactions in the formation of talc from serpentine either by the addition of SiO_2 or of CO_2.

(1)
$$\underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + 1.16\ SiO_2 \rightarrow 0.79\ \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + 0.63\ MgO + \underset{\text{In solution}}{1.21\ H_2O}$$

(2)
$$2\ \underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + 3\ CO_2 \rightarrow \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + 3\ \underset{\text{Magnesite}}{MgCO_3} + 3\ H_2O$$

Gair points out that, if the solutions contained both carbon dioxide and silica, the MgO produced by the first equation would react with the CO_2 to form magnesite also.

It seems probable, given the relatively high magnesite content of the rock, that the altering solutions contained carbon dioxide. As Turner's equation showed, it is also possible that they contained silica. The silica of the peripheral quartz deposits is believed to have been derived from the solutions which altered the original olivine and serpentine to talc. It is possible that the silica might have been picked up by the solutions in the process of altering olivine to serpentine.

Thus the alteration was originally from olivine to serpentine, followed by the alteration of serpentine to talc, all the CO_2 going into magnesite. As the rock became more completely altered, relatively little unaltered serpentine remained and this may have selectively reacted with the CO_2 in the solutions rather than with the SiO_2. Talc and more magnesite would be formed. The SiO_2 would in this case reach the peripheries of the body, where, under changed environmental conditions, it would be deposited in the wallrocks.

No clear indication as to whether the solutions were of hydrothermal or deuteric origin is known. Because the ultramafic magmas are generally considered to be poor in water, because the presence of excess silica in the subsilicic magma is not probable, and because adequate sources for hydrothermal solutions which commonly carry silica are to be found in the later intrusive rocks of the region, it seems probable to the writers that the alteration of the ultramafic rocks and the formation of these large quartz bodies are best referred to hydrothermal activity. Such hydrothermal activity may possibly be related to the emplacement of the granitic gneiss for, on a regional basis as well as in the Itabira district, the more serpentinitic ultramafic bodies seem to be farther removed from the granitic gneiss and the bull quartz bodies are commonly associated with the more talcose rocks.

(2) Quartz veins resulting from the regional metamorphism of metasedimentary rocks:

Characteristic of all the metasedimentary rocks of the Itabira district, except the high-grade hematite deposits, are numerous short, irregular veins of quartz. Most of these veins are at maximum a meter or two long. Many are shorter, although some are as long as 10 meters. The thickness ranges from 1 to 10 or more centimeters. Such veins are concordant with foliation, crosscutting, or both. In many cases they are actually irregular bunches and pods rather than veins. In most rocks they contain only quartz; no feldspar or sulfide minerals have been found associated with them. The veins are most abundant in the more quartzose rocks and in the granitic gneiss; in the purer phyllites and nonquartzose schists they are relatively rare.

In the Cauê itabirite, the laminae of quartz making up the siliceous part of the iron-formation may grade with no megascopically visible change in grain size and with no apparent boundary into thin (0.5–2.0 cm) veins of quartz which cut the iron-rich layers of the iron-formation at moderate to right angles. Locally, delicate flakes of coarse specularite may cross the vein in continuity with the more finely grained hematite of the iron-rich layers. In thin section, some of these veins were seen to have a coarser texture than the quartz laminae, however. Such veins in the itabirite range in length from a few centimeters to as much as a meter and often disappear by grading into one of the quartz laminae.

A common characteristic of these veins in all the rocks is that they are discontinuous and do not seem to be connected with through-going fractures or fissures. No general relation to folds could be deciphered, although in a number of cases such veins are on or near axes of minor folds. Thus, in itabirite, the quartz laminae are recrystallized in the axial regions of minor tight folds into coarse "vein" quartz in many cases.

This type of quartz vein is therefore thought to be formed during the regional metamorphism of the rocks and the quartz of the veins to have been derived from the rocks immediately adjacent to their present location. No reason to believe that the quartz had been derived from faraway sources at depth was found. The process would be one of metamorphic differentiation, whereby the silica was mobilized under the prevailing temperatures and stresses which led to the regional metamorphism of the rock, transported short distances to areas of lower stress, and there deposited. At least some replacement of the wallrocks is indicated by the thin and delicate folia of specularite across the veinlets in itabirite, previously cited. There is no evidence that replacement was also operative in the case of the schistose rocks, but it may well have been.

(3) Quartz veins formed in the Borrachudos granite:

The Borrachudos granite is cut by quartz veins which are thought to be genetically related to that rock. These veins are thin (1–5 cm), short, rarely more than a few meters, and locally highly contorted in a manner similar to the contortions of contacts between the finer and coarser phases of the rock mentioned previously. The larger feldspars grow out from the walls with euhedral faces into the vein material, and there is a slight concentration of fluorite along the contacts of the veins with the granite. It is believed that the veins represent a very late stage of crystallization of the magma which formed the granite. The intricate folds of the quartz veins, when related to the lack of cataclastic textures of the rock and the contact features described, indicate that the folds represent presolidification adjustments in the nearly completely crystallized rock.

(4) Quartz veins of hydrothermal origin:

All the rocks older than the Borrachudos granite are cut by quartz veins which reach a maximum thickness of at least a meter. Some of these veins have been faulted and they are therefore older than the last structural adjustments in the district.

No sulfide minerals have been seen in these veins, but it seems probable that they may have once contained such minerals because they are often iron stained and a few voids, suggestive in shape of pyrite crystals, have been observed. Elsewhere in the Quadrilátero Ferrífero sulfide-bearing veins have been mined for their gold and arsenic content, but there is no way of proving a correlation of the veins in the Itabira district with those elsewhere. In the Itabira district, some quartz veins have been mined for gold.

STRUCTURE

FOLDS IN THE MINAS SERIES

Folds are the major tectonic and structural feature of the Itabira district. The folds range widely in amplitude, and it will be helpful in their analysis to define a few general terms.

(1) A major syncline transects the district. Its identity is clearly defined for 11 kilometers. Southwest of Conceição creek, this syncline will be called the Conceição syncline. It is convenient to separate this part of the syncline from the remainder because it is similar in magnitude, behaves in a similar manner structurally, and is the locus of ore formation similar in magnitude and genesis to the "medium-scale folds."

(2) Medium-scale folds include the Dois Córregos and Cauê synclines and the Chacrinha and Piriquito anticlines. These maintain their identity for 1 to 3 kilometers. The Conceição syncline is included in this category.

(3) Smaller folds include the folds superimposed on those of the previous category, such as those revealed by the outcrop pattern of the Piracicaba group. These may maintain their identity for more than a kilometer.

(4) Minor folds are those too small to show on the map. They range from a few millimeters to a few tens of meters in amplitude.

The major syncline is well defined throughout its extent except for the area between Dois Córregos and Morro do Cruzeiro. Here the northwest limb is clearly defined, but the place where the southeast limb should be present is everywhere covered by the old red lateritic soil described above or by yellow and brown soil formed by the disintegrating rocks. For more than 2 kilometers key horizon markers in the bedrock are hidden.

To locate the Cauê itabirite under the soil cover, a series of traverses with a Hotchkiss Superdip were made in the hope that the irregularly and weakly magnetic iron-formation could be located. Anomalies were found where they would be expected for about 800 meters southwest of Morro do Cruzeiro, but southwest of the road up Grota de Esmeril no anomalies were found. This might be caused by soil cover too deep for effective use of the instrument, by invasion of this limb of the syncline by the granitic gneiss and destruction of the iron-formation, or by squeezing of the iron-formation to such thinness that it could not be located. This limb is squeezed to only a few meters thickness in the town of Itabira.

Another locality in which the structure as depicted in plate 1 is not clearly understood is on the Serrinha hill, just to the northeast of Campestre. Here the Cauê itabirite seems to thicken abruptly. Inadequate exposures prevent certainty, but it seems probable that the formation is repeated by folding, possibly reflecting complications caused by the Chacrinha anticline.

With the exception of these two uncertainties and the locational uncertainties caused by poor exposures at the east end of the Cauê syncline, the structure of the district is believed to be reasonably well defined.

A series of 66 structure sections through the Cauê itabirite, many of them through the various medium and small folds, were prepared to illustrate the distribution of iron ore (pl. 8). The sections, in conjunction with plate 2, which shows in detail the areal distribution of the Cauê itabirite in the district, illustrate the tectonic style of these rocks as shown by surface and underground data. They show that the Conceição syncline is in part isoclinal and overturned, the Dois Córregos syncline is overturned but not isoclinal, and that the Cauê syncline is open and shallow.

The outcrop pattern shows that the keel zone of the medium-scale synclinal folds is characterized by a notable thickening of the Cauê itabirite. Conversely, the flanks of these folds and of the major syncline locally have a notable thinning of the Cauê itabirite away from the keel zone. Generally speaking, the tighter the medium or large scale fold, the greater the thinning of the flanks and, probably, the greater the thickening of the axial zones.

The apparent variation in thickness of the Cauê itabirite in the Conceição syncline ranges from about 20 meters at Córrego de Conceição to at least 400 meters in the axial zone at Conceição Peak, some 2,000 meters west. Other notable variations may be observed on plate 2.

Three possible causes for this variation may exist: 1, differences in primary sedimentation; 2, repetition of the Cauê itabirite as a whole by folding; and 3, plastic flow of the material in the Cauê itabirite from high pressure areas of the folds to low pressure areas.

(1) There is no reason to believe that a chemical sediment such as the Cauê itabirite would vary abruptly and erratically in thickness, particularly one which is deposited on a regional scale. Examples are the Biwabik iron-formation on the Mesaba range or the Ironwood iron-formation on the Gogebic range in the United States. The Cauê itabirite does not characteristically vary abruptly in thickness in the Quadrilátero Ferrífero except in areas of structural complexity.

(2) Elsewhere in the Quadrilátero Ferrífero, there may well be repetition by folding of the Cauê itabirite as a whole in a number of places. However, in the Itabira district this is not thought to be the cause of the thickening because the trace of the base of the formation is smooth and regular, and shows none of the minor deviations which would be expected to be present were the formation as a whole tightly folded. The basal contact is accurately located in most cases and, were such deviations present, they would have been found. Moreover, the extreme thinning of the formation, which would not be caused by simple folding, suggests that the thickening must be related to some process other than repetition by folding.

(3) It is therefore believed that the thickening and thinning of the Cauê itabirite was caused by solid plastic flow of material from high pressure areas of the folds to low pressure areas. The even trace of the bottom of the formation and the nearly bulbous shape of the keel zone in the tightly folded Conceição syncline strongly indicate this. The thickening and thinning cited above also indicate it. The internal folding and crenulation of the iron-formation in the axial areas and the strong lineation and squeezing on the flanks of the folds, features that are characteristic, indicate plastic flow. Minor structures and crenulations in the itabirite characteristically show thickening on the crests and keels of folds and thinning on flanks which can only result from small-scale plastic flow similar to that in the formation as a whole.

The tremendous amount of material physically transported by this means may be judged by the differences in thickness cited above.

Although in the medium and large scale folds notable thickening by plastic flow took place in the axial zones, smaller folds are superimposed upon them which, away from the axial zone, cause repetition of part of the Cauê itabirite. Thus, in the Conceição syncline, the upper part must be repeated by folding four times in the area east of the peak. The long thin septa of Piracicaba group shown on plate 1 are infolded, tightly compressed synclines, separated by a tightly compressed anticline of Cauê itabirite.

The trace of the outcrop of the base of the formation proves that these folds affect only the upper part of the Itabira group. They are the type of folds which are to be expected in an isoclinally folded plastic formation. The open fold of the Cauê syncline is modified at its east end by a subordinate anticlinal fold which, were the Cauê syncline compressed to the same extent as the Conceição syncline, would produce an identical type of outcrop pattern as that found in the latter.

Inspection of the district maps shows a close relation between the degree of compression of the medium and small scale folds and their position with regard to the axis of the major syncline. The closer to that axis, the tighter is the medium or small scale fold. In all cases in which comparison may be made, the southeast limb of the folds is the more sheared.

LINEAR STRUCTURE AND DEPTH OF SYNCLINES

A prominent linear structure in the rocks of the district is formed by the parallelism of axes of minor folds and crenulations, the intersection of fracture cleavages, the orientation of elongate minerals and mineral aggregates, the orientation of pebbles in conglomerates, and the orientation of elongate pipes of quartz in the itabirite where this rock has been strongly squeezed. All these elements are mutually consistent. With isolated exceptions, this linear structure plunges generally toward the east at angles ranging from 10° to 40°.

There is no direct information as to the depth to which the east-plunging synclines may extend. No prospecting has been directed toward resolving this question. The only available evidence bearing on it is the plunge of the linear structure and the dip of the Cauê itabirite at its outcrop on the keels of the synclines.

Because minor structures related to the major structures usually are fairly reliable guides to those major structures, it is believed that the linear structure may be used for rough calculation of the depth to which the major and medium-scale synclines may extend. The use of the linear structure to predict depth gives results generally consistent with those arrived at by using the apparent dip of the base of Cauê itabirite in the vicinity of the outcrop of the keels of the folds. The Conceição syncline seems to plunge between 30° and 40° to the northeast, the Dois Córregos syncline between 20° and 35° to the northeast, and the Cauê syncline between 15° and 25° to the east. Linear structure on the southeast limb of the major syncline away from the Conceição area plunges between 15° and 30°. At Córrego de Conceição, the keel of the major syncline must be about 800 meters below the outcrop. At Dois Córregos creek, it may be as much as 1,500 meters below the outcrop, taking into account the flattening of the pitch to the northeast.

ORIGIN OF CRENULATIONS IN IRON-FORMATION

The iron-formation, not only in the Itabira district but throughout the Quadrilátero Ferrífero, is characterized both by erratic and systematic minor folds and crenulations of great complexity. These folds have amplitudes ranging from millimeters to tens of centimeters. Many are isoclinal, with the axial plane subparallel to the bedding planes. Such folds may involve a minor stratigraphic thickness, with the under- and overlying beds undisturbed. Folding of this type is characteristic of iron-formation throughout the world, and elsewhere has been attributed by some authors (Moore, 1946; Spencer and Percival, 1952, p. 381; Bond, 1952, p. 823) to preconsolidation slump, or plastic flow of the unconsolidated material. This explanation, although undoubtedly valid in some cases, is not the entire explanation either in the Itabira district or in the rest of the Quadrilátero Ferrífero. Here the fold axes are almost invariably parallel to the regional lineation and, in fact, produce that lineation in the iron-formation. It does not seem within the bounds of reasonable possibility that preconsolidation slump should always occur in the same direction over an area of thousands of square kilometers. It is even less probable that the direction of this slump would always be subparallel to linear structures in schists which are produced by the preferred orientation of acicular metamorphic minerals, and of folds, and of cleavage intersections in the schists and quartzites.

The minor folds and crenulations are evidently due to plastic flow of the rock after consolidation. They must be contemporaneous with the major regional folding which resulted in the imposition of the general east-trending linear structure. If preconsolidation slump did occur in this area, it has been effectively concealed by later tectonic deformation.

Under intense folding and progressive metamorphism, the rock slowly recrystallized and, as the crystals grew, the rock became brittle. The brittle rock shattered under stresses, producing breccia zones such as that found in mine 7 on Cauê Peak. The evidence for this is that early breccias are produced in semiplastic rocks and may be seen to be intimately related to intense overfolding which passed into small scale thrust faulting with miniature nappes, whereas the later breccias are connected with tabular, cross-structure faults, fractures, and fracture zones.

FOLDS IN OTHER ROCKS

The general accordance of the Rio das Velhas series with the Minas series was described in discussing the contacts between the two groups of rocks. It was concluded that a small angular unconformity probably exists, but that evidence for strong folding of the older rocks in pre-Minas time, such as occurred elsewhere in the Quadrilátero Ferrífero, is lacking. It was also brought out that the granitic gneiss was derived, in part at least, from the older sedimentary rocks and that its foliation is generally parallel to that of the rocks with which it is in contact.

Owing to the very scattered exposures and obscure bedding of the rocks other than the Minas series, perhaps the best proof of the reflection in these other rocks of the major folding so clearly shown in the Minas series is the course of the upper part of the Rio de Peixe. On plate 1, it may be seen that this stream rises to the north of Conceição Peak and flows in a semicircle around it, following the structure as would be expected. There is no evidence of reflection of the medium scale folds in the older rocks but, since these folds were undoubtedly synchronous with the major folding, no doubt the older rocks were similarly folded.

The Borrachudos granite is not marked by cataclastic textures. Moreover, the rock shows no influence of the structures in the Minas series in its outcrop pattern. This rock must have been emplaced after the folding had occurred and, judging by its generally straight trend, after the compressive stresses which produced the folding had been relaxed in large part. The remarkably uniform direction over tens of kilometers of the linear elements in this rock indicate that it crystallized under gentle directed regional stress. This stress might well have been connected with the emplacement of the rock.

FAULTS

Thrust faulting is unimportant in the Itabira district. The great thrust faults which may be traced elsewhere in the Quadrilátero Ferrífero for many kilometers are not present, possibly because in this district only the roots of deeply downfolded structures are exposed. The only thrust faults found are on a centimetric scale and result from overfolding of the plastic iron-formation and of the phyllites and schists.

High-angle faults crosscutting the major structural trends are present in several places (pl. 1). These are of not less than two ages, although definite proof of more than two ages is lacking.

There is no means of dating the cross-fault which offsets the northwest limb of the major syncline in the vicinity of the Piriquito ore deposits except as post-Minas.

The ore deposits, particularly those on Cauê Peak, are cut by several known faults. In mine 7, Cauê Peak, a broad zone of unenriched brecciated itabirite may be observed near the portal. The faults are not well enough exposed to work out their geometry, but one of them must have a displacement of not less than 50 meters, because a crosscut in mine 7 revealed a displacement of the footwall of at least that amount. Dikes are found along some of these faults.

A post-Borrachudos fault was mapped near the type locality of the formation. The unusual offset of the generally straight contact of that granite with the granitic gneiss is the chief indication of this fault.

It is probable that much more faulting exists in the district than was mapped. The lack of horizon markers in most of the rock precludes certainty as to faulting in most of the area and the stream pattern is such that few throughgoing features suggestive of faulting are to be found.

METAMORPHISM

All the rocks of the Itabira district, except those described as Tertiary and Quaternary, a few dikes, and the Borrachudos granite, have been metamorphosed. All the metamorphic rocks have been subjected to one period of regional metamorphism and the older rocks are thought to have been subject to two. Thermal metamorphism has affected the rocks near their contacts with the granitic gneiss.

A thorough petrographic study of the metamorphic characteristics of these rocks is precluded by the lack of fresh rocks for this purpose. No typical thermal metamorphic rock was seen which was coherent enough for cutting thin sections. Only a limited part of the Rio das Velhas series could be studied in thin section, and that part was complicated by proximity to the granitic gneiss. In the Minas series, only rocks of the Cauê itabirite were coherent enough for thin sections. Thus, most of the conclusions concerning metamorphism were based on megascopic observation of weathered rock in limited outcrops. These conclusions are therefore subject to modification resulting from study of less weathered rock elsewhere in the region.

REGIONAL METAMORPHISM

The rocks of the Rio das Velhas series are believed to have been subjected to regional metamorphism before the deposition of the overlying Minas series. This earlier metamorphism is thought to have been of greater intensity than the later one which affected the Minas series and therefore the later one can have had only minor (possibly retrograde) effects on the older rocks.

The first metamorphism is thought to have been the stronger because the bedding and other primary sedimentary features which are still well preserved in the younger rocks have been obliterated in the older ones in the Itabira district and, except in the quartzites and other nonsensitive rocks, generally in the Quadrilátero Ferrífero. The characteristic grain size in the older rocks seems considerably coarser than in the younger ones, with micas in aggregates of such size that they can easily be distinguished megascopically, whereas in the younger rocks the phyllites are composed of silky sericite in which the individual crystals and aggregates are too small to be distinguished except microscopically. The individual quartz grains in the older rocks of this district are characteristically coarser (except for the coarse clastic rocks) than in the Minas series.

Although these megascopic features perhaps are individually not diagnostic of two periods of metamorphism, collectively and in the regional context they are strongly suggestive of a metamorphic unconformity between the two rock groups. It may be argued that these features can be explained by metamorphic zoning; that the beds of the Minas series were not so deeply buried and therefore are not so highly metamorphosed. Were there any sign of such metamorphic zoning within the Minas series, were the rocks of the Caraça group more similar in their apparent metamorphic features to the immediately subjacent Rio das Velhas series rocks than to the more remote Piracicaba group rocks, this interpretation might be valid. Such, however, is not the case and no signs of dynamic metamorphic zoning related to stratigraphic position in the Minas series of this district are known.

The lack of thin section material in the pelitic rocks of the Minas series makes a close comparison of metamorphic facies impossible. However, the metasedimentary hornblende schists found in the older rocks have not been observed in the younger ones. Biotite is very abundant in the older rocks and has not been observed in the younger ones in this district. Sericite is the characteristic mica of the Minas series in the Itabira district. Chlorite is also a prominent rock-forming mineral of the older rocks which has not been definitely identified in the rocks of the Minas series. Thus, from a petrographic viewpoint, the presence of a metamorphic unconformity between the two groups of metasedimentary rocks is strongly suggested.

The post-Minas dynamic metamorphism probably occurred at lower temperatures than the earlier metamorphism and with a moderate depth of burial. The second metamorphism, based on present information, appears to have been relatively low grade. In those zones where temperature was locally raised well above the regional average by the intrusion of the granitic gneiss, the rock which was formed from the Minas series has aspects very similar to the majority of the Rio das Velhas series rocks.

Some of the granitic gneiss, particularly the unfoliated and slightly foliated rock, is thought to have formed from magma intimately intruded into other rock types. However, much of the biotite gneiss and schist and particularly the quartz-mica gneiss and gneissic meta-arkose is believed to have been formed by a combination of metasomatic alteration and dynamic metamorphism from rocks of the Rio das Velhas series and, to a lesser extent, from rocks of the Minas series. It is quite conceivable that gneissic rocks thought to be igneous in origin may have been derived from metasedimentary rocks by complete anatexis.

Although the rocks of the Minas series do not contain minerals indicating higher rank than low-grade dynamic metamorphism (the greenschist facies), caution must be exercised in assuming the conventional low-grade environment for these rocks. Yoder (1955) has shown that the presence of water in a metamorphic environment inhibits the formation of key minerals which, in an anhydrous environment, would normally form to indicate a higher metamorphic grade. James (oral communication, 1954) has measured the grain size of itabirite in the Itabira district and believes that this feature indicates a higher metamorphic rank than that of the green-schist facies. As will be discussed in later pages, there is reason to believe that the metamorphism of the Minas series was strongly affected by the presence of aqueous fluids. The writers believe that the metamorphic environment was higher than the greenschist facies indicated by the wallrocks and that indicator minerals did not form either because the composition was not right or, more probably, because the metamorphism took place in a wet environment.

THERMAL METAMORPHISM

Rocks of both the Rio das Velhas series and of the Minas series generally contain at their contact with the granitic gneiss a group of minerals rare in other parts of the district, and which are considered to indicate thermal metamorphism. These minerals include garnet, staurolite, and locally kyanite. The first two minerals, with few exceptions, do not occur outside a band of varying width which parallels the contact.[8] Maximum width of the band is approximately 200 meters. The contact minerals generally occur only in micaceous rocks which were probably originally pelitic rocks; none are to be found in itabirite[9] near the contact, and they are sparse or absent in the more quartzose rocks. However, these contact minerals may be found where the proper stratigraphic zone occurs in juxtaposition to the granitic gneiss and is not hidden by soil.

Thus, in the Minas series just northeast of Morro do Cruzeiro, the Cauê itabirite adjacent to the granitic gneiss contains no contact minerals and only sparse and thin pegmatites. Adjacent to the Cauê itabirite, the overlying Piracicaba group is highly quartzose; this zone contains a very few garnets, but the mica is much more coarsely crystalline than in outcrops of this zone elsewhere in the district. In the phyllites above the quartzose rock, a zone about 10 meters thick is encountered in which garnet and kyanite are found and in which they are locally very abundant. Stratigraphically above this zone, all signs of thermal metamorphism disappear. Along the road to the CVRD chácara similar relations are to be found, except that the micaceous quartzite in the Piracicaba above the Cauê itabirite is not coarsely recrystallized. Here the Minas series is in contact with quartz muscovite gneiss which probably acted as a shield between the intrusive granite and the Minas series, thus reducing the contact effects.

Commonly, the Rio das Velhas series rocks show stronger thermal metamorphic effects than the Minas series, probably because of the shielding effects of the inert itabirite in the Minas series or because of inappropriate composition of the Minas series rocks.

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[8] The spessartite garnets which were found in the Piracicaba group near the place where the main Campestre–Santa Barbara road crosses Dois Córregos are considered hydrothermal in origin and to be related to the manganese deposits of the vicinity, rather than to thermal metamorphism. Similarly, the quartz-kyanite veins of Chacrinha and elsewhere are thought to be hydrothermal in origin.

[9] This rock is evidently mineralogically nonreactive to metamorphic conditions. Itabirite surrounded by granite elsewhere in the Quadrilátero Ferrífero shows only moderate recrystallization and incomplete alteration of hematite to magnetite.

The garnet zones in the older rocks are much thicker and the garnets much larger. Excellent examples of the thermal metamorphic zone in these rocks are seen along the Itabira–Santa Maria road, and along the old road from Conceição to Itabira, where there are garnets as much as 2 centimeters in diameter.

Thin sections from drill cores in the Rio das Velhas series on Cauê Peak reveal some features, which could not survive in normal weathered outcrops, that indicate metasomatic activity in these rocks. The cores cut a series of schists intercalated with granitoid rock near the contact of the granitic gneiss with the older rocks, probably a transition zone between the two rock types. These schists contain porphyroblasts of feldspar, muscovite, carbonate, and tourmaline in mineral assemblages and textures suggestive of metasomatism of the schistose rock. Thus in one thin section of dolomite-quartz rock, large crystals of feldspar occur along what were assumed to be bedding planes. The edges of the feldspar anastamose around finer quartz and carbonate crystals. In other sections, ragged-edged porphyroblasts of feldspar are to be observed that are crossed by lines of inclusions continuous with layers in the fine-grained groundmass of the schists. Porphyroblasts of carbonate including quartz and biotite and astride boundaries of schistose layers are also to be found. Were fresh specimens of the rocks in the contact zones in other areas available for study, it is almost certain that much other petrographic evidence for thermal metasomatism could be cited.

IRON ORES

According to present usage, the term "ore" in the strict sense should be applied to material that can be mined and sold at a profit. The criterion changes from day to day and the term in this sense is useless in discussing a mining district which will have an active life of 50 to 100 years. Therefore the term "ore" will be used hereafter in a wider sense to indicate both material which is profitable to mine today and also material which, during the life of the district as a mining center, will probably become profitable to mine even though today it is not. In 1954 the only saleable iron ore was hard high-grade hematite that had an average tenor of 68.5 percent Fe. Material of this grade comprises only about 10 percent of the total reserves of easily mineable ferriferous material in the district.

Physical characteristics of iron ores are as important as chemical quality in determining their use and price; therefore it is necessary to consider both in detail in any discussion of the Itabira iron ores.

A wide variety of ore types is present in the Itabira district. For the purpose of this report, these can be divided into:

1. High-grade bedrock hematite
   a Hard ore
   b. Soft ore
   c. Intermediate ore
2. Rubble ore
3. Canga ore
4. Itabirite

Hard hematite ore is used as charge ore in open hearth furnaces. It is low in impurities and especially in silica. It is much sought after and premium prices are paid for it. The ore has sold (1951) for as much as U.S. $18.50 a ton FOB Vitória.

Soft hematite ore had found no export market up to 1955, probably because the limited transportation facilities were preempted by the more profitable hard hematite. It is used domestically in blast furnaces after sintering, with excellent results; and will probably enter the export market as soon as shipping facilities permit. This material will be an ideal raw material for direct reduction plants because of low percentage of impurities.

Intermediate ore is an ore that develops considerable "fines" during mining. It must be screened to produce saleable lump ore.

Rubble ore is a deposit of hard hematite boulders. It is shipped direct or may have to be screened to remove clay or other fines.

Canga, because of the high percentage of fines it produces and the relatively low iron (53–62 percent Fe) and high phosphorus (0.08–0.20 percent P) content, is not at present an export ore. It is successfully used in domestic charcoal blast furnaces, in which its light weight and easy reducibility are advantageous.

Itabirite, because of its high silica and relatively low iron content, will never be a direct shipping export ore. It can easily be concentrated to a 65–68 percent Fe product, however. These concentrates will also be of premium grade for the direct reduction process. Hard itabirite is now charged directly in domestic blast furnaces as a source of silica for slagging purposes.

HIGH-GRADE HEMATITE ORES

"High-grade" ore in the Quadrilátero Ferrífero is an ore averaging over 66 percent iron and having definite physical and chemical characteristics. There is much ore in the area that might be called high grade elsewhere because it averages between 58 and 66 percent iron. However, it has quite different physical and chemical characteristics from the plus 66 percent ore and should, therefore, be distinguished from the latter.

The high-grade hematite ore closely resembles the massive hematite and blue dust of India, the rich hematite ores of the Middleback ranges of Australia, the rich ores of the Fort Gouraud district in Mauritania, the rich ores of the Krivoi Rog district of Russia, and the El Pao district of Venezuela. The lower grade ore has more in common with the normal shipping ores of India, the ores of the Burnt Creek and similar bodies in Labrador, the Mesabi and similar ores of the United States, and the Cerro Bolivar ores of Venezuela.

"Hard" and "soft" are also relative terms. The hard high-grade ores of the Itabira district are not as tough, generally, as the hard ores from the western side of the ferriferous area. The latter are generally more granular and closely knit than the specular ores from the eastern part. The Itabira hard ores drill easily with ordinary drill steel, whereas carbide bits must be used to penetrate the hard ores of some other deposits.

A visual classification of the ore into hard, intermediate, and soft ore was made by the writers during the mapping. This subjective classification was based on the estimated percentage of material that would, after mechanized mining, crushing, and screening, be above one-half inch (the present lower size limit of saleable lump ore) in minimum dimension. The basis of the classification used is as follows:

		Percentages greater than one-half inch in diameter (*percent*)
Hard ore		100–75
Medium-hard ore	Intermediate ore	75–50
Medium-soft ore	Intermediate ore	50–25
Soft ore		25–0

These terms are not the most precisely descriptive imaginable, but, because they have been used for more than 50 years in the literature, they cannot be abandoned now. Ideally, "hard ore" is compact, tough, and hard. Ideally, "soft ore" is completely pulverulent. As a practical matter, except in relatively small bodies, no hard ore is completely hard and no soft ore is completely soft. Most of the "hard ore" exported from the Itabira district has actually been won by screening from ore which, in the ground, would be classed as "intermediate ore." This intermediate ore and some of the soft ore is a mixture of pulverulent or very weak, nearly disaggregated hematite and hematite that is hard, strong, and very resistant to abrasion. The distinction between the ore types is important for economic reasons; from a geologic viewpoint, the ore types merely represent different stages in the weathering of originally hard hematite.

The subjective classification given above was checked by an objective test on a considerable number of samples to make sure that visual estimates were not radically in error. The test is essentially a friability test, in which the ore sample was crushed and then screened. The tests showed that the visual estimates were valid and that the differences in ore types were measurable.

The ores were classified in detail only in mapping the underground workings and certain detailed measured sections, illustrated in plates 3, 4, and 6, and figure 23. For the rest of the area the medium-hard and medium-soft ores are generally lumped together as intermediate ore because the data available in surface exposures (only hard and some medium-hard ore crops out) and from old maps of inaccessible workings do not permit a more detailed breakdown. A more detailed classification would have considerable value in planning future operations and in market studies and should be made in future exploratory work.

The maps may be difficult to read until these conventions have been studied and understood. In compensation, the result is a picture of the rock types and distribution which more closely approaches the actual conditions found than a simpler system could give, for the distribution of the various rock types is as complicated as the map indicates.

The maps of mine 6 (pl. 3) and mine 7 (pl. 4), as well as of some of the other mines, are somewhat unconventional in that they attempt to illustrate both the textural and physical conditions of the ore. The physical condition, that is, whether the ores are hard, intermediate, or soft, is shown by color. The textural condition, that is, whether the ores are massive, schistose, or brecciated, is shown by line patterns. Color and line patterns are combined to show hard schistose ore or soft schistose ore and the other possible combinations.

A further complication is introduced by the attempt to illustrate the relative percentage of ore types in mixed ores by showing inclusions of one type in the other in the relative percentage in which they occur in the rock over adit distances of some meters. This may result in showing a patch of soft ore in a hard ore matrix at a point where it may not actually occur in the drift. However, with distances over 5 meters, it results in a much more accurate picture of the exact conditions of the rock than could otherwise be represented at the scale of the map; to represent all these conditions accurately would require a scale of 1:100 or larger.

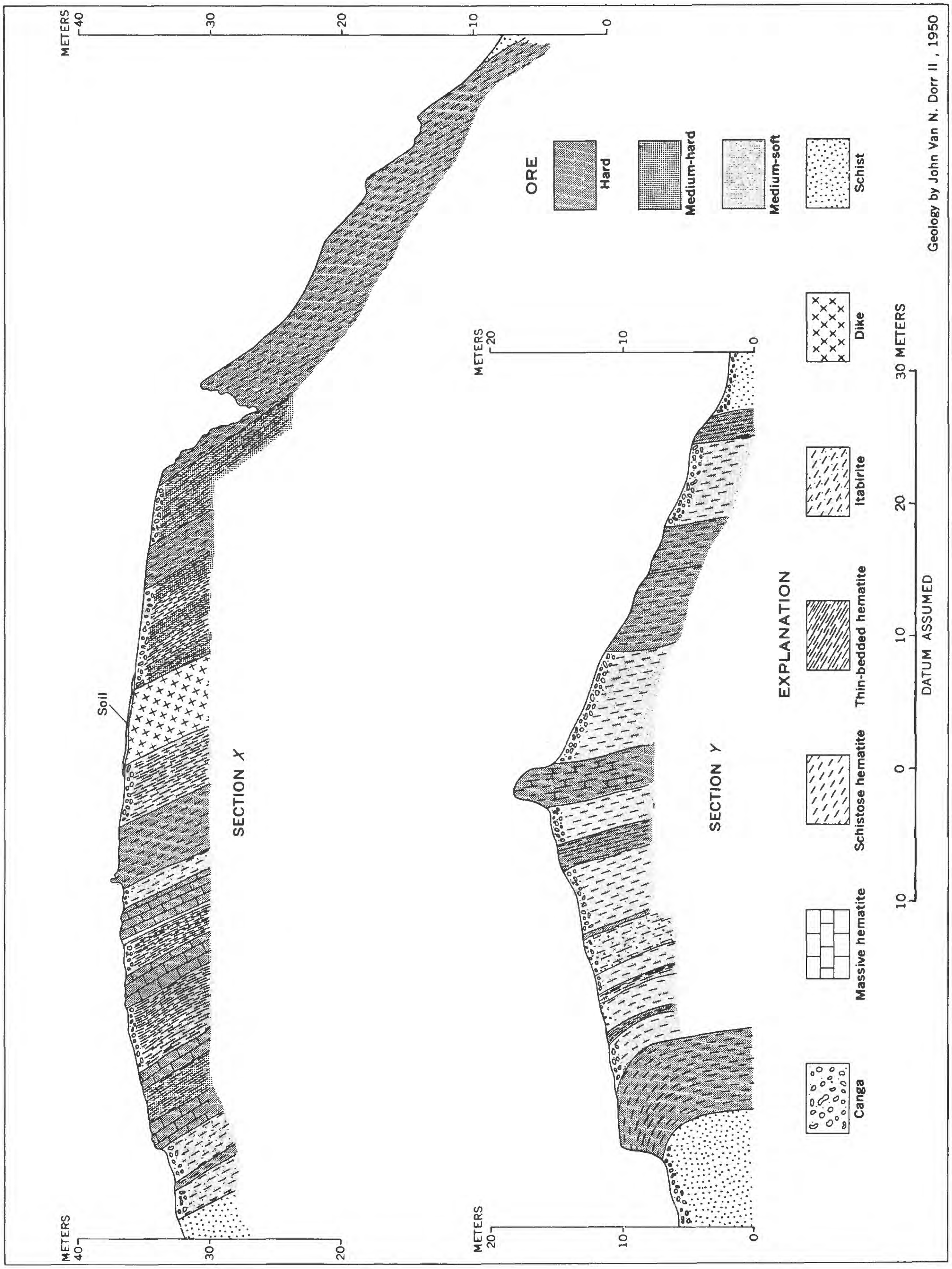

FIGURE 23.—Sections (*X* and *Y*) across ore body, the Conceição area (locations on pl. 2).

CHEMICAL CHARACTERISTICS

The hematite ores are high grade. Sampling of the intermediate and soft types must be considered inadequate as they relate to individual deposits, because details of the sampling done during the exploratory work of the Itabira Iron Co. have been lost, and resampling on a large scale has not been undertaken. Shipment of 7.5 million tons of hard hematite extracted from benches which contained all types of ore (dominantly intermediate) provides accurate knowledge of the chemical composition of the hard ore as it is recovered from screening of the intermediate type and by mining of true hard-ore bodies. Table 3 shows the average chemical composition of the ore shipped.

TABLE 3.—*Average composition of hard hematite ore shipped from Itabira district by Companhia Vale do Rio Doce, 1948–54*

Element	Percentage	Approximate tonnage represented by analyses
		(In thousands of tons)
Fe (dry basis)	68.66	7,500
P	0.0247	7,500
SiO_2	.353	1,170
Al_2O_3	.674	1,080
CaO	.066	45
MgO	.059	63
Mn	.056	342
S	.013	540
H_2O (−)	.73	1,900

Neither the CVRD or the buyers regularly analyze for elements other than Fe and P. Some buyers occasionally make analyses for other elements and include reports in the settlement analyses for shipload lots, which average a little over 9,000 tons each. The above figures for elements other than Fe and P are therefore buyers' analyses. The figures for Fe and P are company analyses, made by Sr. Arturo Pinedo of the Departamento de Minas. These for Fe are systematically a fraction of a percent below the buyers' analyses, probably owing to loss of fines in shipment. The P is consistent. H_2O (+) is so low that neither buyer nor seller analyze the ore for it.

The highest grade shipload lot, 9,120 tons shipped on the SS *Attica* on June 24, 1952, contained 69.91 percent Fe, 0.024 percent P, and 0.38 percent H_2O, buyer's analysis. This is very near to the theoretical purity of pure hematite, which is 69.94 percent Fe. There is no reason to believe that this shipment contained magnetite in more than minor amounts.

Most of the hard ore in the Itabira district will have a composition very close to that indicated by the 7.5-million-ton sample, for this sample included ore not only from the major Cauê mines, but also from other deposits in the district. However, notes left by the Itabira Iron Ore Co. indicate that certain of the smaller bodies on the west end of the Conceição syncline have a higher silica content and contain only 66–67 percent iron. The *G* ore body in Conceição also seems somewhat more siliceous than the average.

The chemical composition of the soft ore bodies is only generally known. The best indication of the composition of this ore is contained in information from the files of the late Percival Farquhar and is given in table 4.

TABLE 4.—*Average analysis of soft hematite exposed in workings in Conceição Peak*

[Data from Itabira Iron Ore Co. records]

	(Percent)
Fe	68.16
Insol	2.17
S	.022
P	.017

The detailed records from which this composite analysis was derived are lost. The information available from the files of Mr. Farquhar states that the above figures are an average of 44 groups of samples taken from over 1,461.82 meters of workings in soft hematite. This statement was signed by Thomas Charlton on February 2, 1935.

It perhaps should be noted that the analyses of the Itabira Iron Ore Co. from which these data were taken, are characteristically slightly lower in phosphorus than modern analyses. "Insolubles" in these analyses is to be taken as silica plus alumina. These analyses probably represent an adequate sampling of several tens of millions of tons of soft ore from the Conceição ore bodies.

The intermediate ores as such have not been sampled, but may safely be presumed to lie betwen the analyses cited above.

The stockpiles of fine material on Cauê Peak screened out in the preparation of the hard ore for shipment cannot be considered representative of the undersized material in the hematite ores. This fine material has been diluted by itabirite, soil, and canga mined with the ore.

The high-grade hematite ore as mined averages somewhat over 68 percent metallic iron, less than 2 percent alumina and silica combined, less than 0.03 percent phosphorus, less than 0.02 percent sulfur, and only minor amounts of CaO, MgO, and Mn. Except in the outer skin of the ore bodies, the water of crystallization is negligible. The water content of the ore as shipped varies systematically with the month and correlates closely with the rainfall (table 1). The average is about 0.7 percent H_2O in the hard ore shipped.

MINERALOGICAL CHARACTERISTICS OF THE HEMATITE ORE

The hematite ores of the Itabira district are composed dominantly of very fine grained specularite. The completely disaggregated soft ores may contain more than 75 percent of minus 200 mesh (smaller than 0.074 mm) material. The individual crystals are flat and of irregular outline. The blue hematite rock gives a bright reflection on fresh faces owing to the generally uniform orientation of the individual crystals. Locally the hematite is more granular and does not have preferred orientation. Where the rock has been sheared strongly, the hematite has recrystallized into larger plates, in extreme cases with millimetric (1–10 mm) dimensions, and the rock is black. Such material is locally called "lustrous ore," as it commonly is mirrorlike in the sun.

Magnetite and martite also occur in the ores. Megascopically, these minerals are found disseminated in the hematite rock as irregular bunches and knots, and as veins.

A typical occurrence of disseminated crystals of magnetite and martite was found on the 1,200 bench on Cauê Peak. Here octahedral crystals were sparsely scattered throughout the massive, well foliated hematite. Folia of the hematite do not bend around the crystals. The individual crystals all have a thin selvage of tan talc, apparently identical to the gangue. The magnetite-martite crystals may average 2–3 mm across and are all nearly the same size. Zones containing such crystals are rare and in those zones the crystals are not abundant.

Magnetite and martite are also found in a few localities in irregular pockets up to several meters across. The crystals of martite and magnetite in this type of occurrence are much larger than those referred to above, averaging perhaps 7–10 mm across and running up to 25 mm or more in maximum dimension. Specular hematite with foliation conformable to the surrounding rock may be interstitial to these large crystals. The foliation does not bend around the crystals. This mixture of minerals is unusually hard and tough and can be drilled only with great difficulty. In hand mining, these pockets are left in place and not extracted, despite their grade of over 70 percent Fe. An excellent example of this type of occurrence was exposed by the mining of the Conceição *G* ore body in 1954. The pocket was about 4 meters by 2 meters with an exposed height of possibly 3 meters.

Magnetite and martite also occur as veins, such as the ones which cut the ore in the Piriquito ore body. These are generally rather thin, averaging perhaps 20 cm wide, and they may be either crosscutting or concordant with the structure of the surrounding hematite. The veins are composed of a dense aggregate of idiomorphic equigranular crystals and generally contain no specular hematite. The crystals are commonly smaller than those found in the irregular deposits. One such vein in the Conceição *A* ore body is at the contact of a dike with the ore; others cannot be so related. Most of the dikes have no magnetite at their contacts.

Abundant float of magnetite-martite rock is present on the southeast flank of the hill called Serrinha (pl. 1), but the source of the material could not be located. This is very close to the intrusive granitic gneiss contact. A small vein of magnetite cuts the footwall schist about 40 meters below the footwall at 52,248 N.,–48,660 E. on Cauê peak.

These sporadic occurrences of magnetite and martite in the high-grade hematite bodies are largely of geologic interest. Quantitatively they are insignificant.

GANGUE MINERALS

The high-grade hematite ores are more than 97 percent hematite and average more than 68 percent iron. The gangue minerals are so minor that the ore appears to be pure hematite. Weathered faces, from which the less resistant gangue minerals have been removed, are actually pure hematite.

The most prominent gangue minerals on the fresh faces exposed in the benches and underground workings are mixed talc and chrysotile. These minerals were identified by X-ray methods by E. Tavora of the Departamento Nacional do Produção Mineral. Previous identifications by chemical and optical means had identified the minerals as talc or talc plus an unknown mineral. This mixture of minerals occurs as irregular blebs and smears of tan, buff, and brown flaky material ranging from 2.0 to 20 mm in length and parallel to the foliation of the rock.

These blebs and smears are most abundant near the dikes which cut the ore bodies in many places. In mine 6 (pl. 3) and in other mines, it is apparent that this gangue is closely related genetically to the dikes, for the quantity often radically increases as the dikes are approached and, where postore shearing has been intense, the material may locally grade into dike material. The more massive ore is poor in these minerals, whereas the more schistose ore is generally richer. The minerals make up a very minor part of the ore bodies, as may be seen from the quoted analyses.

Green talc in plates a centimeter or more across and very coarse black specularite in plates as much as several centimeters across are often associated on joint faces in the hematite ore, and locally apparently replace the ore in zones of crushing. The coarse specularite is far more common than the talc. These minerals were evidently deposited very late in the evolution of the ore deposits because they cover all other features except the limonitization going on in the present erosion cycle.

There seems to be a basic percentage of about 0.025 percent phosphorus in the pure hard hematite. It is not known in what form this occurs. Mining has proved that the phosphorus content decreases with depth below the original land surface. On the upper benches of Cauê Peak near the original surface (at shallow depth), phosphorus averaged about 0.035 percent and at depth averages about 0.025 percent, indicating that the phosphorus was concentrated by supergene agencies near the weathered surface. Surface samples commonly are below average in phosphorus, indicating surface leaching with redeposition at shallow depth. Locally, as in a small part of the Conceição *A* ore body that is thoroughly brecciated, the phosphorus is concentrated to appreciable depths (about 40 meters) on fracture planes in the form of films and mammillary growths of wavellite(?). Ore so contaminated must be discarded to maintain grade.

Table 3 indicates that the ore contains 0.67 percent of Al_2O_3. It is not known in what mineral this alumina occurs, but it may be presumed to occur in a clay mineral, thus accounting for much of the silica as well. Pods of pure white kaolin [10] are rarely found in the ore.

Hard-ore float on the eastern flank of Cauê Peak contains holes left by some acicular mineral. These holes are as much as 10 mm long, but no specimen was found that contained remains of the original mineral. Tourmaline has been reported from the Pico de Itabirito, 100 km southwest of Itabira (Sanders, 1933, p. 11). Sanders also states "Some of the hard ore from the large outcrop at Cauê exhibits markings and cavities which have been almost certainly caused by groups of small tourmaline crystals, although these are no longer themselves in evidence."

STRUCTURES IN THE HEMATITE ORE

All three types of the bedrock high-grade hematite ores share vestiges of structures clearly shown in the itabirite. These include the even and regular lamination of that rock and, more strikingly, the intricate and detailed folds and crenulations characteristic of the itabirite. These are most graphically shown on weathered outcrops of hard massive hematite, rock that, on freshly broken faces, may reveal no internal structure whatsoever. The outcrops are similar to leached polished specimens and have the advantage of showing, in the aggregate, the detailed structure of thousands of square meters of the ore. Thus a better sample of the detailed megascopic structure of the ore bodies can be secured from studying weathered outcrops than polished specimens, which represent a few square centimeters at most.

The etched outcrops show conclusively that the dominant structure in the hematite rock is a smooth and even lamination, broken at varying intervals by minor normal and high-angle reverse faults that have millimetric (1–10 mm) offsets. Usually such microfaults are sparsely distributed and hardly noticeable; their length is measured in centimeters or tens of centimeters. Locally the faults are spaced at centimetric (1–10 cm) intervals or less, commonly much more widely.

Figures 24 and 25 illustrate a typical specimen of the evenly laminated hard hematite as it appears on an outcrop face etched by weathering and after polishing. The polished face shows several small crosscutting features which are interpreted as hematite replacements of minor crosscutting quartz veinlets, attributed to probable diagenetic quartz. This type of unbrecciated, unfolded, evenly laminated ore is the common ore in much of the district and is particularly abundant in the ore bodies on the limbs of the

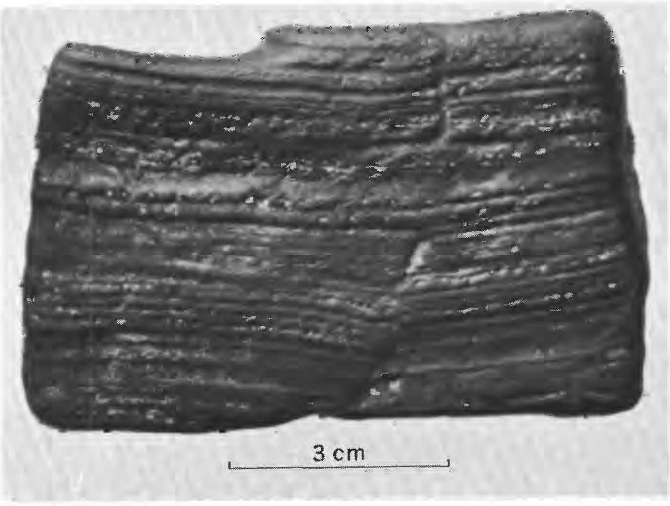

FIGURE 24.—Photograph of weathered surface of hard hematite.

[10] *X-ray* determination by E. Tavora, Departamento Nacional da Produção Mineral.

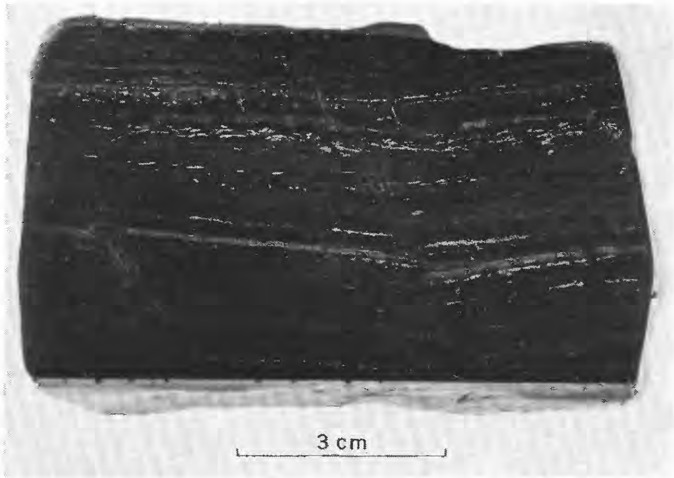

FIGURE 25.—Photograph of polished face of hard hematite. White polishing compound accentuates bands of greater porosity marking the original position of quartzose bands. Crosscutting white streaks mark the former position of quartz veinlets now also replaced by hematite.

synclinal folds where the original itabirite is believed to have been squeezed.

The ore characterized by tight folding and crenulation is, on the other hand, abundant in a number of the ore deposits, particularly those in the axial zones rather than on flanks of the folds. These crenulations show what is believed to be typical flowage phenomena. Figure 26 illustrates such a fold as it appears in polished section, and figure 27 illustrates a typical etched outcrop.

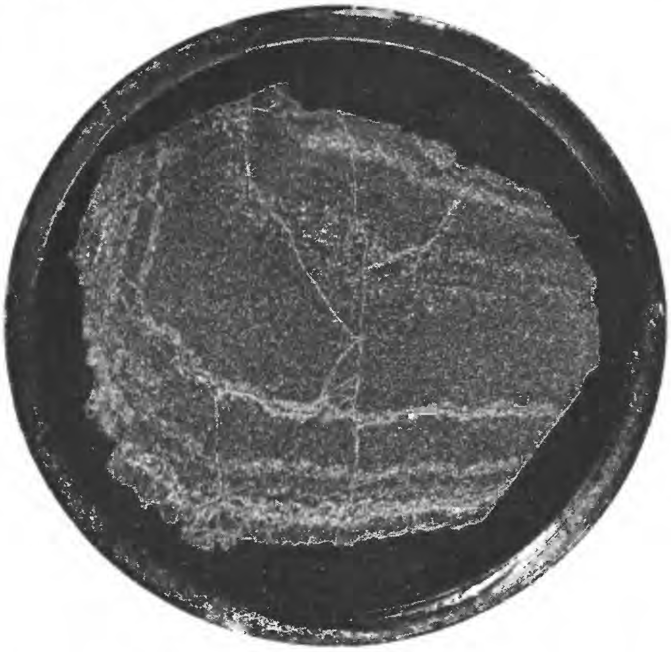

FIGURE 26.—Photograph of polished section of schistose ore showing minor fold or crenulation. The greater porosity of certain laminae is indicated by white dotted bands where polishing compound has filled openings. Magnification about 2.5 times.

It should be emphasized that freshly broken faces of ore only rarely show the internal structure of the rock. They commonly show only featureless blue hematite. Chemical etching of polished sections or weathered faces are needed to reveal details of internal structure.

True breccia structures are rare. In brecciated zones the ore has been crushed and the brecciated material recemented by blue hematite and, in a few cases, by hematite which is now reddish to purple and softer than the fragments of hard ore. This cementing material is thought to be postore, for the fragments are of the same kind of hematite as the rock in general, whereas the cementing material is smaller

FIGURE 27.—Photograph of outcrop of thin-bedded hard hematite ore, etched by weathering. Light-gray color is caused by lichen which has preference for more porous layers that were originally quartz.

in grain size and has a different aspect. In most cases the cementing material is not foliated. The very late hematite that covers joint planes mentioned above may be of the same generation as that cementing the breccia, although this cannot be proved. The coarse talc associated with that hematite indicates that late hydrothermal solutions were active in the area, and it is to be expected that they would be channelized by breccia zones. Such breccia zones are believed to be associated with the postore faults previously described. They are quantitatively minor and of no importance in ore genesis.

No structures have been found in the high-grade hematite bodies which could be taken to indicate origin of this type of ore by residual enrichment. Slump structures, such as are characteristic of deposits of this origin, are not present in the Itabira district. As will be discussed on later pages, other ore types have resulted from residual enrichment.

HARD ORES

Hard hematite is the most resistant rock of the Itabira district to both chemical and mechanical weathering. In many localities, it forms bold scarps and crags. The typical mode of outcrop is as sharp ridges or spines where the dip is steep, or as hogbacks where the dip is more moderate. In many cases, relatively small hard ore bodies form low inconspicuous outcrops on rubble-covered hillsides. The rock generally is surrounded by canga and is partly covered by hard ore rubble on the more gentle slopes. It supports a sparse and characteristic xerophytic vegetation.

The rock is generally gray to blue on the outcrop and blue on fresh faces. It rings to the hammer and in some places, generally characterized by strong lineation, the larger fragments ring like a gong when struck.

MASSIVE ORE

Much of the hard hematite is massive. Massive ore commonly occurs in beds ½ to 3 meters thick. Figure 28 shows the dense texture of the rock under the microscope. Freshly broken faces are conchoidal and show dense, blue, apparently structureless hematite. In some places, even the etched weathered faces show no structural details, although in others, weathering brings out many details of intricate structures and fine lamination not apparent on fresh surfaces. The individual specularite crystals are normally so well oriented parallel to foliation that they gleam together in the sun like mirrors. Massive ore is not porous and almost always hard. Only very locally and on a small scale is massive hard ore contaminated by appreciable quantities of soft or intermediate ore.

Figure 29 illustrates a face of massive ore on Cauê Peak.

Massive ore constitutes the premium ore of the district for it is rarely contaminated by visible gangue and produces very little undersized material on crushing, screening, and shipping because of its resistance to abrasion.

SCHISTOSE ORE

The most widespread type of ore in the Itabira district based on texture is the schistose (figs. 30, 31, 32). This texture is found in hard, soft, and intermediate ores. The ore is typically blue to gray, has an ex-

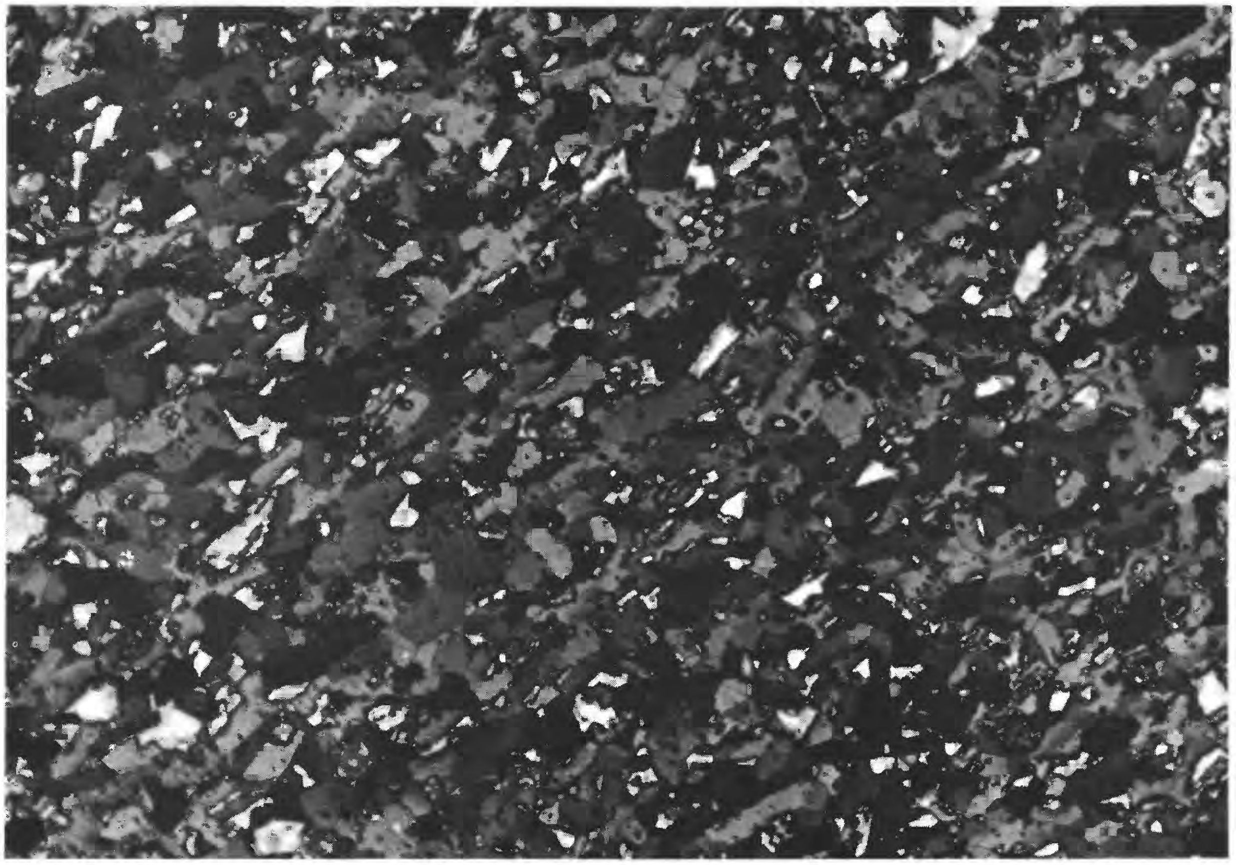

FIGURE 28.—Photomicrograph of hard massive hematite. A dense texture is indicated by the lack of white polishing powder on the section. A faint foliation is visible. Magnification × 100; crossed nicols.

tremely variable grain size, breaks with a hackly fracture, is quite variable in porosity and hardness both across and along the strike, and often appears to have been sheared parallel to the pronounced foliation. It occurs in beds from a few centimeters to possibly a meter thick, but bedding is normally obscure in this ore type and only the foliation is prominent. In this type it is often possible to distinguish alternating layers of fine and coarser crystals which are interpreted as representing the iron rich and iron poor bands of the itabirite; the finer, more granular and more porous bands are believed to represent the original silica bands. Irregular replacement of the original iron-formation is also apparent.

FIGURE 29.—Massive hematite ore, Cauê Peak.

Even though schistose ore may be extremely hard and tough, this type of ore usually yields an appreciable percentage of fines on crushing. When it has been softened by weathering and the porosity is higher, the percentage of fines becomes much greater.

The schistose ore gives rise to most of the soft and intermediate ores of the Itabira district. The greater porosity and permeability of this type of material, both inherent and owing to the shear planes which ordinarily cut the rock, gives much easier access to through-passing solutions than the denser and more evenly grained massive type. Linear structure is often well developed in schistose ore.

Formation of soft ore from hard schistose ore takes place in irregular pockets controlled in part by jointing, in part by bedding, and in part by the linear structure. In the underground workings, it is common to find zones of schistose ore saturated with moisture (permeability is not great enough to produce drips of water from the walls, but the rock is moist),

FIGURE 30.—Hard schistose ore showing irregular replacement, variation in porosity, and tight internal folding.

whereas the massive ore is usually dry and dusty except where water penetrates along joints or faults. That the moisture in the schistose ore is actually in movement is shown by the fact that in drifts the updip side of the working is locally quite moist whereas the downdip side may be dry. This feature is well exemplified in mine 6 in Cauê Peak.

Caves in schistose hematite ore have been found in a number of places in the Itabira district. These are as much as 5 meters in height, 7 meters in width, and 15 meters in depth. The most striking of these

FIGURE 31.—Polished section of hard schistose hematite showing some features as in figure 30 on a smaller scale. Magnification about 2.5 times.

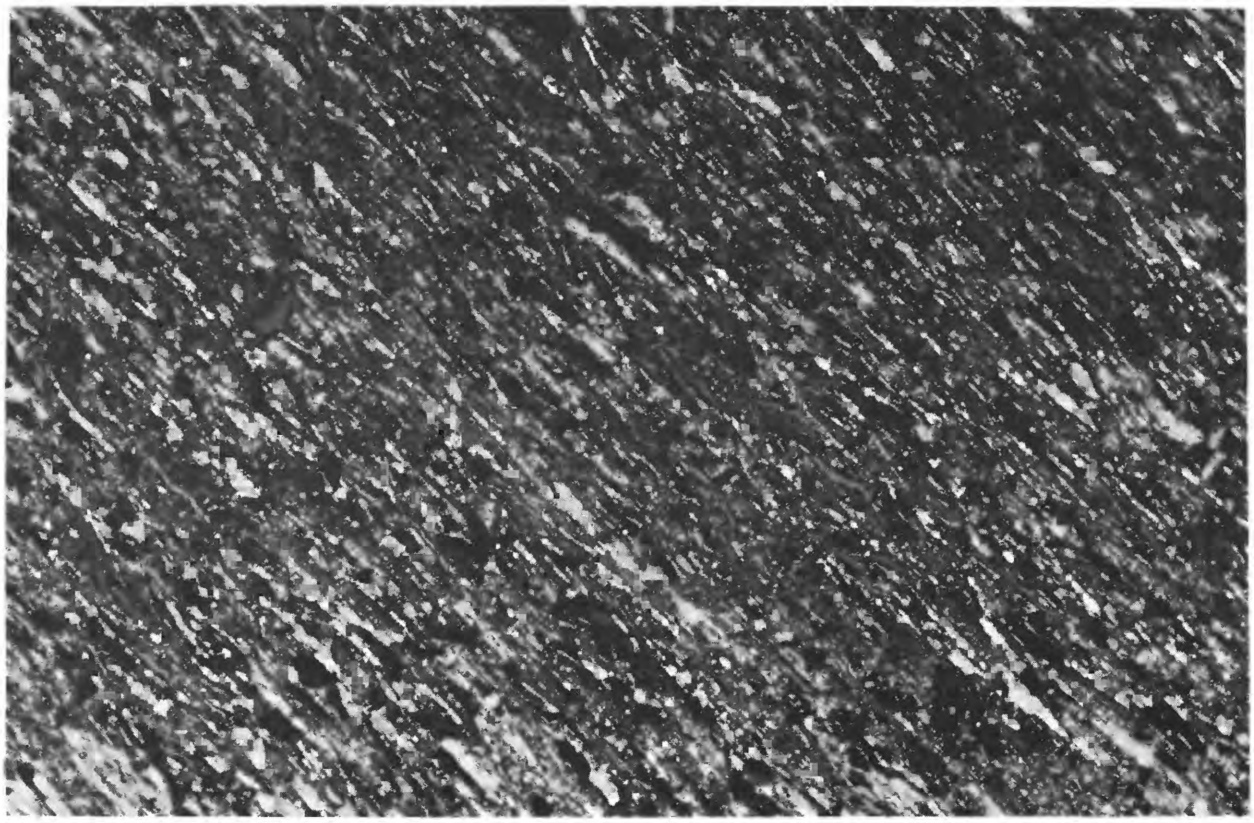

FIGURE 32.—Photomicrograph of polished section of the more porus part of hard schistose hematite showing the microtexture. Magnification × 100; crossed nicols.

were located at the following points: (1) 45,210 N, 44,132 E; (2) 44,892 N, 44,740 E; and (3) 45,510 N, 47,732 E; two others formerly existed near the top of Cauê Peak. These caves are always in high-grade hematite, commonly of the schistose variety, although they may have limonite deposited near the mouth and on the floor. One cave had much canga on one side of the mouth. The walls of some of the caves are composed of soft ore; the walls of others are of hard and intermediate schistose ore. None of the caves found thus far were more than 15–20 meters below the surface. The irregular floor always slopes toward the portal of the cave, which in several cases, was much smaller in cross-section than the inside of the cave. It does not seem probable that these large caves were formed by complete solution of the hematite, but no sign of other material which might have been dissolved out has been seen in the caves or in the exploratory adits at depth. The writers believe that they were formed by the mechanical removal of soft incoherent hematite by surface water which entered the zone along joints and fissures in the overlying rock.

THIN-BEDDED ORE

Thin-bedded ore occurs largely on the squeezed flanks of the synclines and anticlines of the Itabira district and grades into the schistose and, less commonly, into the massive types of hard ore. This material occurs in beds of blue specularite which range from one-half centimeter to several centimeters thick and which may be continuous for many meters along the strike. Usually the grain size is as uniform as that of the massive ore and often the fracture in the individual plates is also conchoidal. The bedding is accentuated by etching on weathered surfaces and is noticeable on fresh surfaces. The material breaks along the bedding plane into slabs. It is much more easily attacked by leaching than the massive ore because the bedding planes permit infiltration of surface waters. A relatively large part of it crumbles to fine dust when broken. Locally it is reduced to soft blue hematite, but retains the aspect of the original platy structure. Only rarely does the thin-bedded ore show the intricate contortions characteristic of some of the massive ore on etched faces.

SOFT HEMATITE ORE

Many large and small bodies of soft hematite are to be found in the Itabira district. These bodies never crop out and their presence is revealed only in mine workings, along road cuts, and in other artificial openings. The soft hematite is characteristically incoherent when dry but has enough cohesiveness when damp to stand well in adits and other workings. When it is completely saturated and has a high head of water behind it, as in some underground workings, it may flow.

The grain size and physical characteristics of soft ore vary widely. Figure 7 shows the range in grain size of soft ores from three different environments. One shows that 21 percent of the material is minus 200 mesh,[11] another shows that 58 percent is minus 200 mesh, and the third shows that 73 percent is minus 200 mesh. The widely varying grain size of the soft ore is caused by the differing degrees of disaggregation of the originally hard hematite. The coarser fragments are composed of aggregates of individual specularite crystals. These aggregates in some cases are strong and hard; generally they can be crushed between the fingers into fine powder.

Soft ore may be blue or black. Soft material derived from hard massive ore or the thin-bedded ore is generally blue and is commonly finer and more completely disaggregated than the material derived from schistose ore. It is similar to the "blue dust" of India.

The black soft ore derived from schistose ore by weathering in many localities is characterized by "pseudobrecciation." (See main drift, mine 7 (pl. 4), Cauê Peak.) The pseudobreccia consists of small angular fragments of hard ore, commonly less than 2 centimeters in maximum dimension, in a matrix of finely divided hematite. The individual fragments seem to be bounded in part by planes parallel to joint and bedding planes, in part by irregular surfaces. Although on superficial examination, such rock appears to be the result of crushing, the fact that the "fragments" have not been rotated and are structurally continuous with each other and with the matrix, as shown by the undisturbed foliation and bedding planes, indicates that the pseudobreccias are not tectonic but are the result of irregular disaggregation of the rock.

Joints are locally preserved in the soft hematite and there is no deflection in the direction of the joints when they pass from the hard hematite into the soft, proving that the joints were imposed on a single type of rock—not two.

FIGURE 33.—Elongate slabs of hematite ore from Dois Córregos deposit. The ore is more than 98.5 percent hematite.

Particularly in the Dois Córregos ore body, zones of coarsely crystalline blue-gray hematite may be traced for many tens of meters along the strike. The material is quite soft and has an unctuous feel. It disintegrates easily and therefore is classed with soft ore even though it breaks out into large pieces on mining. In Dois Córregos, this material may break because of the linear structure into "logs" more than a meter long (fig. 33).

INTERMEDIATE ORE

Ore which on mining proved to contain enough fine material to place it in the intermediate classification crops out in a number of places in the Itabira district. Outcrops of this ore are characteristically low and unobtrusive, and in many cases consist of small irregular patches of blue hematite isolated in areas of rubble or canga. In many localities the weathered surface of the ore is pocked with small irregular voids. Only ore which contains a relatively high percentage of hard material crops out; soft ore is hidden.

The material classed as intermediate ore is seen on fresh faces to be a mixture of soft and hard hematite in varying proportions. The hard portion occurs in pieces, blocks, and beds in the softer material where

[11] To secure consistent results from screen tests of soft ore and soft itabirite, the tests must be standardized. All screen tests made for this report were made in a rotap machine. Period of operation of the machine was exactly 10 minutes.

the ore is dominantly soft; where the ore is dominantly hard, the soft fraction occurs along bedding planes, in irregular pockets, and locally replacing the hard material in the middle of beds and in large masses. In short, there is a complete gradation between the two end members of the hard ore-soft ore series. However, with exceptions, the hard ore fraction in the intermediate type ore, particularly of the schistose ore, seems to be less hard, more porous, and to give more fines upon breaking or crushing than the hard ore of the massive hard hematite beds.

In many localities, as on the 1,303 bench of Cauê and in the Conceição *A* ore body, the hard ore contains small pockets of black powdery hematite or, more commonly, irregular voids 2 centimeters or less in length in the blue hard hematite, lined with black powdery hematite.

In the Quadrilátero Ferrífero there seems to be a zone of cementation near the surface of the high-grade ore deposits in which the ores are "case hardened" and recemented by dense limonite which may be dehydrated at the surface to hematite or a magnetic oxide of iron. At depths below a few to 10 meters or more, where alternate wetting and drying does not take place and the material is always damp, the ore is commonly softer than at the surface. This effect is particularly marked in the schistose ores, which are more permeable and porous than the massive. The massive ores rarely are soft. It is believed that the softening process in the hard ores will be found to go to the permanent water tables, where stagnation of the ground water will have prevented effective solution. For these reasons, it is believed that the high-grade hematite will deteriorate in physical quality downward from the surface to an irregular but limited depth, and below that will improve in physical quality with depth. Improvement in physical quality should be apparent within 150 to 250 meters of the original ground surface in most deposits.

SIZE AND SHAPE OF THE HIGH-GRADE HEMATITE ORE BODIES

The hard, intermediate, and soft hematite bodies are closely related in origin and are intergradational. Therefore their modes of occurrence are described jointly, and distinction made between them when necessary.

High-grade hematite bodies occur in all sizes ranging in length from a few centimeters to 2,800 meters of nearly unbroken outcrop as in the case of the Conceição *A* ore body and its extension into the Piriquito area. The maximum stratigraphic thickness of an ore body is probably found in Cauê Peak, which had not less than 150 meters of nearly pure ore before mining began. The Conceição *C* ore body has an exposed width of over 300 meters but it has been repeated by folding.

There is a swarm of small hematite bodies and a few large ones in Conceição Peak; in Cauê Peak there are a few small bodies and one large one (pl. 2). Between these geographic extremes of the district, many small and medium-sized bodies are found. The ore bodies generally lens out abruptly at the ends, irregularly grading into the itabirite within a few centimeters. The termination of the ore bodies, in most cases, is probably much more ragged than shown on the map, with the ore and itabirite interfingering over a distance measured in meters or tens of meters. These relations are usually obscured by the canga cover on the outcrop, but may be seen in working faces and exploration adits.

The ore bodies are generally concordant with the enclosing itabirite, often strictly concordant for tens of meters. Locally, however, they sharply crosscut the enclosing rocks. The peculiarly shaped ore body in the vicinity of coordinates 45,100 N, 44,800 E, is an excellent example of general concordance combined with radical crosscutting of the local structure. Such features are particularly well illustrated by a number of the minor ore bodies near the west end of the Conceição area, as shown in plate 2.

All major ore bodies that have been explored by subsurface workings were found to continue downdip to the maximum explored depth. At the west end of Conceição Peak, adits were driven by the Itabira Iron Ore Co. under several minor outcrops to test their continuation in depth. In some cases the ore lenses showed continuation; in others they did not. Some small bodies which did not crop out were encountered in exploratory work. In general, adequate information is not available as to continuation downdip of the hematite ore bodies, for the bottom of a major deposit has not yet been exposed.

In Cauê Peak, the major hematite lens crops out without a significant break for more than 1,200 meters to the northeast of the highest point of outcrop; the difference in elevation between the highest and lowest exposed points of the footwall is nearly 300 meters and the difference in elevation between the highest and lowest known points of the ore body is 450 meters. How much greater than 450 meters the vertical range of this ore body may be, is not yet known. Under any theory of origin of the ore deposits except that of supergene concentration in the present erosion cycle, it can be assumed that the larger lenses extend to considerable depths.

Zones and streaks of itabirite, ranging in thickness from a few centimeters to tens of meters, occur within the high-grade ore lenses. Plate 6, which illustrates three stratigraphic sections measured within a few tens of meters of each other on Cauê Peak, demonstrates the fact that these itabirite splits usually can not be correlated over any great distance and that their occurrence is often most irregular. Plate 3, on the other hand, which shows the geology of mine 6 in Cauê Peak, shows that this generalization is not everywhere valid, for in that mine two itabirite zones that vary widely in thickness can be traced for nearly 150 meters in the high-grade hematite. As a broad generalization with acknowledged exceptions, the itabirite zones in the pure ore are discontinuous and sporadic, although tending to follow stratigraphic zones. Their occurrence is most difficult to predict.

In summary, the bodies of high-grade hematite of the Itabira district range from centimeters to nearly 3 kilometers in length, from centimeters to about 150 meters in thickness, and extend an unknown distance, in one case at least 300 meters, downdip. They are roughly tabular and concordant but crosscut the structure of the enclosing rocks in many cases.

LOCALIZATION OF THE ORE BODIES

Structural control over the loci of high-grade hematite ore bodies is apparent. How this control operates is less apparent.

Ore formation is related to folds in the itabirite, to local abrupt steepening of the linear structure characteristic of the Quadrilátero Ferrífero, or to combinations of both. These folds need not be sharp folds, and whether they are anticlinal or synclinal seems to be unimportant. Thus the Casa da Pedra deposit in the Congonhas district was mapped by Guild as being on the crest of an anticlinal fold, the Chacrinha and Piriquito deposits in the Itabira district are on the flanks of anticlinal folds, and other large and small deposits are so located. Deposits on synclinal folds would include the Morro Agudo deposit in the Monlevade district, the Cauê and Dois Córregos deposits in the Itabira district, and several other large deposits. Examples of steeply pitching ore deposits are the Jangada and the central hard spine at Pico de Itabira.

Whether or not ore formation is also related to faulting is difficult to demonstrate; although a number of ore bodies are close to or cut by faults, in many cases these faults are postore and in other cases the age of the faulting is indeterminate. There are certainly many ore bodies, including those of the Itabira district, completely unrelated to faulting. The presence of thrustfaulting in or near ore bodies has been demonstrated in several instances. It has not yet been demonstrated that this thrusting is earlier than the principal ore-forming period.

The structural control which caused the localization of a few of the major deposits, such as Aguas Claras in the Belo Horizonte district, has not been determined.

Major ore deposits are not confined to the axial zones of the folds, although where the fold is not tight, this is a favored locus. They also occur out on the flanks of the folds as much as 2,000 meters from the axial zone. The tighter the fold, the farther away from the axial zone the deposits may occur.

Stratigraphic control over the localization of high-grade hematite is not clearcut. Although unquestionably the larger ore bodies are in most cases in the lower or lower and middle two-thirds of the Cauê itabirite, both in the Itabira district and elsewhere smaller ore bodies may occur at any horizon, even in minor itabirite zones in the overlying dolomite of the Gandarela formation. The largest ore bodies, such as the Cauê body or the *A* ore body at Conceição, transgress the whole width of the Cauê itabirite. However, when these bodies begin to play out, their extensions continue farthest in the lower part of the Cauê itabirite.

The reason for this stratigraphic selectivity cannot be definitely stated. The upper third of the Cauê itabirite commonly contains a higher percentage of a carbonate mineral than the lower and middle thirds, as far as can now be established, although in the Itabira district dolomitic itabirite is insignificant. Perhaps the more siliceous zones were more reactive with the fluids which aided the metasomatism. Possibly the higher dolomite content tended to seal the intergranular openings through which the fluids passed, owing to the tendency of carbonates to flow under stress.

ORIGIN OF THE HIGH-GRADE HEMATITE ORES

REVIEW OF PREVIOUS IDEAS

The origin of the high-grade hematite ores of the Quadrilátero Ferrífero has been debated for many years. Harder and Chamberlin (1915, p. 395) suggested that the high-grade hematite ores were a primary sediment deposited in a deltaic environment. This hypothesis followed naturally from their belief that the itabirite was a clastic sediment, rather than a chemical one as demonstrated in recent years.

In view of the crosscutting relationships between the high-grade hematite ores and their host itabirites, the sedimentary hypothesis hardly seems tenable.

Within the rocks, there is no evidence of the structures or textures usually associated with deltaic environments, although bedding is well preserved in many localities. Interfingering between ore and itabirite is locally far too abrupt to attribute to a sedimentary environment. Boxworks and dikelike bodies of high-grade ore in itabirite could not be explained by such an hypothesis.

A general hypothesis of origin suggesting that the ores were formed by supergene residual enrichment of the iron-formation first achieved publication in 1913 (Gathmann, 1913, p. 234–240). This hypothesis has been held for many years by geologists familiar with the ore deposits in the Lake Superior area of the United States and has recently been put forward again (Percival, 1954, p. 56). There are two variants of this theory; the first suggests enrichment during the present cycle, the second suggests enrichment in premetamorphic time.

Although supergene residual enrichment is undoubtedly taking place at the present time, as shown by the data presented in table 5 and as discussed on pages C78–80, the writers have observed no evidence that this process can produce the material called high-grade hematite ore in this report, that is, blue or black hematite or mixed hematite-magnetite ores containing 66 to 70 percent iron. In extreme cases, supergene enrichment may produce ores containing as much as 66 percent Fe, but this material is relatively soft, unfoliated, locally slumped, porous, and, to a minor extent, hydrated. It is reddish rather than blue. Commonly the ores produced by secondary enrichment are between 55 and 62 percent Fe, and grade downward into normal itabirite. In no case known to the writers does ore formed by supergene enrichment maintain a grade of 62 percent or more at depths greater than 50 meters below the present surface, whereas the high-grade hematite ore has been proved in some localities to maintain its grade unchanged to more than 200 meters below outcrop. It is also most difficult to explain the foliated nature of the ore and the presence of nests of magnetite crystals by this hypothesis.

The theory that the ore might have formed by premetamorphic supergene enrichment can account for the foliated nature of the ore. The presence of the isolated nests of magnetite and martite crystals would not be much more puzzling than in any other hypothesis of origin. It might be supposed, according to this hypothesis, that the Itabira group was subjected to subaerial erosion either before the Piracicaba group or before the Itacolomi series was deposited. During this subaerial erosion, quartz (or chert) is supposed to have been removed from the iron-formation by leaching and the hematite to have remained, as postulated for some of the Lake Superior ore deposits.

Against this hypothesis two major objections arise: First, it is peculiar that the dolomite (Gandarela formation) which stratigraphically overlies many ore deposits (as at Aguas Claras, Belo Horizonte quadrangle) and interfingers with the Cauê itabirite in which the high-grade hematite deposits are found, was not removed before the iron-formation was enriched, since it is relatively much more soluble than the quartz of the iron-formation, at least under present environmental conditions, which are known to produce residual enrichment;

Second, it is peculiar that slump structures have not been found in common association with the high-grade hematite deposits. The *C* ore body in Conceição has been shown by exploration to be 300 meters wide at its thickest part. If the simple removal of silica from iron-formation is responsible for this ore body, the original thickness of iron-formation, assuming a 45 percent Fe original composition, would have been 670 meters and a compaction of 470 meters would have been caused by removal of the silica. This should leave some evidence. Commonly, the major high-grade hematite ore deposits in the Quadrilátero Ferrífero are in the thicker, rather than the thinner, parts of the iron-formation. This does not seem reasonable if the ores were formed by simple leaching of the quartz (or dolomite) from the iron formation.

A third variant of this hypothesis was suggested as a possibility and tentatively rejected in 1952 (Dorr, Guild, and Barbosa, 1952, p. 298–299). The senior author has observed supergene replacement of the quartz in oxide facies iron-formation by hematite and goethite to be one of the ore-forming processes at the Noamundi mine in India. This process would avoid the third objection cited above, the lack of slump structures, and might explain boxworks and dikes of high-grade ore in itabirite, but would not, in the authors' opinion, satisfactorily explain the dominant stratigraphic localization of the ore or the presence of dolomite above high-grade hematite or bodies. More seriously, a series of complex geologic events unsupported by other evidence would be needed to explain the observed facts. The evidence cited later in the report that the ore is synmetamorphic is difficult to avoid.

The obvious objections to the primary sedimentary hypothesis and the supergene enrichment hypotheses, plus certain positive evidence, led Sanders (1933, p. 10) to imply a replacement origin for the high-grade ores. He did not go into detail as to possible environments or mechanisms of replacement in his excellent descriptive paper. Grösse and others (1946, p. 112) suggested an epigenetic origin for these ores.

Dorr, Guild, and Barbosa (1952, p. 295) suggested that the high-grade hematite ores had been formed by the metasomatic replacement of the quartz bands in the itabirite by hematite derived from the iron formation itself and carried by through-passing fluids. It was suggested that the control of ore deposition was by stress foci in the iron-formation and that the process might well have taken place under metamorphic conditions. No extended discussion of the ore-forming process was attempted in that short paper.

In 1953, Guild (1953, p. 667–669) suggested that the high-grade hematite deposits of the Congonhas district were hydrothermal replacement deposits and that the loci of replacement were governed by breccia zones formed during extensive thrust faulting. A discussion of this paper was published in 1954 (Dorr, 1954).

PRESENT HYPOTHESIS OF ORIGIN

The hypothesis of origin presented here states that the high-grade hematite deposits were formed by metasomatic replacement of siliceous and, to a minor extent, dolomitic itabirite by hematite mobilized from the iron-formation as a whole by throughpassing fluids. These fluids were of hypogene origin, and were probably genetically related to the granitic gneiss. The replacement process took place during the metamorphic epoch at elevated pressures and temperatures. The ore-forming process is supposed to have been governed by the changing solubility of quartz under rising temperature conditions. The ore bodies are localized by zones of increased porosity in the iron-formation governed by differential stress caused largely by folds and local changes in plunge of lineation.

METASOMATIC ORIGIN OF THE HIGH-GRADE HEMATITE ORES

There seems to be ample evidence that the high-grade ores were formed from itabirite by the metasomatic replacement of the quartz by hematite.

1. Except for a few minor veins of very coarsely crystalline unfoliated and unoriented specularite in the footwall rocks, almost all the high-grade hematite ore is enclosed in itabirite. Minor quantities are enclosed in dolomite. The high-grade ore is laminated in many cases and locally the grain size and porosity in adjacent laminae are different. The denser and coarser grained laminae can locally be traced into the hematite-rich laminae of the itabirite, the finer and more porous laminae into the quartz-rich laminae of the itabirite. (In most cases the rock is so thoroughly recrystallized that these variations can only be observed on weathered or etched surfaces.)

2. The high-grade hematite ore abruptly crosscuts the bedding of the itabirite with a gradational zone between itabirite and ore which ranges from a millimeter to as much as 20 centimeters. Locally the two rocks interfinger, with a zigzag contact; locally the contact is relatively straight across the bedding. The smaller bodies on Conceição Peak illustrate these crosscutting relations very clearly. The major axis of the larger ore bodies is, however, almost always subparallel to the bedding of the itabirite, in the Itabira district; in other districts this is not always the case.

3. Within the itabirite, boxworks and crosscutting veins of hematite parallel to prominent joints nearly normal to the lineation of the itabirite (Q joints) can be found. These would seem to indicate replacement of the quartz of the itabirite by hematite aided by fluids following joints and bedding planes.

4. Quartz veins and segregations are fairly common in all the rocks of the Itabira district except the high-grade hematite. Only one example of vein quartz in a medium or large high-grade hematite ore body was seen, this near a postore dike. Polished faces (figs. 12, 25) suggest that vein quartz once existed in the original rock and that it was replaced by hematite, presumably at the same time the quartz laminae in the itabirite were replaced. This evidence is discussed in greater detail later on page C69.

5. In itabirite, vein quartz cutting the bedding at low to steep angles is common. Some of these quartz veins have from a few millimeters to a few centimeters of high-grade hematite on their walls, which in turn grades into itabirite. A possible interpretation of this feature is that the quartz of the vein was derived from the adjacent itabirite as the hematite replaced the quartz. The quartz in the vein did not have time to be completely removed before the ore-forming process stopped. Where this process had gone to completion, the features described in (4) were formed.

6. The itabirite is closely folded and crenulated. The high-grade hematite is also closely folded and crenulated in what is apparently an identical manner. It does not seem reasonable to suppose that a hard, dense, brittle, monomineralic rock such as hematite, occurring in bodies as much as 150 meters and more in thickness, would deform in a manner similar to a plastic laminated bimineralic rock like iron-formation. Therefore it seems reasonable to suppose that the folding now seen in the hematite is a relic structure from original iron formation rather than a primary one imposed on the hematite.

7. Although commonly the replacement process has gone to completion and the high-grade material shows no megascopically visible quartz, in certain zones enriched "itabirite" can be seen that contains perhaps 62 to 65 percent iron. These zones, which may be as much as 8 to 10 meters in width, grade into normal itabirite and some also grade into high-grade ore. The quartz is normally present in discontinuous irregular veinlike bodies a few centimeters or decimeters long in a matrix of rather pure hematite.

This quartz has the aspect of vein quartz rather than that of layered quartz of the itabirite. Because of the lack of continuity of these veinlike bodies, it is reasonable to infer that the veinlike quartz represents material mobilized from the normal itabirite but incompletely removed from the mobilization site at the time the ore-forming process ended. These enriched itabirite zones are now commonly soft; this is taken to indicate that the material was left porous by incomplete introduction of hematite at the time the ore-forming process ended. (This aspect will be discussed at more length in the chapter on origin of the soft ores.)

As a generalization with exceptions, it may be stated that the quartz of itabirite containing more than 62 percent iron (except the itabirite enriched by supergene residual enrichment) has the aspect of coarse vein quartz rather than finely crystalline quartz of the normal itabirite. The inference follows that most itabirite containing over 62 percent iron has been to some extent enriched by the same process that produced the high-grade ores.

Although the replacement is believed to have been metasomatic, that is, a replacement of the quartz in the itabirite by hematite with no notable change in the original volume of the rock, it should be added that only in the harder, denser, more massive ores is complete replacement believed to have taken place. The greater porosity in the laminae which were originally quartz, noted in some ores, would indicate that this metasomatic replacement was not complete in all cases. Although enough iron was brought in to maintain the original structure and most of the volume of the rock, enough may not have been available to replace all the quartz of the itabirite. Therefore some of the quartz in the itabirite was removed by what should be called leaching rather than by replacement. It is believed that this incomplete replacement may have been caused by local scarcity of iron in the throughpassing solutions which brought in the iron and removed the silica, or by local vagaries in the geochemical environment. Quantitatively, metasomatic replacement was by far the more important process.

Because there is little dolomitic itabirite in the Itabira district, there is little evidence for evaluating the relative replaceability of normal siliceous itabirite with respect to dolomitic itabirite. The abundant high-grade hematite ore in this district gives ample evidence that normal siliceous itabirite is easily replaced under the proper conditions to form high-grade ore. Guild's suggestion (1953, p. 667) that beds with greater carbonate content are more susceptible to replacement and form massive and thick-bedded ores certainly meets with no support from the field evidence in the Itabira district, for the few dolomitic horizons known show no sign of preferential replacement; in fact, in the exposures in the Dois Córregos area the siliceous itabirite has been locally replaced to form hard ore pods whereas nearby (20 meters) dolomitic rocks are unenriched.

It might be argued that the high-grade hematite deposits represent dolomitic itabirite which was completely replaced, leaving unreplaced only the siliceous itabirite. Such an argument is impossible to refute by direct evidence, for it presupposes that all evidence as to the nature of the original rock was destroyed by the replacement process. However, this explanation seems unlikely, for the locus of the high-grade hematite deposits would be controlled by the original distribution of the dolomitic iron-formation versus the normal siliceous iron-formation. The distribution of the two rock types would in turn be controlled by Eh and pH conditions in the environment. It seems unlikely that these conditions would abruptly crosscut the bedding, but rather that they would gradually change over distances measured in tens of meters or more, rather than in millimeters or centimeters along strike of the individual laminae.

TIME OF ORE FORMATION

The Itacolomi series, which unconformably overlies the Minas series in parts of the Quadrilátero Ferrífero, contains abundant pebbles, cobbles, and even boulders of itabirite. In no case has a pebble or cobble of high-grade hematite ore been found in the Itacolomi. Hard hematite is much more resistant to abrasion than itabirite. Today detrital material derived from hard ore deposits is carried many kilometers downstream from the deposits. Assuming that the itabirite cobbles in the Itacolomi were derived from the Cauê itabirite, this would seem rather conclusive evidence that the high-grade hematite ore is epigenetic, formed after Itacolomi time.

The high-grade hematite ore in the Itabira district is foliated. The foliation cuts across the minor folds and crenulations in the ore. Thus the ore must either be premetamorphic in age or must have formed during the metamorphism.

The regional parallelism of the fold axes in the itabirite and in the ore to the linear orientation of acicular metamorphic minerals and other linear features in the wallrocks strongly indicates a close relation in time between the formation of the folds and of the wallrock lineation. It is conceivable that there might have been an earlier period of folding unrelated to later metamorphism but with the same orientation of forces, but it does not seem probable. No evidence pointing toward such an interpretation is known.

The fact that the ore faithfully preserves minor structures of the itabirite was mentioned on previous pages. The conclusion was drawn that the folding must have preceded the formation of the ore.

The ore bodies are cut by postore dikes which are foliated parallel to the foliation of the enclosing rocks. Thus the ore must have been formed before the end of the metamorphic period that foliated the dikes. Because these dikes, now highly talcose, are structurally weak, forces which could produce such foliation need not have been strong and the foliation may have been imposed during the waning stages of the metamorphism if the dikes were altered soon after their emplacement. The fact that the talcose dike material has been squeezed out into joints in the wallrocks would indicate that this was the case. Whether the fluids which altered the dikes came from the dikes themselves or from some other source cannot be determined.

For the reasons given above, it seems probable that the high-grade hematite ores were formed during the period of metamorphism which affected all the rocks of the Minas series. In the writers' opinion, this metamorphism took place over a rather long period of time, probably measured in millions or tens of millions of years, during which the environment and physical nature of the rocks underwent slow and progressive change.

Geological events which were possible in the earlier stages of the metamorphism would have been impossible in the later stages, owing to intervening changes in the rocks themselves. For example, it is clear that the iron-formation was an extremely plastic rock during the early stages of the metamorphic cycle, when the rocks of the area were thrown into large and small folds of great intricacy, but that in the later stages of the metamorphic cycle, the same rock failed by breaking and brecciation without notable folding. The change in structural competence of the rock may be attributed at least in part to the intervening period of recrystallization in which the grain size of the rock grew from very fine grained chert and hematite, now typical of unmetamorphosed oxide facies iron formation, to medium-grained itabirite, the metamorphic equivalent of the same rock. By the same token, the change in grain size must have had considerable effect on the potential reactivity of the rock to metasomatic influences and on its permeability.

An attempt to portray qualitatively the changing environment is presented in figure 34; it should be clearly understood that this is an uncontrolled graph in that the absolute temperatures and pressures are unknown and the time element is also unknown.

In the western part of the Quadrilátero Ferrífero, foliation of the high-grade hematite ore is less well developed than in the eastern part. In some deposits, the hematite is granular rather than micaceous. Whether this change in ore type indicates a later period of ore formation or a different environment is not yet clear.

PRESSURE CONDITIONS DURING ORE FORMATION

It is evident from inspection of the regional map (pl. 1) that no direct evidence as to depth of burial of the Minas series rocks of the Itabira district can be adduced. Only thin infolded slivers of the Piracicaba group remain. Whether this group here attained a thickness of 4,000 meters or more in incomplete sections, as in the west, is a matter of conjecture. Also a matter of conjecture is the question whether the Itacolomi series was ever present in the Itabira district and, if so, what its thickness may have been. Where it crops out, the Itacolomi series is metamorphosed and therefore these rocks were in turn covered by younger rocks which have since been removed.

The Minas series as now preserved in the Itabira district represents the roots of a major syncline. Thus the effective depth of burial was undoubtedly considerably greater than merely the original sedimentary cover, and a confining pressure of perhaps 1,000 bars or more seems probable.

In addition to the confining or hydrostatic pressure on these sediments, there must have been exerted a shearing or differential pressure between the various parts of the folds. This is shown by the plastic flowage of rock from the flanks of the folds toward the axial zones, where the iron-formation is generally the

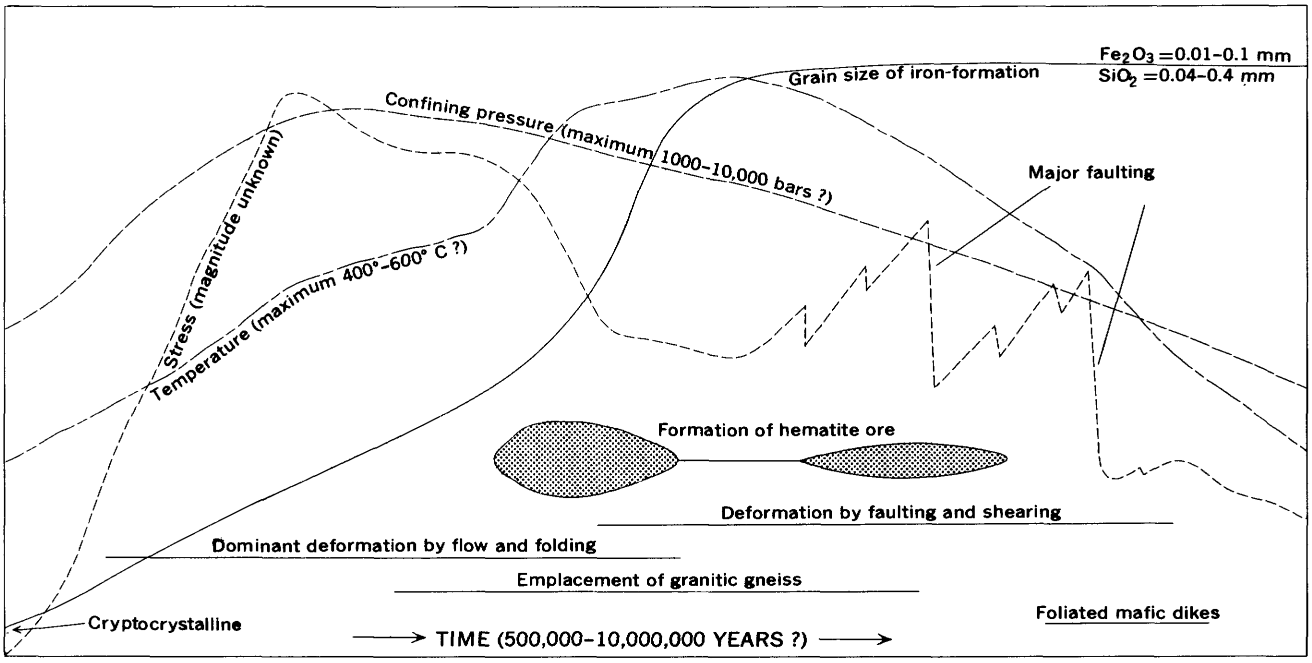

FIGURE 34.—Schematic diagram suggesting the sequence of geologic events and the changes in physical environment in relation to the formation of hematite ore.

thickest. Again, the amount of differential pressure is impossible to analyze quantitatively, for the constants of the rock are unknown, the time available also unknown, and the temperature at which the movement took place only surmised.

The amount of water present is also a matter of conjecture. Were it assumed that the iron-formation has been dehydrated by rock pressure and the normal geothermal gradient, there need have been very little water present. Had the dehydration occurred during the folding, the water included in the iron-formation may have had significant effect upon the amount of stress needed to accomplish the deformation. Guild (1957, p. 49) discussed data of Aldrich concerning the dehydration of silica gel and concludes that the final dehydration took place only under orogenic stress. The writers have observed dehydrated oxide facies iron-formation which has never been involved in orogeny (Dorr, 1945) and are therefore somewhat skeptical of the influence of water from this source as an essential factor in the deformation, particularly in view of the crenulations in the wallrocks.

It is assumed by the writers that metamorphism of the iron-formation in the Itabira district occurred at relatively low confining pressures (800 to a few thousand bars) and with relatively high shearing stress. There are no data to support a more precise statement.

TEMPERATURE CONDITIONS DURING ORE FORMATION

No more precise statement as to temperature conditions during ore formation can be made than for the pressure. Low to medium-grade metamorphism, such as that in the Itabira district, is often supposed to take place at temperatures ranging from about 200° C to slightly over 400° C. Recent work by Yoder (1955) has shown that the presence of water in a given metamorphic environment results in the formation of hydrous minerals that indicate a lower grade of metamorphism than minerals which might have formed in a similar but anhydrous environment. Thus the accepted metamorphic thermometer must be considered quite unreliable in the present stage of geologic knowledge. Work by Nelson and Roy (1958) shows that some chlorites are stable to much higher temperatures than had been formerly supposed (to 700° C).

In any case, it seems probable that the temperature environment during the metamorphism must have changed rather rapidly. The early deformation of itself could not have radically raised the temperature of the rocks over that caused by the normal geothermal gradient (Turner and Verhoogan, 1951, p. 570–571). However, the downwarping of the steep and narrow syncline of Minas series rocks must have pushed the rocks now exposed into a zone of higher temperature. The invasion of the area by the granitic gneiss, which occurred during the metamorphic cycle, supplied another source of heat which raised the temperature of the rocks and may also have supplied aqueous fluids which could have inhibited the formation of minerals usually indicative of higher metamorphic rank. The fact that the foliated dikes show no sign of chilled borders may indicate rather high temperature conditions during intrusion.

At the present time, no conclusive evidence is available as to the temperature environment during ore formation, but it is probable that the maximum temperature was over 250° C, and it may well have been over the critical temperature of water, 374° C.

SOURCE AND NATURE OF THE FLUIDS

The source of fluids responsible for the metasomatic alteration of rocks at considerable depths is not easily proved.

There is evidence (p. C11–14) of alkaline metasomatism in the rocks which underlie the ore deposits. It is most probable that the emplacement of the granitic gneiss, which caused this metasomatism, was contemporaneous with the metamorphism and thus with the formation of the high-grade ore deposits. The presence of tourmaline in the aluminous footwall rocks might well indicate a hypogene origin for through-passing fluids. Talc and chrysotile, the most common gangue minerals in the ore, are commonly considered to be formed under metamorphic, autometamorphic, or hypogene conditions.

As pointed out by Turner and Verhoogan (1951, p. 577) the emplacement of a magma is preceded by a wave of aqueous fluid. The transformationists likewise cite a wave of fluids as a major postulate for their theories.

In sum, the scanty evidence available points toward a hypogene origin for the ore-forming solutions and there is indirect evidence that the solutions may have been alkaline in nature.

The fact that the ore bodies are hematite rather than magnetite indicates that the solutions were not reducing in nature. The nests of magnetite crystals that cut foliated hematite might indicate local changes to reducing conditions late in the ore-forming cycle.

No evidence for major localized channelways has been found; these would hardly be expected in the rocks which had deformed by flowage. It is believed that the fluids penetrated the iron-formation as a whole.

SOLUBILITY OF QUARTZ AND HEMATITE

It has long been inferred from geologic field evidence that quartz becomes much more soluble at elevated temperatures and pressures than at near surface environments. Laboratory evidence gathered in recent years is starting to give quantitative expression to this increased solubility. The effects under such conditions of other substances in the solvent upon the solubility of quartz is, however, still unknown except for a few compounds. Data on the solubility of hematite at varying elevated temperatures and pressures are still most rudimentary.

Morey and Hesselgesser (1951, p. 832–833) have investigated the solubility of hematite alone and hematite plus silica at 1,000 bars pressure and 500° C. According to these authors, the silica had crystallized into quartz in the last three runs made in their experiments. These three runs showed that hematite under such conditions was less soluble in the presence of quartz than in its absence, whereas the solubility of quartz was not affected by the presence of hematite. Under these conditions, quartz is about 250 times more soluble than hematite where the two minerals are present together. Unfortunately, it is not known whether this difference in solubility is accentuated or attenuated under subcritical conditions. It is also not known whether the presence of hematite affects the solubility of quartz under subcritical conditions. Geological evidence provided by the residual enrichment of iron-formation under supergene conditions proves, of course, that a notable difference in solubility between hematite and quartz exists at low pressures and temperatures.

The solubility of quartz alone at subcritical temperatures and pressures has been investigated by Kennedy (1950, p. 638). He says:

> At temperatures below 140°C the solubility of quartz in liquid water is so small that it cannot be measured by the methods employed. The solubility of quartz in liquid water rises at a fairly constant rate until a temperature of approximately 332°C, at which point it reaches a maximum of approximately 0.075 percent. At temperatures above this, the solubility in liquid water falls off sharply until the critical temperature of approximately 374.11° is reached. At this point, the solubility is approximately 0.023 percent.

Kennedy also shows that increased pressure increases the solubility of quartz to a slight extent but that increased temperature is much more important. He also shows that at subcritical conditions, the vapor phase is negligible as a solvent of quartz (although of course extremely effective at supercritical conditions).

Except for the single set of conditions investigated by Morey and Hesselgesser, how the presence of hematite affects the solubility of quartz is not known. It is understood (Morey, oral communication 1949) that the introduction of CO_2 into the system hematite-quartz decreases the solubility of quartz and increases the solubility of hematite. This might possibly explain the fact that most hematite ore bodies are found in the more siliceous, rather than the more dolomitic, zones of the Cauê itabirite.

GENESIS OF HIGH-GRADE HEMATITE DEPOSITS

The mechanisms proposed demand two basic conditions: Regional metamorphism of oxide-facies iron-formation[12] at least to the green-schist facies, and a source of fluids and heat during part of the metamorphic epoch, commonly provided by a large igneous intrusion or a granitization front.

It is believed that the hematite in the high-grade deposits was derived from the iron-formation itself and was not introduced from outside sources. No such outside source is apparent or even probable in either the Itabira district or elsewhere in the Quadrilátero Ferrífero. The iron-formation was a completely adequate source of the iron in the high-grade hematite deposits.

Steps in the process are as follows:

1. The rocks, including the iron-formation, were strongly folded during the early phases of the metamorphic cycle. This created local stress differentials of some magnitude, sufficient to produce rock flowage on a grand scale in relatively plastic rocks such as the iron-formation.

2. The temperature of the iron-formation was increased, secondarily as a result of downfolding of the sediments into deeper geothermal zones, but primarily as a result of the invasion of a granitic magma or a granitization front (or, more probably, both).

As temperatures increased, the iron-formation recrystallized, aided by water of crystallization in the rock. Metamorphism caused a growth in the size of crystals; the original chert lost many of its impurities and developed into clear quartz; and all water was driven off.

3. As the granitic magma or granitization processes advanced, they were preceded by a wave of aqueous fluids which permeated the rocks. These found a higher permeability in the recrystallized iron-formation than in the argillaceous rocks and their metamorphic equivalents and therefore tended to stream through the former rocks. Under conditions of steadily increasing temperature, the quartz was continually more soluble and quartz was locally replaced by the less soluble hematite. Thus the essence of the ore-forming process is thought to have been the dynamically changing physiochemical environment, which increased the solubility of the quartz. It is inferred, but not known, that the solubility of hematite did not increase as rapidly as that of the quartz, thus causing the metasomatic replacement of quartz.

4. Mineralization continued until (a) the temperature of decreasing solubility of quartz (p. C72) was reached and passed or (b) until the temperature of the rocks began falling, not having reached the point of decreasing solubility of quartz or (c) until the source of fluids was exhausted. There is no sure criterion known to the writers to decide this point. It is very conceivable that in some deposits, one condition obtained, in other deposits, another.

5. If (a) is correct, the solubility of quartz would fall off as the temperature increased above 332° C until the temperature passed the critical, according to Kennedy's data cited above. This decrease in solubility would soon stop or radically slow the formation of ore. If (b) is correct, the solubility of quartz would also decrease and the replacement would also stop. If (c) is correct, the fluids transporting the quartz away from the replacement site and the hematite into it would be lacking and the replacement process would therefore end.

The replacement could have taken place under stress and the hematite would then grow in platy specularite crystals oriented by the local direction of stress. Had the stress, which caused the folding and local rock flowage, been relaxed or resolved by structural adjustments, the hematite may have assumed unoriented crystal forms. There seems to be no particular reason why stress might not have been present in some districts and not in others during the ore-forming process. For that matter, stress could be expected to change in space and time in the formation of a single large ore body.

6. The writers believe that condition (a) described above probably obtained, that is, that the temperature continued to increase above Kennedy's point of inversion of quartz solubility in the rocks now exposed in the Itabira district and perhaps in some other deposits of the Quadrilátero Ferrífero. Under these conditions, hematite might continue to increase in solubility but would not continue to replace quartz owing to the decreasing solubility of that mineral. However, the fluids carrying the hematite may have penetrated the wallrocks to a limited extent, depositing there in the different environment the veins of practically pure hematite or mixed hematite and magnetite. The pods and pockets of coarsely crystalline hematite and magnetite within the ore bodies may have been formed at this time, also with a slight or local change of Eh of the solution. The high-grade hematite bodies which already had been formed were

[12] The authors know of no high-grade hematite deposits anywhere in the world which are associated with iron-formation other than oxide facies.

brittle even under these conditions, as shown by the emplacement of the foliated dikes along faults and joints in the ore bodies.

7. There is no proof that conditions attained the supercritical and that the solubility of the quartz of the iron-formation increased enough to form a second generation of ore at supercritical conditions. It is conceivable that this may have occurred, as two or more generations of hematite are clearly present in some ore bodies. Even if supercritical conditions were not reached, a second generation of ore would probably also form during conditions of falling temperature had the temperature passed 332° C, for as the temperature fell toward 332° C, quartz would be increasingly soluble again.

8. The writers believe, but cannot prove, that in the Itabira district the supply of fluids fell off sharply during the time of decreasing temperatures and that little record was left of this declining period except for the complete alteration of the foliated dikes and possibly the formation of hard high-grade hematite associated with some of the quartz veins cutting the itabirite. These veins were clearly formed after the rock became brittle enough to fracture.

It is conceivable that the gold disseminated in the itabirite was introduced by the throughpassing solutions, but there is no way of proving this.

SOFT HIGH-GRADE HEMATITE ORES

"Soft ore" is the end member of a gradational series. Any explanation of the origin of this material must be applicable to ores which contain varying amounts of harder and more resistant hematite and must account for the gradation from extremely dense hard hematite to pulverulent hematite.

Complete metasomatic replacement of the quartz in itabirite by hematite, advocated on previous pages, would result in an extremely dense, hard, pure hematite rock. It was pointed out on page C62 that the metasomatic replacement was not complete everywhere and that certain zones in the ore bodies were somewhat porous, possibly because of inadequate supplies of hematite in the carrying solutions, or possibly because of local vagaries in the geochemical environment. It is believed that these slightly porous zones had great influence in the localization of soft and intermediate ores. Fragments and zones of coherent ore in the soft ore zones are now commonly more porous and less hard than the material that is normally called hard ore. These harder fragments in the soft ore can locally be broken with the fingers.

Zones of more porous ore grossly follow bedding and foliation. However, locally they crosscut both these features and in many places have quite irregular boundaries with denser ore.

Specific data on the actual porosity of these porous zones has not been secured; the porosity is so variable that quantitative figures would be deceptive. The range in megascopic porosity is from zero to possibly 15 percent in the various types of hard ores.

Great tonnages of soft ore exist in the Itabira district and elsewhere in the Quadrilátero Ferrífero. Table 4 shows that in the Itabira district 1,400 meters of gallery revealed that the average tenor of soft ore was over 68 percent iron; this is in accordance with data from other districts of the region. Commonly the soft ore contains a little more SiO_2 than the adjacent hard ore, possibly because of incomplete replacement.

PRESENT HYPOTHESIS

The origin for the soft ore advocated in this paper is amplified from that advanced in a preceding one (Dorr, Guild, and Barbosa, 1952, p. 294).

It is believed that the soft ore (and the intermediate ores) was derived from the originally hard hematite ores by supergene leaching of small quantities of hematite at crystal boundaries, thus disaggregating the rock. Where the process has gone to completion, the rock is completely disaggregated; where it is incomplete, the rock is an intermediate ore.

The control is both physiographic and due to local primary variations in the rocks. Brecciation, mylonization, or other processes which promote the intimate contact of circulating ground water with the hematite ore will also promote the softening process.

Field evidence bearing on the origin of soft ore is as follows:

1. Hard ore may grade into soft ore and back into hard ore in the same joint block.
2. In many cases, joints form the hard ore–soft ore boundaries indicating that the soft ore was once hard.
3. Joints are preserved in soft ore, which is now too soft to permit joints to form.
4. Residual fragments of hard ore, locally more porous than the normal hard ore, are found in the soft ore in structural conformity with the soft material, indicating lack of slump.
5. Soft ore is equally contorted and in the same manner as the hard ore and the itabirite. Had the material always been soft, deformation of a different type than that occurring in the hard rocks would have occurred.
6. Complex minor structures run from hard ore into soft ore and back into hard ore without break,

indicating that both types of material originally had similar physical characteristics.

7. As discussed on page C33, boulders, blocks, and cobbles of soft hematite, which is now incoherent, are found buried in ancient stream gravels and talus deposits. Such boulders must have been hard when the gravels and talus deposits formed.

8. Slump structures are rare in the high-grade soft hematite ores in the Itabira district. In some other districts, they are more common.

To this should be added the fact that in adit 6 North on Cauê Peak the updip side of a drift through hard ore was appreciably softer superficially than the corresponding horizon on the downdip side of the drift. The updip side was continually moist with through-passing water, the lower side dry because the mine opening cut off circulation along the bedding planes and foliation planes. This drift has been open about 35 years.

The effect of original porosity on softening of hematite ore is well illustrated in example 7 above. In such ancient boulder beds, commonly buried in soil, some of the boulders are hard hematite, some are completely disaggregated hematite, and some soft itabirite. The hard hematite boulders are typically dense and with no megascopic porosity. When broken, they are apparently dry inside even if wet on the outside. The soft hematite boulders, of the same chemical composition as the hard ones, are commonly wet inside if in a wet environment and are of a texture often indicating some primary porosity when found on outcrop. The hard and soft boulders, lying adjacent to each other in these boulder beds, obviously have shared the same environment since they came to rest. The only apparent cause of their different physical state must be the different primary porosity.

The soft hematite boulders cannot have formed from leaching of dolomitic itabirite or siliceous itabirite because the overlying soil would certainly show the original size or shape or, if the soil had collapsed around the shrunken boulder, such collapse would probably be evident in at least a few examples. The porosity of the boulders is not high enough to permit the residual enrichment of normal dolomitic itabirite (containing perhaps 45 weight percent iron) without collapse, such a concentration would demand the removal of more than 50 volume percent of the original volume of the boulder.

Whether the process advocated above is an adequate hypothesis of origin for the soft ore depends in considerable part upon whether hematite is sufficiently soluble under supergene conditions to be subject to significant solution in the climatic environment of Minas Gerais. Guimarães (1953, p. 25) has stated his belief that it is not sufficiently soluble.

The laterization process in general results first in the concentration and later in the removal of ferric iron from soils by supergene solutions. Therefore the generally admitted insolubility of ferric iron is only relative and time is a major factor.

In the iron-formation of the Minas series, the chemical weathering process dissolves ferric iron from the hematite in itabirite, transports it greater or lesser distances, and redeposits it again in ferric form as the "limonite" that is the essential mineral in canga. There are probably more than 500 million tons of canga in the Quadrilátero Ferrífero. This is clear proof that ferric iron is sufficiently soluble under supergene conditions to move large tonnages.

There is no way of telling how much of the ferric iron that went into solution was entirely removed from the area by streams during the course of chemical weathering; possibly only a very minor percentage remains fixed in the canga. It has been shown (Dorr, 1945, p. 44) that ferric iron can be leached and that the iron can be transported long distances underground by supergene water, to be deposited later in ferric form on the surface. The great canga chapada southeast of Agua Quente, Minas Gerais, which is on granite and Tertiary lake beds, proves the same thing.

Furthermore, solution cavities and pits on the outcrops of the high-grade hematite are commonplace in many deposits. Locally, a miniature karst topography, with the relief measured in centimeters or tens of centimeters, may develop on high-grade hematite in localities where mechanical erosion is not effective. The natural differential etching of high-grade hematite outcrops, illustrated in figures 24 and 27, is also clear evidence of the limited solubility of hematite.

Notable fluting and formation of chimneys in the high-grade hematite deposits of Liberia, reported by Thayer (written communication), indicate that hematite is soluble also in other parts of the world.

Thus it appears that hematite under present conditions is soluble enough to permit the minor amount of solution necessary to this hypothesis. Natural supergene solutions, which are difficult or impossible to duplicate in the laboratory, seem to be able to dissolve enough hematite from the rocks to account for the softening of originally hard hematite ore. To disaggregate such rock, only a minute amount of hematite need be dissolved from each crystal edge.

The water analysis given on page C106 proves that the solution of iron is now in progress in the Itabira district.

OTHER HYPOTHESES

Previous writers have suggested a variety of origins for the soft high-grade hematite ores. Percival (1954, p. 56) attributed soft ores both in India and Brazil to the supergene leaching of silica from iron-formation. (He did not distinguish between soft residually enriched itabirite and high-grade soft ore.) Whatever may be the case in India, this origin for soft high-grade hematite ore is not important in Brazil. To the general field evidence cited above may be added the fact that supergene leaching of iron-formation in Brazil is commonly accompanied by slight or major hydration of the hematite. The high-grade soft hematite bodies are not hydrated but are composed of blue or black hematite entirely similar to the hard ore.

Had the soft ores formed by the supergene leaching of itabirite, which averages less than 45 percent iron by weight when fresh and of which no samples over 55 weight percent iron have been taken from hard fresh material in the Itabira district, a minimum of 50 percent by volume of the original rock would have been removed in the process of forming soft ore containing 68 weight percent iron. About 70 percent of the volume would have to be removed to form soft hematite ore by the leaching of the silica from average fresh itabirite in the Itabira district. The removal of this volume of material would have certainly caused slumping on a grand scale. Slumping except on quite local and small scales is not evident in the Itabira district. In the case of the *C* ore body, Conceição, which has 300 meters of soft hematite, the equivalent of 470 meters of quartz would have had to be removed by supergene solution without causing notable slumping. This hardly seems probable.

One of the earliest hypotheses of origin of soft ores is that they were formed by the residual enrichment of dolomitic itabirite by hydrothermal solutions. This hypothesis still has its defenders (Guimarães, 1953, p. 26). Against it can be cited:

1. The same problem discussed in the previous paragraph concerned with the volumes of rock involved. High-grade hematite deposits, whether hard or soft, are commonly found in the thicker rather than the thinner parts of the iron-formation.

2. The lack of any direct evidence near many of the ore bodies of the existence of dolomitic itabirite, either now or in earlier epochs. Dolomitic itabirite has a characteristic weathering product that is not likely to be overlooked.

3. The lack of important bodies of soft hematite ore in many localities where dolomitic itabirite is known to be present and abundant.

4. The softening of high-grade hematite boulders in old talus deposits now buried in soil. There is no sign in the enclosing soil of hydrothermal activity. Nor is there sign of dolomitic itabirite in the boulders.

RUBBLE ORE

Erosion has plucked large tonnages of hard high-grade hematite fragments from numerous craggy hard ore outcrops in the Itabira district. These fragments have accumulated as talus or rubble on the slopes below the outcrops and form the so-called rubble ore. Landslide blocks of hard hematite may also be considered as rubble ore. The total production of rubble ore from the Itabira district has already exceeded a million tons, and during the early days of hand mining, before the benches on Cauê Peak were large enough to use heavy equipment, this material was the most important source of ore.

Rubble ore occurs in two ways. The first is as loose talus of hard ore cobbles generally lying on canga and exposed to the direct effects of sun, wind, and rain. This material accumulates to thicknesses of more than 10 meters, although usually less than a meter. Locally this surface rubble is preserved by the formation of a dense canga cap over the loose material. This cap in turn may become covered by more rubble.

The size and shape of the individual pieces of the rubble are to some extent governed by the joint spacing and bedding characteristics of the material from which they were derived. They average possibly 10–20 cm in longest dimension and 4–8 in the other dimensions, giving a length-thickness ratio of about 1:2 to 5. These cobbles are almost invariably well rounded and resemble stream worn cobbles even though they have moved by creep only a few tens of meters at most from their original source. This is due to the softening of the angular corners by chemical weathering, followed by mechanical removal of the softened specularite by wind and rain. When exposed to the direct sun, these pieces become so hot that they can hardly be picked up with the bare hand; the alternate heating and cooling, particularly rapid cooling by the intermittent showers, must promote chemical and mechanical weathering. The effect of abrasion on the individual pieces must be almost nil, as they have not been transported fast or far except during their first fall from the outcrop.

These cobbles usually are oriented with their long axes parallel to each other and to the slope. This type of ore was especially common on the Dois Córregos bodies and the Conceição *D* and *G* ore bodies. There is also a wide cover of such material in the central portion of the district.

Another type of rubble ore is found in the soil that overlies the rocks of the hanging walls and footwalls of the iron-formation. In many places this soil contains many hematite blocks which are recovered with comparative ease. Part of the flanks on Cauê Peak have been worked to a depth of a meter or more for the contained hematite and the Dois Córregos area has been particularly productive of such ore, which there occurs more than a kilometer from the nearest uphill outcrop of hematite.

The rubble ore in soil is much more variable in size and shape than the type described above. Much of the material is 2–3 cm in largest dimension, but is thoroughly mixed with cobbles and boulders of ore as much as a meter in largest dimension. The material is much more angular than that described above and is often protected by a thin layer of limonite. The protection from the direct sun afforded by the soil accounts for the differences. Generally this ore is also quite hard. An exceptional deposit occurs along the road to the C ore body, Conceição Peak, where a thick layer of angular hematite blocks is perched on the hillslope. Here many of the blocks, which originally must have been hard to have withstood transportation to the site of accumulation well out in the footwall, are now soft. Figure 7 gives a screen analysis of material removed from one of these softened boulders.

Three large blocks of hematite, all of which have been mined to some extent, have slid more than 200 meters from the cliffs of Cauê Peak. The one known as mine 8, centering on 51,250 N, 48,000 E (pl. 2), has yielded about 100,000 tons of high-grade hematite and possibly as much more remains. The smallest block, off the detailed map (pl. 2) but adjacent to the Sixpercent road up Cauê and northwest of the mine 8 body, has a very small tonnage. The largest one, centering on 52,050 N, 48,000 E (pl. 2) and known as Mina São José, has yielded almost a million tons of ore and is nearly mined out. The ore in these landslide blocks contains up to 0.05 percent phosphorus. The erratic dips show that the blocks are thoroughly fractured on a large scale. The São José block was more than 15 meters in maximum thickness, the mine 8 block even more than this. The profusion of large to huge angular boulders of ore scattered for more than a kilometer to the north and northeast of São José indicate that this landslide block may formerly have been much more extensive.

CANGA ORE

Canga is a rock name that originated in Brazil in the early days of mining, when it was the preferred ore for the Catalan forges and other small furnaces of the time. Use of the term is spreading to other countries, for the term conveniently describes a weathering product that is widely distributed in tropical and semitropical regions that have oxide-facies iron formation outcrops and seasonal rainfall.

Canga is a broad term. The essential characteristic of the rock is hydrated iron oxide (limonite) which has been precipitated at or near the surface. This limonite may cement fragments of iron-formation or iron ore, or, more rarely, nonferruginous rocks. It thus forms sheets over rocks of diverse character. In exceptional cases, the chemcially precipitated limonite may compose 95 percent or more of the rock; generally it is much less abundant. Hard ore rubble cemented by limonite is known as Canga Rica in Brazil and may contain as little as 5 percent limonite. As used in Brazil, the term canga includes rocks ranging from about 40 percent to 68 percent metallic iron. The rock is characteristically porous to cavernous, but it is not highly permeable and pools of rainwater may stand on it for days.

Canga is important physiographically because it is practically inert to chemical weathering and quite resistant to mechanical weathering and thus forms high ridges and chapadas, protecting the softer rocks beneath from mechanical erosion and permitting leaching to proceed to considerable depths. It is important economically because, owing to its porosity and relative lightness, it constitutes a good iron ore for charcoal blast furnaces.

Canga forms throughout the world in a rather restricted range of environments. One essential seems to be seasonal rainfall. Another seems to be the presence of oxide-facies iron-formation.[13] A third essential seems to be a tropical or semitropical climate. It is possible that a fourth condition might be a stillstand in mechanical erosion. Further analysis and information is needed to clarify this point.

ORIGIN OF CANGA

Canga is thought to form by the precipitation in ferric form of dissolved iron at or near the surface of the ground during the dry season. During the rainy season the iron-formation beneath the surface becomes saturated with water. This water, possibly aided by

[13] This may not be absolutely essential. The authors have seen the rock restricted to oxide-facies iron-formation on three continents, but it conceivably could form on other types of iron-formation. The literature is of little help, as it does not distinguish clearly between the various types of iron-formation.

carbon dioxide absorbed from the air and organic acids in the soil, dissolves minute quantities of iron while in the iron-formation. During the dry season some of the water rises to the surface through capillarity and evaporates, leaving the iron as limonite. After the formation of some thickness of canga, the limonite may be deposited on two interfaces, the air-canga interface and the canga-bedrock interface, depending on climatic, topographic, and bedrock conditions. The upper interface is poor in silica and is commonly hard and tough; the lower interface is porous, soft, and richer in silica. Rock debris lying on the upper interface becomes incorporated into the canga, locally being replaced by limonite, locally maintaining its original identity.

Canga may form in localities far removed from the source of the iron. Canga forming on mica schists topographically 500 meters below the iron-formation and as much as 2 kilometers away from the nearest iron-formation outcrop has been observed in Mato Grosso (Dorr, 1945, p. 44). Here the iron-rich waters which passed downward through the iron formation found their way to the surface along faults and formed linear deposits of canga on rock which normally does not produce this material.

Canga may also form by the leaching of silica from itabirite with the simultaneous partial hydration of the hematite to limonite. This form of canga, which in Minas Gerais may be as much as 10 meters thick, in many places preserves the structure of the preexisting rock. Because hydration and residual enrichment characteristically die out erratically downward, it is believed this process is due to supergene leaching and hydration. It is essentially supergene enrichment of the itabirite. Such material always overlies either soft itabirite or, very locally, soft high-grade hematite ore. When it overlies itabirite, compaction of the leached rock below may take place, for open spaces as much as a meter in vertical dimension and several meters parallel to the lower surface of the canga cap are common.

Collapse of cavernous interfaces, producing long cracks in the overlying canga sheets, are an important mechanism in the mechanical erosion of canga. If the slope is such that one part of the canga sheet moves and the underlying soft itabirite can be transported away by rainwash faster than new canga forms, the sheets are rapidly undercut and break off in large blocks, forming abrupt scarps. Deep canyons such as Grota de Esmeril formed in this manner. If the slope is such that the break heals itself with new limonite, a type of "slump ore" (Percival, 1954, p. 48) is formed. Renewed collapse and healing may produce considerable thicknesses of such ore.

In cases where the canga originally contained an appreciable percentage of aluminous material (canga formed on phyllite), the iron is gradually removed under continued laterization and an iron-rich aluminous laterite results.

NATURE OF CANGA

From the description of the genesis of canga, it is evident that it is nearly impossible to generalize about the thickness or the chemical and physical characteristics of the ore. The average chemical composition of 34,589 tons of canga shipped from the Itabira district to the Cia. Ferro e Aços S. A. steel plant in Vitória during 1949–1951 was 56.7 percent Fe, 4.81 percent SiO_2, 3.19 percent Al_2O_3, and 0.128 percent phosphorus. This material, which was formed from itabirite, was selected and cannot be considered typical. If canga which is too high-grade is used in charcoal blast furnaces, the burden becomes too heavy and the charcoal is crushed. Large quantities of higher grade material are available and could be mined.

Phosphorus becomes concentrated in canga and many analyzed samples have contained more than 0.2 percent of phosphorus. It is probable that large-scale mining of canga in the Itabira district would produce an ore with between 0.10 and 0.15 percent phosphorus and possibly between 56 and 59 percent iron (natural basis) or about the same as the canga produced from the Cerro Bolivar deposits of Venezuela.

ITABIRITE

Itabirite should be considered as a potential ore for two reasons. First, it can be concentrated easily by cheap methods into a very high-grade product. Second, tens of millions of tons of the material must be mined and moved in order to extract the high-grade hematite bodies that are enclosed in it. Therefore the cost of concentration will be the only major charge against this type of ore.

Furthermore, the high-grade concentrates obtainable from itabirite will be an ideal feed for the new direct reduction processes now in the pilot plant stage, for this process demands ore of the highest possible grade and the fine grain of the concentrates will facilitate reduction.

As illustrated by plates 2 and 8 itabirite is very widespread in the district. The total length of the continuous body is in the order of 22 kilometers and the stratigraphic thickness may average 150 meters. Only the itabirite which has been softened by weathering can now be considered potential ore because blasting and crushing of the unweathered material would be too expensive.

The itabirite has been disaggregated by weathering to varying depths (see pl. 8). Hard itabirite crops out in several areas, but it is known through underground workings in Cauê Peak that at least locally the material has been softened to depths well over 100 meters below the present surface.

GRADE OF ITABIRITE

The grade of the mineable itabirite varies widely, as illustrated by the analyses of 21 samples given in table 5, which follows. The average of these samples is not the average for the district, for the total reserves are so large that it would be sheer coincidence if these few samples were representative. Moreover, most of the samples were taken from within 40 meters of the original surface. The itabirite that will be moved in the course of stripping operations to uncover the ore bodies on Cauê Peak may average between 52 and 55 percent Fe within the first 40 meters of the present surface and about 43 percent Fe below that. The great mass of itabirite in the lower slopes of Cauê may average possibly 45 percent Fe. Soft itabirite in the other parts of the district should have comparable tenors.

Figure 8 shows the average chemical composition of five typical itabirite samples in various granulometric divisions and the same data for two specimens of rich itabirite. The concentration of the quartz in a rather limited intermediate size range and the predominance of the iron in the upper and lower size ranges is typical and has been confirmed in many analyses. This feature is of importance in choosing the mode of concentration of the ore, for simple screening at 35 mesh would get rid of most of the quartz without losing too much iron. The minus 35 mesh material could be concentrated by more complicated means were this desired.

The characteristic difference in the shapes of the Fe and SiO_2 curves in the graphs illustrating the size distribution of itabirite (figs. 7 and 8) and soft hematite should be noted.

RESIDUAL ENRICHMENT OF ITABIRITE

It is evident from the estimates of the grade of the itabirite to be stripped above and below 40 meters from the present surface that residual enrichment of

TABLE 5.—*Analyses of itabirite, Itabira district*

[CVRD analyses by Artur Penido, Department of Mines, Comp. Vale do Rio Doce, sampling by Dorr. I.I.O. Co. analyses from Itabira Iron Ore Co. records, analyst unknown. "Hard" of I.I.O. Co. is undoubtedly roughly equivalent to "compact" of present authors. Adits are collapsed and close comparison is now impossible]

Sample	Location of sample	Meters of samples	Nature of itabirite	Percent						Source of analysis
				Fe	Insoluble	Al_2O_3	SiO_2	P	S	
1	Mine 7, Cauê Peak	5	Compact	42.6	41.0−			0.012		CVRD.
2	do	5	do	36.6	45.6−			.029		CVRD.
3	do	5	do	50.4	26.1−			.021		CVRD.
4	do	5	do	33.5	50.7−			.021		CVRD.
5	do	5	do	45.5	33.9−			.021		CVRD.
6	Mine 16, Conceição	17	Very hard	36.9	47.34−			.002	0.021	I.I.O. Co.
7	Mine 18, Conceição	14	Medium hard	46.9	33.0+			.004		I.I.O. Co.
8	do	5	Very hard	41.9	40.2+			.008		I.I.O. Co.
9	Mine 19, Conceição	10	Hard	56.4	19.0+			.016		I.I.O. Co.
10	do	10	do	54.1	22.2+			.017		I.I.O. Co.
11	Mine 16, Conceição	31	do	41.8	39.6+			.002		I.I.O. Co.
12	Mine 17, Conceição	50	Medium hard	50.0	28.5+			.009		I.I.O. Co.
13	Mine 14, Conceição	19	Hard	49.9	28.4+			.004	.009	I.I.O. Co.
14	Mine 17, Conceição	40	do	43.9	36.7+			.005	.015	I.I.O. Co.
15	Mine 16, Conceição	35	do	44.0	36.5+			.001	.010	I.I.O. Co.
16	Adit 74, Cauê area	5	Soft	62.2	9.6+	7.40	2.20	.027		CVRD.
17	Shaft 442, Cauê area	4	do	58.5	15.8+	7.40	8.40	.019		CVRD.
18	Adit 51, Cauê area	?	do	57.2	15.6+	3.40	12.20	.019		CVRD.
19	Shaft 443, Cauê area	3	do	57.0	18.0+	3.50	14.50	.022		CVRD.
20	Adit X, Cauê area	5	do	56.7	17.40+	8.20	9.20	.024		CVRD.
21	Shaft 439, Cauê area	2	do	55.6	18.40+	3.60	14.80	.020		CVRD.
22	Shaft 439, Cauê area	4	do	55.6	19.50+	4.30	15.20	.020		CVRD.
23	Shaft 439, Cauê area	3	do	52.9	20.30+	2.70	17.60	.024		CVRD.
24	Trench 105, Cauê area	4	do	48.6	29.20+	3.60	25.60	.029		CVRD.
25	Adit 105A, Cauê area	5	do	45.9	31.8+	8.00	23.80	.019		CVRD.
26	Excavation for primary crushing plant, Cauê	2	do	61.1	10.8+			.023		CVRD.
27	1100 level, Cauê area	2	do	52.8	25.0+			.019		CVRD.
28	1280 level, Cauê area	5	do	57.7	17.0+			.020		CVRD.
29	1100 level, Cauê area garage excavation	20	do	46.1	34.9+			.019		CVRD.
30	1100 level, Cauê area near crusher	20	do	52.2	24.8+			.017		CVRD.
31	Mine 7, Cauê Peak	25	do	49.0	29.6+			.004	.010	I.I.O. Co.
32	Mine 6, Cauê Peak	17	Soft hydrated	58.2	9.18+			.10	.049	I.I.O. Co.
33	Mine 7, Cauê Peak	26	Soft	53.5	23.5+			.009	.010	I.I.O. Co.
34	Mine 19, Conceição	4	do	45.9	33.8+			.008		I.I.O. Co.
35	Mine 7, Cauê Peak	30	do	51.7	25.9+			.005		I.I.O. Co.
36	do	30	do	51.7	25.4+			.003		I.I.O. Co.
37	Mine 13, Conceição	35	Unknown	50.7	27.8			.013		I.I.O. Co.
38	Mine 18, Conceição	49	do	47.3	32.8			.004	.015	I.I.O. Co.

Average of all hard itabirite samples:
Fe .... percent .. 44.96
Insoluble .... do 35.24

Average of all soft itabirite samples:
Fe .... percent .. 53.81
Insoluble .... do 21.69

the itabirite by selective removal of quartz is believed to have taken place. Reference to the discussion of the cause of the softening of the itabirite on pages C26 to C31 gives the details of and evidence for this process.

In the Itabira district, relatively little itabirite has been concentrated to more than 60 percent iron by this process. Elsewhere in the Quadrilátero Ferrífero, in such deposits as the great Alegria deposit (fig. 2), tens or even hundreds of millions of tons of ore containing between 58 and 66 percent iron have been formed by a process of residual enrichment. Ore so formed does not reach the purity of the material called high-grade hematite in this report and is of entirely different physical aspect. It is porous, locally contains appreciable percentages of goethite and a mineral that appears to be supergene hematite and often has slump structures. This ore is related to the present erosion surface because, unlike the high-grade hematite bodies, tenor decreases with depth.

In the Itabira district, residual enrichment of the itabirite has increased the iron content 10 to 25 percent. In no place known to the writers has it removed virtually all the quartz, as it has elsewhere. The reason for the incomplete removal of quartz is that the grain size of the quartz in this district is larger than in the districts farther to the west where such enrichment has occurred. Grain size in Itabira district ranges from 0.04 to 0.4 mm, averaging over 0.1 mm, whereas in the Belo Horizonte quadrangle, the quartz in the itabirite averages 0.05 mm according to Pomerene (oral communication).

INTERMIXING OF ORE TYPES

It cannot be emphasized too strongly that, although it is possible to separate ore types for the purpose of discussion and analysis of the occurrence and nature of the ore, in actual mining of the deposits it is not practical to make a careful separation of ore types except for canga and itabirite. The lower grade itabirite is mixed with and often overlies the high-grade hematite. In the systematic large-scale mechanical mining which is essential to secure low costs and yield large tonnages, all the material must be moved.

Extraction of ore down to the 1300 level of Cauê has not been particularly hampered by overlying itabirite, although a large pocket had to be mined out. However, below about 1,300 meters, it will be necessary to start stripping itabirite on a significant scale and each successive bench below that level will require more stripping before the pure hematite can be extracted. As will be shown, the total tonnage of itabirite and of pure hematite above the 1100 level on Cauê Peak is about the same. Similarly, it is usually not possible to avoid soft and intermediate ore in the mining, for these ores are intimately mixed, at least within 100 meters of the present surface, with the hard ores. Nor is it possible to avoid the schistose ore in order to mine the massive ore. The main practical value of the above analysis of ore types is to permit an evaluation of the problems that will be met in extracting and preparing the ore for shipment and also to permit a gross forecast of the amounts of the various size ranges that will be yielded by mining and treatment of the ore.

DESCRIPTIONS OF THE HIGH-GRADE ORE BODIES

CAUÊ AREA[14]

The Cauê area contains the largest body of hard high-grade hematite ore in the Itabira district and a number of smaller, poorly exposed bodies. Mining had removed 70 meters from the top of Cauê Peak by 1954, but, as each bench becomes progressively larger than the one above, the rate of lowering of the peak becomes steadily less. Cauê Peak was originally a spectacular crag of hard ore with a practically sheer scarp of 130 meters on the west end and a long slope off to the east, walled to the south by sheer hard ore scarps 20–50 meters high. It is little wonder that the peak has attracted the imagination of miners and promoters for many decades, or that it became known as the mountain of iron ore. It is a magnificent ore body.

MINING

The main ore body is being attacked by modern methods. Fifteen meter benches are sliced off the top of the mountain. Two to three benches are mined simultaneously and heavy mechanized equipment for drilling, digging, and hauling are used. The flowsheet and details of crushing and screening the ore were recently described (Effenberger, 1954) and the details will not be repeated here. It should be noted that the original crushing and screening plant did not take into account the extreme weight and abrasiveness of the ore, nor did the designers realize that the ore body contained as high a percentage of fines as it does. The plant has had to be remodeled and strengthened at critical points. The designers also

[14] See plate 2 for the distribution of iron ore, plates 3, 4, and figure 35 for mine maps, plate 8 for sections across the ore bodies, figure 9 for a map of the Santa Barbara mine, plate 6 for columnar sections and figure 36 for columnar sections based on diamond drilling.

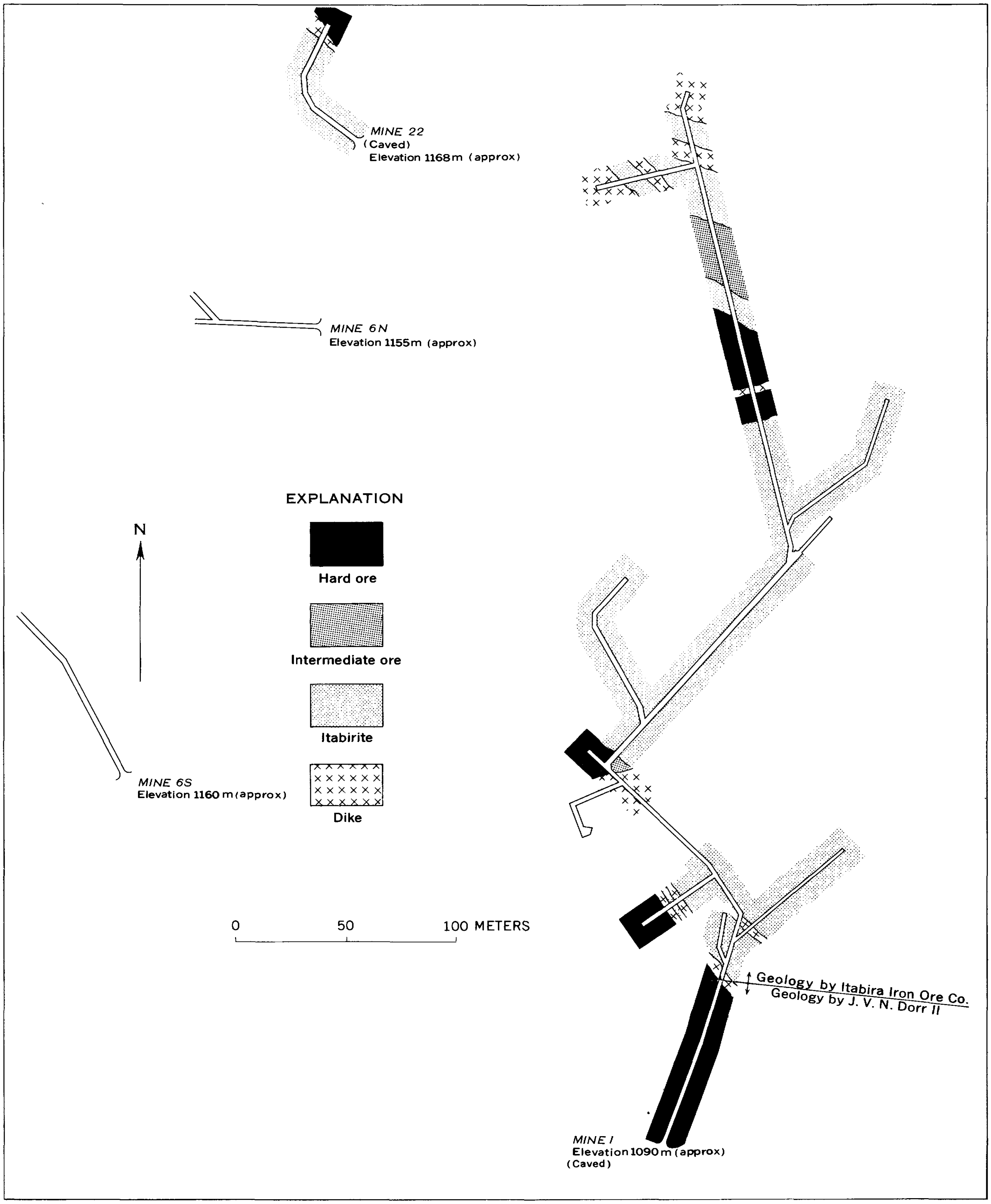

FIGURE 35. Geologic map of mines 1 and 22, Cauê area.

did not realize that dropping the hard ore from conveyor belts to ore piles would produce an unduly high percentage of fines. Large-scale plants to be designed in the future should take advantage of these early mistakes which were caused by inadequate knowledge of the ore characteristics and by the pressure of war conditions.

EXPLORATION

Three major and one minor adits were driven by the Itabira Iron Ore Co. in the Cauê area in the second decade of the century. Possibly a hundred shafts and adits were driven during the old gold mining days of past centuries. Six diamond-drill holes were drilled by the Cia. Vale do Rio Doce in 1949–1950. Most of the older adits and shafts have collapsed and no records of the rock encountered or the ore produced exist, but the dumps give good indications of what was found in the workings. The CVRD reopened in part all of the major exploration adits and these were remapped as part of the present work (pls. 3 and 4). The information gleaned from these workings was essential in deciphering geologic relations of the ore and in making the ore estimates.

Results of the core drilling are given in figure 36. This work was carried on by two companies, one American, the other Canadian. The drillers were expert. The poor results obtained are a measure of the difficulty of diamond drilling in this type of iron ore. It is possible that with heavy equipment and NX and BX bits, better results might have been achieved, but this is far from certain. The cost per meter of hole was about twice the cost of driving an adit at the time the drilling was done. Much valuable information was secured but not one hole could be driven to the target, the footwall of the Cauê itabirite.

The maps and sections presented in this report (pls. 2 and 8) show all the available information. Both for mining and for geological purposes the data are so sparse that large margins for error exist. The most serious hiatus in information is the almost complete lack of precise data about the location and conformation of the footwall and about the nature of the material in the northern third of the Cauê syncline.

The writers have little confidence in the structure and distribution of ore at depth as shown in the sections to the east of section 8 because they believe that these matters cannot be safely inferred from surface data and there are no subsurface data. The sections were drawn conservatively, but there is no good evidence for the magnitude of the main east-west fault shown on the map and sections, and it might well be greater than estimated, thus reducing reserves. The block to the north of this fault has never been explored. The sections to the east of section 5 are purely hypothetical as far as the conformation of the footwall is concerned; there is no subsurface control.

STRUCTURE

The detailed structure as inferred from the information available is illustrated by the sections 1–12, plate 8. These show a relatively open and shallow syncline pitching about 15°–25° to the east, complicated between sections 3–4 and to the east by a rather distorted anticline with low dips. This anticline may be related to the east-west fault inferred in the western end of syncline. Such a minor anticlinal structure in the center of a larger syncline is characteristic of the Itabira district.

The synclinal structure seems to be definitely established by the outcrop pattern and the underground workings of mine 6 (see sec. 11) and mine 7 (see sec. 8). The surface dips do not confirm this synclinal structure except at the western end, but this is thought to be caused by the intricate flowage folding that accompanied the folding of the iron formation. Were the sections across the syncline constructed to follow the surface dips, the part north of the apparent axis of the syncline would be found to contain far too little material to match the southern part.

This may be the case, for much material may have flowed during the folding from the northern half into the southern. The axis of the syncline cannot be closely located on the basis of surficial dips. The extremely intricate and random folding in itabirite exposed in the center of the syncline by the road leading north from the Sixpercent road just below the 1150 contour is an excellent illustration of what was taken to be flowage folding in itabirite.

Although the base of the iron-formation is hidden nearly everywhere by debris fallen from above, it could be located very closely along the northern flank and at about half a dozen places along the southern flank. Under Cauê Peak, the base of the formation could be located only within a few tens of meters, but it is probable that the mapped position is not far from correct. The extensive cover, however, prevents certainty as to whether the east-west fault shown on the sections displaces the contact. The dike which marks the position of this fault for 800 meters is not seen in the good outcrop above, and so the fault was assumed to have died out toward the western end of the syncline. The dike is found, however, on the east side of the 1288 bench.

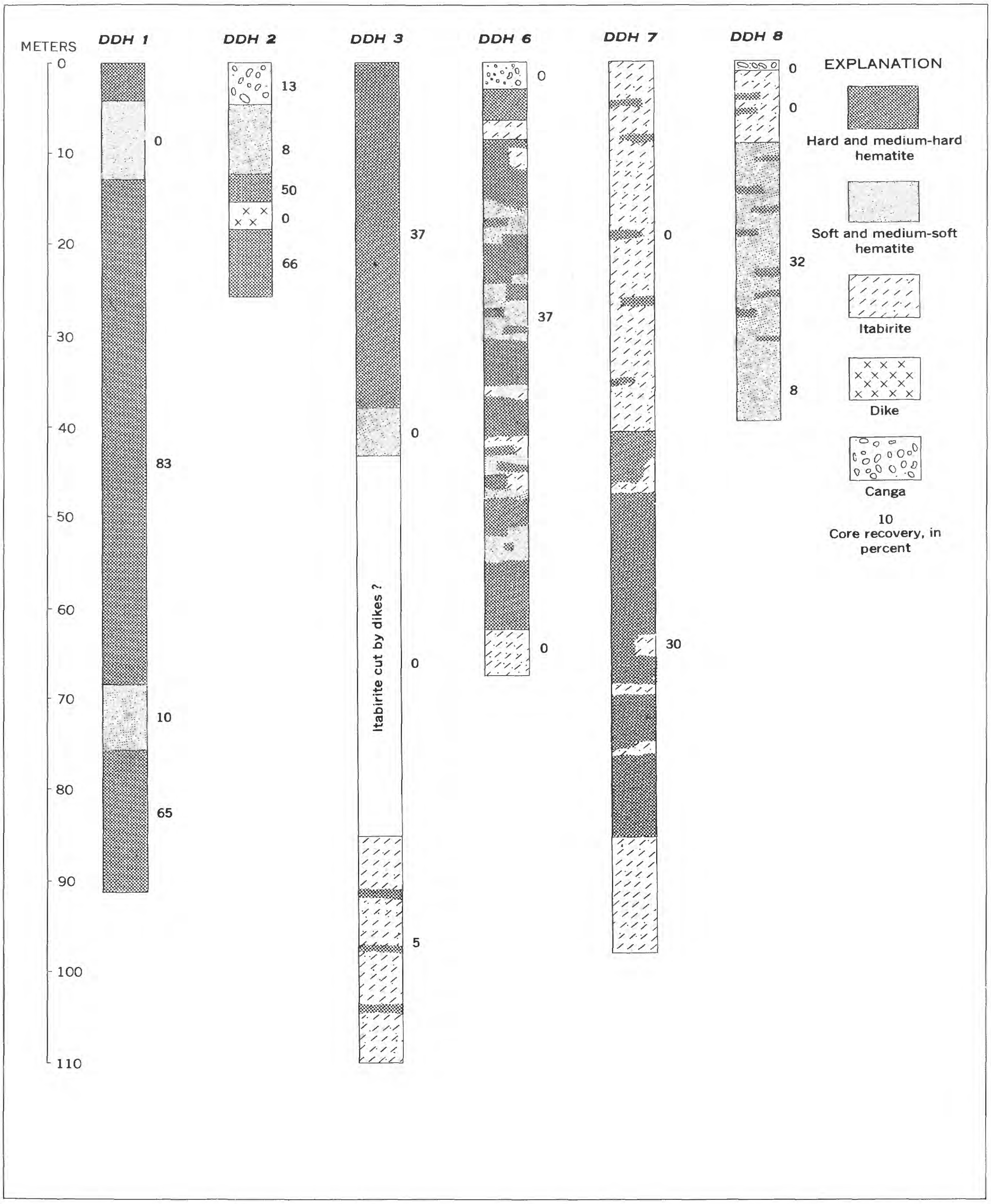

FIGURE 36.—Columnar sections based upon diamond drilling on Cauê Peak. Location of drill holes shown on plate 2.

This fault is somewhat hypothetical. Its presence is inferred from three lines of reasoning as follows: (1) The trace of the supposed fault is occupied by a dike mineralogically identical with those which seem to occupy pre-dike faults in mines 6 and 7; (2) The difference in apparent thickness of beds between the north and south sides of the Cauê syncline seems to call for a fault in addition to the flowage indicated by the intricate crenulations; and (3) A long and persistent lens of hard hematite terminates against the supposed fault for a linear distance of nearly 800 meters. This lens, now almost completely hidden by the debris of early hand-mining operations, had a maximum exposed thickness of 25 meters and an average exposed thickness of perhaps 10 meters. It was intersected at a depth of 30 meters below the outcrop by mine 22 (now collapsed), driven through the dike by the Itabira Iron Co., indicating a potential thickness of more than 40 meters for this ore. As the lens has not been identified south of the hypothetical fault, it seems logical to suppose that it was faulted, as ore bodies of such size do not commonly end so abruptly.

It is probable that this hard ore lens may be equivalent to the hard ore exposed in mine 6 a short distance to the south of the fault. About 40 meters in from the northern portal of mine 6, the hard ore is overlain by itabirite. (There has been some movement along this contact.) If this contact could be proved by exploration to be the same as the itabirite-hard ore contact to the north of the fault, as might be indicated by mine 22, the inferred hard ore reserves of Cauê Peak might be radically increased and the itabirite reserves somewhat decreased.

The two large faults offsetting the southern limb of the syncline near mines 6 and 7 have not been definitely recognized either in underground or surface workings. The contact between the iron-formation and the footwall is, however, offset to the extent shown. This is indicated by adequate exposures. Conceivably, this might be the result of minor folding, but the solution shown seems the most reasonable. An extensive breccia zone in itabirite may be seen just inside the portal of mine 7, which probably represents the more easterly fault. Mine 7 shows much postore faulting and brecciation, but enough information to solve the problems of extent and direction of movement is not available.

DISTRIBUTION OF ORE

The main Cauê ore body may be traced with breaks of not more than a few tens of meters from the 1200 contour on the north limb of the syncline (52,070 N, 48,860 E) to the portal of mine 7, near the 960 contour (51,145 N, 48,960 E) on the south limb of the syncline. The linear distance along the outcrop is approximately 2,200 meters. The difference in elevation between the highest and lowest known points was more than 400 meters before mining began. The greatest stratigraphic thickness of the ore body was about 150 meters.

As may be seen on the map and sections, most of the ore seems to be concentrated in the middle and lower thirds of the Cauê itabirite, except under Cauê Peak itself, where the ore body seems to have transgressed into the upper parts of the iron-formation. The center of the syncline, which includes the stratigraphically higher beds, is composed of itabirite with relatively little high-grade ore, except for the 800 meter lens just north of the fault.

The main Cauê hematite body is not a simple tabular or lenticular mass. It has projections into itabirite and reentrants of itabirite as well as inclusions and lenses and tabular bodies of itabirite within it. Although the shape of the pure hematite bodies as indicated by sections 1–5 is necessarily somewhat hypothetical, there is enough sure data from the surface and underground work to permit reasonable confidence in the general shape of the bodies as shown. Naturally this irregular shape will complicate mining and will necessitate the extraction of much itabirite in order to extract the high-grade ore.

The major pure hematite body in Cauê is, like all the other known ore bodies, composed of both hard and soft ores and has many intermediate gradations between these classifications. All the surface and underground workings reveal this, as do the diamond-drill holes.

The screening plant which treats the ore extracted from the benches on Cauê Peak is provided with scales which weigh the different fractions of ore as they come out of the plant. Thus a close approximation of physical state of the ore after crushing can be made.

In 1954, a total of 1,689,590 tons passed through the crushing plant. The primary screening plant removed 401,754 tons of minus one-half-inch material (or 23.8 percent of shipments) and 250,525 tons of minus one-half-inch material, or 20.0 percent of the remainder was removed by the secondary screening plant, giving a net production of 1,037,311 tons. Possibly 5 to 7 percent of this tonnage was undersize and was screened out at Vitória before loading on ship. As delivered to the consumer in the United States, as much as 10 percent of the ore is undersized, the result of breakage during later handling. Thus, about 45 percent of the ore mined in 1954 was too weak or too fine to be sold as lump ore. This percentage is reported to have increased in later years.

During the period in which the weightometers have been functioning, a lens of soft itabirite appeared on the benches and was mined and shipped to the screening plant. Much of this itabirite therefore is included in the minus one-half inch material which was stocked. (Part of it was thrown off the cliff or used in road fill.)

Mechanized iron mining cannot be very selective, and therefore it seems probable that in future operations such lenses will be included in the mining operations and must therefore be considered as part of the ore from the mining point of view. The fact that the primary reject pile averages 63.5 percent Fe and the secondary reject pile averages 65.6 percent Fe is evidence that about 12 percent of the fine material rejected in the primary screening was derived from itabirite. Were a plant erected to concentrate the itabirite, the fine higher grade material could be simultaneously recovered.

No adequate data on the size distribution of the fine fraction of the medium-hard and medium-soft ores exists. The benches from which the weighed material was produced contained very little ore which the writers would have mapped as true soft ore, but they did contain soft itabirite. Much of the ore mapped as soft ore is rarely more than a 25 percent plus 10 mesh, as illustrated in the screen analysis presented in figure 7.

Considerable discrepancy exists between estimates of physical hardness made by the writers and by the engineers who mapped the underground exploratory workings driven by the Itabira Iron Ore Co. many years ago. This discrepancy exists because at the time the original mapping was done, no premium was paid for iron ore suitable for open-hearth feed and all ore was looked at from the point of view of blast furnace feed, for which plus 10 mesh was suitable. The present work has tried to differentiate between ore suitable for the open hearth furnace and other ore.

Because the only records of many of the underground mines lie in old maps made years ago, some comparison of the conventions used then with those used in this report is essential in order to interpret them. Table 6 gives a summary of the writers' estimate of the physical state of the ore in mines 6 and 7 and also the estimates made 30 and more years ago for the same rocks. Percentage of hard ore in this report is radically different from that in the original mapping, for the earlier estimate was 67.5 percent hard ore in mine 6 against 47.8 percent in the present estimate, and the earlier estimate for mine 7 was 69.0 percent against 28.7 percent in the present estimate.

The "medium hard," "medium soft," and "soft" ores of the present report correspond not only to the old "intermediate ore," but also include some of the old "hard" ore.

The distribution of the hard, soft, and intermediate ore in the main Cauê ore body is most difficult to predict. The maps of mines 6 (pl. 3) and 7 (pl. 4) illustrate well the impossibility of projecting ore type any great distance with assurance. On those maps it can be seen that material which is hard and massive may turn into medium-hard and even medium-soft ore in a few tens of meters or less along strike. Certain zones tend to have more hard ore than others, it is true, but within these zones patches and lenses of softer material may well be found.

It is believed that the southern limb of the Cauê syncline and the central part of the valley of Canal da Serra above the 1100-meter level will prove to have the best hard ore reserves and the lowest percentage of soft ore. This opinion is based on the

TABLE 6.—*Comparison of the ore and rock thicknesses in mines 6 and 7, Cauê area, as mapped 1913–22 and 1948–54*

	Mine 6				Mine 7			
	Old mapping		Recent mapping		Old mapping		Recent mapping	
	Meters	Percent	Meters	Percent	Meters	Percent	Meters	Percent
Hard ore	646	67.5	456	47.8	685	69.0	286	28.7
Intermediate ore	16	1.7			159	16.0		
Medium-hard ore			85	8.9			246	24.6
Medium-soft ore			139	14.6			161	16.1
Soft ore			6	.6			129	12.9
Itabirite	243	25.4	241	25.3	126	12.7	139	13.8
Dikes	52	5.4	27	2.8	23	2.3	37	3.7
Total	957		954		993		998	

outcrop pattern, the results of drilling, and the evidence derived from the tunnels.

The area along the north limb of the syncline extending from 48,160 E, to 48,710 E, shown on plate 2 as continuous outcrop, is actually composed of many lenses of hard schistose ore, too small to map individually, cropping out through the canga cover. Mining will undoubtedly reveal a rather low percentage of hard ore in this area and much medium-soft ore as well as some rich itabirite. The material might improve physically downdip, but only exploration can prove whether this will be the case.

Mines 1 and 7 show that there must be much hard and soft pure ore available below the 1,100 m contour. Although sections 5 and 9 indicate that the pure ore gradually lenses out down the pitch of the synclines, it should be emphasized that there is no direct evidence for this. It is very possible that notable reserves of high-grade iron ore lie at greater depths in the unexplored keel zone, where the sections show only itabirite. In fact, ore is geologically expectable in that area. The Santa Barbara adit (fig. 9) at 51,105 N, 50,510 E, at an elevation of 920 meters and 500 meters east of mine 7, showed soft hematite at the farthest point to which it was possible to penetrate (the mine was partially collapsed). Certainly mine 7 showed considerable quantities of both hard and soft ores at elevations of about 965 meters, and also showed that the ore was there concentrated in the bottom of the iron formation. Only exploration along the keel of the syncline can resolve this question.

A number of other smaller bodies are exposed in the Cauê area. Along the 52,000 N coordinate for some 300 meters east of the 49,000 E, coordinate (pl. 2) are found a group of small high-grade hematite outcrops which may be connected under the canga cover with each other and possibly with the main Cauê body to the west. Most of these are below the 1150 m contour. The nature of the outcrop ore suggests that a considerable part of these bodies will be composed of intermediate and soft ores, rather than hard ore.

Two bodies of mixed ore lie just south of the 52,000 N coordinate between 49,000 E and 50,000 E. The more easterly of these bodies contains a rather high percentage of itabirite intimately mixed with the high-grade ore. A short adit which penetrated the other body showed mainly soft ore. A gold adit which started in canga between these two bodies at 51,962 N, 49,800 E revealed in a winze (fig. 37) a body of soft and intermediate ore which was not suspected from surface indications. This probably indicates that there are other similar bodies which do not crop out. Most of the ore will be soft and intermediate ore, for the physiographic setting of this part of the area indicates that leaching must have been active for a relatively long time.

Near 51,485 N, 49,565 E several small bodies of hard and intermediate ore crop out. In a prospect pit at 51,780 N, 49,470 E highgrade itabirite was found and it seems quite possible that soft ore might lie under the canga in the environs of these outcrops. Here too it seems probable that hard ore will not be abundant, because of the physiographic environment.

RESERVES

The method of calculating reserves used in this report and the basic assumptions made will be discussed in detail here and will not be repeated in the descriptions of the other ore-bearing areas except as such assumptions vary from the norm.

Cross sections at a scale of 1:5,000 (reduced to 1:10,000 for publication) across the iron-bearing rocks were made at intervals of 250 meters throughout the entire district, supplemented by subsidiary sections generally but not invariably at 125-meter intervals where underground information was particularly good. These sections are marked on plate 2 and are presented on plate 8. In all, 66 sections were made for ore calculations. At the east end of the Cauê syncline, where data are most insecure, sections were made every 400 meters. Certain subsidiary sections crossing the others were made to clarify structure, but were not used in calculations.

All subsurface workings which crossed the line of section were plotted. Accurate elevations were not available for the subsurface workings but it is thought that they are correct within a few meters. Most of the underground workings are caved and the rock identification and contacts of the original maps had to be used. Ore and contacts were not projected more than 50 meters onto the sections from isolated underground exploration. Where underground exploration is reasonably continuous, as in part of Conceição Peak and in part of Cauê Peak, ore which crops out continuously at the surface is projected at depth from one section to another without hesitation even where the sections themselves do not cut underground workings. Certain drill holes were projected in the Cauê area; the greatest distance of projection was 40 meters.

All outcrops of hematite were plotted where the sections cut them. Unless there was good evidence for the existence of high-grade ore under canga, it has been assumed that the outcrops showed the true width (taking into account the dip of the rock) of the bodies. That this is somewhat too conservative is shown by recent mining operations on Conceição

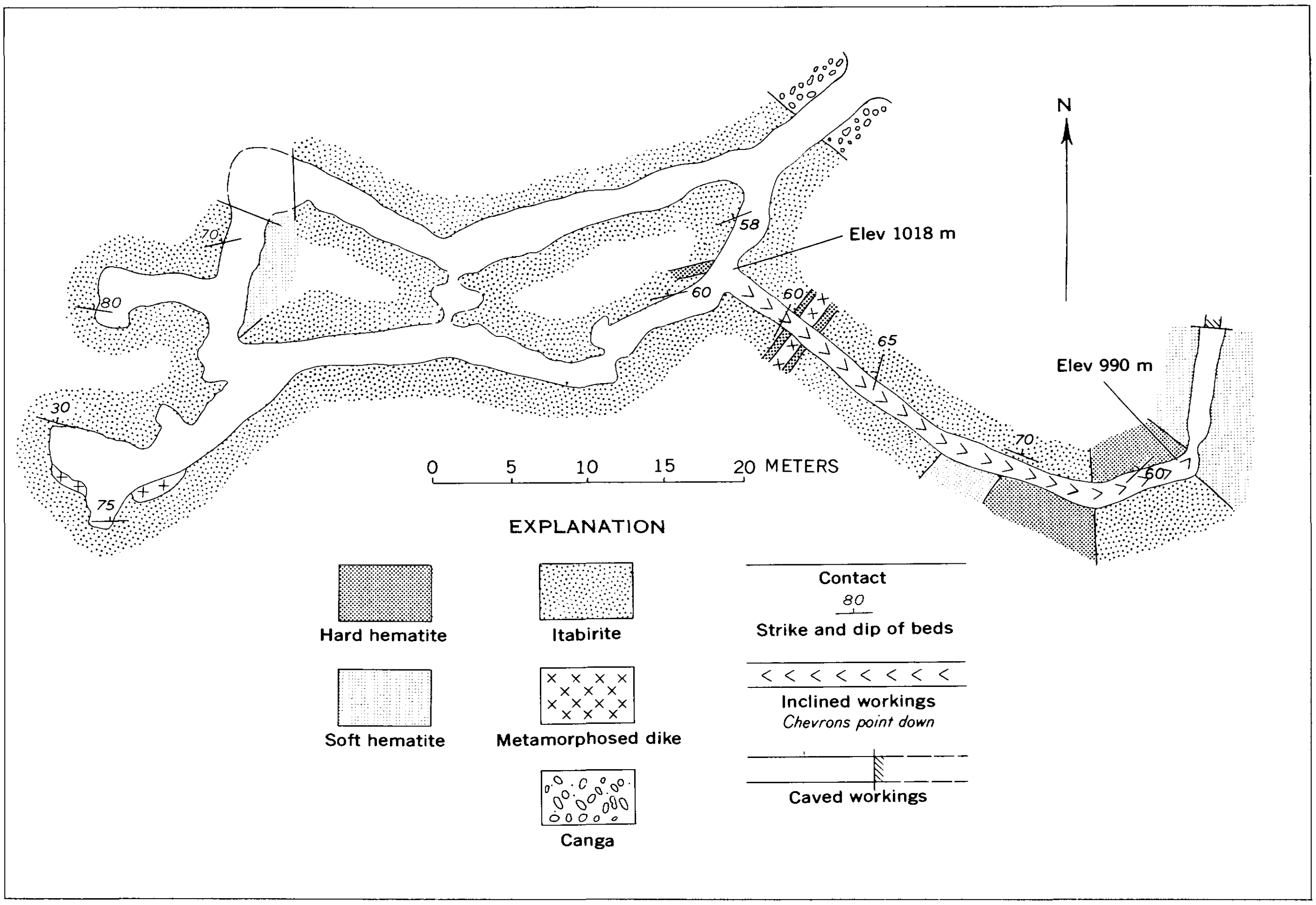

FIGURE 37.—Geologic map of an old mine at 51,962 N, 49,800 E. Cauê area.

Peak, *G* ore body, where a face of 110 meters of good ore has been opened beneath a canga body which originally showed only a 30-meter outcrop of hard ore. However, other workings have demonstrated that the basic assumption that hard hematite usually crops out is valid in most cases. Errors introduced by this assumption will be on the conservative side. Soft ore and intermediate ore, on the other hand, rarely crop out and undoubtedly many bodies of such ore exist under the canga cover which are not considered in the ore estimate.

ORE CLASSIFICATION

Instead of classifying the pure ore according to the conventional system as "measured," "indicated," and "inferred," the high-grade ore has been divided into two clases only. The first of these is called "reasonably assured ore" for it includes only ore within 50 meters of the surface except in cases where the presence of ore at greater depth is assured by underground workings.

The mine maps and the trace of the mine and drill holes plotted on the detailed maps and sections of the ore body give the evidence available on which such projections were based. The sections have drawn on them the lower limit to which this classification of ore was projected, marked with a line. It is believed that the order of error of the tonnage estimate for this type of ore should not be over 25 percent, and, because soft ore is not included except where cut by underground work, the overall estimate is probably low.

The other classification of ore was termed "inferred." This classification includes ore more than 50 meters below the surface outcrops and varying distances downdip from underground workings. The writers believe that the inferred classification gives a minimum tonnage of ore which may be found by underground exploration and that the actual amount present may be much more.

The outlines of the inferred ore as shown on the sections cannot indicate actual contacts of ore bodies. These outlines indicate where the more favorable zones for prospecting are located and give some idea as to the size of the bodies to be expected.

The minor outcrops are short and lenticular. Many are not cut by the cross sections, and others, which may be 300 meters long, are cut by only one section. Such outcrops pose problems as to depth of projection and weight to be given. In general, such bodies were projected to a depth equal to their length. With few exceptions, these bodies which were not cut by sections were not considered in the reasonably assured classification but, in those areas where small lenticular bodies are abundant, similar bodies were projected below 50 meters depth in about the same abundance as they occur along strike on the surface. Thus such bodies do not enter into the "reasonably assured" classification but do in the "inferred" classification.

In the Cauê syncline, all the itabirite down to the 850-meter level was included in ore estimates, as it seems probable that, owing to the shape of this syncline, the itabirite has been softened to a greater depth than in the case of the other parts of the area. The depth of projection will be discussed separately for each area. The itabirite tonnage estimates can be considered to be only order-of-magnitude estimates, for the shape of the fold, the regularity and degree of softening, and the grade of the itabirite at depth are all unknown factors except in that part of Cauê Peak where some underground information is available.

METHOD OF CALCULATION

To calculate the tonnage of the high-grade hematite, the areas of ore on each section were measured by a polar planimeter. These areas were then multiplied by half the distance to the adjacent sections to give the cubic meters represented by each section. Obviously, this simple method introduces errors, but the errors tend to be compensating and the data are not sufficiently refined to justify more complex methods of arriving at volume. In the case of nonparallel sections, the appropriate formulae were used. A specific gravity of 4.5 was assumed, although the hard high-grade hematite rock in place averages over 5.0. The lower figure was used in order to give more weight to the more porous soft, medium-soft, and medium-hard ores.

The same general method was used in calculating the reserves of soft itabirite. A specific gravity of 3.0 was used for this rock.

There is no way of accurately predicting the physical state of the high-grade ore to be found in the different parts of the district, as no quantitative data are available except for Cauê Peak. Because this is such an important factor in the future of the district, the writers have made an estimate for each area considered, based on their familiarity with the rocks as seen in outcrop, on the nature of the canga, on the scanty information available from first hand underground observation, from the new surface mines, and from interpretation of old maps. Although these estimates will not be correct, quantitative work on small parts of the area have provided new basic data and they therefore have some value. Where information permits, estimates are made for individual large ore bodies.

TONNAGE ESTIMATES, CAUÊ AREA

In the case of the Cauê area, tonnage estimates were made for ore and itabirite above 1,100 meters, the elevation of the present crushing and screening plant, as well as for the area as a whole. The estimate above 1,100 meters includes both reasonably assured ore and inferred ore; owing to the better exploration above this elevation, relatively little of the ore is classified as inferred ore. The estimates are given in table 7.

TABLE 7.—*Tonnage estimates, Cauê area*

[In millions of metric tons]

Locality	Reasonably assured ore [1]	Inferred ore	Itabirite above 850 meters [1]
Sections 6–12 (explored area)	96	71	166
Sections 1–5 (poorly exposed area)	17	31	672

[1] Above 1,100 meters, reasonably assured ore is estimated to total 87 million tons, and itabirite to total 88 million tons.

The material termed ore will average more than 67 percent Fe; the itabirite may be assumed to average between 43 and 46 percent Fe. Thus the deposit contains approximately 143 million tons of metallic iron in the high-grade ore and 370 million tons of metallic iron in the itabirite. It is estimated that possibly 50 percent of the high-grade ore will furnish material of more than half an inch in minimum dimension and of the remaining 50 percent approximately a half will be plus 18 mesh. The itabirite is estimated to be not less than 75 percent soft and suitable for concentration with a bare minimum of crushing and blasting. The material resulting from the concentration of the itabirite would have to be agglomerated before use in a blast furnace.

CHACRINHA AREA

The Chacrinha area, shown on plates 2 and 8, contains a large body of pure hematite ore, most of which is probably intermediate and soft. Surface features did not indicate a major ore body in this area and it was located only after four adits had been driven into the body and mining had started on insignificant outcrops. This discovery gives reasonable assurance that much more ore is present than is indicated by surface features.

Much of the area is covered to a depth of at least 10 and possibly more meters by laterized transported soil, which is believed to represent ancient valley fill, of the type mentioned on page C32. Most of the remaining area is colored light-yellow by the cementing iron hydroxide.

Float of hard magnetite-hematite rock occurs in the soil above the outcrops along the 920 contour. A large boulder, weighing several tons, was encountered during mining operations but could not be drilled or broken with the equipment at hand. In the railroad cut at about 49,570 N, 48,360 E a small irregular pocket of this material may be seen in place in the medium-hard to hard hematite. The hematite matrix has softened in spots and magnetite-martite crystals as much as 2 centimeters across may be picked out of the rock.

MINING

All of the Chacrinha area except the northeast end belongs to the Cia. Aços Especiaes do Itabira. Several tens of thousands of tons of hard hematite have been removed by simple hand methods supplemented by machine drilling from the outcrop along the Sixpercent road. The outcrops shown on the same plate to the southwest of that mentioned, at an elevation of about 920 meters, have been joined by a bench which extends some distance to the northeast of the outcrops shown. Only hard ore and rich canga was removed; when soft and medium-soft ore was encountered to the northwest of the hard rib, mining was abandoned.

EXPLORATION

The body is poorly exposed but has been opened by four adits, one of which was driven during the 1930's and was covered during the construction of the Sixpercent road up Cauê, and three of which were mapped and are illustrated in figure 38. The covered adit, which is said to have been located about 30,300 N, 48,900 E, is said to have cut 20 meters of hard ore. No record of the exact location, the direction, or the rocks encountered has survived. The size of the dump, which is now obscured by later mining operations and the fill of the road, seemed to indicate a somewhat longer adit than 20 meters. The other adits, marked A, B, and C on plate 2, were driven as haulage adits at a time when it was intended to mine the deposit. They were never used and are now mostly caved.

STRUCTURE

The Chacrinha area occupies the south flank of the east-pitching anticlinal fold which is formed by the junction of the Cauê syncline with the major syncline which runs northeast-southwest through the Itabira district. The northeast end of the area is almost on the anticlinal axis, and therefore the main ore body is close to the major fold, even though it shows a simple monoclinal structure at the present erosion level. Neither the ore nor the itabirite where seen show minor folding or crenulation, but the ore exposed in the three lower adits seems brecciated to some extent and has been severely squeezed as shown by pronounced lineation. Several zones show strong recrystallization into rather coarse soft micaceous hematite with notably strong pencil structure. Some of this ore has a greasy feel and is physically similar to soft ore in the Andrade deposit in the Monlevade district, about 17 kilometers to the south-southeast. The brecciation is locally healed by dense goethite and hematite, resulting in a high-grade ore.

DISTRIBUTION OF ORE

The scattered outcrops do not permit a clear idea of the distribution of ore and iron-formation in this area. The contact with the overlying Piracicaba group is nowhere exposed. The basal (topographically higher) contact is better exposed, as there are two outcrops in 900 meters and the contact can be located with some assurance elsewhere by soil changes. At the northeast end of the Chacrinha area, there is absolutely no evidence as to the distribution of ore except as shown along the road. Soil covers all the northeastern half of the area. It is possible that the material which was shown in the sections in this part of the body as itabirite may prove on exploration to be soft hematite. Sections 18 and 19 show a considerable thickness of high-grade hematite; this is revealed by the exposures provided by the railroad and highway cuts and by adits *A* and *C*. Further exploration might prove that estimates of ore in other sections are too conservative. Although there is no outcrop of either hematite or itabirite near section 20, a body of ore at a depth of more than 50 meters was postulated based upon the possible extension of this body.

RESERVES

Inferred high-grade hematite ore was calculated to an elevation of 600 meters. The tonnage of Itabirite was calculated to a depth of 150 meters below the lowest point on each section because the physiographic development of this area and the presence of the laterized valley fill which overlies much of the area make it probable that much time has been available for softening the itabirite. Reasonably assured ore was calculated to total 38 million metric tons, inferred ore 134 million tons, and itabirite 104 million tons.

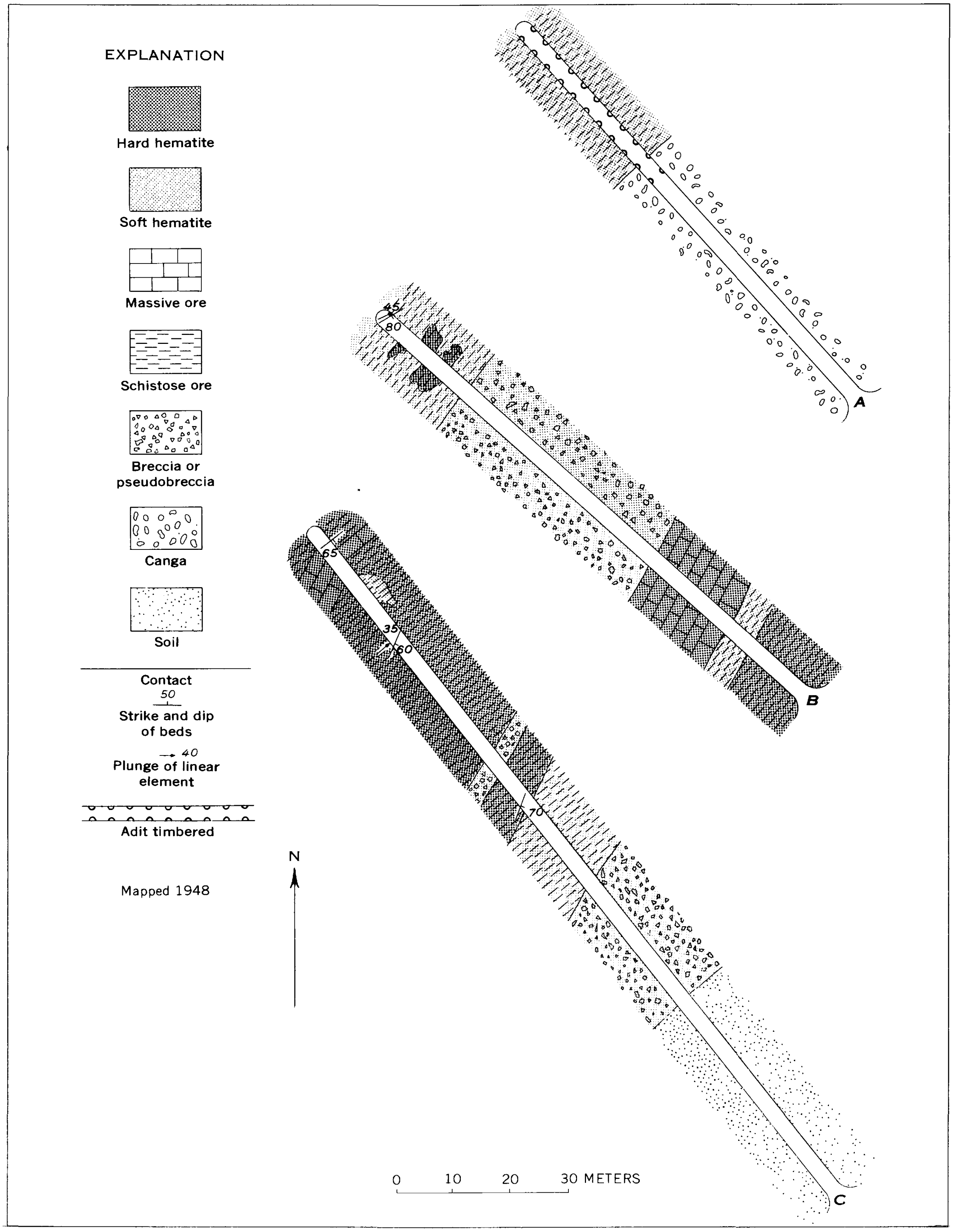

FIGURE 38.—Geologic maps of adits in the Chacrinha area.

The material noted as ore should average over 67 percent Fe. The itabirite should average between 44 and 50 percent Fe. Thus this part of the Itabira district is estimated to contain approximately 115 million tons of metallic iron in the rich hematite ore and 46 million tons of metallic iron in the itabirite. It is estimated that only about 30 percent of the reasonably assured ore will be, after mining and screening, plus half inch and of the remaining 70 percent less than one-half will be plus 18 mesh.

ONÇA AREA

The Onça area, shown on plates 2 and 8, sections 21–29, is characterized by poor outcrops and nearly continuous canga cover in the southwest part. All of this area is the property of the Cia. Aços Especiaes do Itabira.

MINING

No systematic mining has been undertaken in this area. Several tens of thousands of tons of rubble ore have been removed in the vicinity of 48,675 N, 47,150 E in irregular benches which show that the detrital hard ore (rubble ore) here is locally more than four meters thick. Bedrock ore has not been mined.

EXPLORATION

No systematic exploration has been done in this area. Canga has been mined in the vicinity of 48,400 N, 47,300 E. Several short tunnels and pits have been dug in the canga area. One very important short adit (5 meters), located at 48,502 N, 47,100 E, revealed the presence of hanging-wall rocks under the canga shield and confirmed the presence of the tight synclinal fold shown on sections 21–28 Some previous ore estimates had considered the canga in this area to be underlain by ore and itabirite. Another short adit at 48,350 N, 47,075 E revealed soft ore under the canga. There is no way of judging the magnitude of this body, which might be large.

STRUCTURE

The structure of the Onça area is much more complicated than that of the areas described above. As illustrated on plate 2 and in the sections already referred to, the iron-formation in this area is folded into two extremely tight folds, one synclinal, the other and more southerly, anticlinal.

The extension of the hanging-wall rocks under the soil to the west of the short adit mentioned in the section on exploration is probable but not proved. No outcrops or exploratory work confirm that the rocks are distributed as shown; it was so mapped because a long narrow tongue of soil extends in the expected direction and because, in a similar situation on Conceição Peak, mapping of a similar fold on the basis of soil distribution was proved justified by later exploratory work.

West from section 21, the southern anticline develops and broadens, manifesting itself in a narrow sickle-shaped outcrop of itabirite; in sections 29 to 37, the fold becomes the broad Piriquito anticline. In the western part of the area, there are 1,520 meters of continuous outcrop of itabirite across the strike of the canga, hydrated itabirite, and ore. However, this does not justify the enormous tonnage estimated by previous writers, for the ferriferous material is quite thin in many places owing to its position on the fold.

The synclinal fold which was the dominant structure from sections 21 to 29 becomes subordinate to the west, forming the Dois Córregos syncline from sections 30 to 35. Just west of section 35, erosion has removed the itabirite and ore, and the syncline is unrecognizable.

It will be evident from inspection of the sections and the outcrop patterns that this tight and nearly isoclinal folding has produced a notable thickening and thinning of the iron-formation (and of the other rocks as well). Thus, in section 23, the itabirite zone is only about 70 meters thick (stratigraphic) and even less in section 24, whereas in section 25, the zone is more than 100 meters thick and in section 27 must be more than 150 meters. Much of this thickening and thinning is undoubtedly due to actual physical transfer of material over considerable distances as discussed in the chapter on structure.

DISTRIBUTION OF ORE

Owing to the unusually poor exposures in this part of the Itabira district and to the almost complete lack of exploration, it is most difficult to determine the distribution of pure hematite in the Onça area with any assurance. Small sums spent in exploration might radically increase the known reserves in this area, for the structural environment is right for ore formation. The widespread existence of hard ore cobbles on and in the canga and the considerable thickness of detrital hard ore in certain places might be taken to indicate the presence of important bodies whose presence now can only be suspected. Much rubble ore in large angular blocks is found overlying the Piracicaba group near the east end of the Onça area.

The most southwesterly outcrop of the Chacrinha body is 1,150 meters east of the nearest large outcrop of ore in the Onça area. In this distance there are

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only two small outcrops of high-grade hematite. This is the longest extent of iron-formation without significant high-grade ore bodies in the ore-bearing zone of the Itabira district. Between these small hard hematite outcrops and the major body that begins cropping out at 48,710 N, 47,190 E bodies of soft or intermediate ore may well be concealed under the canga cover. From the locality cited above to the southwestern edge of the Onça area, there are numerous small hard high-grade ore outcrops along the footwall of the itabirite zone and it may be that these are connected under the canga by soft ore zones as far west as the hard-ore body cropping out near 48,270 N, 46,250 E. For some distance west of this body the overlying canga is siliceous and probably overlies itabirite, whereas to the east, the canga is not siliceous.

The major known ore body in the Onça area is that which crops out at 48,710 N, 47,190 E and extends with intermittent outcrops about 500 meters to the west-southwest. Although there are some excellent outcrops of hard ore in this body, most of the outcrops are small and scattered and it seems probable that the material will prove to be mostly intermediate type ore. The maximum outcrop width of the body is 200 meters, the average much less.

A number of small discontinuous lenses of hard ore occur in the itabirite on the anticlinal fold to the south of the main body but these represent a minor tonnage.

In the Grota de Esmeril, the deep erosion gully formed by the rapid removal of soft itabirite gives a measure of the depth of softening of the itabirite, for in the bottom of this gully may be found several outcrops of fresh hard itabirite. These are at least 120 and probably 150 meters below the old erosion surface, although fangs of hard and medium-hard itabirite project upward for as much as 50 meters into the softer material above.

RESERVES

No inferred ore was assigned to sections 21 and 22. Inferred ore was calculated to an elevation of 650 meters in sections 24 and 23, to an elevation of 700 in sections 25, 26, and 27, to 800 meters in section 28, and to 850 meters in section 29. These changes in cutoff elevation make the bottom of the inferred ore about 350 meters below the outcrop.

Itabirite was calculated to a depth of 125 meters below the lowest point on the section for sections 21 to 23; for the other sections it was calculated to a depth of 100 meters below the lowest point in the section. In sections 22, 23, and 24, in which the itabirite is divided into two distinct parts by the septum of Piracicaba group, the distance below the outcrop was measured separately for each individual part, because the septum is so deep that the hydraulic system is probably different in the two parts.

Reasonably assured ore was calculated to total 12 million metric tons in the Onça area, inferred ore 41 million tons, and itabirite 309 million tons.

The material totaled as ore should average over 67 percent Fe and the itabirite may be assumed to average between 43 and 46 percent Fe. This area is estimated to contain approximately 35 million tons of metallic iron in the high-grade ore and 172 million tons of metallic iron in the itabirite.

It is estimated, on the basis of surface showings only, that possibly 35 percent of the high-grade ore will furnish plus half-inch material and of the remaining 65 percent, possibly 40 percent will be plus 18 mesh. The remainder would have to be agglomerated before use.

PIRIQUITO AREA

Rocks in the Piriquito area are badly hidden by canga and rubble ore in the higher portions and by soil, heavy vegetation, and talus in the lower parts (pls. 2, 8; secs. 36–47). Uncertainties about the detailed structure and the extent of the ore will persist until more exploration has been accomplished.

MINING

The Cia. Aços Especiaes do Itabira, owner of the Piriquito area, has mined several tens of thousands of tons of canga and probably more of rubble ore and intermediate and soft bedrock ore. No systematic or orderly mining operations have been undertaken, as all the work was done by contractors. A number of benches, actually merely roads driven across the ore body with no particular attention paid to maintaining level, have penetrated the original surface a few meters. They show the material beneath the canga cap and the cover of soil or rubble ore to consist of soft and intermediate high-grade ore, generally too soft to stand long transportation without breaking into small fragments.

EXPLORATION

The only significant exploration in the area is the adit that starts at about 47,150 N, 47,040 E and crosscuts most of the ore body, extending perhaps 100 meters into the footwall (see fig. 39). Several short adits have been driven in the canga and in the ore elsewhere in the area but they give little useful information.

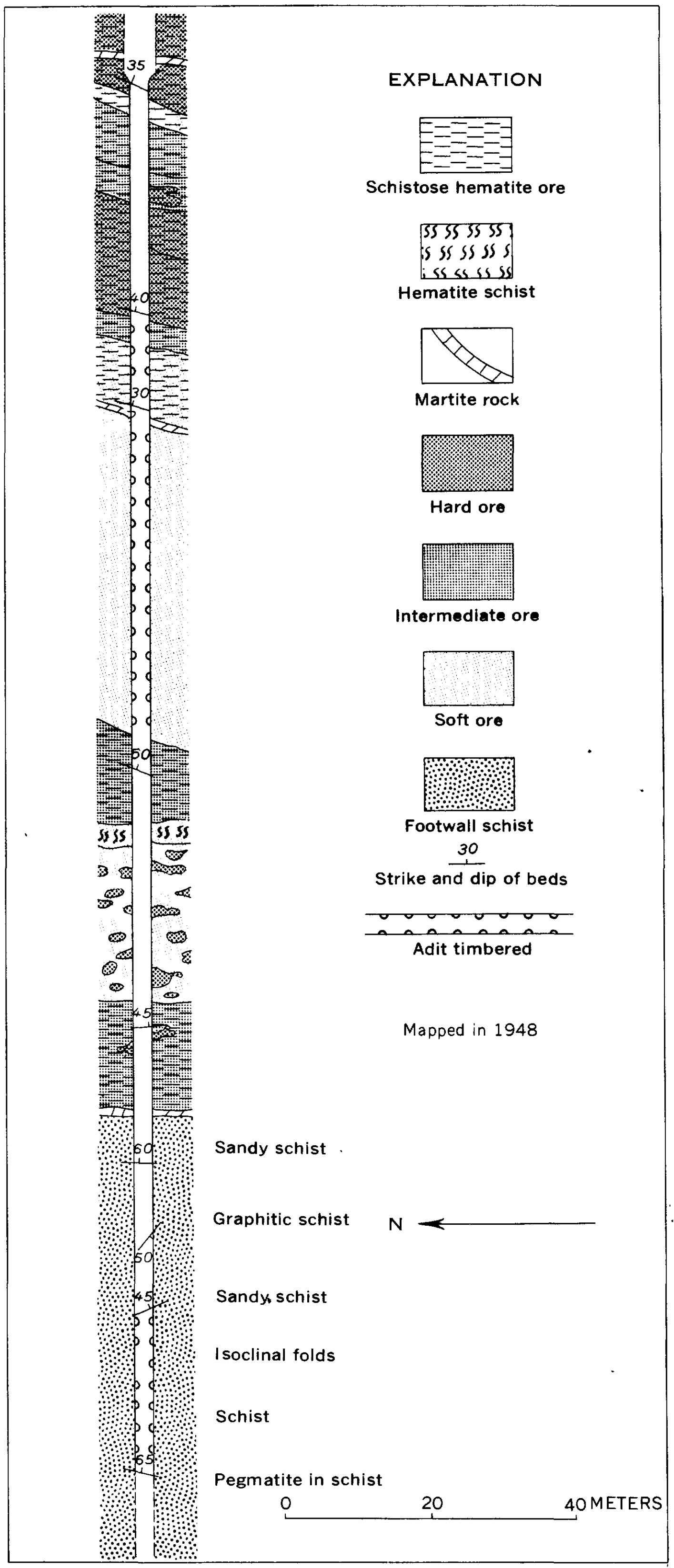

FIGURE 39.—Geologic map of main Piriquito adit, Piriquito area.

To explore the area, several additional adits should be driven across the body to the footwall, preferably at a lower elevation than the existing adit. A short adit should be driven at about 46,650 N, 47,000 E to determine whether the itabirite doubtfully mapped in that area actually exists and whether soft ore might be present in that area. The area west of Dois Córregos creek could be best explored in a preliminary manner by driving an adit from a low level parallel to the strike, with crosscuts to the walls of the body each 100 meters.

STRUCTURE

The Piriquito area lies on the northwest flank of the major syncline in the zone where this flank is transitional into the Conceição syncline (the southwest end of the Piriquito area) from the Piriquito anticline (the northeast end of the area). The Piriquito anticline is formed by the intersection of the subsidiary Dois Córregos syncline with the major syncline, of which the Conceição syncline is the western end.

The area is cut by a major cross fault which seems to offset the iron-formation nearly 100 meters in Dois Córregos valley. The fault has not been seen but is postulated for the following reasons:

1. The iron-formation changes strike and dip abruptly from N. 45 E., dip nearly vertical, to N. 5 E., dip about 45° E., at this valley.
2. The iron-formation seems to thicken abruptly from one side of the postulated fault to the other, suggesting a strong vertical as well as horizontal component.
3. Unless a fault is postulated, it is most difficult to explain the presence of the small itabirite outcrop near the sharp bend of the highway where it crosses the Dois Córregos valley.

If the fault is not present, the tonnage of itabirite calculated will be less, but the amount of high-grade ore will not be significantly affected.

DISTRIBUTION OF ORE

In the part of the Piriquito body which lies between sections 38 and 44 (pl. 2), the ore and itabirite form nearly a dip slope. Because there is almost 200 meters difference in elevation between the top and bottom outcrops, there appears to be a much larger ore body present than actually exists. The ore merely veneers the surface and probably does not average more than 50 meters in thickness. In contrast, the part of the body which lies to the southwest of Dois Córregos creek may well be much larger than appears on the surface. Exploration there might increase the tonnages estimated on the basis of surface exposures. The percentage of hard ore might well be higher than in the other part of the Piriquito body, although much of the ore will be soft or intermediate.

The ore-bearing area between sections 38 and 44 is largely covered by canga and talus, through which protrude outcrops of hard ore that vary in size. The larger ones were mapped, but about 25 percent of the area mapped as canga to the south of the large outcrops and north of Dois Córregos creek consists of hard thin-bedded ore in outcrops too small to illustrate at map scale. This indicates that the body will be very mixed in physical nature at depth. The faces of the benches which have been cut in the hillside since the area was mapped confirm this opinion.

The major adit cutting the Piriquito body showed that much of the ore was soft at depth. It also showed that a zone of martite-magnetite rock a few tens of centimeters thick lies at the portal and also at the footwall contact of the ore. A martite-magnetite dike 10 centimeters and more thick was located on the surface at about 47,240 N, 46,853 E. This may be the same as the martite zone mapped in the adit near the portal. The percentage of magnetite and martite is insignificant.

High-grade hematite near the footwall may continue to the north over the crest of the anticline. However, no ore was shown at this horizon in sections 37 and 38 because proof of its existence could not be found.

RESERVES

Inferred ore was calculated to an altitude of 700 meters. Itabirite was calculated to a depth of 100 meters below the lowest outcrop. Reserves were calculated as 61 million metric tons of reasonably assured ore, 84 million tons of inferred ore, and 129 million tons of itabirite.

The ore should average more than 67 percent iron; several tens of scattered samples of the surface material taken by the Brazilian Iron and Steel Co. averaged over 68 percent iron. There is no information on the grade of the itabirite, but it probably averages between 44 and 50 percent iron, judging from analyses on other parts of the district.

There is no control as to the percentage of hard or soft ore, but it is believed, from observation and careful estimate of the area of hard ore outcrops in the canga surface, that perhaps 30 percent of the high-grade hematite ore will be plus half-inch after mining and crushing. Of the remaining 70 percent, perhaps 35 percent will be plus 18 mesh.

DOIS CÓRREGOS AREA

The west end of the Dois Córregos area (pls. 2, 8; secs. 33–35) was originally characterized by spectacular outcrops of hard blue hematite projecting through canga and rubble. The central and eastern parts of the area are covered by a thick and heavy canga mantle through which protrude a few small outcrops of hard ore. The canga usually gives no hint as to the rock below it. The exploration adit being driven in 1954–55 revealed only itabirite, insignificant bodies of hematite, and dike rock in the first 100 meters.

The Dois Córregos area is almost entirely the property of the Companhia Vale do Rio Doce.

MINING

Extraction of ore from the Dois Córregos bodies started in 1950. Most of the ore produced has been from bedrock deposits but an appreciable tonnage of rubble ore has been shipped. Up to the end of 1954, mining was done by contractors, mainly by hand methods. The deposit is well suited topographically for mechanical extraction of ore and it is expected that after a projected aerial tram to the railway has been completed, the mine will be mechanized.

EXPLORATION

Very little exploration has been done in the area except that incidental to mining and the building of roads. In 1954 an adit was started at about 47,530 N, 46,168 E. By the end of the year it had progressed about 106 meters in a N. 85° W. direction and had cut only itabirite except for 2–3 meters of pure hard hematite. The purpose of the work was to test the extension in depth of the main Dois Córregos ore bodies, which lay another 150 meters beyond the end of the adit in December 1954. A branch of the adit was driven some 80 meters N. 60° E. from near the portal. It encountered a deeply weathered and saturated dike and probably penetrated to the footwall. This branch, which was intended to explore at depth the small hematite bodies which crop out near section 31, collapsed and was abandoned. A shallow test pit was dug near 48,000 N, 46,800 E to learn the nature of the rock under the soil cover in this area. Canga was encountered.

STRUCTURE

As illustrated in sections 30 to 35, the structure of the Dois Córregos area is that of an asymmetrical syncline, locally overturned. The syncline pitches to the east and extends into the Onça area. The southern limb of the syncline is very steep and locally overturned, whereas the northern limb seems to have only moderate dips, although the very poor exposures in this area make definite information impossible to secure without underground exploration.

In the Dois Córregos syncline, as interpreted on sections 30 to 33, a notable thickening of the iron-formation probably occurs. This is a continuation of the abnormal thickness in the Onça area, discussed on page C91 which is thought to be attributable to the same cause. The very strong linear structure, which locally obscures all signs of original sedimentary structures and is accompanied by a very coarse crystallization of the hematite in the pure ore, lends weight to this concept.

As mentioned above, the ore in the main Dois Córregos bodies has been subjected to great stress. Impressive logs of hematite, fragments as much as 2 meters long and 30 to 40 centimeters in diameter, are characteristic of parts of the major body. Another feature of the main body is a zone of soft greasy specularite a meter or more thick, which has been traced along strike for several hundred meters. The material is pure specularite composed of plates as much as a centimeter across. The zone seems concordant with the vestiges of the bedding and probably represents a shear. It is close to, although not adjacent to, a dike. Solutions from the igneous body may have promoted recrystallization.

A road driven to explore a small outcrop of hematite on the north flank of the syncline revealed that the thin infold of phyllite and quartzite of the Piracicaba group mapped in the Onça area extends to the Dois Córregos area. Several meters of dolomite weathering product, somewhat manganiferous, were revealed on the hanging wall of the iron-formation.

DISTRIBUTION OF ORE

The main mass of ore in the Dois Córregos syncline occurs, as elsewhere in the region, in the lower part of the iron-formation. Considerable quantities of ore occur higher in the section also on the south flank, but on the north flank, most of the outcropping ore is near the lower contact. Most of the larger ore bodies are in the keel zone of the syncline and near the axis, but because of inadequate exploration, the presence of soft-ore bodies under the canga cover cannot be affirmed in the large hill-slope east of the main valley. It seems probable, however, that along the north flank there should be more ore than is shown on the map or in the sections, although it probably will be soft ore. The high-grade hematite bodies are cut by many thin interbeds and pods of itabirite.

RESERVES

Inferred ore was calculated to an altitude of 850 meters above sea level, and itabirite was calculated to a depth of 100 meters below the lowest outcrop on each section.

Reserves were calculated as 19 million metric tons of reasonably assured ore, 45 million tons of inferred ore, and 212 million tons of itabirite.

The material totaled as ore should average over 67 percent iron; the 130,065 tons shipped from the area in the first half of 1954 had the following composition:

	Percent
Fe	68.4
SiO_2	.79
Al_2O_3	.65
P	.026

The itabirite may average between 44 percent and 50 percent iron. Data on the grade of the itabirite away from the new adit is completely lacking; there it is generally high grade and firm. Thus the ore from this area may contain about 43 million tons of metallic iron and the itabirite some 95 million tons of metallic iron.

No data have been kept during present mining operations on the percentage of fine ore produced during mining. As a visual estimate, it seems probable that, with mechanized mining and crushing, about 30 percent of the pure hematite would be plus one-half inch and of the remaining 70 percent, possibly 40 percent would be plus 18 mesh.

CONCEIÇÃO AREA

The Conceição area (pls. 2 and 8; secs. 48–66) probably contains the largest reserves of high-grade hematite ore and certainly is the most interesting and complicated area from a geologic viewpoint in the Itabira district. The area culminates in a salient triangular peak which reaches an elevation of 1,351 meters, originally lower than Cauê but now the highest peak for many tens of kilometers. The peak is composed largely of hard itabirite, with minor quantities of hematite, but the long spurs trending toward the east, each representing one limb of a tight complex syncline in the itabirite, contain large reserves of high-grade hematite. The high relative elevation of the peak is due to the greater resistance to erosion and disintegration of the iron-rich rocks than of the granitic, gneissic, and schistose rocks which surround it on all sides but the east.

Numerous adits and shafts were developed during the period of gold exploitation of the 18th and 19th centuries. Vestiges of old canals and concentrating plants are common. The complete lack of tailings and, with very few exceptions, dumps from the old workings attests the rapidity of erosion of loose sand and quartz in this steep country, where only heavy and hard hematite and canga can stand up to the torrential rains of the wet season. The old workings have been collapsed for many years but one is struck by the many field note references of the Itabira Iron Ore Co. engineers of intersection of their workings with those driven by the gold miners.

The Conceição area contains three major ore bodies which are called herein the *A*, *C*, and *D* and *G*. These bodies are marked on plate 2. The Itabira Iron Ore Co. designated by letter several of the other small bodies which are lumped herein under the term "miscellaneous." They also separated the *D* and *G* ore bodies, which seem to be one. The *A* ore body is the long narrow body (pl. 2) which extends from the west end of the Piriquito area with an almost unbroken outcrop 2,000 meters to the west along the north flank of the syncline. The eastern 500 meters (not included in the 2,000 meters crop mentioned above) is considered as part of the Piriquito area because of the change in ownership at the low divide between the Córrego de Conceição and Dois Córregos drainages; geologically the two parts are a unit. The *C* ore body is the large outcrop along the south flank of the major structure formed by a subsidiary syncline and somewhat separated from the main trends. It is entirely to the northwest of the Peti powerline. The *D* and *G* body forms the large outcrops along the south flank of the major structure, the greater part of which lies to the southeast of the powerline. Separate tonnage estimates were made for these bodies.

MINING

By the end of 1954, mines had been opened in all three of the major ore bodies. The most extensive work has been in the *A* ore body, where three benches have been opened. Production from the *D* and *G* body has been smaller, while the *C* ore body was only opened in late 1954 and production has been small. All mining has been by contractors with hand labor.

When a projected aerial tram has been completed, it is probable that all these mines will be mechanized.

EXPLORATION

The larger ore bodies have been explored by adits driven by the Itabira Iron Ore Co. during the second and third decades of the century. In all, a total of 6,090 meters of gallery were driven. The detailed records of assays and the samples of the ore and rock which were taken by the original company disappeared shortly after the CVRD took over the property and the only records which remain of most of the work are the maps which are reproduced herein (pl. 8). Almost all the adits collapsed long ago. The missing data would be most valuable to the company if they could be located, as today it would be very expensive to repeat the work.

Even without the assay data and sampling records, the old maps are most useful in that they definitely confirm interpretations of structure which would seem most dubious without the data provided by the maps. For example, the anticline separating the *C* ore body from the main mass can only be suspected from surface indications. There are no outcrops. The maps show clearly that the footwall quartzites and schists are brought to the surface here and the numerous crosscuts localize the contact with considerable accuracy. The underground data are much more complete than the surface data.

STRUCTURE

As may be seen on plate 2, the structure of the Conceição area is that of a tight, locally overturned major syncline containing medium-scale synclines and anticlines formed by plastic flow of the upper part of the iron-formation and of the hanging-wall rocks during the major folding. In the area cut by section 61, the iron-formation is repeated, in part at least, four times, which accounts for its outcrop width of more than 1,100 meters. This repetition cannot be observed clearly on the outcrop, for the surface of the interior valley is almost entirely covered by a thick layer of canga and by rubble ore which effectively mask the underlying rock. The evidence for the complicated structure must be sought in the distribution of the soil and the percentage of sand in the canga and checked against subsurface data provided by adits.

These adits are widely spaced and were not located to elucidate structure; therefore the information they provide is not sufficient to locate the contacts and fold axes with precision. It is to be expected that later mining and exploration work will correct many errors in location. Thus, the adit driven in 1952–53 into the *A* ore body from the north side (pl. 5) cut the hanging wall of the subsidiary syncline and necessitated moving the mapped contact about 20 meters. It did, however, confirm the presence of the hanging-wall rocks (Piracicaba group) which before then had only been suspected as they do not crop out and had only been revealed by mine 20, which has collapsed and could not be mapped.

The presence of the hanging-wall rocks in the middle of the valley and in the middle of the main syncline is demonstrated by outcrops along the road in the valley of Córrego de Conceição, by two small quartzite outcrops near 45,480 N., 45,300 E. and by the fact that the old maps show quartzite between the portal and the ore in several of the adits driven south from the central valley (see pl. 8).

The presence of the subsidiary anticline between the two synclines discussed above is proved by the presence of itabirite and ore just to the north and northwest of the quartzite outcrops cited above.

The presence of the anticline between the *C* and *D* and *G* ore bodies is indicated by exposures in numerous underground workings and by soil distribution (see maps of mines 5, 8, and 10, pl. 7).

The major syncline and all the minor folds but two pitch to the east. The minor syncline of the *C* ore body is erratic in that it pitches to the west instead of to the east. Its bordering anticline does the same. These structures are two of the few structures in this part of the Quadrilátero Ferrífero which have a west, rather than east, pitch and the writers are at a loss to explain the cause. In the rocks exposed by the new road to the *C* ore body, west pitching linear structures were observed, although the dominant pitch in these rocks also is to the east.

DISTRIBUTION OF ORE

Plate 2 shows that in the Conceição area many more small hematite bodies crop out than in the other parts of the district. These bodies were carefully mapped with planetable and telescopic alidade in order to get reliable data as to distribution and shape of the individual bodies. Many of the ore bodies are so small that they will have no possible economic interest until the enclosing hard itabirite can be economically mined for its iron content. The maps illustrate the abrupt transition along strike from itabirite to hematite and the podlike character of the smaller ore bodies. It is clear that certain zones in the itabirite are preferred in ore formation, but that, within these zones, hematite may form erratically and discontinuously.

Stratigraphic control is apparent in the localization of the major ore bodies. The *A* ore body is adjacent to or on the footwall of the iron-formation. Continuing to the west from the end of the *A* ore body, it will be seen that this part of the iron-formation is a preferred locus for ore formation all the way around the outcrop of the major syncline to the east end of the *C* ore body. This is the same zone which is so productive in the other areas of the district. However, the *D* and *G* ore body seems to be an exception to the general rule, for this body is most highly developed near the hanging wall, and, as shown by underground workings, only itabirite lies next to the footwall in this part of the area.

In the area cut by sections 58 to 64 it will be seen that a swarm of smaller bodies occur apparently without much regard to stratigraphic position, although even here the individual bodies tend to occur in lines. Because of the extensive canga cover and scarcity of underground workings in this part of the area, it is not possible to locate the axes of the subsidiary folds closely. It is possible that the folds repeat here the favorable horizon, or it is also possible that the folds localized the ore. With present exposures this question cannot be resolved.

On the axis of the major syncline, at the west end of the area, it is clear that more ore formed than the average for this part of the area. The bodies are thicker, there are more of them, and they occur at horizons which generally are not ore-bearing. Crosscutting relationships are clear, both on a scale too small to illustrate on the map and on a larger scale.

The major ore bodies in the Conceição area contain a higher percentage of soft and intermediate ore and a lower percentage of massive ore than those in the Cauê area. It is probable that this is due to the tighter folding and strong shearing to which the rocks have been subjected.

Surface mapping is seriously handicapped by the canga cover over much of the area, for it is impossible to be certain, even where the original structure of the rock is visible in the hydrated material, whether the material at depth is soft hematite or whether it is itabirite. In case of doubt, the material was classed as itabirite. On the sections, however, a number of places are indicated where subsurface exposures of soft ore suggest that material mapped on the surface as itabirite actually may be soft hematite. If, on further exploration, this proves to be the case, estimates of the tonnage of high-grade hematite would be notably increased.

Although the *A* and *D* and *G* ore bodies are shown on plate 2 as continuous hematite outcrops, they consist of mixed hard and soft ore. Sections were measured at a scale of 1:500 and 1:200 across the *A* ore body before mining began in that body and are reproduced as figure 23. These detailed sections show that less than half of the area mapped on plate 2 as ore consists of continuous hard hematite outcrop. Subsequent mining has fully confirmed the inference made from these sections, for much intermediate and soft ore and some itabirite were exposed.

RESERVES

Inferred ore was calculated to an altitude of 950 meters in sections 61 through 66, 800 meters in sections 59 and 60, 750 meters in sections 55 through 58, and 700 meters in sections 48 through 54. This variation was necessary because of the wide variation in altitude of the surface (900 to 1,350 m).

Reserves of itabirite were calculated to a depth of 100 meters below the lowest point on the outcrop in sections 48 through 56, to a depth of 50 meters below the lowest point on the outcrop in section 57 and in the southern part of section 58. No reserves of itabirite were calculated in the northern part of section 58 or in any of the sections to the west of section 58 because the itabirite in that area is quite hard and not amenable to easy mining and concentration. Tonnage estimates for the Conceição area are given in table 8.

TABLE 8.—*Tonnage estimates, Conceição area*

[In millions of metric tons]

Ore body and sections	Reasonably assured ore	Inferred ore	Itabirite
A, 48–59	31	74	
C, 60–64	54	47	
D, and *G*, 50–58	25	65	
Miscellaneous—			
54–66	20	47	
48–57			142
Total	130	233	142

The material totaled as ore should average more than 67 percent iron; the average analyses of material shipped during the first 6 months of 1954 from the *A* and *D* and *G* bodies are as follows:

Ore body	Tons	Percent			
		Fe	Al_2O_3	SiO_2	P
A	123,429	68.4	0.67	0.77	0.044
D and *G*	25,989	67.2	.99	1.23	.044

The itabirite may average between 42 and 48 percent iron. Thus, there are approximately 243 million tons of metallic iron in the pure ore and 64 million tons in the itabirite.

In the *A* ore body there is little basis for judgment as to the percentage of hard ore which will be found. Present mining operations produce a high percentage of fine material but it has not been evaluated quantitatively.

The *A* ore body outcrops are generally composed of porous hard schistose ore, indicating intermediate ore at depth. It is tentatively estimated that the ore in this body, when mined and crushed by mechanical methods, will yield about 40 percent plus one-half inch hematite and, of the remaining 60 percent, possibly 40 percent will be plus 18-mesh.

There is less data available for the physical nature of the *D* and *G* ore than for the *A*. Mines 4, 8, 9, and 10 cut the ore body and, according to the mapping by early engineers, about 40 percent of the ore cut by the adits was hard; the rest was soft. On page C85, table 6, the difference in usage of the term "hard ore" by previous engineers and in this report is shown. The mines referred to above have collapsed and it was not possible to check the usage of the term in this area but, judging from the Cauê mapping, it seems reasonable to assume that "hard ore" is here used to include both hard and intermediate type ores. Therefore the 40 percent hard ore shown by the original maps should probably be reduced to about 25 percent. Because the original maps show 60 percent soft ore, it seems possible that not more than 30 percent of the balance would be plus 18 mesh. The outcrops of the east end of the body have a more solid appearance than those of the west end and may well yield a physically higher grade product.

The *C* ore body was cut by mines 3, 5, 13, and 15. The original maps show a maximum width of 130 meters of hard ore and about 250 meters of soft. Except at the west end, the ratio is generally 2:1 soft to hard ore. Assuming the hard ore mapped really includes much intermediate ores, as in Cauê, it does not seem probable that more than 20 percent of the body will be plus one-half inch after mechanical mining and crushing, nor that more than 30 percent of the remainder would be plus 18 mesh. It will be clear to the reader that these estimates can be no more than educated guesses because it was impossible to collect first-hand data.

There is no way of estimating how much hard ore is contained in the small miscellaneous group of deposits. All the outcrops show hard ore and the few underground exposures are of hard and medium-hard ore. Because they are in hard itabirite, which has not been attacked by leaching and therefore have probably not been leached themselves, it is believed that these deposits will have a very high percentage of hard ore relative to the other more deeply weathered deposits.

DISTRICT RESERVE ESTIMATE

SUMMARY OF RESERVE ESTIMATES

Reserves of iron ore in the Itabira district have been calculated for six contiguous areas, most of which lie on subsidiary folds in the north flank of a major syncline which traverses the district. The material has been subdivided into two classes of high-grade hematite ore; reasonably assured ore, which lies within 50 meters of the surface except in those cases in which subsurface exploration has proved the continuity of the ore at greater depths, and inferred ore, which generally lies less than 250 meters below the

TABLE 9.—*Reserves of hematite, itabirite, and metallic iron in the Itabira district, in millions of metric tons, and estimate of percent of lump ore available.*

Area	Hematite		Soft itabirite	Percentage of lump ore (+½ in.)	Tons of metallic iron contained in soft itabirite and high-grade ore
	Reasonably assured ore	Inferred ore			
Cauê	113	102	838	50	483
Chacrinha	38	134	104	30	161
Onça	12	41	309	35	207
Piriquito	61	84	129	30	154
Dois Córregos	19	45	212	30	138
Conceição	130	233	142	25	307
Total	373	639	1,734	----------	1,450
Percent of contained iron	67–68.7	67–68.7	44–50	----------	100

reasonably assured ore. The tonnage of soft itabirite, which generally lies within 100 meters of the surface, has also been estimated. Tonnage of hard itabirite has not been included in the estimate. The grade is lower, the rock would be much more expensive to mine and treat, and it will not be of economic importance in the near future.

An estimate of the percentage of lump ore which can be won from the individual deposits of reasonably assured ore has been attempted. This estimate, made, except in the case of Cauê Peak, with no quantitative data as a base, is necessarily inexact and may be in error as much as 50 percent in individual cases. It is to be expected that, as mining continues to depths greater than 100 meters below the original surface, the percentage of lump ore recovered will gradually increase until very little fine material will be produced, except possibly in the broad shallow Cauê syncline.

An estimate of the grade of the deposits has been made, based, in the case of the pure ores, on the grade of over 7.5 million tons of shipped ore, in the case of the itabirite, on scattered samples. The estimated grade of the itabirite is necessarily inexact, owing to lack of data.

An estimate of the amount of metallic iron contained in the mineable material, including both pure ores and the soft itabirite, has been made, using a grade of 67 percent iron for the pure ores and 45 percent iron for the soft itabirite. Table 9 summarizes these results.

GEOLOGICALLY POSSIBLE ORE

The ore estimates were limited by arbitrary assumptions as to continuation in depth, with little regard to geologic theory. Many ore bodies which fell between sections were not taken into account. This results in a rather conservative estimate, made largely from an engineering viewpoint, for the reasonably assured ore and for the inferred ore.

It can be stated categorically that in no case did underground exploration fail to find continuation in depth of major outcropping bodies and that several bodies that are not exposed on the surface, including the major *C* soft ore body, were discovered by such exploration.

From a geologic viewpoint, the reserves of ore in the district must be considered to be much greater than the figures quoted above. According to the theory of origin which the writers believe to be the correct one for these ores (p. C68) there should be no relation between the loci of concentration and the present erosion surface, which is purely fortuitous from the viewpoint of the ore genesis. Thus it is to be expected that deposits of pure hematite will be found to exist at depths greater than the arbitrary base used in the present calculations.

Alternative theories of ore origin lead to the calculation of comparable reserve figures. Thus, if the hematite was concentrated by supergene leaching or replacement of the iron-formation under or close to subaerial conditions, this must have occurred before metamorphism, for the ore is entirely unlike other ores to which this origin has been attributed and is definitely premetamorphic if this theory of origin is assumed. The metamorphism probably accompanied or followed the folding, and so again the pure hematite can have no genetic relationship with the present erosion surface. Even Harder and Chamberlin's theory of sedimentary accumulation of the pure ore, considered untenable by the writers, leads to the conclusion that the ore is genetically unrelated to the present erosion surface.

Since the ore is unrelated to the present erosion surface, that surface might well be taken to be a random sample of the amount of ore to be expected per unit of volume of the iron-formation in the Itabira district.

Thus, if the keel of the Conceição syncline is about 600 meters below the sea level (1,500 m below the outcrop) at Córrego de Conceição, and if the amount of ore in the iron-formation remains constant to that depth, section 11 would represent (250 linear meters of outcrop at a point where the outcrop is thin) some 43 million tons of hematite. In the ore estimate made above, only 7.2 million tons were assigned to this block. If it becomes economic to mine iron ore to such depths in Brazil (much lower grade ore is now being economically minded from more than 1,000 m depth in the United States) the reserves available at depth in the Itabira district will undoubtedly prove to be ample to supply an active industry for more than a century. The *A* ore body alone might well have a total reserve of 600 million tons, projecting the body only half its outcrop length in depth. It will be many years before underground mining of iron ore will become economic in the Itabira district and it would therefore be academic to calculate geologically possible ore for the district as a whole. There is, however, no reason to suppose that the potential reserve of high-grade hematite in the district will not eventually prove to be more than 2.5 billion tons.

If the theory of origin of the soft ores discussed on pages C74 to C76 is correct, namely, that they have formed from the hard ores by supergene leaching, it is to be expected that after the mining penetrates below the permanent water table, the percentage of lump ore will increase and the percentage of fines will decrease. Not only will the high-grade ore become harder, but the itabirite will also become hard at depth and will stand well in underground operations, thus reducing the mining costs.

ECONOMIC AND TECHNICAL CONSIDERATIONS

The presence of the great reserves of high-grade iron ore discussed in the foregoing pages makes essential a consideration of the various economic and technical problems bearing on the exploitation of these ores.

Mining of the Itabira ores presents few problems. The ore bodies form the hills and ridges, thus making practical the removal of a relatively higher percentage of ore by opencut methods than is economic in many iron ore districts of the world. The three exceptions to this statement will be the east end of the Piriquito body, where it is plastered on the surface of a hill in a dipslope, possibly part of the *D* and *G* ore body in the Conceição area, where roughly similar conditions will obtain, and the Chacrinha body.

The hanging walls and footwalls of the iron-formation are decomposed and soft to a greater depth than that reached to date by exploration. Although the end of the adit which cuts the Piriquito ore body is more than 100 meters below the surface, the schist encountered was completely decomposed and could be sliced with a knife. The softness of the wallrocks will make stripping easy to much greater depths than might be practical elsewhere and little blasting will be required. As a corollary, the material will probably not stand well in opencuts and a somewhat lower bank angle than normal will be required to withstand the torrential downpours of the rainy season.

A major problem in the extraction of the hematite ores in the Itabira district (and of all the hematite deposits in the Quadrilátero Ferrífero) is the utilization of the fine ore and of the soft itabirite. The writers estimate for the district as a whole that, within the zone of reasonably assured ore, probably not more than 35 percent of the pure hematite is lump ore. The "fines" contain more than 67 percent iron and should not be discarded.

Similarly, above the 1,100-meter level of Cauê, some 88 million tons of soft itabirite would have to be mined to extract the 87 million tons of high-grade hematite above that level. This itabirite contains some 40 million tons of metallic iron. It is obvious that material which can be easily concentrated into a high-grade product and which must be, in large part, mined and moved in order to extract the premium ore, should not be thrown away.

Because of the limited capacity of the railroad which transports the products of the mine to the coast, the fine ore was being stockpiled in 1954. Much of the itabirite which was being mined with the ore was being sent to the primary screening plant, where the quartz extracted during screening diluted the fines pile. Thus the fines at the secondary screening plant, slightly diluted by itabirite, averaged nearly 65.5 percent iron, whereas those at the primary screening plant, strongly diluted by itabirite, averaged less than 63.3 percent iron. In 1954, two and sometimes three, bulldozers were constantly occupied in moving fines so the screening plants would have a place to discharge. The primary fines pile was, because of the plant design and location, on the top of unmined hard ore. This unhappy conjunction of circumstances was the result of inadequate study of the nature and distribution of ore before construction was undertaken.

If the Itabira district is to produce its potential production of ore in the future years, it is obviously essential to make use of the full range of ore types present and not to burden the lump ore, which will make up less than 20 percent of the total material extracted, with the cost of mining, transporting, screening and throwing away material which contains in aggregate more metallic iron than the material being sold.

In 1948, tests were made under the direction of Dr. Hubert Pinagel of the CVRD on concentrating itabirite by means of a Humphrey Spiral belonging to the Instituto de Tecnologia Industrial of the State of Minas Gerais in Belo Horizonte. The results of one of these tests is given below. The original material is itabirite, all minus 6-mesh (not crushed).

Size of sample	grams	1, 310
Time of run	seconds	8
Concentrates (65 percent Fe)	grams	498
Middlings (25 percent Fe)	do	338
Tailings (10 percent Fe)	do	380
Unaccounted for	do	102

Other tests with different adjustments of the machine gave concentrates containing more than 68 percent Fe.

The wide difference in specific gravity between the hematite and the quartz of the itabirite provides the metallurgist with a most convenient tool for concentration, while the almost complete dissociation of the two minerals in the soft itabirite obviates the necessity for expensive grinding. No comparative studies have yet been made to establish the cheapest method of concentrating the itabirite into a saleable product; the above-cited test merely demonstrates that such a concentration can be done by apparatus that is cheap and simple to operate and maintain. The screen analyses given in figure 8 show that screening at 18-mesh will give a concentrate averaging over 66 percent iron. The undersize could then be treated as desired, with the concentration process facilitated by the preliminary sizing of the material.

The Vitória à Minas railroad now transports the ore from the Itabira district to the port of Vitória. The Vitória à Minas railroad is a meter gage railroad owned and operated by the Companhia Vale do Rio Doce. During the last 10 years, the roadbed has been completely rebuilt and in large part realined with the aid of loans from the United States Export-Import Bank. The roadbed has been ballasted for its whole length, and is reported to be in excellent condition. Derailments decreased from more than 1,000 per year in 1948 to about 30 in 1954. Steam locomotives, in the majority woodburning, have largely been replaced by diesel units, which practically doubled the ore capacity of the railroad. In 1953, before the diesel units were introduced, the railroad was one of the few in Brazil to show an operating profit. The capacity of the railroad at the end of 1954 was estimated at 1.8 million tons of iron per year. By the construction of more sidings, a better system of signals, and complete conversion to diesel units, the railroad might reach an annual hauling capacity of 8 million tons of ore per year. (The railroad also must haul a wide variety of forest and agricultural products from the prosperous valley of the Rio Doce.)

The port of Vitória has (1954) a controlling draft which limits ships entering it to about 10,000 tons capacity. This is, of course, too small for economical ore transport and makes cheap freight rates dependent upon small ships looking for a return cargo from South America to other continents and thus dependent upon regional economic conditions. When a large export of iron ore from the Itabira district is organized, undoubtedly a new port will be built or the port of Vitória improved.

It is banal to say that, given adequate reserves, iron ore mining is essentially a bulk transportation problem. This truism is proved once again in the case of the Itabira ores, for, in 1954, the mining and preparation of the lump ore cost less than 10 percent of the delivered cost of the ore to the North American or European consumer. Obviously the place to reduce costs is in the area of transportation, and, particularly, the transportation from Brazil to the port of destination. This can be accomplished only by securing the benefits of large-scale specialized bulk transport. A standard or wide gage railroad or even a long conveyor belt to the mines would be desirable to supply ships large enough to be economic ore carriers (60,000 ton ore carriers are used for Venezuelan ore) and would radically reduce land-haulage costs in the process.

At average 1954 prices (U.S. $12 per ton)[15], the reasonably assured ore lump ore reserve at Itabira is worth about U.S. $1,800 million and the inferred lump ore reserve is worth about U.S. $3,000 million on board ship at Vitória. Assigning an arbitrary value of U.S. $6 or half the lump ore value, to the fine ore (in October 1954, Old Range Bessemer ore, an ore containing at least 15 percent less iron than the Itabira fine ore, brought $10.30 at lower lake ports), the fine ore in the reasonably assured class would be worth U.S. $1,300 million and the inferred ore class U.S. $2,300 million on board ship in Vitória. Thus the total ore estimated, not including itabirite concentrates, might be worth some $8,000 million on board ship. The capital expense to produce ore at the rate of some 20 million tons per year, which would give the deposits a life of 50 years before the geologically probable ore was needed and without counting on the itabirite concentrates, would be not less than U.S. $500 million including port, railroad or conveyor belt, and ships. Whether this would be a worthwhile investment would depend on many factors.

MANGANESE DEPOSITS

The presence of manganese ores in the Itabira district was not known until the 1940s, when cuts excavated during the construction of the Campestre–Conceição highway and of the railroad from Itabira to Campestre revealed several manganiferous bodies on ground owned by the Acesita Co. Stimulated by these discoveries, numerous small pits and trenches were then excavated by that company, and a few short adits were driven. The total production of manga-

[15] The prices of Itabira lump ore fluctuated from $6.50 to $18.50 per ton FOB Vitória during the period 1944–54.

nese ore is not known but may be about 7,000 tons, some of which was stockpiled in Itabira, most of which was shipped to the Acesita blast furnace. The grade of the ore extracted was extremely variable but may have averaged about 44 percent manganese and 12 percent iron.

TYPES OF OCCURRENCE

All the known deposits of manganese oxide in the Itabira district are in the Piracicaba group and most of them are in a rather narrow zone a few tens of meters above the base of that formation. Stratigraphic control is thus apparent. Within this zone, manganiferous material has been observed to occur in three general types of deposit: (1) in a shear zone, probably concentrated by hydrothermal waters; (2) disseminated in deeply weathered rocks thought to have been in large part dolomitic and tuffaceous; and (3) in soil or canga, thought to have been concentrated by supergene waters.

SHEAR ZONE DEPOSIT

A hundred meters south of the point where the Conceição–Campestre road crosses Dois Córregos creek, the steep road cut revealed masses of hard manganese oxide. This rock was first identified by Dr. Luciano Jacques de Moraes. Exploratory work below the road which included several small benches and an adit driven along the strike for about 17 meters revealed a zone of manganese-oxide lenses as much as perhaps 3 meters in width apparently confined to a zone of crushing and brecciation.

The lenses of manganese oxide are slickensided on the outside surface and may well be boudins resulting from the squeezing of an originally tabular body. All the rock of this area appears strongly squeezed, and the itabirite which crops out nearby has been so deformed that the quartz is disposed in long rods rather than the usual laminae. Soft manganese oxide locally covers the outside of the harder lenses of manganiferous rock in the shear zone.

Veinlets of white talc cut the outside of the lenses, and veins of fibrous quartz with coarse specularite are also associated with these bodies. The long axis of the quartz fibers is across the veins, but the fibers are generally curved, possibly indicating movement during growth. Such fibrous quartz is commonly associated with concentrations of manganese oxide in the Quadrilátero Ferrífero.

This deposit is believed to have formed by concentration of manganese oxide from the rocks of the Piracicaba group through the agency of heated waters during the period of deformation.

RESERVES

The zone in which these lenticular masses are known to occur is about 50 meters long. The total difference in elevation is about 25 meters from the highest to lowest exposures. The individual lenses are most variable in size and thickness. A total reserve of 10,000 tons was calculated by the junior author during the fieldwork, much of which has been already extracted. In deposits of this nature it is not possible to predict extension in depth, nor can extension under the heavy soil cover be predicted. However, owing to the discontinuous nature of the deposit, it is not probable that any significant reserve of manganiferous material of commercial grade is present. Several boulders of manganese oxide have been found in the soil downstream from this occurrence, and it is possible that similar deposits may be found nearby.

The grade of the ore extracted is variable, ranging between 35 and 45 percent manganese, 12 to 15 percent iron, 0.7 to 7.1 percent silica, 3.1 to 11.7 percent alumina, and 0.1 to 0.5 percent phosphorus. The ore is generally hard and steely.

DISSEMINATED DEPOSITS

The presence of manganese oxide disseminated in soft argillaceous and quartzitic rocks of the Piracicaba group in the Chacrinha area was mentioned in previous pages. It is believed that this material, which occurs in bands about 5 meters in stratigraphic thickness, was derived from the weathering of dolomitic beds containing a small percentage of syngenetic manganese oxide as well as aluminous and cherty impurities. The ubiquitous slickensides and slump structures in the rock suggest that the thickness of these beds was considerably greater before the dolomite was removed by solution.

The rocks are now black. They contain up to 34 percent manganese, although they average considerably less, possibly about 23 percent. They are completely soft and do not offer promise as a commercial source of manganese, although similar material from the Congonhas district has been successfully used to filter illuminating gas. Such material is common in the Quadrilátero Ferrífero, and this relatively small deposit offers little commercial promise.

Another type of disseminated deposit is exposed in the old gold workings just north of the town of Itabira, about 300 meters northeast of the deposits just discussed. Here the bedrock is quartzite and phyllite, with some phyllitic material that has a tuffaceous aspect. Manganese oxide is found in the rocks for a strike distance of perhaps 300 meters and for varying distances across the strike, up to perhaps 50 meters.

The grade of the soft disseminated material may vary up to 20 percent manganese; most of the material is lower grade. Local high-grade concentrations are to be found; they are to be measured in kilograms rather than tons. No commercial future for this manganiferous rock is to be expected within foreseeable time.

DEPOSITS IN SOIL AND CANGA

Many of the exploration pits dugs for manganese oxide were located on the basis of high-grade float ore. Such float ore may contain as much as 55 percent manganese and low percentages of iron and other gangue materials. In no case did exploration pits locate a significant body of high-grade manganese ore in place.

The most thoroughly prospected area is that below the Conceição–Campestre road between Dois Córregos creek and the workers' village below the Piriquito ore body, where at least 20 pits and large trenches were sunk. These revealed a relatively high percentage of concretionary manganese oxide nodules in the soil, locally as much as 30 percent. These nodules are normally 1 to 3 centimeters in maximum dimension, but where two or more grow together, larger nodules are formed. They are round and botryoidal. They grow in a red to tan soil underlain by the white phyllites and quartzites of the Piracicaba group. Locally, bodies and concentrations in joints and fracture zones in the rock may permit the extraction of several tons (or in one case, tens of tons) of material suitable for shipment.

In the canga and soil overlying the disseminated dolomitic manganiferous bodies of the Chacrinha area, very high grade cobbles of manganese oxide have been found. It is thought that these are of concretionary origin, with the manganese derived from the underlying low-grade bodies. Similar high-grade cobbles have been found in the canga a few hundred meters east of Córrego de Conceição, as well as southwest of the airport.

SUMMARY

Because all the showings of manganese oxide concentrations have been confined to one stratigraphic zone which has been unsuccessfully prospected by many pits and trenches, there seems to be no reason to suppose that more than small tonnages of manganese ores exist in the Itabira district. The stratigraphic zone which here is manganiferous is also manganiferous in other parts of the Quadrilátero Ferrífero, for example, the Belo Horizonte area, but nowhere have even medium-sized ore bodies been found in this zone. The few medium and large-sized manganese ore bodies of the Minas series are all associated with the Itabira group, which in this district is not manganiferous (Dorr, Coelho, and Horen, 1956).

GOLD DEPOSITS

The gold deposits of Itabira were discovered in 1720 by the Albernaz brothers of São Paulo. Little is known of the development of the deposits, and there is no record of their total production. It is said that during the years 1852–54, inclusive, 905 kilograms of gold were produced from the deposits then in production. According to Scott (1902), in 1874, 2,292 troy ounces (71.28 kilograms) of gold were extracted from one mine on Cauê Peak in 4 months. The same source states that the mines were active in 1902. Henwood (1871) quotes a statement that a single pan of material from Conceição Peak yielded 17.21 troy pounds (6.42 kilograms) of gold and that in 6 years 12,295.55 (troy?) pounds (4,589 kilograms) of gold were extracted from ore mine in the Conceição area. Rumors may be heard in Itabira that, during the exploration for iron ores carried on by the Itabira Iron Ore Co. in the first decades of this century, much gold was extracted.

During the present investigations no prospecting for gold ore was attempted. All but a few of the old mines have collapsed and it is not possible to learn much about the specific distribution of the ore. The general distribution may be inferred from the location of the old workings.

The literature on the gold of the Quadrilátero Ferrífero is voluminous and to some extent contradictory. The papers by Scott (1902) and Bensusan (1929) are the best modern sources. Historical information of great interest may be gleaned from Mawe (1816), Spix and Martius (1824), Von Eschwege (1833), Henwood (1871), and other early engineers and explorers. Paul Ferrand (1894) discussed the gold-mining industry as it was in 1890 and gives much engineering information. Henwood, Burton, Eschwege, and Mawe are even more fruitful, for they were on the spot during the heyday of some of the bonanza mines and were keen observers.

From a consideration of the literature, it would appear that four of the common modes of occurrence of gold in the Quadrilátero Ferrífero are found in the Itabira district. These include alluvial gold, gold in canga, gold in quartz veins in the schistose rocks, and gold in bunches, pockets, veins, and beds in "jacutinga" (see p. C104).

ALLUVIAL GOLD

Nothing is known of the productivity of the alluvial gold deposits. Most of the low-level gravels along Córrego de Conceição downstream from the iron-formation, along the south- and east-draining streams draining the Cauê area, and along the Rio de Peixe have been turned over for gold. Streams draining the central and northern part of the district have not been worked.

GOLD IN CANGA

Early literature frequently refers to flakes and nuggets of gold in canga. Extensive workings in canga and along the contact between canga and itabirite are preserved in Cauê Peak and on the lower slopes in the area known as Sant'Anna. Although most of the workings are along the bottom of the canga, in a number of cases there is a definite linear pattern in the workings. In the Sant'Anna area, half a dozen excavations have been made along a dense flinty geothite vein which could be traced in the canga for several hundred meters. The maximum thickness of this vein was about 25 centimeters.

GOLD IN QUARTZ VEINS IN THE SCHISTOSE ROCKS

There is no certainty that gold occurs in quartz veins in the schistose rocks as the veins are now covered by old dumps and by slope wash. However, some of the most extensive workings in the district are in the Piracicaba group near the town of Itabira. Elsewhere in the Quadrilátero Ferrífero, according to Scott (1902), gold in the schistose rocks is found in narrow ramifying quartz veins. The valley of Agua Santa has been mined intensively, particularly in the vicinity of the manganiferous and graphitic horizons of the Piracicaba group rocks, and it is probable that goldbearing quartz veins cut these rocks. The manganese and graphite might have contributed to secondary enrichment of these deposits.

GOLD IN "JACUTINGA"

The early literature used the term "jacutinga" for both soft ore and soft itabirite. Hussak (1908) states:

> The fragments of jacutinga, rich in gold, from Gongo Socco and Machuiné, examined by me, were formed of schistose hematite, containing very little pyrolusite, earthy limonite, some scales of talc, and certain masses which had the appearance of kaolinite.

Bensusan (1929) who has worked more extensively with "jacutinga" gold ore than other modern authors, defines jacutinga as "a sandy micaceous iron ore, and the constituents are micaceous iron schist and friable quartz, oxide of manganese, and fragments of talc." Scott states (1902):

> This iron formation (itabirite) has been proved to be slightly auriferous in many places, but the gold has only been found in payable quantities in the bands of sandy micaceous iron ore known as *jacutinga*. This gold-bearing formation consists of sandy and micaceous hydrated iron ore, associated with some yellowish talc and an earthy oxide of manganese, the whole having an unctuous touch and running conformably to the enclosing itabiritic rock, in lines 2 to 20 centimeters thick.

On the other hand, Henwood (1871) says, agreeing with Hussak:

> Itabirite consists, for the most part, of granular quartz and of iron-glance (specularite-Dorr) irregularly mixed with oxydulated iron (magnetite?-Dorr), earthy brown iron ore, and hydrous oxide of iron in alternating beds, sometimes separated by laminae of talc * * * In this part of the series gold is rarely found * * * Jacutinga is composed in great measure of iron glance, mixed generally with small quantities of earthy manganese and frequently with minute proportions of oxydulated iron, earthy iron ore, titaniferous iron ore, or the hydrous oxide of iron also; but seldom with all these at once. Talc, either foliated or massive * * * forms isolated masses or thin layers; but quartz is a rare, and an unwelcome, ingredient.

The term "jacutinga" is now used indiscriminately for soft high-grade hematite, soft itabirite, or both, depending entirely upon the locality within the Quadrilátero Ferrífero. In short, it has only a local, not a general meaning and should not be used in scientific description without precise definition. Judging from the literature, most of the gold production of the past came from soft itabirite rather than soft hematite.

According to Scott (1902), the most productive area of the Itabira district at the turn of the century was Cauê Peak. There the gold ore is said to have been localized along the contact between the soft itabirite and the hard hematite.

The profusion of extensive old workings away from the area mentioned by Scott indicates that in his time a previously undiscovered seam was being worked. The distribution of the workings shows that the gold ore was not characteristically localized as he said. In the Cauê area, most of the old gold workings are localized in the valley of the Canal da Serra, which roughly follows the axis of the Cauê syncline for much of its length. In the Conceição area, the old gold workings are in the central valley which follows the axis of the main synclinal structure. Henwood (1871) indicates that the ore shoots in this district and elsewhere were controlled by the linear structure described above, and gives a table showing the direction of the linear structure in various districts in the

Quadrilátero Ferrífero. He is, to the writer's knowledge, the only observer until recent years to have pointed this out and to have recognized the economic significance of the structure.

The gold is said to occur in the "jacutinga" as coarse pallettes and grains of gold, in nuggets, in threads, and in arborescent sheets. It also is mentioned as occurring interleaved with specularite. Gold in "jacutinga" deposits was found in extraordinarily rich pockets and bunches:

Gold in "jacutinga" deposits

[Information from A. J. Bensusan, 1929]

Mine	Year	Remarks
Maquiné	1867	7.2 tons ore yielded 620 troy ounces (19,280 gr) gold.
Do	1867	13 tons ore yielded 530 ounces (16,483 gr) gold.
Do	1893	500 pounds ore yielded 50 ounces (1,555 gr) gold (including a piece 17 in. long).
Gongo Socco	1824	"A capful of ore yielded 10 kilograms gold."
Do	1840	"Capt. Blamey assisted by two miners extracted 1,260 ounces (39,186 gr) gold in 3 hours."

Henwood (1871) cites production figures of the Imperial Brazilian Mining Association (Gongo Socco mine) which show that from 1826 to 1856, 23,381 pounds (8,726,7 kg) of gold were produced as clusters, nuggets, and other coarse gold recovered by hand methods, and 11,146 pounds (4,160,1 kg) of gold were produced in smaller grains from "jacutinga" by stamp mills and mechanical recovery methods. The percentage of recovery of the small grains is not known. By the same token, "high-grading" of the coarser ore is said to have been rife and much gold is thought to have been so lost.

The average grade of the "jacutinga" ore was not extraordinarily high, however. Thus the Maquiné mine yielded an average grade of 23.448 grams/ton from 1866 to 1871, the most successful years. From 1864 to 1882, this mine averaged 13.57 grams per ton. These mines are not in the Itabira district, but the occurrence of ore may be considered to be the same.

Most of the old mines in "jacutinga" did not reach even moderate depths. Gongo Socco was abandoned at 70 fathoms (about 140 meters) and Maquiné was abandoned at a similar depth. In the Itabira district, "Treloars shaft" was said to be 96 meters deep, or about 50 fathoms. Henwood (1871) gives a short table showing the impoverishment with depth of the gold deposits of the Quadrilátero Ferrífero and points out that diminution of grade with depth is most abrupt in the "jacutinga" type of ore. Bensusan (1929), on the other hand, is more optimistic about continuation in depth.

ORIGIN

There is no known evidence in the Itabira district which would permit a direct contribution to the much discussed question of the origin of the gold ores of the Quadrilátero Ferrífero. An attempt at interpretation of the existing data may be of value, however, for it is very probable that more gold will be produced from the Itabira district as a byproduct of the iron mining.

The nature of "jacutinga" is not known from a modern scientific viewpoint. In the course of iron mining in the Itabira district the fresh unaltered material from which the "jacutinga" formed will probably be uncovered; the true gold-bearing "jacutinga" will also be found. It is hoped that a careful scientific description will be made of the occurrence.

From the old descriptions, the "jacutinga" seems to have been formed in many cases by the alteration of dolomitic itabirite, for earthy manganese is said to have been typically present, as well as earthy limonite. These two constituents are characteristic of weathered dolomitic itabirite. The "jacutinga" in many of the old descriptions was more prevalent in the upper part of the iron-formation, also typical of the dolomitic itabirite in many localities.

Scott indicates that the iron-formation is generally auriferous, a conclusion borne out in part by work in the Itabira district by Dr. Gilbert Whitehead of the CVRD, who made concentration tests of many samples of soft itabirite, and by Dr. Jaime Araujo of the DNPM, who made extensive concentration tests of the gold in the soft itabirite of Cauê Peak. On a tonnage basis, the concentration is low, in the order of a gram or two per ton. The source of this gold is unknown.

The concentration of the gold into incredibly rich pockets and seams is most reasonably attributed to secondary enrichment by through-passing supergene waters, since the distribution of the rich ore was closely related to the present erosion surface. Probably the manganese oxide in the weathered dolomitic iron-formation, which is in a very finely divided state and therefore chemically very active, serves as the precipitating agent in the case of the "jacutinga" ores, as suggested by Euzebio P. de Oliveira (1932).

It is of particular interest, considering the great similarity of the Brazilian and Australian iron-formations and iron deposits, that much gold ore has been found in Australia associated with iron-formation. McKinstry (1939) and particularly Miles (1943, 1946) have discussed certain aspects of the gold occurrences. McKinstry (1939) says of the Australian occurrences:

> Gold ore bodies have been found in the banded iron formation in many places, though, unfortunately, they do not as a rule "live" in depth. Values in this rock appear to be especially susceptible to secondary enrichment, with the result that poor ore bodies often afford deceptively rich values in the outcrops and shallow workings.

FUTURE OF THE GOLD ORES

In the course of mining the iron ores of the Itabira district, rich gold ores will undoubtedly be discovered, for the old miners could not have found every lead and deposit. Furthermore, small quantities of gold are disseminated in the itabirite. In making studies of the best mode of concentrating the iron in the itabirite, attention should be devoted to recovery of the gold, which, in some processes, could be recovered at small cost and which might well defray much of the cost of concentration of the iron. This suggestion, backed by engineering data, was originally made in an unpublished manuscript prepared for the Departamento Nacional da Produção Mineral by Dr. Jaime Araujo.

WATER ANALYSES

In the hope of securing factual data about the surface and underground waters of the Itabira district, four samples of surface and spring waters were collected and sent to the chemical laboratory of the Departamento Nacional da Produçãa Mineral for analysis. The results are given in table 10.

These analyses were informally submitted to the Water Resource Branch of the Geological Survey for comment as to possible genetic implications of the waters. There seemed to be nothing of particular significance to be learned from them. The waters were said to have come from a silicate or siliceous, rather than a carbonate-rich terrain. The warm spring waters showed no sign of addition by juvenile waters.

DESCRIPTION OF SAMPLES

Sample A.—Sant'Anna area. A small spring issuing from canga. The water can only have come from the Cauê itabirite and can have traversed no other rock than itabirite. Iron hydroxide was being deposited by algae a meter or so below the point where the sample was collected. Sample is of interest in that it contains the highest percentage of iron and an average percentage of silica.

Sample B.—Córrego de Conceição, near Fazenda de Conceição. This sample is from a stream which derives its water from all types of rock which crop out

TABLE 10.—*Analyses of waters from Itabira-Estado de Minas Gerais*

[Analyses by: A. Vera Magalhães Campos Paiva, D.N.P.M. B. Frida Ciornai, D.N.P.M. C. Helena Falcão, D.N.P.M. D. Helena Falcão, D.N.P.M.]

	Parts per million			
	A	B	C	D
Water discharge (estimated)	3–4 l per min	Not estimated	4 l per min	250–300 l per min
Water temperature (°C)	----------	----------	20	28
Silica (SiO_2)	2.8	2.6	4.0	20
Aluminum (Al)	.2	.4	.4	.7
Iron (Fe), total	.4	2.2	.1	.1
Manganese (Mn), total	.0	.0	.0	.0
Titanium (Ti)	.0	.0	.0	.0
Calcium (Ca)	.7	3.2	.5	14
Magnesium (Mg)	.7	.4	.6	9.8
Sodium (Na)	1.3	1.3	.7	1.0
Potassium (K)	.4	.6	.4	.3
Lithium (Li)	.0	.0	.0	.0
Ammonium (NH_4)	Trace	.1	Trace	Trace
Bicarbonate (HCO_3)	7.4	11	4.2	78
Carbonate (CO_3)	.0	.0	.0	.0
Sulfate (SO_4)	Trace	Trace	Trace	11
Chloride (Cl)	.4	3.2	1.8	2.7
Bromide (Br)	.0	.0	.0	.0
Nitrate (NO_3)	.6	.5	.6	.6
Iodide (I)	.0	.0	.0	.0
Phosphate (PO_4)	.0	.0	.0	.0
Dissolved solids:				
Residue on evaporation at 180° C	11	17	8.0	95
Total hardness as $CaCO_3$ (calculated)	4.6	10	3.7	76
Specific conductance (micromhos at 25°C)	11	29	25	129
pH	5.8	6.7	6	7.1

in the Itabira district. It should approximate average conditions in the district.

Sample C.—A spring issuing from the shear zone near Dois Córregos mentioned on page C102. This sample is of interest in that it contains no manganese even though it issues from a manganiferous zone.

Sample D.—A warm spring in the valley of Agua Santa, Itabira. Temperature, 28°C or 82°F. The temperature of the water of the stream beside the spring is 23°C. The water issues from the Cauê itabirite and the itabirite in this zone is richer than normal. The high-temperature is attributed to the surfacing of deeply circulating supergene water.

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