Geology and Mineral Resources of the Monlevade and Rio Piracicaba Quadrangles, Minas Gerais Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 341-E

Prepared in cooperation with the Departamento Nacional da Produção Mineral of Brazil under the auspices of the Agency for International Development of the United States Department of State

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By ROBERT G. REEVES

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GEOLOGY AND MINERAL RESOURCES OF THE MONLEVADE AND RIO PIRACICABA QUADRANGLES, MINAS GERAIS, BRAZIL

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ABSTRACT

The Monlevade and Rio Piracicaba 7½-minute quadrangles are along the eastern border of the Quadrilátero Ferrífero of south-central Minas Gerais, Brazil. The Quadrilátero Ferrífero, an area of about 7,000 square kilometers, contains numerous high-grade hematite deposits and many billions of tons of iron-formation of intermediate grade (35–50 percent Fe), much of which is easily concentratable.

The principal rocks of the Quadrilátero Ferrífero are Precambrian metasedimentary, metavolcanic, and granitic rocks. The metasedimentary and metavolcanic rocks are divided into three series, which are, from older to younger, the Rio das Velhas, the Minas, and the Itacolomí. The grade of these metamorphic rocks ranges from low in the western and central parts of the Quadrilátero Ferrífero to moderate and, in places, high in the northern, eastern, and, especially, northeastern parts. Large bodies of granitic rocks of several ages either were injected into these metamorphic rocks or were formed by metasomatic and ultrametamorphic processes from them. Smaller bodies of mafic and ultramafic rocks of Precambrian and younger ages intrude both the metamorphic and granitic rocks.

Within the Monlevade and Rio Piracicaba quadrangles, metasedimentary and metavolcanic(?) rocks of the Rio das Velhas and Minas Series are exposed. The grade of regional metamorphism in these quadrangles is higher than that in the Quadrilátero Ferrífero generally. Because metamorphism has obliterated many original features of the rocks and has modified the chemical and mineralogical composition of the rocks, the rock units cannot be correlated with the less highly metamorphosed units in the area to the west. For this reason, several new formation names are used in this report. The oldest exposed unit is the Monlevade Gneiss, probably correlative with the Rio das Velhas Series of the western and central parts of the Quadrilátero Ferrífero. The Monlevade Gneiss consists largely of quartz-biotite and granitic gneiss but contains amphibolite, muscovite-quartz schist, and thin iron-formation. The gneiss probably formed by metamorphism of argillaceous rocks to the upper part of the amphibolite facies, with accompanying metasomatism, and the amphibolite by metamorphism of volcanic rocks or metasomatism of impure calcareous rocks or dolomitic shales. The quartzose units are represented by quartz-mica schist.

The Minas Series, which overlies the Monlevade Gneiss, contains the principal iron-formation and major hematite deposits in the Monlevade and Rio Piracicaba quadrangles and in the Quadrilátero Ferrífero in general. It is divided into three groups: the lower Caraça Group, of predominantly clastic sediments now metamorphosed chiefly to quartzite and muscovite-quartz schist; the intermediate Itabira Group, of predominantly chemical sediments now metamorphosed to itabirite and marble; and the upper Piracicaba Group, of mainly clastic sediments now metamorphosed principally to quartzite, schist, and gneiss.

The Itabira Group is composed of two formations: the Cauê Itabirite and, in the western and central parts of the Quadrilátero Ferrífero, the overlying chiefly dolomitic Gandarela Formation. In the Monlevade and Rio Piracicaba quadrangles, the Sítio Largo Amphibolite, which overlies the Cauê Itabirite, is probably the equivalent of the Gandarela Formation.

The Cauê Itabirite is the principal iron formation of the Quadrilátero Ferrífero; it may have formed from chemical sediments that originated through predominantly chemical weathering of a topographically mature area and that were deposited in a restricted marine or a brackish-water environment.

The Piracicaba Group is represented in these quadrangles by the Elefante Formation, which consists of intertonguing quartzite and quartz-mica schist and gneiss members, thin amphibolite layers, and discontinuous itabirite lenses.

The rocks in the Monlevade and Rio Piracicaba quadrangles are folded into synclines and anticlines and are cut by several major faults. At least three periods of deformation, a pre-Minas (early or mid-Precambrian) and two post-Minas periods (the second dates 500 million years), are recorded in the rocks. The first post-Minas orogeny probably caused the principal folding and faulting. Most of the major folds plunge 20°–45° NE. The major faults trend slightly north of west and show left-lateral and vertical offset, with the north side relatively upthrown. Subsidiary folds, which trend nearly at right angles to the major folds, and high-angle reverse faults which trend north, were probably formed during the second period of post-Minas deformation.

These quadrangles contain one large hematite deposit, the Andrade, and several smaller ones, among which are the Tanque, the Morro Agudo, Morro da Áqua Limpa and the Pé de Serra. The high-grade hematite deposits probably formed where the silica of the itabirite was replaced by iron transported from adjacent or nearby parts of the itabirite by hydrothermal fluids generated during regional metamorphism. The major hematite deposits were formed in the troughs of syn-

clines; some smaller ones were formed in the crests of anticlines, and a few small lenses occur on the flanks of the folds, without any apparent structural control. The Andrade mine furnishes ore to the Usina Monlevade, Brazil's (and South America's) second largest steel works and the largest charcoal steel plant in the world. The Andrade deposit contains about 500 million metric tons of hematite ore and itabirite protore; 75 percent of the deposit consists of high-grade hematite ore that averages 67 percent iron, about evenly divided between hard or compact ore (producing less than 25 percent of ½-inch material during mining and subsequent handling) and soft ore (producing more than 75 percent of ½-inch material).

In addition to the high-grade hematite deposits, the quadrangles contain weathered itabirite, easily concentratable and a potential ore. The itabirite crops out over a length of 77 kilometers and averages 200 meters thick. To the average weathering depth of 50 meters, the Cauê contains 2,700 million metric tons of weathered itabirite of approximately 35 percent iron, or a metallic iron content of 950 million metric tons.

Other mineral resources within the quadrangles are the Água Limpa manganese deposit and several other small and presently uneconomic manganese deposits; the Pé de Serra and Talho Aberto pegmatite deposits, the latter famous for its phenacite (now apparently exhausted); gold placer deposits (now mostly exhausted) along the Rios Santa Bárbara and Piracicaba, and their principal tributaries; granitic rock used for building stone and paving blocks; clay for bricks and tiles; and sand and gravel along the main rivers and their principal tributaries. The manganese deposits are associated with the Cauê Itabirite, locally manganiferous in its upper part, and with the manganiferous clastic sediments and itabirite of the Elefante Formation. The deposits are supergene concentrations of manganese oxides, derived from the weathering of manganiferous itabirite or the almandine-spessartite-bearing parts of the Elefante Formation.

INTRODUCTION

The Monlevade and Rio Piracicaba quadrangles were mapped as part of the study of the geology and the evaluation of the iron ore deposits of the Quadrilátero Ferrífero,[1] central Minas Gerais, Brazil. The mapping was done jointly by the Brazilian Departamento Nacional da Produção Mineral and the United States Geological Survey. This study continued from 1946 to 1962 under the direction of John V. N. Dorr 2d and was financially supported by the United States Government through the Agency for International Development and various other agencies of the Department of State and by the Brazilian Government through the Departamento Nacional da Produção Mineral.

The Monlevade and Rio Piracicaba 7½-minute quadrangles are along the east edge of the Quadrilátero Ferrífero about 75 kilometer air line east of Belo Horizonte (fig. 1). The quadrangles lie between lat 19°45′ S. and 20°00′ S. and between long 43°07′ 30″ W. and 43°15′ W. The two quadrangles are mostly within the Município[2] do Rio Piracicaba; the extreme northern part of the Monlevade quadrangle is in the Município de Itabira, and the southwest corner of the Rio Piracicaba quadrangle is in the Município de Santa Bárbara.

The principal towns are Rio Piracicaba, the seat of government of the município of that name, and Monlevade. Monlevade is the site of the second largest steel plant in Brazil, the integrated Usina Monlevade of the Companhia Siderúrgica Belgo-Mineria (hereafter called CSBM). Many small villages and fazendas (large farms, ranches, or plantations) are scattered throughout the valleys of the Rios Santa Bárbara and Piracicaba and of the principal creeks tributary to them, but the higher mountainous areas are virtually devoid of habitation.

The population of the Município do Rio Piracicaba is between 25,000 and 30,000 (1959 estimate); more than 20,000 live in the Monlevade-Carneirinhos area, about 5,000 in the town of Rio Piracicaba and environs, and the remainder are scattered throughout the município.

Monlevade is linked to Belo Horizonte by a modern paved highway, BR–31, completed in 1960, and by an all-weather graveled road via Santa Bárbara and Sabará; the graveled road was formerly the main means of access. The distance over the new highway is 125 kilometers (77 miles), which may be driven comfortably in 2 hours. The meter-gage Estrada de Ferro Central do Brasil (Central Brazil Railroad) crosses the Rio Piracicaba quadrangle from southwest to northeast and skirts the east boundary of the Monlevade quadrangle, following the canyon of the Rio Piracicaba. Both Rio Piracicaba and Monlevade are on the railroad. The Central do Brasil joins the Estrada de Ferro Vitória à Minas (Vitória to Minas railroad) of the Cia. Vale do Rio Doce at Nova Era, 29 kilometers (18 miles) northeast of Monlevade. The rail distance from Monlevade to Belo Horizonte is 156 kilometers (97 miles), and the rail distance from Monlevade to the important seaport of Vitória is 757 kilometers (470 miles). Monlevade and surrounding area is served by an airport that is 2 kilometers west of the town. Flights are not scheduled regularly, but air taxi service is readily available from Belo Horizonte.

Much of the area of the two quadrangles is accessible by 4-wheel-drive vehicle, and accessibility is continually improving as a result of new roads being constructed by CSBM in conjunction with reforestation. The new highway BR–31 crosses the southern

[1] The Quadrilátero Ferrífero, or iron region of south-central Brazil, is a 7,000-square-kilometer (2,700 square-mile) area containing vast reserves of itabirite (iron formation) and iron ore.

[2] Roughly equivalent to a county in the United States.

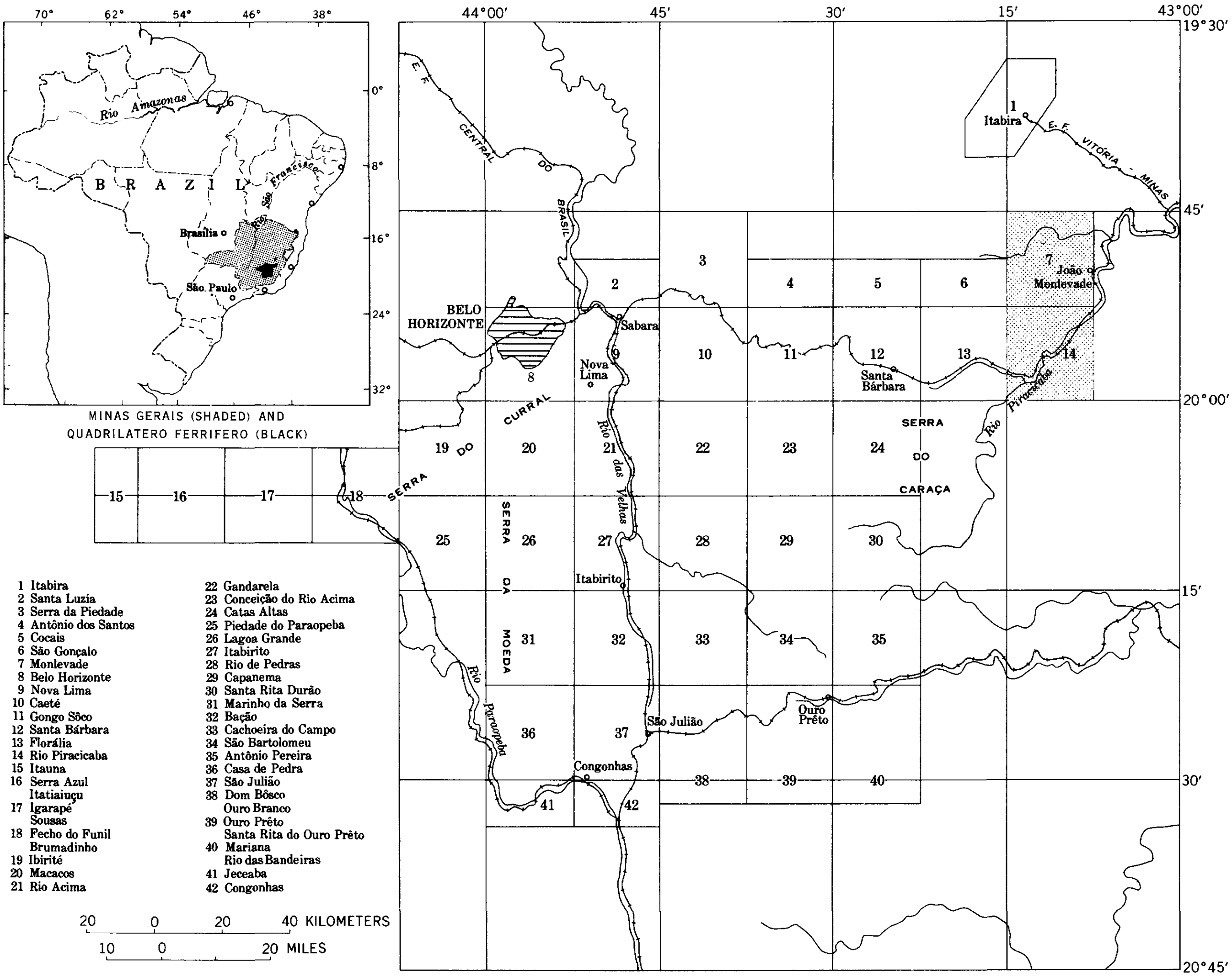

FIGURE 1.—Monlevade and Rio Piracicaba quadrangles in relation to the other quadrangles in the Quadrilátero Ferrífero.

part of the Monlevade quadrangle, and the Santa Bárbara-Sabará road skirts the west edge of the Monlevade quadrangle and then turns eastward and crosses the middle of the quadrangle. An all-weather graveled road that extends southward from Monlevade to Rio Piracicaba, and thence southwestward across the Rio Piracicaba quadrangle, permits easy access to the eastern and southern parts of the area. The mountainous central part of the quadrangles, inaccessible to motor vehicles, is crossed by many mule trails.

TOPOGRAPHIC FEATURES

The Quadrilátero Ferrífero lies athwart the Serra Geral, a part of the Serra do Espinhaço that, in general, parallels the Atlantic coastline from a point about 300 kilometers north of Rio de Janeiro to a point about 1,500 kilometers north. The Serra Geral in the Quadrilátero Ferrífero forms the divide between the rivers that flow eastward directly to the sea and those that flow into the Rio São Francisco basin and thence northward. The Monlevade and Rio Piracicaba quadrangles are on the east flank of the Serra Geral; their west edges are about 25 kilometers east of the range crest.

These quadrangles are drained by the Santa Bárbara and Piracicaba River systems. The Rio Santa Bárbara flows eastward across the north half of the Monlevade quadrangle. The Rio Piracicaba flows diagonally northeastward across the Rio Piracicaba quadrangle, thence northward along the east border of the Monlevade quadrangle to Monlevade. At Monlevade, the Rio Piracicaba leaves the quadrangle and flows northward, east of and parallel to the east border of the quadrangle. The Rio Santa Bárbara flows into the Rio Piracicaba 5 kilometers north-northeast of Monlevade and 3 kilometers east of the east border of the quadrangle. The divide between the two rivers is an irregular crest that trends northward a little west of the center of the quadrangle to the Pico do Andrade; it then trends eastward to the confluence of the rivers.

The principal peaks of the area are along the divide between the two rivers, and are, from north to south, the Pico do Andrade (1,115 m), Serra do Seará (1,333 m; the highest point in the quadrangles) and Serra do Elefante (1,057 m). The lowest point, 535 meters, is where the Rio Santa Bárbara leaves the Monlevade quadrangle. The maximum local relief within the quadrangle is just less than 500 meters, in a distance of slightly less than 3 kilometers from the peak at the east end of the Monlevade airport to the bottom of the Riacho (creek) Jacuí.

Slopes are steep, and many of the main streams and their tributaries have cut deep, steep-walled canyons. Only in the southwestern part of the Rio Piracicaba quadrangle, along the Rios Piracicaba and Valéria, and in the northwestern part of the Monlevade quadrangle along the Rio Santa Bárbara, have the rivers formed flood plains.

CLIMATE AND VEGETATION

The climate of the Quadrilátero Ferrífero east of the Serra Geral differs from that west of the Serra Geral by being more humid and slightly warmer. Even though the Quadrilátero Ferrífero is in the tropics, about 3° north of the Tropic of Capricorn, in general the climate is temperate owing to the elevation. The average annual rainfall at Rio Piracicaba is 1,300 millimeters (51 in.). The rainfall is seasonal; most of it falls in the period from October to April. However, dry, clear periods of 2–3 weeks are not uncommon during the rainy season. Conversely, violent rainstorms occur occasionally at the height of the dry season.

The uplands including the Serra do Elefante and the Serra do Seará are covered with dense patches of brush (cerrados) alternating with open grasslands. The bottom lands in their natural state are covered with dense stands of trees, shrubs, vines, and swordgrass, penetrable with great difficulty and only if one uses machetes or brush hooks. Trails opened through these stands close in a few months and are virtually unrecognizable after one season. The bottom lands of many of the rivers and creeks contain stands of second-growth timber. These tracts have been cut over, probably many times, for firewood, and in most places the timber has been allowed to regenerate naturally. In much of the area around Monlevade and the town of Rio Piracicaba, the land has been cleared for pasture.

CSBM has planted much of its forest holdings with eucalyptus originally imported from Australia. The eucalyptus grows well in the climate and soil of Brazil but for the first several years must be guarded against saúva, the leaf-cutter ant.

HISTORY, MINING, AND STEEL PRODUCTION

According to information in the official archives of the State of Minas Gerais, Rio Piracicaba (originally named São Miguel do Rio Piracicaba) was founded in 1713 by Capitão-Mor [3] João dos Reis Cabral, leader of a group of bandeirantes [4] from São Paulo whose main purpose was to search for gold. The history of Rio Piracicaba is interwoven with that of the neighboring mining districts—Santa Bárbara, Catas Atlas, Cocais—and of central Minas Gerais in general; it was well summarized by Dornas Filho (1957). Throughout most of the early years the overwhelming interest in this area, as in Minas Gerais generally, was in mining, and agriculture was neglected. This overwhelming interest in mining, coupled with extremely poor transportation facilities, resulted in serious famines. Agriculture—principally the raising of sugar cane, bananas, corn, and livestock—is now an important activity; however, the area is not yet self-sufficient and is a net importer of foods.

The search for gold and precious stones was responsible for the exploration and settlement of the Rio Piracicaba area, and mining in one form or another has been an activity there for nearly 250 years. The earliest mining consisted of placering the gravels along the Rios Piracicaba and Santa Bárbara and their tributaries. Records of these operations are meager, but the remains of old workings and appurtenances indicate that operations consisted of ground sluicing and other forms of placer mining on a fairly large scale. The following areas contain the most conspicuous and most extensive remnants of this activity: Southwest of Rio Piracicaba, along the Córrego do Diogo; northwest of Rio Piracicaba; between Rio Piracicaba and Ponte Saraiva; and along the Rio Santa Bárbara north of the Andrade mine. Some placer mining still is being done along the Rios Piracicaba and Valéria west of the town of Rio Piracicaba.

At the beginning of the 19th century, movement toward independence from Portugal began to manifest itself; this movement necessitated iron for armaments. This demand for iron, along with its requirement for

[3] Capitão-Mor was a title bestowed upon the leaders of Portugal's exploration expeditions.

[4] The name given to members of exploring, prospecting, and slave-hunting expeditions, many of whom remained as pioneer settlers.

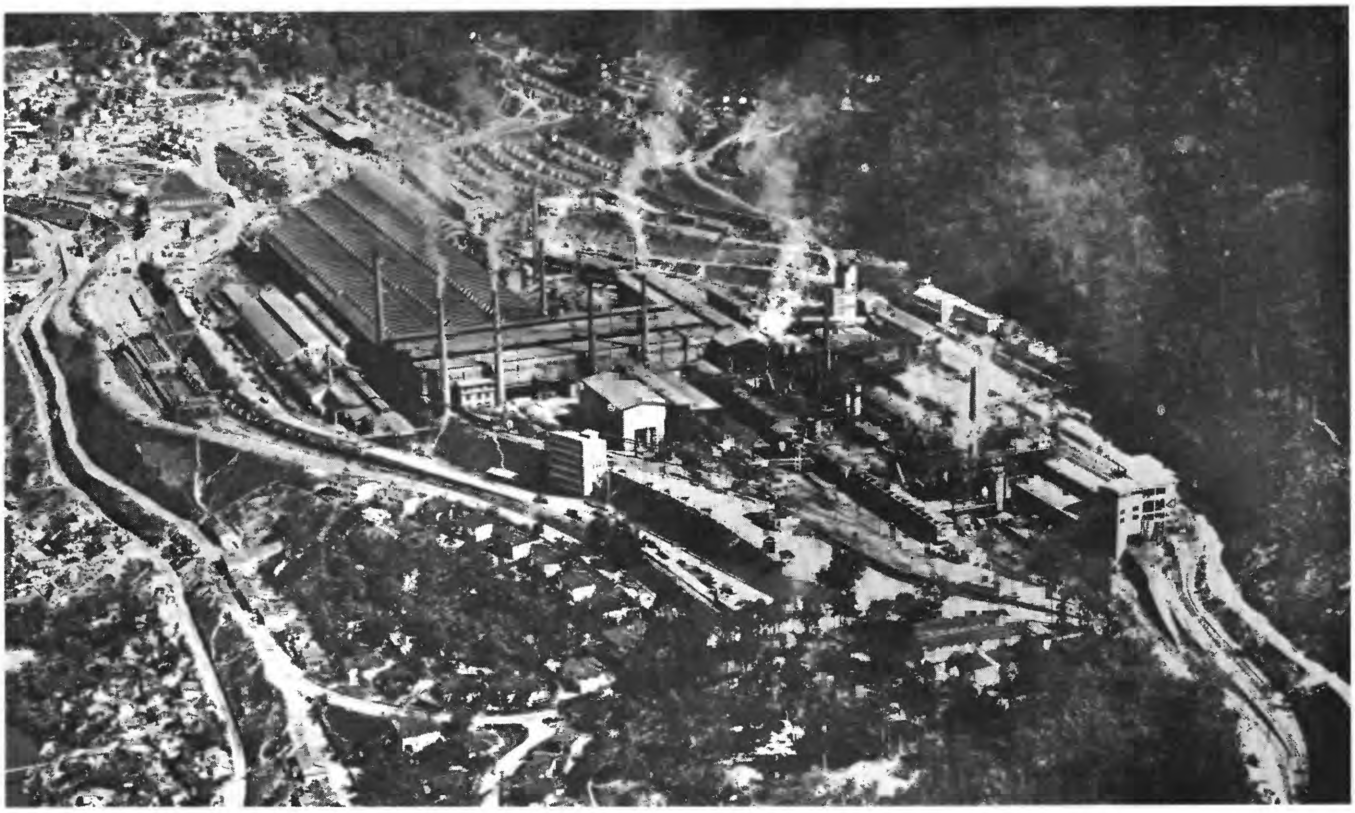

FIGURE 2.—Steel plant of CSBM at João Monlevade. (Photograph, courtesy of CSBM.)

mining and agricultural tools and other purposes, resulted in the construction of numerous small reduction works in the area now known as the Quadrilátero Ferrífero. The most famous of these in the Rio Piracicaba district was that operated by João Monlevade. In 1853 the usina of São Miguel (Fazenda de Monlevade) was already producing 30 arrobas[5] of iron per day. Almost all the iron was used at the fazenda for the manufacture of hatchets and axes, hardware, crushers for mining, tips (for arrows and spears), anvils, saws, canemills, and hoes.

The first iron ore was mined in the early years of the 19th century in order to provide ore for these local furnaces. This mining, which consisted largely of collecting boulders of iron ore or of stripping the easily accessible surface canga, was done almost exclusively by slaves. The exploitation of the pegmatites for phenacite and other semiprecious stones started shortly after the turn of the present century.

In 1922 CSBM acquired the Fazenda de Monlevade and the Fazenda de Andrade in a farsighted move to increase its (and Brazil's) steel production. It was not until 1932, when the Estrada de Ferro Central do Brasil rails reached Monlevade, that the awaited expansion began to take place, and not until 1937 did modern iron-ore mining commence at the Tanque mine, providing raw material for CSBM's steel works, the Usina Monlevade.

The Usina Monlevade, the largest charcoal steel plant in the world, had a yearly production in 1959 of about 200,000 metric tons of pig iron and 350,000 metric tons of steel products (fig. 2). The integrated plant consists of furnaces and of rolling, wire, and tube mills. In 1959 the works consisted of four blast furnaces with a total daily capacity of 700 tons of pig iron, four Siemens-Martin open-hearth furnaces with a total daily production of 500 tons of steel, and two 30-ton Linz-Donnewicz oxygen convertors with average daily capacity of 600 tons of steel. The operation of the oxygen convertors, the first in the southern hemisphere, is described by Meyers and Schlacher (1959).

The rolling mill, with a total capacity of 800 tons per day, produces blooms, billets, plates as wide as 24 inches, and assorted shapes and rods. The wire mill has a capacity of 60,000 tons per year and produces much of Brazil's wire. The tube mill produces 20,000 tons per year of pipe and tube with diameters as large as 2½ inches.

[5] One arroba equals 15 kilograms or 33.6 pounds.

In 1947 a sintering plant was built in Monlevade, just east of the Tanque mine, to treat fines produced during the mining, crushing, and transporting of the ore. Ore, charcoal, return sinter fines, and dolomite are mixed together in a pan and ignited by an oil-fired ignition car. The pans are rotated over a 1-inch grate to discharge the sinter into railway cars. The less than 1-inch material is returned for reuse in the sintering process. A more complete discussion of this sintering process is given by Greenawalt (1938, 1942) and Poll (1952), and the complete ore beneficiation process at Monlevade is described in detail by Pinto de Souza (1954).

The sinter is a highly porous, easily reducible material. The use of dolomite produces a self-fluxing sinter, eliminating the separate addition of flux at the blast furnace and thus decreasing charging time. The exclusive use of sinter increases the blast-furnace productive capacity 25–50 percent and results in a large overall decrease in the amount of charcoal required.

The original sintering plant did not have sufficient capacity to enable exclusive use of sinter in the blast furnaces, and a new plant, using the same system, was under construction in 1961 at the Andrade mine.

The blast and open-hearth furnaces and sintering plant in Monlevade consumed in 1958 about 1 million cubic meters (500,000 metric tons) of charcoal. Most of this charcoal was produced from trees grown on land belonging to CSBM. Employees of that company or contractors carbonized the wood in small beehive ovens. This production of charcoal requires a large Serviço Florestal (forest service), and the problems of obtaining sufficient high-quality charcoal are probably much greater than are those of obtaining the other raw materials necessary for the production of iron and steel.

Charcoal is made from native wood—principally jacaré, jacarandá (rosewood), and pau-novo—and from eucalyptus grown on immense hôrtos (tree farms). The role of the eucalyptus in the production of steel by CSBM was discussed by Osse (1957). At the end of 1958, nine hôrtos were in operation, and more were planned. The company planted about 10 million trees in 1958, making a total of more than 30 million trees planted, and plans call for planting 300 million trees on 120,000 hectares (297,000 acres) by 1970. The first production from the eucalyptus trees originally planted in 1949 was in 1958.

The charcoal is transported to Monlevade by mule, truck, and railroad, and, from the region to the east, by a 52-kilometer (33½-mile) aerial tram. The production and transportation of the charcoal consumed in Monlevade requires the services of about 5,000 men, several thousand mules, and several hundred trucks.

FIELDWORK AND STUDY

The concentration of mineral wealth—principally gold, precious stones, and iron and manganese ores—in central Minas Gerais, and particularly in the Quadrilátero Ferrífero, has resulted in many geologic studies of this area. International attention was first drawn to the immense size and the purity of the iron ore deposits of the Quadrilátero Ferrífero by Derby at the beginning of the 20th century (Derby, 1910), and from that time on, these deposits have been the object of many and increasingly detailed studies.

At the end of 1958, about 1,300 articles dealing with the geology and mineral resources of Minas Gerais had been published. In spite of this large number of papers, no systematic detailed study based on regional geologic mapping of the Quadrilátero Ferrífero had been made prior to the study begun jointly by the Brazilian Departamento Nacional da Produção Mineral and the United States Geological Survey in 1946. The early workers labored under a dual handicap—the lack of adequate large-scale base maps and the extreme difficulty of travel. For these reasons, most of the early reports were descriptions of small areas or of minerals or were reconnaissance studies of the area as a whole.

Very few geologic studies have been made in the Monlevade and Rio Piracicaba quadrangles. Von Eschwege (1833), Harder and Chamberlin (1915) and Freyberg (1932, 1934) referred to geologic features in these quadrangles, principally in the Rio Piracicaba quadrangle.

In addition to the few published works on the geology and ore deposits of the Monlevade and Rio Piracicaba quadrangles, the report files of the Brazilian Iron and Steel Co. (given to the U.S. Geological Survey upon dissolution of the company) contains a number of unpublished reports. Among these unpublished works are reports by the American geologists E. C. Harder, R. T. Chamberlin, and Harmon Lewis on the Rio Piracicaba district and the principal iron ore deposits of that district. The files of the CSBM contain a report on the Andrade mine and reports by Dr. James Büchi on exploration for manganese in the Rio Piracicaba quadrangle and adjacent areas to the south and east. These unpublished reports have been the source of valuable information on now inaccessible workings and on historical material.

This study of the Monlevade and Rio Piracicaba quadrangles is a part of the overall geologic study of the Quadrilátero Ferrífero. The general geology of that region has been discussed in both Portuguese and

English by Dorr and others (1960). Fieldwork by the author in these two quadrangles was started in early 1958 and continued, except for interruption by the rainy season (November–March), until mid 1959. About 9 months were spent in fieldwork, of which 7 were spent in areal mapping and 2 in detailed mapping of the ore deposits. The author was assisted from February to November 1958 by Rubem Cobra, whose work was made possible by a grant from CSBM.

The geology was mapped on aerial photographs at a scale of about 1:25,000 and was transferred to base maps, at a scale of 1:20,000, made from these photographs by photorammetric methods.

The principal ore deposits were mapped by several means. The Andrade mine was mapped on 1:10,000-scale aerial photographs taken in 1958 and on the 1:4,000-scale base map made from these photographs. The Água Limpa mine was mapped by plane table and telescopic alidade; the Morro Agudo deposit was mapped on base maps supplied by the owners; and the Morro da Água Limpa deposit was mapped on a base enlarged from the 1:10,000 manuscript quadrangle map controlled by plane table and telescopic alidade.

About 15 months were spent in the preparation of this report, during which time approximately 150 thin sections and 35 polished sections were examined. Plagioclase composition was determined by measurement of indices of refraction, extinction angles, and optic sign. Modal analyses were made by the Rosiwal method and by point count, using a specially adapted mechanical stage (Chayes, 1955). Use of the method of staining of plagioclase developed by Bailey and Stevens (1960) materially aided in distinguishing between untwinned oligoclase and quartz in amphibolite.

ACKNOWLEDGMENTS

The author is grateful to those whose courtesies and assistance contributed greatly to this study. To the staff of CSBM, and in particular to Dr. Joseph Hein, general superintendent; Dr. Francisco Pinto de Souza, chief of the Raw Material Department; Dr. Henri Meyers, superintendent of the Monlevade works; Dr. James Büchi, chief geologist of the company; and Dr. Peter Zwetkoff, chief engineer of the Andrade mine, the author expresses his sincere appreciation for their cooperation, hospitality, and access to and permission to use company maps and other data.

This study was made under the immediate supervision of John Van N. Dorr 2d of the U.S. Geological Survey, from whom the author received much help and advice. Beth Madsen of the U.S. Geological Survey made several X-ray determinations of garnets, staurolite, and plagioclase feldspars. Profs. M. L. L. Formosa and Maurício Ribeiro of the Escola de Geologia of the Universidade do Rio Grande do Sul also kindly made X-ray mineral determinations.

GEOLOGY

REGIONAL SETTING

The Quadrilátero Ferrífero (fig. 3) is part of the Central Highlands province of Brazil. The Central Highlands are underlain by highly deformed Precambrian metasedimentary and metavolcanic rocks with granitic, mafic, and ultramafic rocks intruded into them. In the Quadrilátero Ferrífero, a combination of uplift followed by erosion of younger formations has exposed these Precambrian rocks. To the east, recognizable Precambrian metasedimentary rocks disappear into or under a thick sequence of granitic paragneiss and syntectonic granite that extends to the Atlantic coast, which is about 600 kilometers (air line) east of the eastern border of the Quadrilátero Ferrífero. To the south and west the Precambrian metasedimentary rocks gradually thin and are lost in a vast sea of granitic rocks.

Within the Quadrilátero Ferrífero the Precambrian sedimentary rocks are divisible into three series (Dorr and others, 1960), which are from older to younger, the Rio das Velhas, Minas, and Itacolomí; each of these series is unconformably separated from the others (fig. 4).

The present subdivision of the metasedimentary rocks (Dorr and others, 1960) is the latest in a long series of attempts to divide and correlate these rocks; the attempted division and correlation started with Derby (1906) and continued through Harder and Chamberlin (1915), Guimarães (1931), Lacourt (1936), Barbosa (1954), Guild (1957), to Dorr and others (1957).

The rocks in the Quadrilátero Ferrífero are folded into complex anticlinoria and synclinoria and are cut by normal and thrust faults of considerable magnitude. In the western part of the area, the principal folds trend northward and intersect a northeast-trending fold system, about 10 kilometers south-southwest of Belo Horizonte. In the southwest corner, the north-trending folds swing eastward, continuing along the southern border of the Quadrilátero Ferrífero. In the southeast corner, the structural pattern is complex, but many of the folds and faults trend northward along the eastern border. In the northeast-central part, and on to the eastern and northern border, the dominant regional structures are northeast-trending folds and

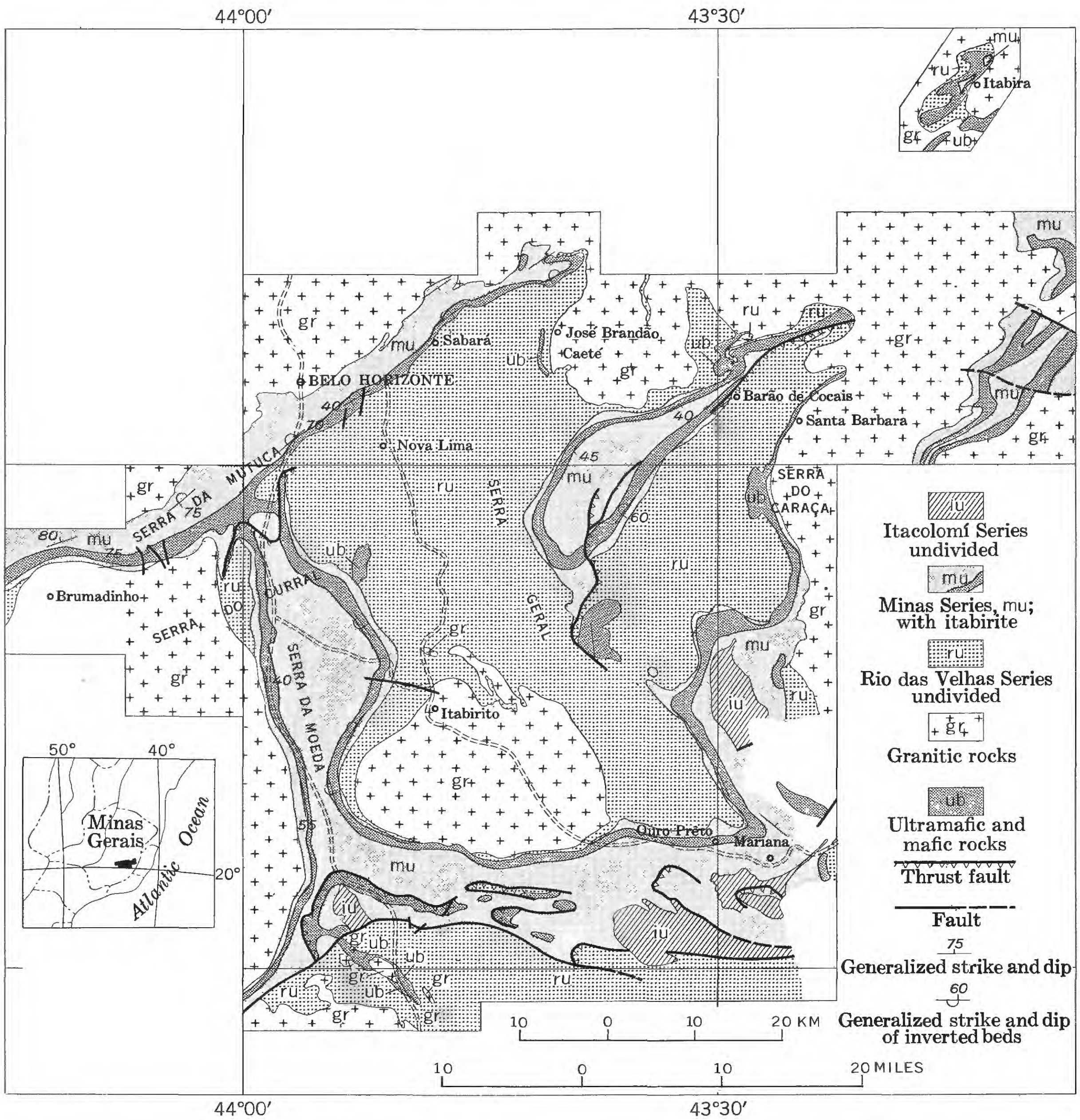

FIGURE 3.—Map of the Quadrilátero Ferrífero of central Minas Gerais, Brazil, showing the principal geologic features.

faults. Locally, in the northeast corner, west-northwest or northwest-trending faults cut the folds.

The Monlevade (pl. 1) and Rio Piracicaba (pl. 2) quadrangles are chiefly underlain by the Minas Series and by a thick section of granitic paragneiss probably formed from the Rio das Velhas Series; the Rio Piracicaba quadrangle includes a part of the west edge of granitic paragneiss or syntectonic granite that is correlated with the Rio das Velhas Series granitic paragneiss. Within the Monlevade and Rio Piracicaba quadrangles, the metasedimentary and metavolcanic rocks are folded into northeast-trending anticlines and synclines (pl. 3) that are offset laterally and vertically by two major northwest- and west-trending faults.

RIO DAS VELHAS SERIES

The oldest mapped metasedimentary and metavolcanic rocks in the Quadrilátero Ferrífero are those of the Rio das Velhas Series, named for exposures along the Rio das Velhas in the Nova Lima, Rio Acima, and Itabirito quadrangles (Dorr and others, 1957). Locally in the central part of the Quadrilátero Ferrífero, this series has been divided into the older Nova

	WESTERN/CENTRAL QUADRILATERO FERRIFERO[1]			MONLEVADE AND RIO PIRACICABA QUADRANGLES		
Series	Group	Formation	Thickness	Formation	Member	Thickness
Itacolomí	Series not subdivided		200m	Not present		
Minas	Piracicaba	Sabará	4000m	Elefante	Bicas Gneiss	Not known
		Barreiro	125m			
		Taboões Quartzite	120m			
		Fecho do Funil	300m		Pantame	10-200m
		Cercadinho	200m			
	Itabira	Gandarela	2-1200m	Sítio Largo Amphibolite		0-400m
		Cauê Itabirite		Cauê Itabirite		125-350m
	Caraça	Batatal	30-1000+m	Batatal		20-50
		Moeda		Moeda		90-500
Rio das Velhas	Tamanduá	Unnamed formation	1000m	Monlevade Gneiss		Not known
		Unnamed formation				
		Unnamed formation				
		Cambotas Quartzite				
	Maquiné	Upper formation	1800m			
		Lower formation		?		
	Nova Lima	Group not subdivided	4200m			

[1] After DNPM (1960) except for Tamanduá Group.
Tamanduá Group after Simmons. (1962)

FIGURE 4.—Precambrian metasedimentary and metavolcanic rocks of the Monlevade and Rio Piracicaba quadrangles compared with those of the western and central parts of the Quadrilátero Ferrífero.

Lima Group and the younger Maquiné Group.[6] Rocks of the Rio das Velhas Series are separated from the overlying Minas Series by an angular unconformity in parts of the Quadrilátero Ferrífero (Rynearson and others, 1954) and by a disconformity in other parts.

The Rio das Velhas Series consists of at least 6,000 meters of metasedimentary and metavolcanic rocks. The lower 4,200 meters (Nova Lima Group) is mainly phyllite but has subordinate graywacke, quartzite, dolomite, conglomerate, chert, and itabirite. The upper 1,800 meters (Maquiné Group) is mainly phyllite and quartzitic schist overlain by conglomerate and massive quartzite. Locally, the Nova Lima and Maquiné Groups are separated by an unconformity.

The Rio das Velhas rocks are intruded by the Itabirito granite and perhaps by the older Engenheiro Correia granite, although the relationship is not clearly shown in the few exposures of the contact.

MONLEVADE GNEISS

In the Monlevade and Rio Piracicaba quadrangles, rocks underlying the Minas Series consist of gneiss and subordinate quartz-mica schist, amphibolite, quartzite, and itabirite [7] and are probably the highly metamorphosed and metasomatized equivalent of the Rio das Velhas Series. These rocks are here named the Monlevade Gneiss for excellent exposures at and near the town of Monlevade.

The Monlevade Gneiss forms the cores of the Monlevade, Carneirinhos, Pacas, and Elefante anticlines. The northwestern and central parts of the Monlevade quadrangle and the northwestern, west-central, and southeastern parts of the Rio Piracicaba quadrangle are underlain by this gneiss. The best exposures of fresh unweathered gneiss are in quarries 2.5 kilometers northwest of Monlevade and 2 kilometers west of the Monlevade airport and in the Andrade mine-Usina Monlevade railroad tunnel. Slightly to highly weathered gneiss is well exposed along the Monlevade-Santa Bárbara road south of Pacas, along the Rio Santa Bárbara west of the Andrade mine, along the Córrego do Monjolo east of the Água Limba manganese mine (on the west flank of the Serra do Elefante), and along the Riacho Jacuí southeast of the Monlevade airport.

The Monlevade Gneiss is separated from the Minas Series by an angular unconformity. This unconformity is best observed along the northwestern limb of the Tanque syncline on the Monlevade-Carneirinhos road, where the Monlevade Gneiss contains distinguishable units of tightly folded amphibolite and quartzite that trend toward the contact at an angle of approximately 90°. The greater amount of deformation that the Monlevade Gneiss has undergone, contrasted with the lesser amount undergone by the Minas Series, is also shown by the intricate folding and contortions in an itabirite member 2 kilometers south of the Monlevade airport.

Elsewhere, foliation in the gneiss and bedding in the overlying rocks are parallel so that the rocks appear to be conformable, although they are not. The latest foliation in the gneiss was produced by the same stresses that folded the Minas Series, and these stresses obliterated many preexisting features of the gneiss and produced foliation concordant with the major structures (and contacts).

The formation consists mostly of banded feldspathic (granite) gneiss, augen gneiss, and quartz-biotite gneiss, but it includes layers and lenses of amphibolite, quartz-mica and staurolite schists, quartzite, and itabirite. The proportion of granite gneiss is higher in the eastern and southeastern parts of the area of exposure, and the proportion of biotite gneiss and schist is higher in the western and northern parts.

The principal amphibolite layer, because of its extent and structural importance, was mapped as a separate unit, the Pacas Amphibolite Member. One other extensive layer of itabirite was also mapped, but many smaller layers and irregular bodies of amphibolite, quartzite, quartz-mica and staurolite schists, and itabirite were not mapped. It may be possible and desirable in the future, after more detailed work, to further formally subdivide the Monlevade Gneiss.

One of the principal characteristics of the gneiss is its great variability, from a fine-grained nearly equigranular layered rock to a coarse-grained highly inequigranular augen gneiss. Some is very coarsely banded, consisting of bands of silicic or felsic composition separated by mafic bands that are mostly hornblende and biotite. Fine- and medium-grained varieties make up by far the greater part of the gneiss, perhaps as much as 90 percent. The variability probably results both from differences in composition of the primary sediments and from differences in metamorphism. Chemical compositions of the Monlevade Gneiss are given in table 1.

[6] After this report was written, Simmons and Maxwell (1961) defined and named a third and upper group, the Tamanduá, of the Rio das Velhas Series. This group consists of a lower quartzite, the Cambotas overlain by unnamed phyllite and iron-formation. It is locally separated from the underlying Maquiné Group by an angular unconformity.

[7] Itabirite is a metamorphosed chemical sediment characterized by alternating layers of quartz and hematite and in some places magnetite. The definition, history, and origin of the term and physical, chemical, and mineralogical descriptions of itabirite are given on pages E24–E30.

TABLE 1.—*Chemical analyses of granitic gneiss and schist from the Monlevade and Rio Piracicaba quadrangles*

[Analyses by Paul L. D. Elmore, Samuel D. Botts, and Ivan H. Barlow, U.S.G.S.]

	1	2	3	4
Laboratory No	154082	154083	154084	154085
Field No	Ha-36	Ha-37	Ha-38	Ha-39
SiO_2	76.5	69.6	71.9	67.8
Al_2O_3	11.8	12.2	13.3	14.5
Fe_2O_3	.7	1.5	1.0	1.1
FeO	1.1	4.7	2.1	4.0
MgO	.10	1.3	.20	2.1
CaO	.70	3.4	1.5	2.8
Na_2O	2.8	3.1	3.2	2.2
K_2O	5.2	1.3	4.7	2.6
H_2O	.33	.80	.68	1.3
TiO_2	.10	.77	.45	.68
P_2O_5	.00	.14	.12	.18
MnO	.02	.08	.04	.14
CO_2	.05	$<.05$	.05	.21
Sum	99	99	99	100

1. Medium-grained granitic gneiss of the Monlevade Gneiss from the Andrade mine-Usina Monlevade railroad tunnel.
2. Staurolite schist interlayered with Pacas Amphibolite Member of the Monlevade Gneiss taken where Rio Santa Bárbara crosses the gneiss.
3. Medium- to coarse-grained granitic gneiss of the Monlevade Gneiss from along BR-31 at west border of Monlevade quadrangle.
4. Bicas Gneiss Member of the Elefante Formation from Rio Piracicaba rock quarry.

The fine-grained variety of the Monlevade Gneiss is a light-gray rock consisting of layers of quartz and feldspar 1–2 millimeters thick separated by very fine laminae of biotite. Microscopically, the gneiss consists of interlocking potassium feldspar and quartz, and minor amounts of plagioclase (An_{20}). The biotite imparts a definite layering to the rock.

The fine-grained gneiss is composed of about 50 percent potassium feldspar, 25 percent quartz, and about 10 percent each of oligoclase and biotite. Sericite and fine-grained clay minerals formed by alteration of the feldspar make up the remainder. Zircon is the most common accessory mineral.

Most of the potassium feldspar, although it shows the quadrille structure of microcline, is optically positive and has a 2V of about 85° to nearly 90°; it is therefore isomicrocline (Winchell and Winchell, 1951, p. 309), a less common form of microcline. Much of the isomicrocline is perthitic.

The least weathered medium- to coarse-grained gneiss was found in the Andrade mine-Usina Monlevade railroad tunnel. It is a layered rock composed chiefly of pink microcline and quartz and subordinate biotite and plagioclase. The microcline is in large aggregates, flattened parallel to layering, from ½ to 1 cm long and from 2 to 5 mm thick. The quartz is in lenses, and, along with the biotite flakes and tabular microcline, gives a pronounced gneissic layering to the rock. The chemical analysis is given in table 1, analysis 1.

Under the microscope, the gneiss is seen to consist of about 38 percent microline, 38 percent quartz, 15 percent plagioclase (An_{15}), and 7 percent biotite. Sericite, calcite, and a small amount of apatite are present. The texture is inequigranular, with interlocking grains of microcline, quartz, plagioclase, and biotite. Most of the microcline grains are between 0.3 and 1 mm in diameter. The quartz grains vary more in size, from a few hundredths of a millimeter to about 1 mm in diameter. Most of the plagioclase ranges from 0.2 to 0.5 mm in diameter; the biotite ranges from a few hundredths of a millimeter to 1 mm in length and from a few hundredths of a millimeter to 0.3 mm in width.

Microcline is readily distinguishable by its quadrille structure. It contains relatively few inclusions, most of which are sericite and a few of which are apatite and biotite. Much of the microcline contains irregular intergrowths of oligoclase. The microcline and oligoclase are not intimately intergrown, as in typical microperthite; the oligoclase occurs as separate individual grains.

Quartz occurs in discrete interlocking grains; some of the larger ones contain microscopic inclusions of mica, apparently both sericite and biotite, and large inclusions of microcline and oligoclase.

Most of the plagioclase contains many inclusions of sericite, biotite, and a few inclusions of quartz and potassium feldspar.

The augen gneiss of the Monlevade Gneiss is a mottled gray-pink rock consisting of pink augen of microcline set in a medium-dark-gray matrix of biotite and felsic minerals (fig. 5). The augen are from a few millimeters to more than 3 cm long and are as much as 2 cm thick. The matrix consists of thin laminae of black biotite separated by laminae composed chiefly of fine-grained felsic minerals, mostly plagioclase but partly potassium feldspar and quartz.

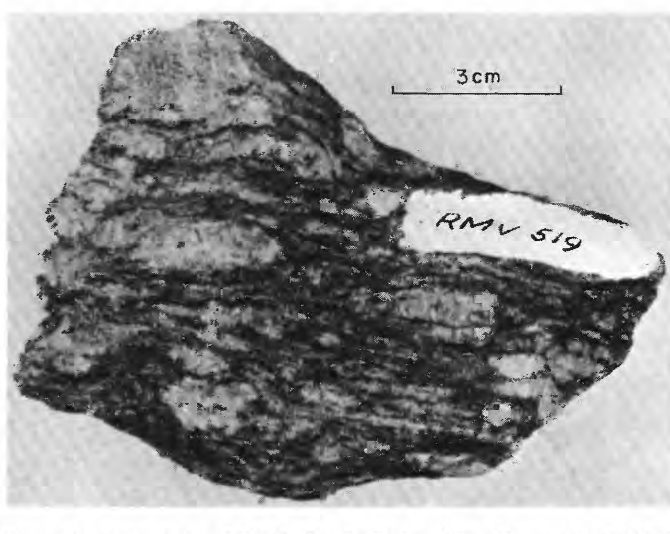

FIGURE 5.—Augen gneiss of the Monlevade Gneiss. Microcline metacrysts (light colored) in layers of biotite-quartz-plagioclase.

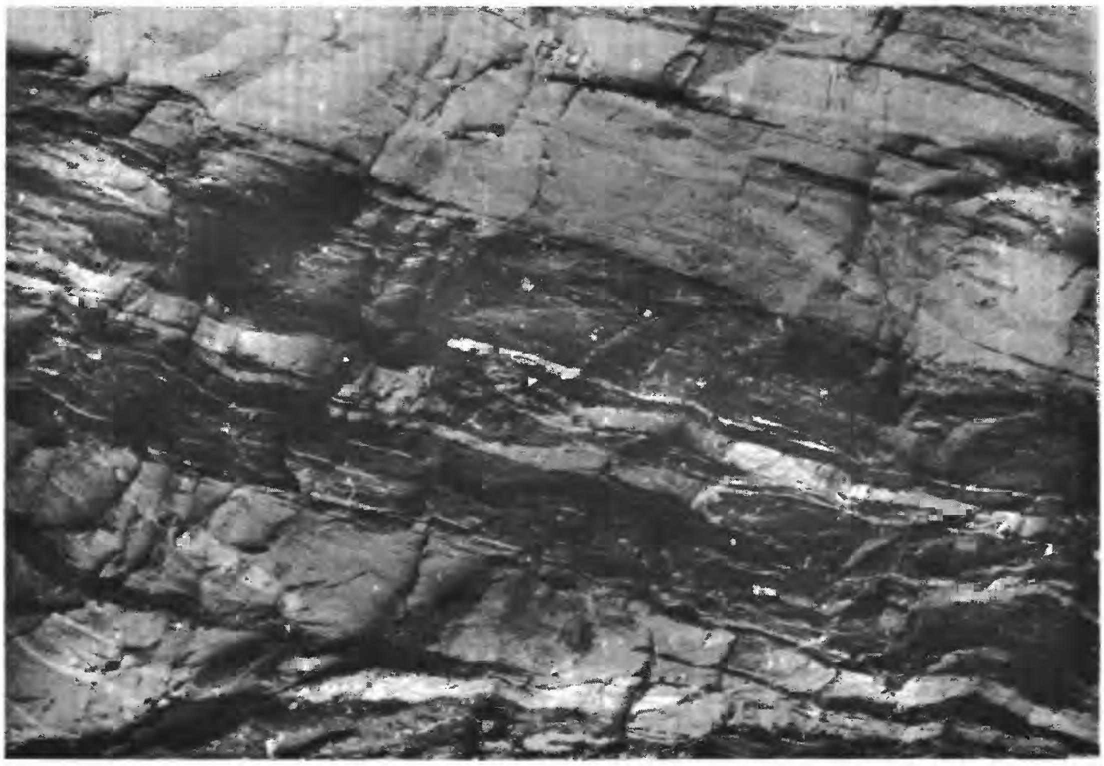

FIGURE 6.—Grossly banded Monlevade Gneiss. Dark bands are chiefly hornblende; light bands are composed mainly of quartz and potassium feldspar. Width of field, 2.5 meters.

The laminae bend around the augen, and some are included as septa between two or more augen or as penetrations in an individual augen.

Grossly banded gneiss is associated with the augen gneiss, principally in the souhtwestern part of the Monlevade quadrangle. This grossly banded gneiss consists of alternating white to light-gray and black bands which range from a few centimeters to 10 cm in thickness (fig. 6). The light bands are composed chiefly of quartz and plagioclase and subordinate potassium feldspar and biotite. The black bands are composed almost exclusively of biotite but contain a small quantity of hornblende. This gneiss was deformed during or subsequent to the last metamorphic recrystallization, as indicated by the microfolds in the less competent black layers.

The grossly banded gneiss may have formed through the metamorphism of a sedimentary rock composed of alternating quartz-rich and argillaceous layers, or through metamorphic differentiation, or through both. If the original rock was crudely layered, the contrasting composition of the layers may have been accentuated by metamorphic differentiation.

In the west-central part of the Quadrilátero Ferrífero, in the mapped areas closest to the Monlevade and Rio Piracicaba quadrangles, Rio das Velhas Series rocks are mainly schists and phyllites, thin-bedded iron-formation, dolomite-ankerite rock, graywacke, and sericite-quartzite of the Nova Lima Group; rocks of this series are overlain by quartzite, schist, and conglomerate of the Maquiné Group (Dorr and others, 1960). Most of the series is composed of pelitic metasedimentary rocks. These metasedimentary schists and phyllites consist predominately of quartz, sericite-fuchsite, chlorite, and carbonate in varying proportions. Where feldspar is locally abundant, the schists have the composition of graywacke or arkose. Most of the metavolcanic schists contain mineral assemblages typical of regionally metamorphosed mafic rocks—especially chlorite-epidote or clinozoisite, chlorite-plagioclase, and chlorite- or epidote-amphibole; these schists have been metamorphosed to the greenschist facies of regional metamorphism.

This same general sequence of Rio das Velhas rocks continues to the east into the Santa Bárbara and Cocais quadrangles, about 20 kilometers west of the Monlevade and Rio Piracicaba quadrangles (G. C. Simmons, written commun., 1963). In the Santa Bárbara and Cocais quadrangles, this sequence has the same or a slightly higher degree of metamorphism. An increase in the degree of metamorphism and metasomatism resulted in the formation of the Monlevade Gneiss of the Monlevade and Rio Piracicaba quadrangles. Exposures are poor and the rocks cannot be continuously followed, but the Monlevade Gneiss appears to occupy the same stratigraphic position as the Rio da Velhas Series and to be a more highly metamorphosed equivalent of it. The overlying Minas Series, especially the distinctive Cauê Itabirite, provides a definite stratigraphic marker to which the underlying units can be referred.

The pelitic rocks of the Rio da Velhas Series, which in the vicinity of Santa Bárbara appear to make up most of the series exposed at the surface, have been metamorphosed to biotite-quartz gneiss. In the western and northwestern part of the Monlevade quadrangle, the gneiss appears to have formed mainly by reconstitution and recrystallization with very little addition of material; it is chiefly a layered quartz-biotite rock, showing only minor segregation of quartz and potassium feldspar into lenses and irregular shapes. The gneiss contains extensive lenses and beds of quartz-mica schist and a few phyllite zones.

The banded feldspathic (granite) gneiss may have formed through the metamorphism of rocks more silicic than the normal pelitic rocks which were metamorphosed to form the biotite-quartz gneiss, or it may have formed by more intense metamorphism, including metasomatism, of the normal pelitic rocks. Although the gneiss is more silicic than ordinary pelitic rocks, it is no more so than some siliceous shales (Pettijohn, 1957, p. 364). As evidence is insufficient, one cannot choose between these alternatives.

PACAS AMPHIBOLITE MEMBER

The Pacas Amphibolite Member of the Monlevade Gneiss is here named for its excellent exposures along the Rio Santa Bárbara and the Monlevade-Santa Bárbara road, about 2 kilometers east of the town of Pacas. It consists mainly of amphibolite; locally, however, thin layers of quartzite and quartz-mica and staurolite schist are interbedded with the amphibolite.

The Pacas Amphibolite Member extends from the northwest corner of the Monlevade quadrangle, trending first eastward and then south nearly to the southwest corner of the quadrangle. It does not cross the new Belo Horizonte-Monlevade highway (BR-31) and apparently ends about 0.5 kilometer west of it. Exposures in the area from the highway to the west are poor, owing to thick soil cover, and are limited mainly to the bottoms of the several major creeks and to a few deep cuts along the new highway.

The unit is approximately 70–100 meters thick. It is folded into a northeast-trending anticline that plunges 60°–70° NE. and adjacent syncline that plunges 28°–30° NE. In general the member is concordant with foliation in the gneiss; however, at one place, about 1 kilometer north of the Monlevade-Santa Bárbara road, a similar amphibolite cuts the gneiss at nearly right angles.

The amphibolite, a medium-dark-gray-green to a very dark-greenish-black rock, is finely laminated, with alternating hornblende-rich and plagioclase-quartz-rich layers. The layers parallel the contacts between the overlying and underlying rocks.

Under the microscope, the rock is seen to be crudely banded, with lenses of plagioclase and quartz separating nearly continuous bands of hornblende (fig. 7). The plagioclase-quartz bands are 0.6–1.2 mm thick, and the hornblende bands are 1–1.5 mm thick. The hornblende has a subparallel orientation, which produces a definite lineation. A Rosiwal modal analysis gives a composition of 79 percent hornblende, 15 percent plagioclase, and 5 percent quartz. Accessory minerals are apatite, garnet, and opaque minerals, mostly hematite. A chemical analysis is given in table 2, analysis 1.

TABLE 2.—*Chemical analyses of amphibolites from the Monlevade and Rio Piracicaba quadrangles*

[Analyses by Paul L. D. Elmore, Samuel D. Botts, and Ivan H. Barlow, U.S.G.S.]

	1	2	3	4	5	6	7
Laboratory No	154077	154081	154078	154079	154080	154075	154076
Field No	271	421	413	416	420	10	119
SiO_2	49.3	49.3	47.5	49.7	48.1	54.2	45.4
Al_2O_3	15.7	15.8	15.8	15.4	15.2	14.7	16.6
Fe_2O_3	2.0	2.2	4.5	1.9	2.2	1.9	4.6
FeO	9.4	9.7	10.3	10.4	11.1	7.9	8.7
MgO	6.4	7.0	5.8	6.4	6.8	6.2	7.0
CaO	10.0	9.1	8.9	11.0	8.3	10.0	8.0
Na_2O	2.2	2.1	1.2	1.8	1.2	1.9	1.0
K_2O	.51	.26	.16	.14	.21	.20	.29
H_2O	1.5	1.2	3.6	1.6	4.6	1.2	6.4
TiO_2	1.5	1.7	1.2	1.1	1.3	1.0	1.2
P_2O_5	.16	.19	.10	.08	.11	.14	.10
MnO	.21	.29	.20	.20	.20	.19	.22
CO_2	<.05	<.05	.05	<.05	.06	<.05	.08
Sum	99	99	99	100	99	100	100

1. Pacas Amphibolite Member of the Monlevade Gneiss, where crossed by old Santa Bárbara-Monlevade road.
2. Amphibolite in Monlevade Gneiss, along west border of the Rio Piracicaba quadrangle, 2 km south of the Monlevade-Rio Piracicaba quadrangle boundary.

3-6. Sítio Largo Amphibolite:
3. 1 km south of Sítio Largo.
4. 1 km west of Sítio Largo.
5. 1 km northwest of Ponte Saraiva.
6. Along Rio Santa Bárbara, 2 km northeast of the Andrade mine.

7. Amphibolite in Elefante Formation, undivided, 1 km north of Rio Piracicaba.

The hornblende occurs in euhedral to subhedral grains that are 0.1–0.3 mm wide and as much as 2 mm long. Smaller subhedral grains surround the larger grains; they are 0.02–0.06 mm wide and as much as 0.2 mm long. The hornblende is pleochroic: X=very light yellow, Y=light yellowish green, and Z=medium yellowish green. Maximum measured Z is 17°. Minute inclusions in the hornblende are subhedral quartz, anhedral plagioclase, apatite(?), and opaque ore, probably hematite. Most of the hornblende grains contain very few inclusions, but some have as much as about 20 percent other minerals.

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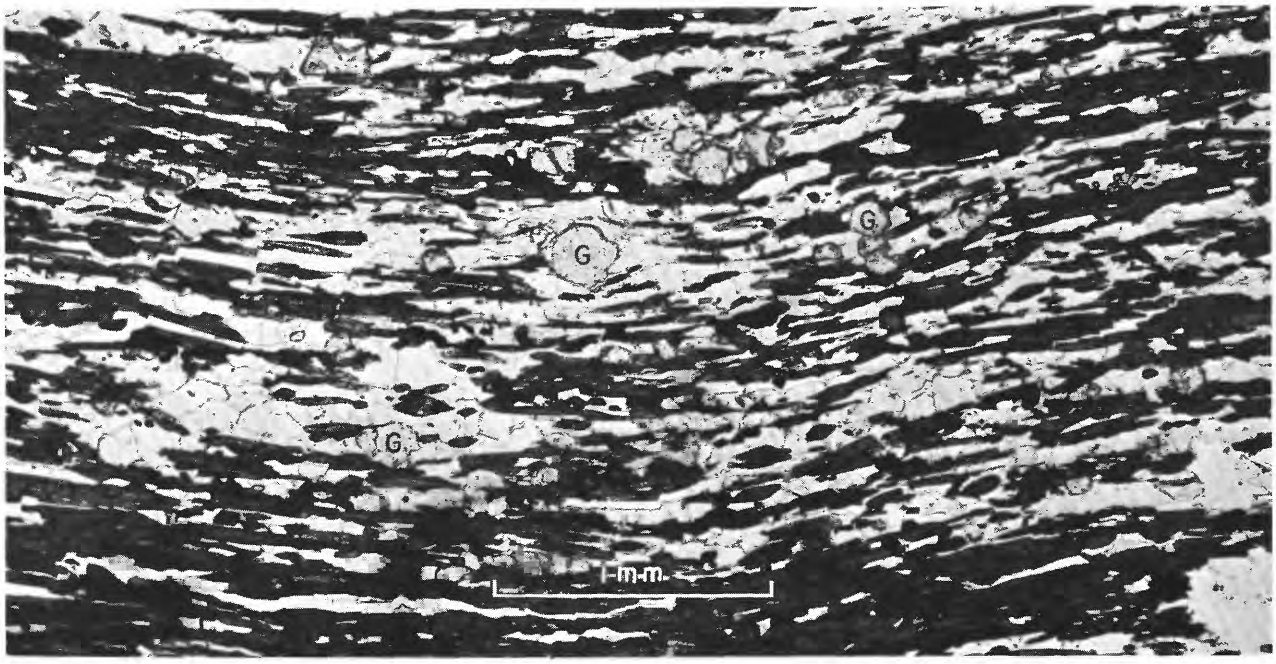


FIGURE 7.—Pacas Amphibolite Member of the Monlevade Gneiss. Partially crossed nicols. Laminae are of hornblende (black) and quartz-plagioclase (white to light gray). Abundant garnet (G).

In the plagioclase- and quartz-rich layer, the quartz and plagioclase (An_{25-30}) occur as interlocking anhedral grains that are generally 0.1–0.2 mm in diameter. Twinned plagioclase is rare.

The genesis of the Pacas Amphibolite Member is open to question. The original rock may have been an impure dolomite or dolomitic shale, a mafic tuff, or a sill intruded into the Rio das Velhas sediments; the chemical and mineralogical evidence are inconclusive. The close association and interlayering of the amphibolite with quartzite and quartz-mica schist, however, indicate that the rocks are sedimentary in origin, although this evidence does not rule out their being volcanic, especially pyroclastic in origin. Similar amphibolite about 1 kilometer north of the Santa Bárbara road both crosscuts layering in the gneiss and trends normal to the main body of Pacas Amphibolite Member; this relationship suggests a feeder dike for a sill or flow, although the dike may have been introduced much later. This amphibolite is badly weathered, and no fresh material was found that could be compared chemically or mineralogically to the amphibolite of the Pacas Member; in gross aspect, however, the amphibolite is similar to that of the Pacas Member.

QUARTZITE AND SCHIST

The layers and lenses of quartz-mica schist and quartzite that occur in the Monlevade Gneiss are for the most part thin and discontinuous and are scattered at random throughout the gneiss. In some areas, however, particularly in the northwestern part of the Monlevade quadrangle, beds several tens of meters to more than 100 meters thick persist for several kilometers. The rock shows the effects of extreme deformation; the beds are highly contorted, and the rock within them is highly deformed.

All gradations exist from slightly micaceous quartzite to quartz-mica schist; however, quartz-mica schist is by far the most prevalent rock type. Most of the schist is composed of layers of muscovite separated by layers of quartz; biotite, hornblende, and a few feldspars occur in minor amount. Garnet is almost everywhere present, although in some beds and areas it is scarce. Scattered pods and laminae of coarse-grained recrystallized quartz and aggregates of hornblende and microcline show the effects of mobilization and limited migration of silica and other constituents. Texture indicates that the metamorphic recrystallization took place under dynamic conditions (fig. 8). Where the segregation and recrystallization of quartz and other minerals increased, the schist grades into gneiss.

A staurolite-muscovite-quartz schist layer occurs at the base of the Pacas Amphibolite Member in the northwestern part of the Monlevade quadrangle. It is a medium-gray-green rock that has a pronounced foliation imparted by the muscovite. The muscovite layers show microfolding. In hand specimen quartz, muscovite, staurolite, and biotite are recognizable.

Under the microscope, the schist is seen to consist of layers of equigranular, interlocking quartz grains sep-

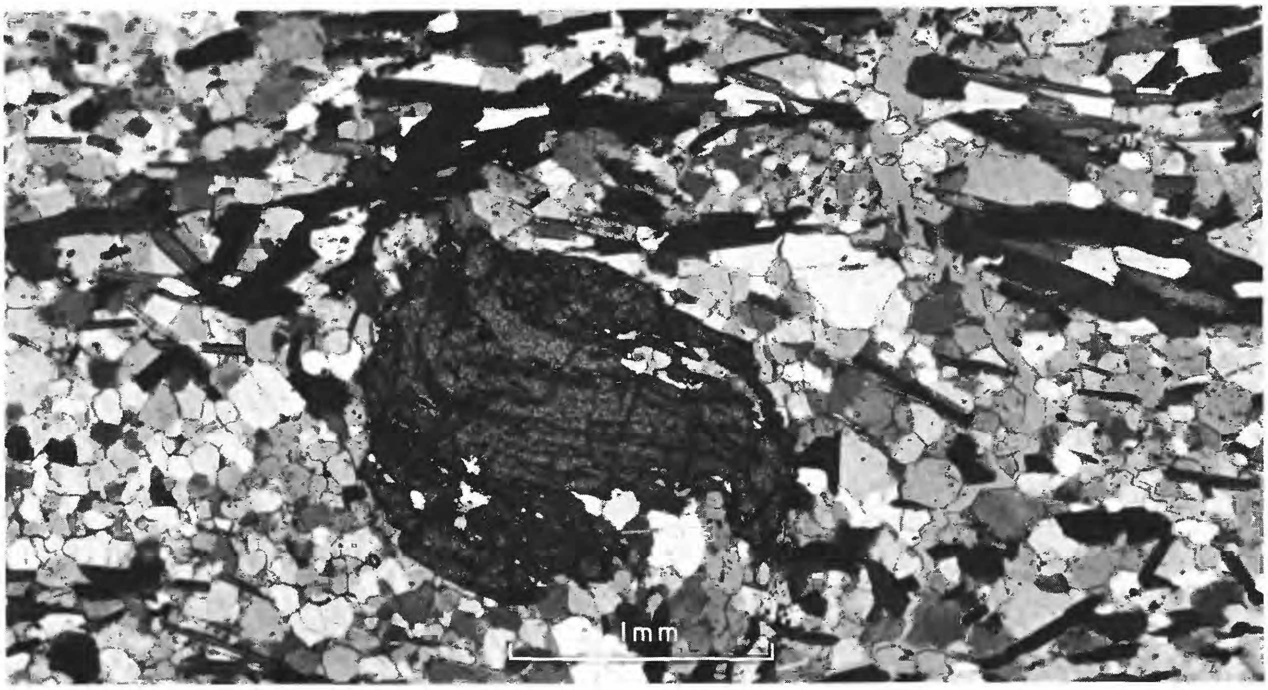


FIGURE 8.—Garnetiferous muscovite-quartz schist of the Monlevade Gneiss. Garnet shows snowball structure, indicating movement during growth. Crossed nicols.

arated by thin laminae of muscovite. The muscovite is bent and fractured, and the staurolite grains are rounded and fractured, possibly resulting from rolling during and after their formation. The quartz-rich layers are 0.1–0.3 mm thick, and the mica laminae are a few hundredths to 0.1 mm thick (fig. 9).

The schist is composed chiefly of quartz, 60 percent; muscovite, 20 percent; and staurolite, 15 percent. Biotite and sericite together make up about 5 percent of the rock; the biotite is partly altered to chlorite. Small grains of iron oxides and here and there very small garnet and apatite(?) grains constitute the accessory minerals. The chemical composition is given in analysis 2, table 2.

Staurolite is characteristic of rocks rich in alumina and iron and deficient in potassium (Williamson, 1953); as a result this mineral is rarely associated with potassium feldspars (Harker, 1939). Neither potassium nor plagioclase feldspars occur in the part of the staurolite schist studied in detail. Rocks of this mineral assemblage are assigned by Turner and Verhoogen (1960) to the staurolite-almandine subfacies of the almandine-amphibolite facies of regional metamorphism.

ITABIRITE

Itabirite extensive enough to be mapped at a scale of 1:25,000 has been found in only one place in the Monlevade Gneiss on the northeast side of the Jacuí fault. The itabirite bed is 10–25 meters thick and can be traced from the fault northeastward for about 2 kilometers; on the southwest, it is cut off by the fault, and the faulted segment is not exposed. Small lenses and beds of itabirite are scattered throughout the Monlevade Gneiss, but they are neither numerous nor extensive enough to be shown on the maps.

The itabirite of the Monlevade Gneiss resembles the itabirite of the overlying Minas Series Cauê Itabirite, and it is not possible to distinguish between the two in individual specimens. Both the itabirite bed and the itabirite itself are highly contorted and deformed. Part of the itabirite has been converted to almost pure compact hematite and magnetite through the replacement of silica by iron. These hematite bodies are 1–5 meters thick and are too small to be considered as ore bodies at the present time.

MINAS SERIES

The Minas Series was named and defined by Derby (1906) to include the metamorphosed sedimentary and volcanic rocks resting unconformably on the coarsely crystalline basement. The series was subdivided by Harder and Chamberlin (1915) into five formations, from older to younger, the Caraça Quartzite, the Batatal Schist, the Itabira Iron Formation, Piracicaba Schist and Quartzite, and Itacolomí Quartzite.

Subsequently Guimarães (1931) recognized a major unconformity between the Piracicaba and Itacolomí Formations; he elevated the Itacolomí to series rank,

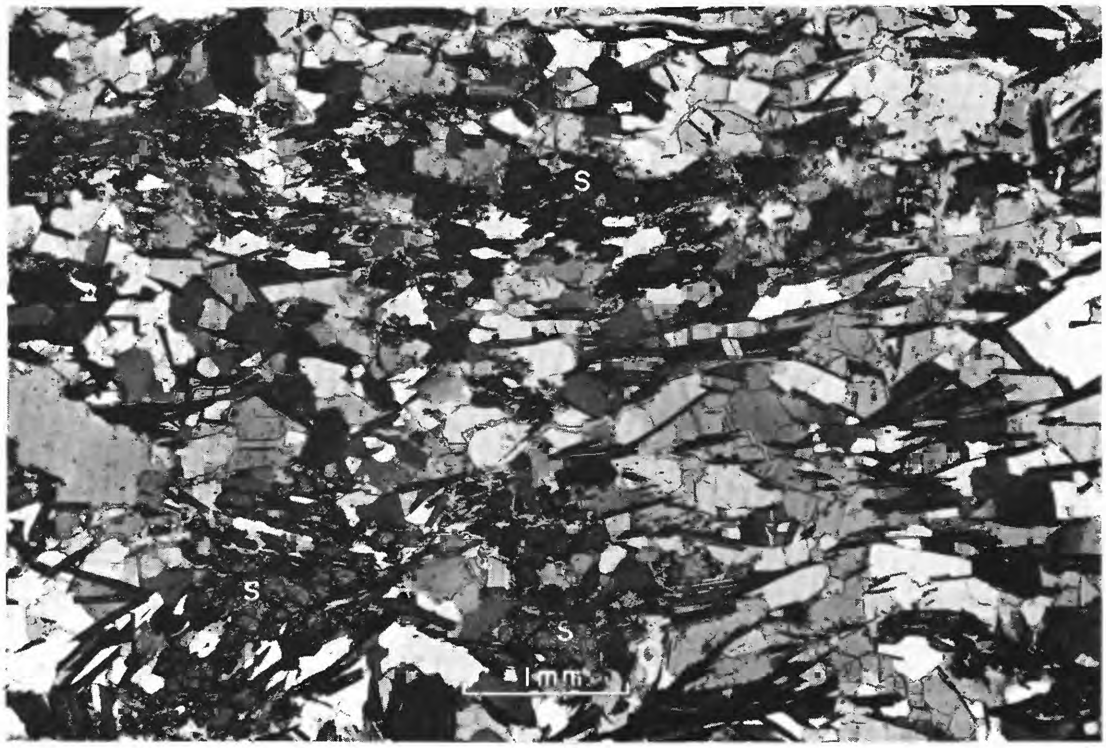


FIGURE 9.—Staurolite schist of the Monlevade Gneiss, interlayered with garnetiferous muscovite-quartz schist (fig. 8) and Pacas Amphibolite Member (fig. 7). Staurolite, S; dark-gray laths, muscovite; light-gray areas are mostly quartz, but some are plagioclase. Crossed nicols.

thus restricting the Minas Series to the four oldest formations of Harder and Chamberlin.

The Minas Series was subdivided into three groups as a result of the combined work of the geologists of the Brazilian Departamento Nacional da Produção Mineral and the U.S. Geological Survey (Dorr and others, 1957). The main subdivision was based on the origin of the rocks: the lowermost group contains predominantly clastic sedimentary rocks; the middle group, predominantly chemically precipitated sedimentary rocks; and the uppermost group, also predominantly clastic sedimentary rocks. The groups are also separated by local unconformities or disconformities.

The Minas Series extends from the center of the north border of the Monlevade quadrangle to the west border of the Rio Piracicaba quadrangle, about 5 kilometers north of its southwest corner. The contact between the Monlevade Gneiss of the Rio das Velhas Series and the Minas Series is clear cut.

The upper limit of the Minas Series is difficult to ascertain. Within the central and western parts of the quadrangles, rocks overlying the Minas, as well as those of the upper part of the Minas, have been removed by erosion. The Minas Series and perhaps overlying rocks have apparently been converted to gneiss and intimately intruded by syntectonic granite in the eastern and northeastern part of the Monlevade quadrangle and beyond. As a result, the contact between the Minas Series and overlying rocks has been obliterated; the contact is inferred, however, to lie somewhere east of the quadrangle.

Owing to the uncertainty of the upper contact and to possible repetition by folding, an accurate thickness of the entire Minas Series in these quadrangles cannot be given. The maximum thickness of the lower two groups is about 800 meters, on the west flank of the Serra do Seará and the total thickness of the Minas Series remaining is about 1,600 meters; this thickness probably does not represent the maximum thickness in the area. The maximum measured thickness from the base of the Minas to the top of the Pantame Member of the Elefante Formation, the last clearly sedimentary unit, is about 1,250 meters on the east flank of the Serra do Elefante.

CARAÇA GROUP

The lowermost group of the Minas Series is the Caraça Group named and defined by Dorr and others (1957) to include the two lowest formations of Harder and Chamberlin (1915), the Caraça Quartzite and the Batatal Schist. When the group was defined, it was stated that the Caraça Group is divisible into as many as five lithologic units mappable at scales of 1:50,000 to 1:20,000. This division has since proved to be impractical for the region as a whole, and the group has been divided into two formations, the Moeda below and the Batatal above. Locally, the Moeda is divisible into three members.

MOEDA FORMATION

The Moeda Formation was named from exposures in the Serra da Moeda in the Marinho da Serra quadrangle (Wallace, 1958). Wallace stated that the formation consists of three members at the type locality but that in many places throughout the Quadrilátero Ferrífero the formation is composed entirely of quartzite. In the Monlevade and Rio Piracicaba quadrangles, the Moeda Formation ranges in thickness from a minimum of about 90 meters in the northern part of the Monlevade quadrangle to a maximum of about 500 meters on the west flank of the Serra do Seará. The formation appears to be even thicker in the core of the Monlevade anticline, in the Rio Piracicaba quadrangle northwest of the town of Rio Piracicaba, but the increased thickness is probably due to repetition and structural thickening by minor folds. The thickness of 500 meters on the west flank of the Serra do Seará is also due in part to thickening by minor folds but in part probably to primary deposition. The thickness of the formation gradually decreases to the southwest, opposite the town of Rio Piracicaba. It apparently thins abruptly southwest of that area, to a uniform thickness of about 50 meters.

The Moeda Formation consists predominantly of fine- to medium-grained micaceous quartzite and finer grained quartz-mica schist. In some areas, as in the vicinity of the Andrade mine, the quartzite is ferruginous. Here, the formation consists of quartzite and quartz-muscovite schist and two layers of ferruginous quartzite. The two ferruginous quartzite layers are stratigraphically near the middle of the formation. The lower layer is 1.5 meters thick and is separated from the upper 1-meter-thick band by 3.5 meters of quartz-mica schist. These ferruginous quartzite bands are well exposed in a cut on the mine railroad and on the 1,112-meter-high peak west of the Pico de Andrade.

The ferruginous quartzite is a fine- to medium-grained mixture of quartz and hematite. On the peak west of the Pico de Andrade, the ferruginous quartzite has been converted through metamorphism to a coarse-grained quartzite containing layers and pods of specularite and fine-grained hemitite. Much of the specularite occurs in layers parallel to bedding, but some of the specularite and much of the fine-grained hematite occur in pods or small lenses both parallel to and crosscutting the bedding. The specularite layers range from a fraction of a millimeter to several millimeters in thickness. The pods are several millimeters to 5 cm thick and up to 15 cm long. Both the hematite-specularite and quartz layers and pods show the effects of strong deformation and are lineated and irregularly contorted.

In railroad cut A on the Andrade mine-Usina Monlevade railroad (pl. 4), most of the Moeda Formation is quartz-muscovite schist. The micaceous part of the rock is finely laminated, with laminae of muscovite a few tenths of a millimeter thick separating fine-grained quartz-rich layers as much as 0.5 mm thick. The rock contains segregations of coarse-grained quartz 10–25 cm long and 2–5 cm thick. These coarse-grained quartz segregations both parallel and crosscut the schistosity.

West of railroad cut A the Moeda becomes more quartzitic, and its grain size increases. The Moeda rocks on the peak west of the Pico de Andrade and in the saddle between these two peaks are very coarse grained, largely owing to recrystallization.

In the central and southern parts of the Rio Piracicaba quadrangle, the Moeda Formation consists typically of fine-grained micaceous quartzite and muscovite-quartz schist. The proportion of quartz to mica ranges from 2:1 to 5:1. In a typical specimen, the quartz occurs in discrete angular grains 0.2–0.4 mm in diameter. The muscovite occurs as thin laminae 0.01–0.05 mm in thickness and 0.2–0.5 mm in diameter. The average distance between the muscovite layers is about 0.5 mm. The layers are microscopically folded, concordantly with the larger minor folds in the formation. They give a pronounced foliation to the rock.

The formation in places, particularly in the southwestern part of the Rio Piracicaba quadrangle, contains widely disseminated grains of magnetite, now partly altered to martite. Most of the grains are perfect octahedrons or dodecahedrons. These crystals range from about 0.5 to about 2 mm along the face (octahedrons) or in diameter (dodecahedrons).

In addition to the fine-grained quartz, the quartzite contains saucerlike quartz lenses. These lenses have a considerable range but average about 10 cm long and 2 cm thick. The quartz occurs as interlocking grains and closely resembles vein quartz. Surrounding and cutting into these lenses are layers of light-gray-green mica, which was determined from optical properties to be muscovite or paragonite. The quartz lenses also contain magnetite-martite grains.

All specimens of Moeda Formation examined under the microscope show the effects of metamorphism; in none was the original sedimentary texture apparent. The quartz is recrystallized, forming an interlocking mosaic. Original argillaceous material has been converted to muscovite, sericite, or, rarely, biotite. Feldspars, both potassium and plagioclase, are exceedingly scarce. Common accessory minerals are zircon, apatite, staurolite, kyanite, opaque minerals (mostly hematite), and garnet.

BATATAL FORMATION

The name Batatal Schist was given by Harder and Chamberlin (1915) to the metasedimentary formation overlying the Moeda Formation (Caraça Quartzite of former usage) exposed in the Serra do Batatal in the south-central part of the Capanema quadrangle. This unit was redesignated the Batatal Formation "because throughout much of the Quadrilátero Ferrífero it occurs as a phyllite rather than as a schist" (Maxwell, 1958).

In the Monlevade and Rio Piracicaba quadrangles, the Batatal Formation commonly is 20–50 meters thick. It conformably overlies the Moeda Formation with gradational contact; locally, because no break is apparent between the two formations, they are mapped as Caraça Group undivided. In some areas, however, particularly in the northern part of the Monlevade quadrangle, the gradation between the Batatal and Moeda Formations is abrupt.

The Batatal Formation consists almost exclusively of quartz-mica schist. This schist is a layered rock composed of alternating muscovite-rich and quartz-rich layers. In some areas and in some stratigraphic intervals, however, the rock is composed mainly of mica, principally muscovite and, rarely, biotite. The mica is ordinarily in subparallel to virtually parallel orientation, but in some specimens, especially those composed almost exclusively of mica, part of it is oriented in a random fashion. Common accessory minerals are zircon, apatite, kyanite, staurolite, and opaque ore (mostly hematite). Garnet (almandine) is almost everywhere present, and in some stratigraphic intervals and in some areas, such as at the Água Limpa manganese mine and the Andrade iron ore mine, it makes up as much as 10 percent of the schist.

The Batatal Formation is highly variable through short distances vertically and laterally in grain size and proportions of mica and quartz. Much of this apparent variability is due both to the effect of the degree of deformation and metamorphism on the grain size of the component minerals and to the original differences in the amount of coarse clastic material and fine-grained argillaceous material deposited.

ITABIRA GROUP

The name Itabira was first formally applied to the main iron-formation of the Minas Series by Harder and Chamberlin (1915, p. 385). In their revision of the Precambrian stratigraphy of the Quadrilátero Ferrífero, Dorr and others (1957) elevated the Itabira to a group composed of two formations, the Cauê Itabirite below and the Gandarela Formation above (Dorr, 1958a, b). Within the Monlevade and Rio Piracicaba quadrangles, the Itabira Group consists of the Cauê Itabirite, which crops out extensively, and the overlying Sítio Largo Amphibolite, which probably is the metamorphic equivalent of carbonate-rich sediments of the Gandarela Formation.

CAUÊ ITABIRITE

The Cauê Itabirite, the principal iron-formation of the Quadrilátero Ferrífero, was named by Dorr (1958a) for exposures on Cauê Peak in the Itabira district. In the Monlevade and Rio Piracicaba quadrangles, the Cauê Itabirite conformably overlies the Batatal Formation of the Caraça Group or quartzite and quartz-mica schist of the Caraça Group undivided. The contact in these quadrangles, which is not sharp and well defined owing to the alternation of itabirite and phyllite or schist in the lower part of the Cauê Itabirite, is placed at the base of the lowermost itabirite beds (fig. 10). The contact between the two formations is well exposed in the roadcut south-southeast of Pico de Andrade. Here, the contact zone is about 15 meters thick.

The contact of the Cauê Itabirite with the overlying Sítio Largo Amphibolite or Elefante Formation is

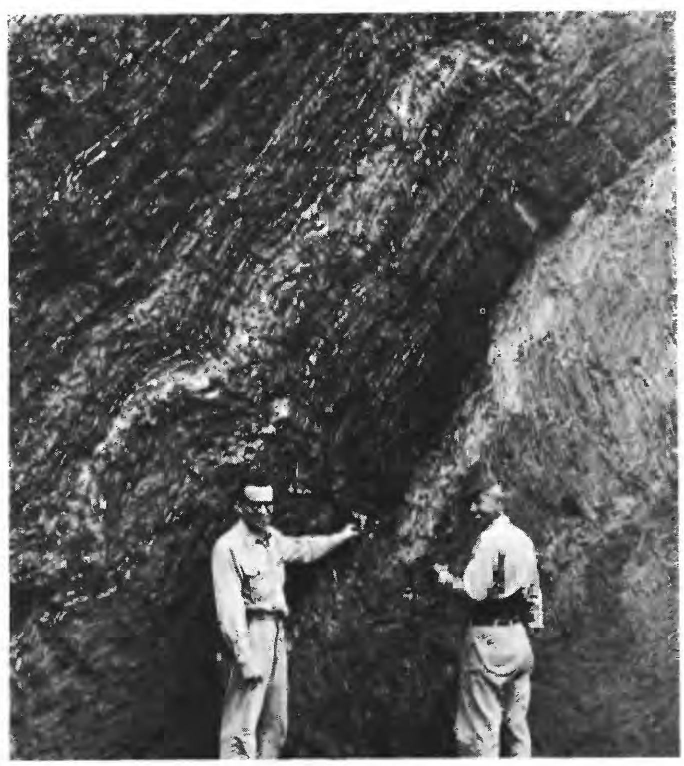


FIGURE 10.—Contact between Cauê Itabirite (dark, to left) and Batatal Formation (light, to right). The itabirite is complexely folded and crumpled near the contact. Roadcut in village of Bicas, central part of the Rio Piracicaba quadrangle.

sharp where seen, and no alternations of itabirite and clastic rocks, as at the base of the Cauê, are known. However, the contact is generally not well exposed. The best exposure is in the railroad cut 0.5 kilometer southeast of Pantame.

The Cauê Itabirite characteristically forms cuestas or hogbacks along most of its length in the Monlevade and Rio Piracicaba quadrangles (fig. 11). This topographic expression is due in part to the superior erosional resistance of the itabirite itself but even more to the resistance of the canga capping formed over the itabirite and ore.

In the Monlevade and Rio Piracicaba quadrangles, the Cauê consists mainly of itabirite, locally manganiferous, and a small proportion of fine-grained clastic material that is now muscovite-quartz schist. Elsewhere in the Quadrilátero Ferrífero, the formation may contain dolomite and quartzite in addition to schist (Dorr and Barbosa, 1963).

The Cauê Itabirite ranges in thickness from 350 meters in the northern part of the Monlevade quadrangle to about 125 meters in the southwestern part of the Rio Piracicaba quadrangle. Part of this variation is due to initial variation in depositional thickness, and part is the result of structural thickening on the crests and in the troughs of folds and of thinning on their flanks. For this reason, it is difficult to arrive at a reliable average thickness, but 200 meters is a fair estimate.

SÍTIO LARGO AMPHIBOLITE

The Sítio Largo Amphibolite is here named for excellent exposures southwest of the Fazenda do Sítio Largo in the northeast corner of the Rio Piracicaba quadrangle. The formation consists mostly of amphibolite but includes minor amounts of intercalated quartzite and quartz-mica schist.

FIGURE 11.—Typical cuesta formed by resistant canga on dip slope of Cauê Itabirite. Southwest of town of Rio Piracicaba.

The Sítio Largo Amphibolite conformably overlies the Cauê Itabirite. At the type locality, the formation is about 400 meters thick. It thins to the southwest and west and is not present in the west-central part of the Rio Piracicaba quadrangle or in the southeastern part of the Monlevade quadrangle, south of the Jacuí fault. Because elsewhere in the Quadrilátero Ferrífero (Dorr and Barbosa, 1963) the Piracicaba Group locally overlies the Itabira Group with slight angular unconformity and because fragments and pebbles of Gandarela Formation dolomite are found in the Cercadinho Formation (basal Piracicaba Group), the Sítio Largo was probably eroded from this area before deposition of the Elefante Formation.

The amphibolite is a fine- to medium-laminated dark-gray-green to black rock composed predominantly of hornblende and minor quartz and plagioclase. Much of the amphibolite resembles itabirite, especially the amphibolite in the little-weathered exposures along the road south of the Rio Santa Bárbara.

Under the microscope, the amphibolite is seen to consist of laminae composed predominately of hornblende alternating with laminae composed chiefly of quartz and plagioclase. The hornblende bands are usually 1–3 mm thick, and the feldspathic bands are usually a few tenths to 1 mm thick. The hornblende mostly occurs as small subhedral to euhedral grains 0.05–0.2 mm across and as much as 1 mm long. Optical measurements and pleochroism indicate that the hornblende is the actinolitic-tremolitic-rich variety. Quartz and plagioclase (An_{25-30}) occur in anhedral grains, mostly from 0.1 to 0.3 mm in diameter. The quartz has a pronounced preferred crystallographic orientation with *c* parallel to schistosity. The plagioclase is mostly untwinned and is extremely difficult to distinguish from quartz; staining the plagioclase greatly facilitated distinguishing of the two. Apatite and opaque ore (hematite) are the principal accessory minerals; garnet and zircon(?) are present but scarce.

The mineralogical composition, as determined by the Rosiwal method, is similar in the many sections examined. Hornblende ranges from 74 percent to 80 percent, plagioclase from 10 percent to 15 percent, and quartz from 5 percent to 10 percent.

The chemical composition of the Sítio Largo Amphibolite from various parts of the quadrangles is similar (table 2). With one exception, the silica content ranges from about 45 to 50 percent and the alumina content ranges from about 15 to 16 percent. In the exception, the silica content is 54 percent and, as expected, the amount of quartz is highest and the hornblende and plagioclase content lowest in that specimen.

The original rock from which the amphibolite was formed cannot be ascertained with certainty from the chemical and mineralogical data; however, certain tentative conclusions may be drawn from these data and other information. The chemical composition of the amphibolite is remarkably similar to that given for basalt by Clark (1924, p. 460) and Nockolds (1954, p. 1021). However, the same approximate chemical composition may result from a mixture of 80–85 percent normal shale and 15–20 percent dolomite, and some calcareous shales are known to have this same approximate composition. A sedimentary rather than an igneous origin is suggested for the amphibolite by the following evidence: It is stratigraphically above the Cauê Itabirite, as it occupies the position of the Gandarela Formation, an interval which in other parts of the Quadrilátero Ferrífero contains calcareous and dolomitic rocks, and it is intimately associated and intercalated with rocks of undoubted sedimentary origin.

PIRACICABA GROUP

The name Piracicaba was first applied by Harder and Chamberlin (1915) to an assemblage of argillaceous and quartzitic schists, quartzite, limestone, dolomite, and iron-formation overlying the Itabira iron-formation. These units are well exposed in the headwaters of the Rio Piracicaba between Fazenda da Alegria and Santa Rita Durão. The Piracicaba was elevated to group rank and redefined by Dorr and others (1957). In the western part of the Quadrilátero Ferrífero, the Piracicaba Group is divisible into five formations (Gair, 1958; Pomerene, 1958a, b, c; Simmons, 1958). In the Monlevade and Rio Piracicaba quadrangles, what is probably the equivalent of the Piracicaba Group is represented by a single complex unit, here named the Elefante Formation.

ELEFANTE FORMATION

The Elefante Formation is named for exposures on the northwest, northeast, and southeast flanks of the Serra do Elefante in the west-central part of the Rio Piracicaba quadrangle. It consists of metamorphosed chemical and fine- to coarse-grained clastic sediments.

The Elefante Formation overlies the Sítio Largo Amphibolite and, in some areas, the Cauê Itabirite. It crops out from the northeastern and south-central part of the Monlevade quadrangle to the north-central and southwestern part of the Rio Piracicaba quadrangle. The top of the formation is not exposed in either quadrangle. North and east of the Monlevade quadrangle and east of the Rio Piracicaba quadrangle north of the Rio Piracicaba fault, gneiss of the Elefante Formation grades into granite gneiss that is similar in appearance to the Borrachudos Granite of the Itabira district (Dorr and Barbosa, 1963).

The maximum thickness of known Elefante Formation is in the trough of the Tanque syncline just south of the Jacuí fault. Here, the formation is about 900 meters thick. This thickness is probably due partly to structural thickening by minor folding in the center of the syncline. Along the nose of the Elefante anticline on the northeast flank of the Serra do Elefante, the formation is about 600 meters thick. In both of these localities the upper contact of the formation has been removed by erosion.

The Elefante Formation contains quartz-biotite gneiss, quartzite and micaceous quartzite, quartz-mica schist, and itabirite and manganiferous itabirite. In many places one or the other type of rock predominates, or, more commonly, the various types are so intermixed as to preclude separation at the scale of mapping used for this report. In other areas, however, the formation is divisible into three members, the Pantame Member (quartzite and quartz-mica schist), the Bicas Gneiss Member, and an itabirite member.

PANTAME MEMBER

The Pantame Member is named for excellent exposures in the railroad-cut 300 meters south of Pantame station and on the ridge 1 kilometer southwest of the top of the Morro da Jacutinga. It changes from a pure white coarse-grained quartzite at the type locality and elsewhere along the south and southeast limb of the Pantame anticline through a fine-grained micaceous and locally ferruginous quartzite to fine- and coarse-grained quartz-muscovite schist. In nearly all areas, quartz predominates over mica and generally is three or four to many times more abundant.

Along the south and east flanks of the Pantame syncline, from the west border of the Rio Piracicaba quadrangle to the Rio Piracicaba fault, the Pantame Member ranges from 10 to 25 meters thick. The member thickens to the north and northwest along the north and northwest flank of the syncline and on the nose of the adjacent Elefante anticline; there it is about 200 meters thick. In the area north of Monlevade, it is 150 meters thick.

At the type locality the Pantame Member is separated from the underlying Cauê Itabirite by about 5 meters of weathered gneiss. Elsewhere it may rest directly on Cauê, as at the Água Limba manganese mine, or it may be separated from it by as much as 300 meters of Bicas Gneiss Member, as on the northeast flank of the Serra do Elefante. The Pantame Member may be correlative in part with the Cercadinho

Formation (Pomerene, 1958a) of the western and central parts of the Quadrilátero Ferrífero.

BICAS GNEISS MEMBER

The Bicas Gneiss Member is here named for exposures along the railroad track from 0.5 to 1 kilometer north of Bicas in the south-central part of the Rio Piracicaba quadrangle. Fresh gneiss is also well exposed in a quarry 3 kilometers west-southwest of Rio Piracicaba. The gneiss is light gray and is generally fine to medium grained. It is far more uniform in texture and color than the Monlevade Gneiss, although varieties of each are so similar in appearance that they cannot be distinguished from one another.

At the type locality the Bicas Member is about 500 meters thick, the maximum thickness known. In the northeastern part of the Monlevade quadrangle and in the extreme northeast corner of the Rio Piracicaba quadrangle, the Bicas overlies Sítio Largo Amphibolite. Elsewhere, the member overlies Cauê Itabirite or Pantame Member quartzite and quartz-mica schist.

The Bicas Gneiss Member may be the equivalent of the Barreiro and Sabará Formations of the western and central parts of the Quadrilátero Ferrífero (Pomerene, 1958c; Gair, 1958).

In the west-central and central parts of the Quadrilátero Ferrífero, the Piracicaba Group contains thick and extensive metapelite units (Gair, 1962; S. L. Moore, written commun., 1958; Dorr and others, 1960). These are mainly phyllite and micaceous schists. In the Monlevade and Rio Piracicaba quadrangles, the Elefante Formation occupies the same stratigraphic position as these metapelite units. In the south-central part of the Rio Piracicaba quadrangle, the Elefante consists mainly of a banded quartz-biotite paragneiss. Here, what are probably remnants of the original sedimentary layering are seen, and the paragneiss apparently has formed through recrystallization and reconstitution, with very little addition of material. Quartz and other felsic constituents have segregated to form small lenses and irregular masses, but only on a small scale.

In the northeastern part of the Rio Piracicaba quadrangle and the southeastern part of the Monlevade quadrangle, and especially to the east outside the boundaries of the quadrangles, the metamorphism has been more intense, with extensive segregation of felsic and mafic components.

In the northeastern part of the Monlevade quadrangle, north of the Rio Santa Bárbara, the most intense metamorphism and metasomatism of Piracicaba Group rocks in these quadrangles is found. Here, the gneiss is composed chiefly of large linearly oriented biotite clusters, microcline, and quartz. Fluorite is a common accessory mineral, widely disseminated throughout the rock in this area. Layering and segregation similar to that probably produced elsewhere by metamorphic differentiation are widespread. The gneiss here resembles gneissic Borrachudos Granite of the Itabira district (Dorr and Barbosa, 1963, p. 41).

STRUCTURE

The Precambrian metasedimentary rocks of the Quadrilátero Ferrífero are folded into a series of major anticlines and synclines, many of which are overturned. These structural fold features are in turn cut by normal, reverse, and thrust faults, some of considerable magnitude. In the western part of the Quadrilátero Ferrífero, the major structural trend is northward (fig. 3). Along the western part of the southern border, the dominant direction is northeast, swinging to east in the central part of the border. In the southeast corner the structural features are exceedingly complex and structural trends literally box the compass. In the central and northeastern parts of the area, the dominant trend is northeastward.

The major structural features of the Monlevade and Rio Piracicaba quadrangles trend northeast although they swing to nearly north in the southeastern part of the Rio Piracicaba quadrangle and east in the west-central part.

MAJOR STRUCTURAL FEATURES

The major structural features of the Monlevade and Rio Piracicaba quadrangles (pls. 1, 2, 3) are folds and steep normal or reverse faults. Three distinct fault blocks are recognized within the quadrangles; the Jacuí fault separates the northern from the central block and the Rio Piracicaba fault separates the central from the southern block.

FOLDS

REGIONAL FOLDS

The dominant regional fold pattern is one of northeast-plunging anticlines and synclines. In the northern block, the three major anticlines are the Pacas, Carneirinhos, and Monlevade. The intervening synclines from northwest to southeast are the Andrade and the Tanque. The anticlines and synclines are symmetrical, upright, open, and the noses and troughs formed by the top of the Itabira Group, plunge 40° NE. under the overlying amphibolite and gneiss of the Elefante Formation. The distance between the traces of the axial plans of these major folds are about 3 kilometers, except between the traces of the axial planes of the Monlevade anticline and Tanque syncline, where the distance is 1.5 kilometers.

In the central block, the Minas Series is folded into the Seará syncline and adjacent Talho Aberto anticline to the southeast. What are probably continuations of the Andrade syncline and Carneirinhos anticline are expressed in the Monlevade Gneiss northwest of the Seará syncline. The distance between the traces of the axial planes of the Talho Aberto anticline and the Seará syncline ranges from 3 kilometers just south of the Jacuí fault to 2 kilometers midway between the faults; this distance increases to 3 kilometers just north of the Rio Piracicaba fault. In the northern part of the central block, the folds are nearly horizontal and, in the Seará syncline, the fold plunges about 10° SW. just south of the Jacuí fault. In the southern part of the block, the folds plunge 20°–30° NE. In the northern part of the block, the folds are normal and open. About 5 kilometers southwest of the Jacuí fault, the folds become tighter and are overturned to the northwest; near the Rio Piracicaba fault, they are virtually isoclinal.

In the southern block, the folds are more closely spaced, and they cannot be correlated with those in the central and northern blocks. Five major folds are recognized: from northwest to southeast they are the Morro Agudo syncline, the Córrego das Cobras anticline, the Morro da Água Limpa syncline, the Elefante anticline, and the Pantame syncline. All except the Pantame syncline are upright open folds. The Pantame syncline is isoclinally folded, and in the southwestern part of the Rio Piracicaba quadrangle, the southeast limb is overturned. Structural features of the Pantame syncline cannot be recognized owing to the homogeneity and the high degree of metamorphism of the rocks.

At the base of the Cauê Itabirite, the Morro Agudo and Morro da Água Limpa synclines close within the Rio Piracicaba quadrangle. The Pantame syncline at this datum closes about 5 kilometers south-southwest of the southwest corner of the quadrangle. The axes of the folds south of the Rio Piracicaba fault are much more variable in direction than those of the folds north of that fault. The axis of the Morro Agudo syncline is arcuate, concave to the north. The axis of the Pantame syncline trends southward and southwestward from the Rio Piracicaba fault for about 5 kilometers, where it swings abruptly to the west. This westward trend continues to a point southwest of Água Limpa, in the adjacent Florália quadrangle, where the axis turns abruptly south. The axis of the Morro da Água Limpa syncline and the axes of the anticlines between it and the Pantame syncline are likewise variable in direction but change direction less abruptly than the axis of the Pantame syncline.

SUBSIDIARY FOLDS

Subsidiary folds in the Cauê Itabirite, Sítio Largo Amphibolite, and Elefante Formation are exposed on the flank of the Talho Aberto anticline in the northeastern part of the Rio Piracicaba quadrangle. Here, the axes of the subsidiary folds trend N. 50° E., approximately parallel to the trend of the regional fold axes in that area. The traces of the axial planes are uniformly about 300 meters apart. These folds have produced an outcrop of the Sítio Largo Amphibolite more than 1.5 kilometers wide. To the northeast, along the east edge of the quadrangle, the folds plunge 20° NE. The plunge decreases to the southwest, and in the vicinity of Ponte Saraiva is about 5° NE.

CROSS FOLDS

A syncline and accompanying anticline are formed on the southeast flank of the Elefante anticline at the Água Limpa manganese mine, near the west border of the Rio Piracicaba quadrangle. The traces of the axial planes of these two folds are approximately normal to those of the regional folds. The folds plunge 40° SE. Other smaller cross folds occur on the southeast flank of the Elefante anticline northeast of Água Limpa manganese mine, but these folds have not been recognized elsewhere in the area mapped.

FOLDS IN THE MONLEVADE GNEISS

Normally, the homogeneity of the Monlevade Gneiss masks structural complexities. Locally, however, as between Monlevade and Carneirinhos anticlines, amphibolite layers in the gneiss are more tightly and in places more complexly folded than the overlying Minas Series. This folding is interpreted to be a result of a post-Minas orogeny that folded rocks already folded during one or more pre-Minas periods of deformation.

FAULTS

MAJOR FAULTS

Two major faults trend west-northwest across the Monlevade and Rio Piracicaba quadrangles; the Jacuí fault in the southeastern part of the Monlevade quadrangle and the Rio Piracicaba fault in the north-central part of the Rio Piracicaba quadrangle. The Jacuí fault, the northernmost, trends N. 60° W. and dips steeply northeast. Based on offset of the Monlevade anticline and Tanque syncline as projected, the fault has a dip-slip displacement of 1,000 meters and a strike-slip displacement of 2,000 meters. The strike-slip movement is left lateral, (classification of Hill, 1947). The fault has been traced for about 6 kilometers; it then disappears under soil and colluvium formed on granitic Monlevade Gneiss. No offset is seen in the Pacas Amphibolite Member of the Monlevade Gneiss where this member crosses the projection of the fault, about 6 kilometers northwest of the last exposure of the fault; this evidence suggests that the fault dies out in the Monlevade Gneiss.

The Rio Piracicaba fault crosses the north-central part of the Rio Piracicaba quadrangle. The fault is not recognizable in the Monlevade Gneiss northwest of Morro Agudo. The fault trends N. 75° W. and is inferred to dip from 80° N. to vertical. It exhibits both strike-slip and dip-slip movement; the strike slip is left lateral, the same as that of the Jacuí fault to the north. The northern side is upthrown with respect to the southern side; vertical offset is computed to be about 1,000 meters along the central part of the fault in the vicinity of Rio Piracicaba and about 200 meters along the western part of the fault in the vicinity of Morro Agudo. These figures are uncertain, however, owing to the difficulty of correlating exact reference points from one side of the fault to the other. The fault is not recognizable in the Monlevade Gneiss west of Morro Agudo.

OTHER FAULTS

The southeast limb of the Seará syncline is cut by a thrust fault that extends south from the Jacuí fault. The Água Limpa high-angle reverse fault along the west edge of the Rio Piracicaba quadrangle west of the Água Limpa manganese mine offsets the Morro Agudo and Pantame synclines and intervening Elefante anticline. The Morro Agudo iron deposit is cut by a reverse or thrust fault that extends southward from the Rio Piracicaba fault.

The thrust fault that extends south from the Jacuí fault trends N. 35° E. and is inferred to dip about 30° SE. This fault has thrust Caraça Group rocks over the Cauê Itabirite and the Elefante Formation. Movement was along planes of schistosity (or bedding planes). The hinge of the fault is in Caraça Group quartzite in the core of the Talho Aberto anticline several kilometers southwest of the Jacuí fault. Maximum displacement, next to the Jacuí fault, is on the order of 1,000 meters.

The Água Limpa reverse fault trends about N. 10° E. and is inferred to dip steeply east. Maximum offset of the Minas Series rocks is approximately 1,000 meters. The probable continuation of this fault offsets rocks on the west end of the Morro da Água Limpa, 2 kilometers north of the Água Limpa mine.

A northward-trending reverse or thrust fault is inferred to cut the Morro Agudo iron ore deposit. There is very little evidence to indicate the existence of this fault, but the surface distribution of the rocks and iron ore and the configuration of the ore bodies as disclosed by subsurface exploration (pl. 5) are strong evidence for its existence. This fault is parallel to the Água Limpa fault. It probably resulted from westward drag of a block south of and adjacent to the Rio Piracicaba fault at the time of left-lateral movement along that fault.

MINOR STRUCTURES

PLANAR STRUCTURES

Planar structures in the rocks of the Monlevade and Rio Piracicaba quadrangles include primary lamination in the itabirite and other metasedimentary rocks and secondary foliation and cleavage in the metamorphic rocks. The striking lamination of the itabirite is the result of accentuation and modification of primary layering during metamorphism—by the crystallization of the silica component to quartz, and possible further separation of quartz and hematite. These laminae, however, are parallel to the contacts of the itabirite with overlying and underlying formations and undoubtedly are parallel to original bedding. Metamorphic rocks of the Elefante Formation exhibit what is interpreted to be original sedimentary stratification, in places little modified by metamorphic processes or deformation.

Most of the planar structures on the rocks of these quadrangles can be attributed to the growth and orientation of minerals—muscovite in the micaceous sandstones and the muscovite-quartz schist and biotite in the biotite-quartz gneiss—during metamorphism and to the segregation of ferromagnesian minerals and quartz into separate bands in the gneiss.

LINEATION

The most important linear features in the Monlevade and Rio Piracicaba quadrangles are the pencil structure produced by rotation and the axes of minor folds. Lineation produced by the elongation of pebbles and cobbles in metaconglomerate, striae due to movement along faults and between strata, and the orientation of elongate minerals are also found.

Lineation produced by rotation, particularly the pencil structures, appears to have been an important factor in the localization of the ore deposits, and it exerts a profound influence on the physical characteristics of the ore. The minor fold axes and pencil structures are generally parallel, as at the Água Limpa manganese mine, where both are well formed and well exposed. Of particular interest is the superposition of one lineation on top of another; this superposition records a change or apparent change in direction of the forces during the orogeny, or possibly a second deformation with forces acting in a different direction. The lineation of the second deformation, mainly produced by closely spaced minor fold axes, obscured the original lineation but did not obliterate it completely. The older lineation is best preserved and exposed in the Elefante Formation in the eastern and southern parts of the Rio Piracicaba quadrangle.

DRAG FOLDS

Other minor structures are the drag folds that were produced as more competent beds slid over less competent beds during folding. The drag folds are prevalent in the muscovite-quartz schist and in the micaceous quartzite and, to a lesser degree, in the itabirite. These folds proved to be extremely useful in working out the major structural features, especially where these features were overturned and partly concealed.

STRUCTURAL DEFORMATION

At least three periods of deformation are recorded by the structural features in the rock of the Monlevade and Rio Piracicaba quadrangles: (1) post-Rio das Velhas, pre-Minas, (2) post-Minas, and (3) a later post-Minas.

The post-Rio das Velhas, pre-Minas deformation is based on the fact that layers in the Monlevade Gneiss are locally more complexly folded or deformed than those in the Minas Series. This deformation is most clearly shown in the central part of the Quadrilátero Ferrífero where highly deformed units in the Rio das Velhas Series have been mapped (Gair, 1962; C. M. Maxwell, written commun. 1963; Pomerene, 1964). In the Monlevade and Rio Piracicaba quadrangles, intense post-Minas dynamic metamorphism and metasomatism have destroyed most of the original features of the Rio das Velhas rocks. The trends of structural features in the Quadrilátero Ferrífero indicate that the older deformation was produced by compressive forces acting in a northwest-southeast direction.

The second period of folding that involved both the Minas Series and older rocks also was the result of compressive forces acting in a northwest-southeast direction. Inasmuch as evidence of much plastic flow but very little indication of faulting is seen where the folding is most intense, it is thought that this compression was not immediately post-Minas but that it took place after the Minas Series and older rocks were deeply buried. This deformation seems to correspond to the period of major post-Minas orogenic activity and the conversion of the Rio das Velhas and Minas Series rocks to gneiss probably took place at this time.

The crossfolding and faulting presumably took place at a much later time, although no evidence is at hand to actually date the faulting. The crossfolds on the flanks of the major folds, the thrust and reverse faults, the slight arching of the major folds, and the later lineation are interpreted as having been formed by compressive forces acting in a different direction, probably east-west or east-northeast–west-southwest. That the rocks failed by faulting rather than by folding is indicative of brittle rocks (of indurated itabirite and quartzite and of other rocks converted to schist and gneiss) whose overburden had become thinner owing to erosion.

MINERAL RESOURCES

The Monlevade and Rio Piracicaba quadrangles are known to contain two large iron ore deposits and several smaller ones, as well as one small deposit of manganese and numerous prospects for manganese. Other mineral resources of value include deposits of placer gold, mica, semiprecious stones, building stone, and clay.

During this study, from 1957 to 1959, only the Andrade, the largest of the known iron ore deposits, was being mined; the other deposits, although known for many years, were idle. The Água Limpa manganese deposit was being mined, and several of the small manganese occurrences were being prospected. Mica was being produced from the Pé de Serra pegmatite mine, and the Talho Aberto pegmatite mine was intermittently operated for semiprecious stones, mainly phenacite and amazonite. Three quarries were operated for building stone and road metal, and numerous clay deposits were being worked to supply raw material for bricks and tile. Sand and gravel were obtained as needed along the principal rivers, but no organized or sustained operations were observed.

IRON

Most of the presently commercial iron ore deposits of the Quadrilátero Ferrífero are high-grade hematite bodies associated with and formed from itabirite; canga formerly was an important ore, and a small amount is still used locally. Rubble ore consisting of boulders and (or) fragments of high-grade hematite is used domestically and is exported. All known deposits are related to the Cauê Itabirite; none are known to have formed from the itabirite in the Monlevade Gneiss or in the Elefante Formation. In addition to the hematite and canga deposits, the itabirite, and especially that disaggregated by weathering and thus easily concentrated, may be considered a potential source of iron ore.

ITABIRITE

The term "itabirite", which is derived from a Guaraní Indian word meaning sharpening stone, was introduced into geologic literature in 1822 by Eschwege (Freyberg, 1932), who used it for the hard hematite of which the Pico do Itabirito [8] is composed. Derby

[8] Formerly known as the Pico do Itabira do Campo; 8 km east of the town of Itabirito and 35 km south of Belo Horizonte.

(1910) used the term for specularite schist; most subsequent authors writing about the iron ore and geology of the Quadrilátero Ferrífero, with one important exception, have used it in this general sense or, more generally, as a synonym for banded iron-formation. The exception is Freyberg,[9] who used it both for banded iron-formation and hard hematite ore. According to Park (1959, p. 573), "By common usage itabirite is now a synonym for taconite, as used in the Lake Superior region. Much of the rock is schistose, but that is not an essential feature." The term has been more precisely and restrictively redefined by Dorr and Barbosa (1963, p. C18) to denote "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." When the rock contains impurities "in the form of dolomite or calcite, clay, and the metamorphic minerals derived from these materials * * * 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 quartz)." They also stated, "The term should not include quartzite of clastic origin with iron-oxide cement even though such rocks are sometimes grossly banded." Therefore, only oxide-facies iron-formation in which the silica is recrystallized to megascopically recognizable quartz should be given the name itabirite; it is in this sense that the term is used in this report.

It is difficult to choose and describe a sample that is representative of "typical" itabirite. Itabirites from many areas, although formed under widely different conditions of metamorphism and deformation, have many features in common and bear a striking resemblance to one another; conversely, one of the characteristic features of itabirite is its variation in minor details from place to place. The greatest variations are in grain size, relative widths of the iron- and silica-rich layers, and the manner in which these layers are grouped together to form relatively dark- or light-colored bands. These variations may result from differences in the relative amounts of iron and silica precipitated owing to changes in sedimentation, to differences in metamorphism and deformation, or to a combination of both.

Individual iron- and silica-rich laminae range in thickness from about 0.25 to 1 cm thick. Light- and dark-colored bands, in which silica- or iron-rich laminae predominate, are as much as several centimeters thick (fig. 12).

[9] Freyberg (1932) gave an excellent summary of the origin and use of the term "itabirite."

FIGURE 12.—Typical outcrop of weathered itabirite, northeastern limb of Água Limpa syncline, Água Limpa mine, Rio Piracicaba quadrangle.

Fresh unweathered[10] itabirite is a dense, hard rock composed of alternating dark iron-rich and light quartz-rich layers; this alternation gives the rock a definite banded appearance. The rock may consist of alternating light and dark layers of approximately the same thickness, or it may have a much coarser banding in which layers of relatively thick iron-rich laminae separated by relatively thin quartz-rich laminae alternate with layers of relatively thick quartz-rich laminae separated by relatively thin iron-rich laminae. Some itabirite is schistose, the schistosity being imparted by thin laminae of specularite. A gneissic variety is composed chiefly of equigranular grains of iron oxides (magnetite, martite, and (or) hematite) and quartz.

The iron oxide mineral grains—hematite, specularite, martite, and magnetite—range in size from about 0.001 mm in the least metamorphosed itabirite in the western and central parts of the Quadrilátero Ferrífero to nearly 1 mm in the more highly metamorphosed itabirite in the Monlevade and Rio Piracicaba quadrangles along the eastern border of the Quadrilátero Ferrífero. In size the quartz grains are comparable to the iron oxide mineral grains, but in a given sample they tend to be intermediate between the maximum and minimum diameters of the iron oxide mineral grains.

[10] Fresh unweathered itabirite is rare in the Quadrilátero Ferrífero, and none is known in the Monlevade and Rio Piracicaba quadrangles.

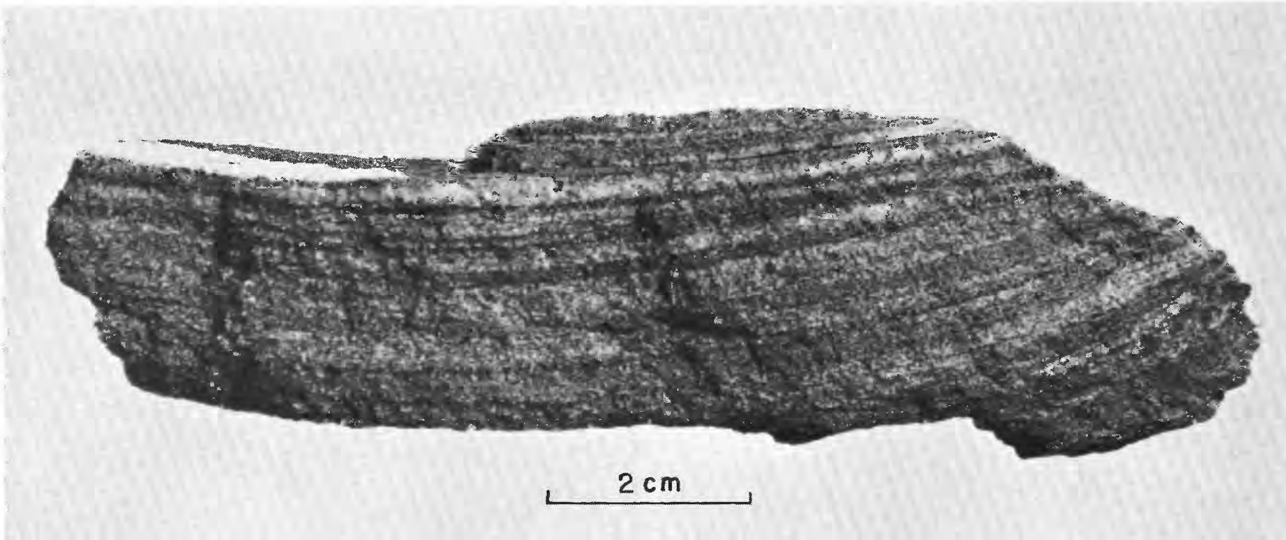


FIGURE 13.—Itabirite, Monlevade and Rio Piracicaba quadrangles. Light-colored layers are quartz rich; dark-colored layers are hematite rich but contain martite and some quartz.

Ordinary weathered itabirite typically breaks into long hackly lath- and pencil-shaped fragments made up chiefly of hematite. The quartz disaggregates and in large part separates from the hematite.

Itabirite from the east limb of the Talho Aberto anticline, 6 kilometers northeast of the town of Rio Piracicaba, is representative of most of the itabirite in the Monlevade and Rio Piracicaba quadrangles. At the surface and in shallow workings it is weathered, and it disaggregates readily upon being struck with a hammer or even with normal handling after being removed from its position in the bed. The rock consists of white and red-stained quartz-rich layers 1.5–3 mm thick and light- to dark-gray iron-rich bands 0.5–5 mm thick, (fig. 13). The layers are fairly persistent.

Under the microscope, the itabirite is seen to consists of subhedral to euhedral octahedrons, now martite, ranging in size from 0.2 to 0.4 mm and anhedral to subhedral quartz grains ranging in size from 0.1 to 0.5 mm. The quartz-rich layers contain a few small hematite (martite) grains between the quartz grains, and some of the larger quartz grains contain hematite inclusions (fig. 14).

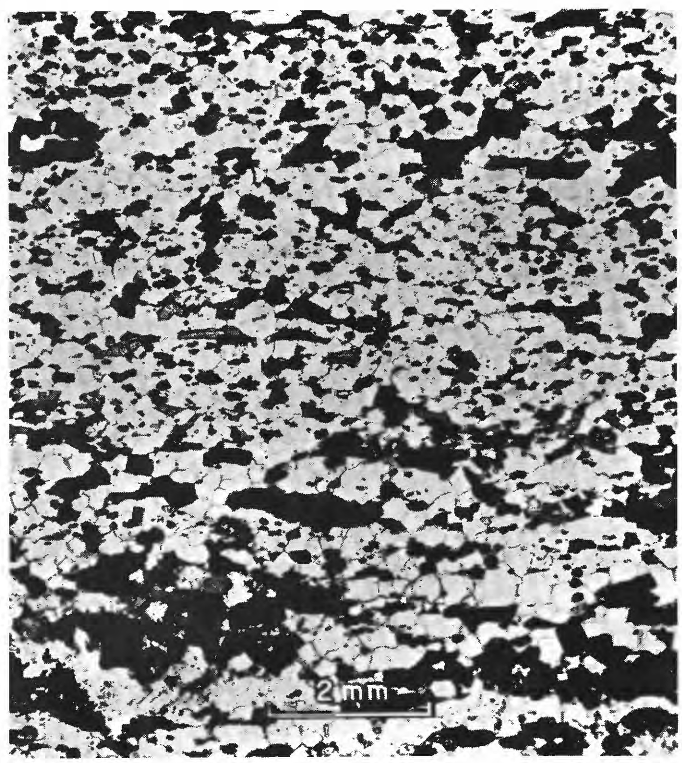


FIGURE 14.—Itabirite from specimen shown in figure 13, Rio Piracicaba quadrangle. Plane light. Black mineral is hematite, white mineral is quartz, and sparsely occurring gray mineral is actinolite-hornblende.

Schistose itabirite, called specularite schist by Derby (1910) and others, consists of very thin and often discontinuous specularite layers and relatively much thicker quartz layers. This itabirite splits easily along the specular hematite layers, producing a shiny, reflecting surface.

The specularite grains are 0.05–0.15 mm thick and as much as 2.5 mm in diameter. The specularite bands are 0.1–0.3 mm thick, depending on the number and the thickness of the individual grains of which they are composed. The quartz is equigranular, and individual grains are 0.3–1 mm in diameter. The quartz-rich bands are generally about 0.5–2 mm thick, although some are thicker (fig. 15).

The highest known metamorphic grade within these quadrangles, the almandine-amphibolite facies of re-

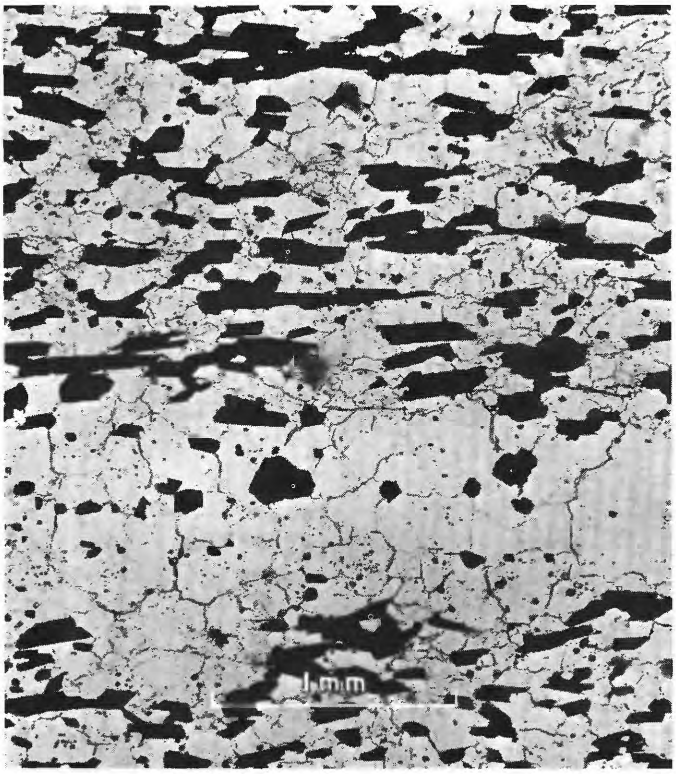


FIGURE 15.—Schistose itabirite (Morro da Água Limpa iron ore deposit, Rio Piracicaba quadrangle); size, shape, and distribution of specularite (black) and quartz (white). Plane light.

gional metamorphism, is in the northeastern part of the Rio Piracicaba quadrangle. The effects of increased metamorphism on itabirite in this area are chiefly an increase in grain size and a more complete separation of the iron and silica. Most of the more highly metamorphosed itabirite observed consists of alternating dark-colored bands composed of relatively thick iron-rich laminae separated by relatively thin quartz-rich laminae and light-colored bands of quartz or quartz and thin hematite laminae.

A typical specimen of the more highly metamorphosed itabirite from the southeast limb of the Talho Aberto anticline, about 3 kilometers northeast of the town of Rio Piracicaba, consists of alternating quartz-rich and iron oxide-rich layers (fig. 16). The quartz-rich layers, 2–10 mm thick, range in color from pure white to light reddish brown or buff. In addition to quartz, the quartz-rich layers contain actinolite-hornblende, sericite-muscovite, biotite, very small garnets, a very small prismatic mineral of high relief and birefringence tentatively identified as zircon, and apatite(?) Locally, the actinolite-hornblende composes 10 percent of the rock. The iron oxide layers range from less than 0.5 to 3 mm thick; some are discontinuous and lens out in the more persistent quartz layers. The grain size of both the magnetite-hematite and quartz is larger than in the less highly metamorphosed itabirite, and the separation of quartz and iron oxide is more complete (fig. 17).

In some areas of higher grade metamorphism, where segregation is more complete, a rock consisting of patches of aggregates of magnetite and hematite set in a matrix of quartz is formed (figs. 18, 19). The name itabirite gneiss or gneissic itabirite has been given to this rock, although for the most part the rock has lost the pronounced banding that is characteristic of itabirite.

Most of the itabirite at the surface is weathered; the deepest known workings, those of the Andrade mine (150 meters below surface), have not reached the bottom of the weathered material. Dorr and Barbosa (1963) concluded that weathering of itabirite may extend to depths of 200 meters or more elsewhere in the Quadrilátero Ferrífero.

The effect of weathering is more pronounced in the less metamorphosed itabirite. The more highly metamorphosed itabirite is coarser grained and more compact and has less porosity and much less grain-boundary area; thus, circulation and solution are less. Even the most highly metamorphosed itabirite, however, shows some weathering effects.

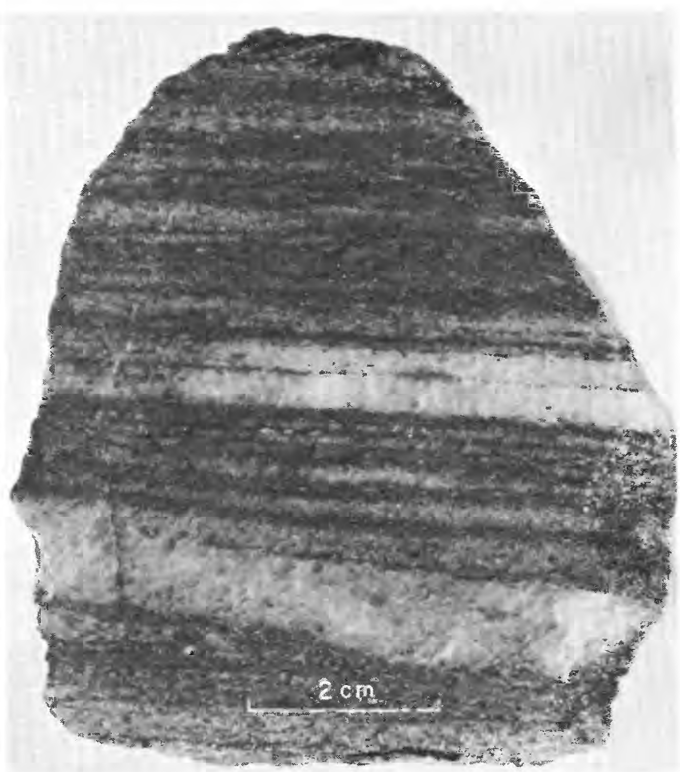


FIGURE 16.—Highly metamorphosed itabirite, Rio Piracicaba quadrangle, showing sharp separation of quartz and hematite into distinct bands.

Weathered itabirite, particularly when it is relatively unmetamorphosed, disaggregates readily and therefore is easily minable. This disaggregation probably results from the loosening of the quartz and hematite grains because of solution along grain boundaries caused by circulating ground water, as discussed by Dorr and Barbosa (1963). The disaggregated itabirite can be concentrated by simple gravity methods and even by screening. Whitehead and Dorr (1950) cited tests indicating that uncrushed itabirite may be concentrated by means of a Humphrey spiral classifier to produce a 65–68 percent iron concentrate, with acceptable recovery. The increasing use of sintered and pelletized blast-furnace feed, caused by an increase in furnace efficiency of 20–30 percent, may make it eventually more economical to concentrate friable weathered itabirite than to mine and crush the high-grade hematite ore.

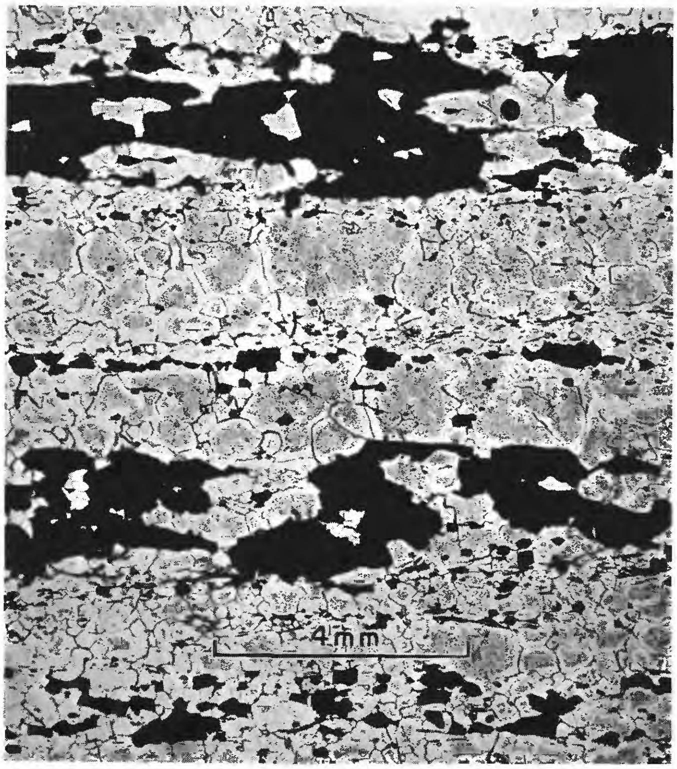


FIGURE 17.—Highly metamorphosed itabirite from specimen shown in figure 16. Plane light.

According to Dorr and Barbosa (1963), itabirite in the Quadrilátero Ferrífero contains 25–40 percent iron. Itabirite that contains 40–57 percent iron is generally referred to as enriched itabirite. Material between 57 and 65 percent iron is called intermediate ore (Dorr, oral commun., 1963). In material that contains less than 25 percent iron, the iron and silica ordinarily are not separated into distinct laminae, and such rock should not be called itabirite.

In the Monlevade and Rio Piracicaba quadrangles, the iron content of the itabirite, enriched itabirite, and intermediate-grade ore ranges from 19 to 65 percent. Material of lower iron content, below 25 percent, retains the banded appearance of itabirite and forms part of the Cauê Itabirite, and the term itabirite is used for it. The chemical composition of itabirite from these quadrangles is compared with that from other areas of the Quadrilátero Ferrífero in table 3.

Only the itabirite of the Cauê Itabirite is considered in computing the quantity of this material in the Monlevade and Rio Piracicaba quadrangles, as that contained in the underlying Monlevade Gneiss and over-

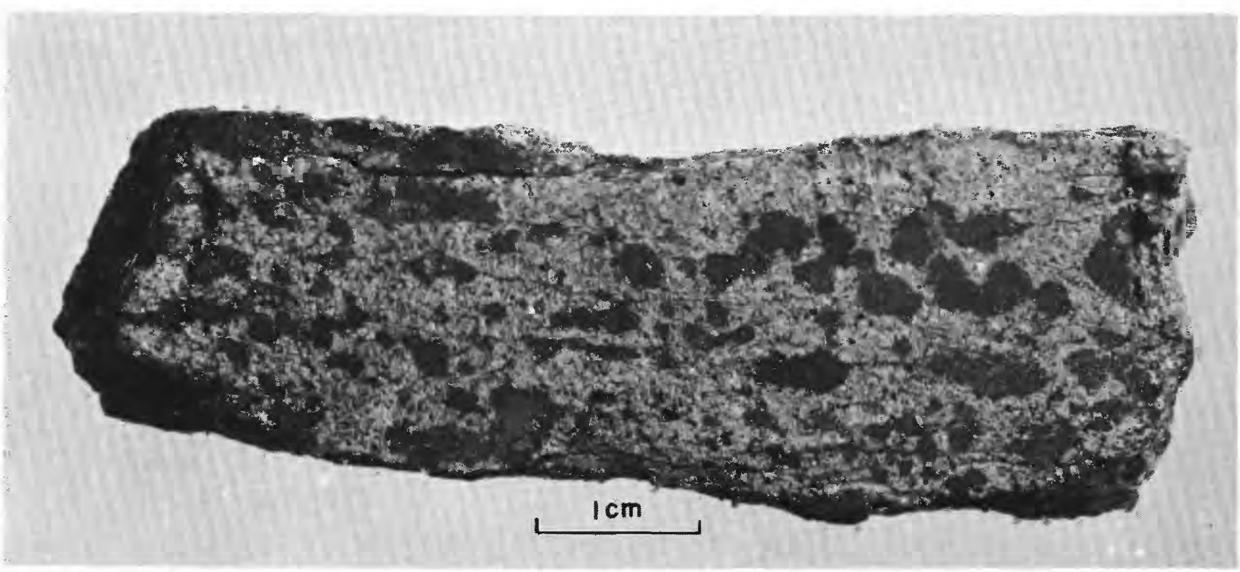


FIGURE 18.—Highly metamorphosed gneissic magnetic itabirite, Rio Piracicaba quadrangle. Light-colored material is reddish-stained quartz; dark spots are aggregates of magnetite and hematite.

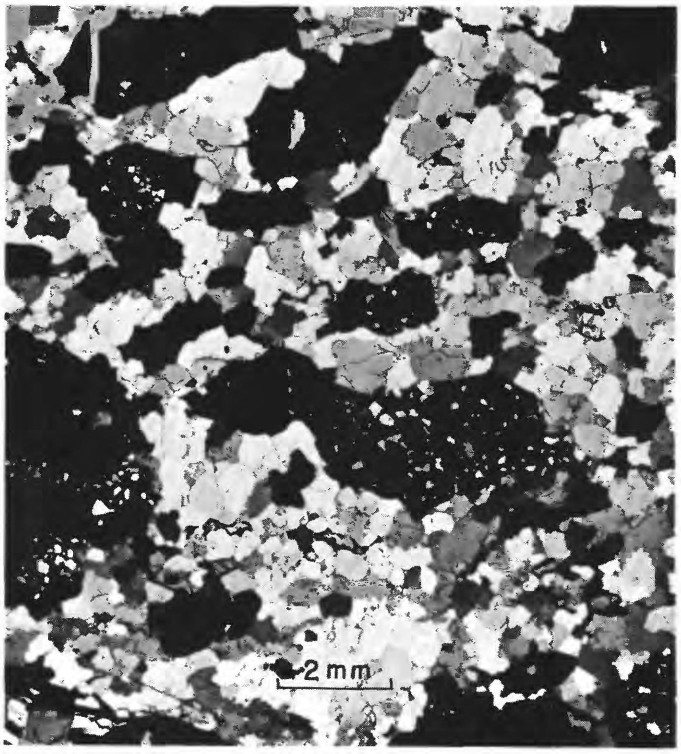


FIGURE 19.—Highly metamorphosed gneissic magnetic itabirite from specimen shown in figure 18. Segregations of aggregates of magnetite and hematite are black; quartz is white to light gray. Crossed nicols.

lying Elefante Formation is in thin and discontinuous lenses and amounts to only a very small fraction of that in the Cauê. Based on a total outcrop length of 77 kilometers, an average thickness of 200 meters, the geologic sections (pl. 3), and the average grade (rounded off to 35 percent iron), the amount of itabirite in the Cauê Itabirite within these quadrangles is 40,800 million metric tons with a metallic iron content of 14,300 million metric tons. The tonnage of potentially usable friable weathered itabirite, based on the outcrop length of 77 kilometers, a thickness of 200 meters, an average depth of weathering of 50 meters, and an average grade of 35 percent iron, is 2,700 million metric tons, with a metallic iron content of 950 million metric tons.

The average grade of eight samples from these quadrangles is 33.4 percent iron, or 5 percentage points less than the average of 39 percent iron (Dorr, oral commun., 1963) for the Quadrilátero Ferrífero as a whole. Whether this represents a real decrease in the amount of iron initially deposited, an increase in the amount of iron removed from the itabirite samples and concentrated in nearby ore deposits, a decrease in removal of silica owing to decreased solubility of the larger grains of quartz, as suggested by Dorr and

TABLE 3.—*Analyses of itabirite from the Monlevade and Rio Piracicaba quadrangles compared with itabirite from other parts of the Quadrilátero Ferrífero*

	Monlevade and Rio Piracicaba quadrangles [1]										Itabira district [2]		Gandarela quadrangle [3]	Gandarela Canyon—Conceição do Rio Acima quadrangle [4]		Congonhas district [5]
	Weathered itabirite								Hard itabirite		Hard	Soft	Average of 11 samples	Soft channel sample	Dolomitic, chip sample across 200 meters	Average of 12 samples
	32	135	Manganiferous 466-1	466-2	475	508-35	508-36	508-37	465	510-16	Average of 15 samples	Average of 19 samples				
SiO_2	30.88	72.14	32.70		65.18	31.82	45.04	38.15	44.97	54.60	35.24	21.96	17.3	40.5	50.0	31.0
FeO	7.41	1.78	8.19						3.09							
Fe_2O_3	55.22	25.02	54.94		33.86				50.15	44.37						
Fe	(44.37)	(18.88)	(44.77)	(42.3)	(23.68)	(46.97)	(37.95)	(42.77)	(37.47)	(31.03)	(44.96)	(53.81)	(55.2)	(41.2)	(29.6)	(46.2)
Mn	.53	.08	1.08	.05	.03				.22	.03			.02			.145
P_2O_5	.27	.04	.1		.03	.080	.046		.05	.07	.011	.021	.05			.064
Al_2O_3	3.17	.46	.87		.54	1.04	1.21		.54	.54			.65			
Loss on ignition	1.90	.46	1.66		.56				.58	.24			3.0			
Ca, Mg															7.7	

[1] All samples analyzed in laboratory of Cia. Siderúrgica Belgo-Mineira, Monlevade, Minas Gerais, except 466-2, which was analyzed in the laboratory of the Inst. Técnico do Rio Grande do Sul, Pôrte Alegre.

[2] From Dorr and Barbosa (1963).

[3] From J. E. O'Rourke, written commun.

[4] From S. L. Moore, written commun.

[5] From P. W. Guild (1957).

32. East limb Tanque syncline, 1 km northwest of Monlevade.
135. Southeast limb Monlevade anticline, 6 km northeast of Rio Piracicaba.
466-1. Underlies ore at Água Limpa manganese mine.
466-2. Overlies ore, northern limb Morro da Jacutinga syncline, Água Limpa mine.
475. From base of Cauê, northwestern limb of Elefante anticline, 1 km north of the Serra do Elefante.
508-35. 200 meters west of adit 31, Andrade mine. (Near middle of Cauê Itabirite.) Chip sample from opencut.
508-36. 200 meters west of adit 31, Andrade mine. Fines from ground at base of cut bank.
508-37. 200 meters west of adit 31, Andrade mine. Chip sample from opencut.
465. South limb Elefante anticline, 1 km west of Água Limpa manganese mine (in Florália quadrangle).
510-16. Underlies hematite ore. Morro do Água Limpa iron deposit.

Barbosa (1963), or merely an apparent difference due to the vagaries of random sampling is not known.

Itabirite is considered by many geologists to have formed by diagenesis and metamorphism of iron- and silica-rich sediments. The iron-and silica-rich sediments that were later converted to the itabirite of the Quadrilátero Ferrífero were probably deposited near the end of a long period of crustal stability, during which a very mature topography formed—nearly complete peneplanation (Harder and Chamberlain, 1915; Rynearson and others, 1954, p. 16). Chemical weathering was the dominant erosional process. There is no evidence that volcanism or other igneous activity directly contributed iron or manganese to these sediments during or subsequent to their deposition.

Most recent studies suggest a restricted marine or fresh-water environment for the deposition of banded iron-formation. The stability fields of iron and silica minerals, in terms of Eh and pH, are such as to rule out deposition in open marine environments (Krumbein and Garrels, 1952). James (1951, 1954) concluded from geologic evidence and consideration of the stability fields worked out by Krumbein and Garrels that the sedimentary iron-formation of the Lake Superior region was formed in a restricted marine environment. Tyler and Twenhofel (1952) suggested that banded iron-formation was deposited in a deltaic or related environment in fresh or brackish water, and Alexandrov (1955) and Hough (1958) both concluded that deposition of banded iron-formation took place in fresh water. The nature and distribution of the itabirite of the Quadrilátero Ferrífero and the stability fields of its component minerals suggest that it was deposited in a shallow fresh- or brackish-water basin.

IRON ORES

The iron ores of the Quadrilátero Ferrífero are of three general types: high-grade hematite ore, canga, and rubble ore. High-grade hematite ore is by far the most important and is the only type presently being mined in the Monlevade and Rio Piracicaba quadrangles. These quadrangles contain several deposits of canga and rubble ore, but high-grade hematite constitutes most of the ore.

HIGH-GRADE HEMATITE ORE

In the Quadrilátero Ferrífero, only hematite-bearing material with an iron content of 66 percent or above is classed as high-grade hematite ore, although elsewhere in the iron-ore markets of the world, material with a much lower iron content is classed as high-grade ore and is used as direct-shipping ore for blast furnace feed or beneficiated to produce high-grade sinter or pellets.

The high-grade hematite ore is black to blue black, generally dull in weathered outcrops and shiny on fresh surfaces. It may be equigranular, schistose, or rodded. Equigranular ore is composed of approximately equidimensional interlocking hematite grains (fig. 20). The grains may range from a few millimeters to a centimeter in diameter but are commonly nearly uniform in size in a given ore body or part of an ore body. Schistose ore consists of tabular hematite crystals in parallel to subparallel orientation (fig. 21). Rodded ore contains rods or pencils of hematite ranging from the size of ordinary lead pencils to the size of logs as much as 1 meter in diameter (figs. 22, 23). Rodded ore frequently breaks into long hackly shapes during mining.

The physical properties of the high-grade hematite ore show far greater variation than does the chemical composition; it is this variation that forms a basis for the classification currently used by the joint ferrous project of the Brazilian Departamento Nacional da Produção Mineral and the U.S. Geological Survey (Dorr and Barbosa, 1963). This ore is classed as hard, soft, or intermediate depending on the tendency of the ore to break down into fines ($<\frac{1}{2}$-inch size) during mining and subsequent handling. Hard ore consists of 75–100 percent $>\frac{1}{2}$-inch material after

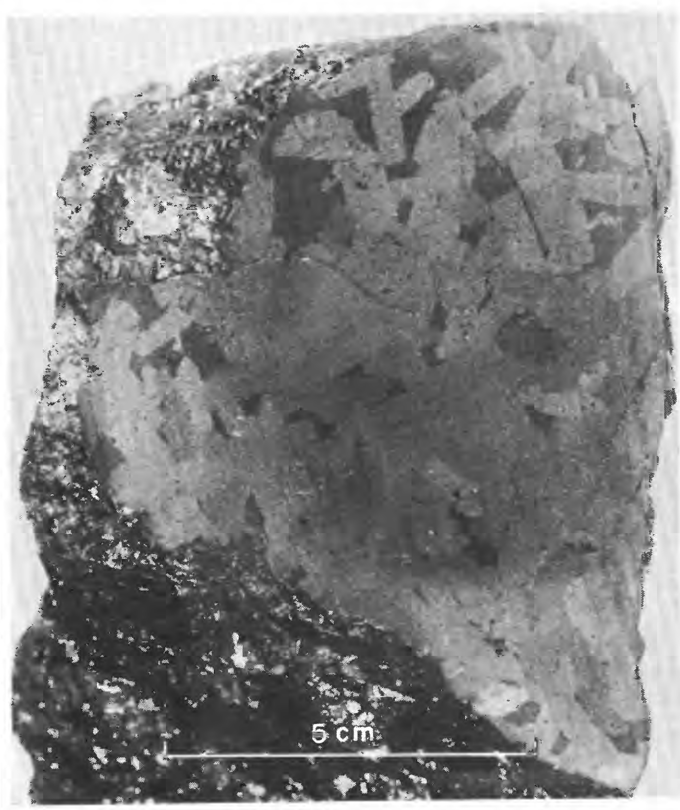
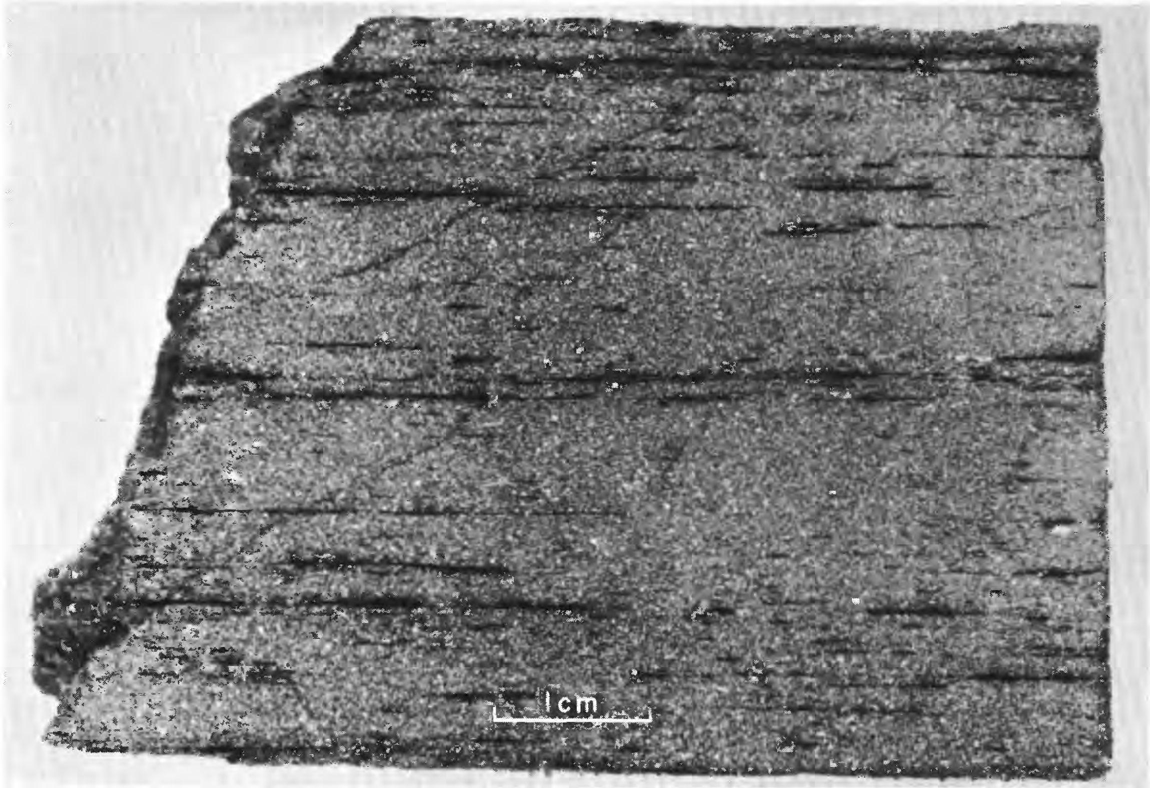
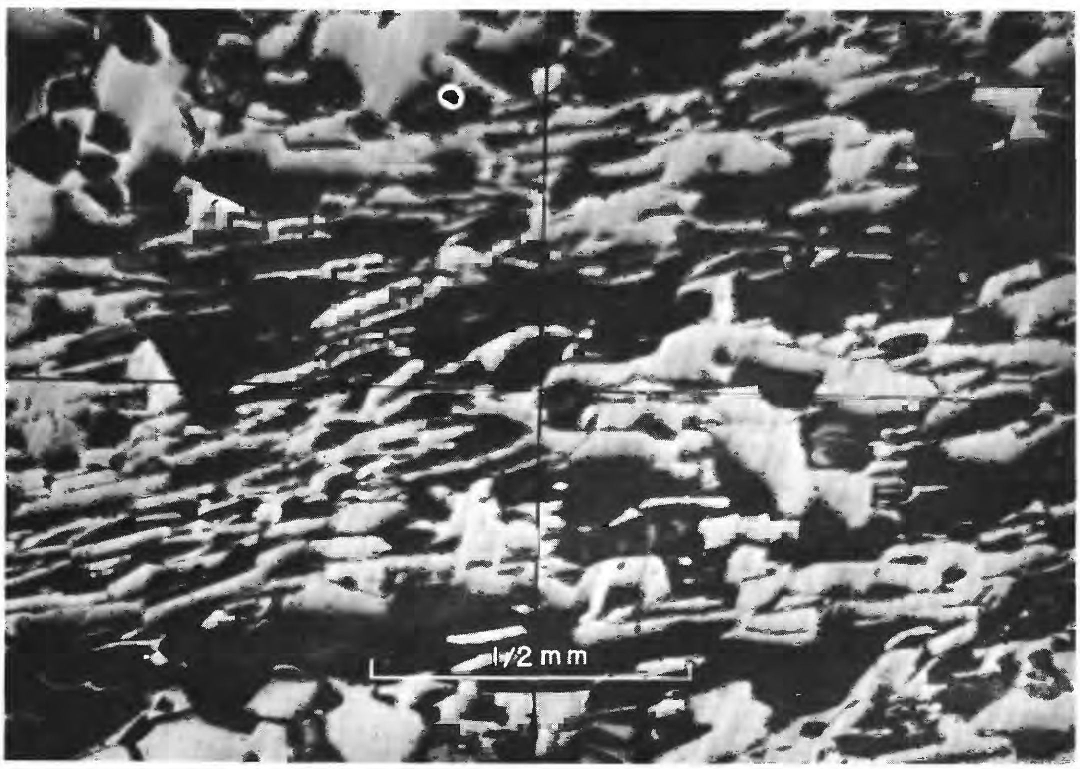


FIGURE 20.—Hard or compact equigranular hematite ore, Andrade mine (sawed surface showing intergrown hematite grains).

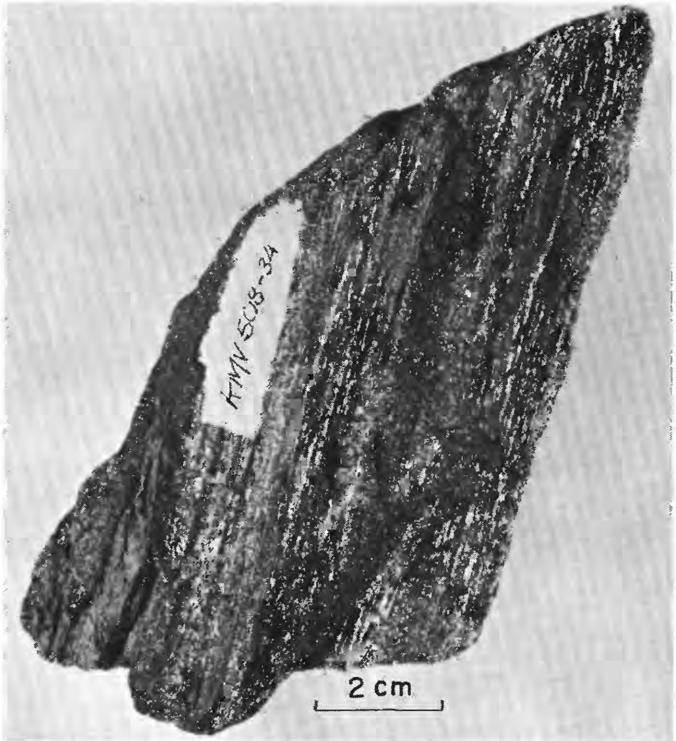


A

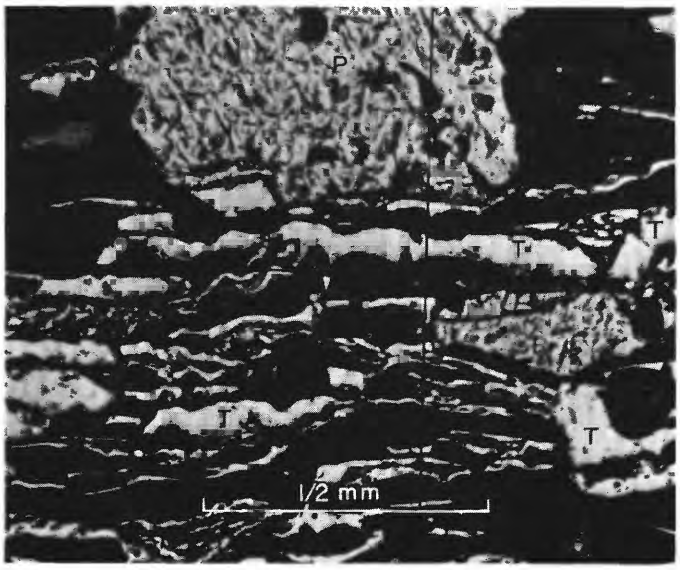


B

FIGURE 21.—Schistose hematite ore, Andrade mine. *A*, Sawed surface showing pronounced schistosity and tabular voids; *B*, photomicrograph showing alinement of hematite (light gray) and voids (black).



A



B

FIGURE 22.—Pencil ore, Andrade mine. *A*, Hand specimen showing lineation produced by microfolding in ore; *B*, photomicrograph of polished section normal to pencils (P) and tabular grains (T) of hematite. Black areas are voids, either naturally occurring or produced during cutting and polishing.

FIGURE 23.—"Logs" of itabirite produced by rodding during folding and formation of the Andrade syncline and subsequently replaced by hematite to form high-grade hematite ore, Andrade mine. Camera on top of largest log is 13 cm long.

mechanized mining, crushing, and screening; soft ore, of 0–25 percent >½-inch material; and intermediate ore, of 25–75 percent >½-inch material. Intermediate ore may be further subdivided into medium-hard ore, which consists of 50–75 percent >½-inch material, and medium-soft ore, which consists of 25–50 percent >½-inch material.

The reasons for the physical differences, in material of about the same chemical composition, are not fully known, but the differences are thought to be caused in part by differences in replacement—either in degree of completeness (Dorr and others, 1960) or in lithology of material replaced—or in part by differences in behavior of the material while it is undergoing deformation during or subsequent to ore formation.

Hard hematite ore is that in which replacement of silica by iron oxides may have been more complete, for one reason or another, and (or) in which leaching of a small amount of hematite did not take place to form soft ore (Dorr and others, 1960, p. 108). The hard ore behaves in a more competent fashion than the finely laminated ore and is in general less sheared. The hematite grains are larger and interlock with each other.

In the Monlevade and Rio Piracicaba quadrangles, the schistose ore is generally finer grained, more finely laminated, and far more porous than the massive or compact ore. It tends to split during mining into flat fragments which have relatively little strength and which therefore produce a higher proportion of fines. All gradations exist, from hard ore producing much less than 25 percent fines to material that breaks down completely to a specularite sand. Schistose ore from the Andrade mine contains slightly less iron, two to three times more silica, and four to five times more alumina than the compact ore; this fact suggests that replacement was not as complete as in the more massive ore. The higher porosity of the ore probably resulted from the solution of silica that was not completely replaced by iron and is a further suggestion that replacement was not as complete as in the compact ore.

Most ore, or at least that exposed at the surface and in comparatively shallow workings, is of high purity and contains little except ferric oxide (table 4). The chief impurities are silica and alumina, generally less than 2 percent and in places less than 1 percent. Phosphorus in most analyses is less than 0.1 percent and often less than 0.05 percent. Locally, as in some zones at the Andrade mine, it may be as high as 6 percent. Sulfur is virtually unknown in these ores and is customarily not determined in routine ore analysis. Silica is present as quartz in talc, or with alumina in clay minerals; only rarely are these minerals visible megascopically, and in much of the ore, none are apparent under the microscope.

The ferric oxide occurs in three forms; as specularite, granular hematite, and martite. Of the three forms, specularite is by far the most prevalent; granular hemitite and martite occur in about the same proportions.

The minable high-grade hematite ore deposits of the Quadrilátero Ferrífero are found within the Cauê Itabirite. Although itabirite in the Monlevade Gneiss and Elefante Formation in the Monlevade and Rio Piracicaba quadrangles contains masses of pure hematite, their small size and insignificant total tonnage makes them uneconomic, at least for the present.

Several theories have been proposed to explain the genesis of the high-grade hematite ore of the Quadrilátero Ferrífero and of similar ore associated with itabirite elsewhere in the world. Chief among these theories are a syngenetic origin, concentration of the iron and replacement of the silica by hydrothermal solutions, and supergene enrichment. These theories have been summarized by Park (1959), who at the same time favors the origin by supergene enrichment. Not all the ore deposits associated with itabirite in the Quadrilátero Ferrífero are of the same origin; some slightly lower grade deposits were evidently formed by supergene processes.

In contrast to current ideas, many of the early workers in the Quadrilátero Ferrífero favored a syngenetic origin for the high-grade hematite ore. Leith and Harder (1911), Harder and Chamberlain (1915), and Freyberg (1932, 1934) all proposed a syngenetic origin, followed by metamorphism. Harder (1914) in particular was a champion of this origin; he cited as evidence the supposed conformable relationship of the high-grade hematite ore to itabirite and the great lateral persistence of thin high-grade hematite beds.

TABLE 4.—*Analyses of high-grade hematite ores from the Monlevade and Rio Piracicaba quadrangles*

[nd, not determined]

	51 [1]	510–10 [1]	510–17 [1]	510–20 [1]	MALH [1]	541 [1]	MAH [2]	Andrade [1]	Andrade production, 1959–61 [1] (unweighted avg)
Fe_2O_3	96.45	98.46	98.04	98.29	----	97.19	nd	----	----
FeO	0	0	0	0	----	0	nd	----	----
Fe	(67.45)	(68.86)	(68.56)	(68.74)	(69.80)	(67.97)	(69.89)	(68.85)	(66.78)
Mn	.53	.03	.03	.02	----	.02	nd	.06	(3)
SiO_2	1.28	1.03	1.00	1.03	.05	1.87	.07	.62	1.90
Al_2O_3	1.37	.71	1.12	.79	----	.75	nd	.83	1.31
P_2O_5	.06	.06	.09	.09	.007	.06	.003	.04	.25
P	(.03)	(.03)	(.04)	(.04)	(.004)	(.06)	(.0015)	(.02)	(.138)
Loss on ignition	1.02	.16	nd	nd	.17	.16	.43	.56	(3)
Total	100.71	100.45	100.28	100.22		100.05			

[1] Analyzed in the laboratories of CSBM, Monlevade, Minas Gerais.

[2] Analyst, Arthur Houle, Santa Rita Durão, Minas Gerais (one sample) and H. K. Shearer (seven samples).

[3] Not given.

51. Hematite ore from the Carneirinhos anticline, 2.5 km south of the Rio Santo Bárbara.
510–10. Hematite ore from the east end of the Morro do Água Limpa deposit.
510–17. Hematite ore from the west end of the Morro do Água Limpa deposit.
510–20. Hematite ore from Morro do Água Limpa peak, highest point of the Morro do Água Limpa deposit.
MALH. Average of three samples of hematite ore from Morro do Água Limpa deposit collected by Harmon Lewis in 1912. From unpublished Brazilian Iron and Steel Co. report.
541. Hematite ore from the lower ore body, Morro Agudo deposit.
MAH. Hematite ore from the upper ore body, Morro Agudo deposit, average of eight samples collected by E. C. Harder and R. T. Chamberlin in 1911. From unpublished Brazilian Iron and Steel Co. report.
Andrade. Average of four samples of typical Andrade mine ore. Written commun., James Büchi, geologist, CSBM.

Gathmann (1913) proposed a supergene origin for the ores, by the leaching of silica from itabirite. The association of iron ore with limestone and the presence of hard high-grade ore 36 meters below the surface was considered by Harder to be counter to this idea. Harder (1914, p. 110) summarized his arguments in the statement: "It does not seem reasonable to think that iron ore should be derived by alteration from a sandy iron rock by the leaching of silica, while at the same time the much more soluble limestone remains unaltered."

Sanders (1933) was the first, so far as is known, to propose a replacement origin for the hematite ore; which he implied that this replacement may have been due to hydrothermal solutions. The role of hydrothermal solutions in the formation of the ore bodies has also been emphasized by many of the recent workers in the area (Dorr and others, 1952; Guild, 1953, and 1957; and Dorr and Barbosa, 1963).

Guild (1953) suggested that the ores from the Congonhas district, in the southwest corner of the Quadrilátero Ferrífero, were formed as a replacement of preexisting itabirite by circulating solutions of moderate temperature. He considered that the introduced iron came from adjacent parts of the iron-formation and not from magmatic sources. He cited the following as evidence that the ore was not syngenetic but that it formed after folding and deposition of the overlying Itacolomí Series: The crosscutting of itabirite by hematite veins; the lack of hematite boulders, which are known to be resistant, in the overlying Itacolomí conglomerate; and the tightly folded ore, which is too competent to have been deformd in the manner in which it now exists. The almost complete absence in the ores of sulfur and other elements generally present in magmatic solutions made it appear to Guild highly unlikely that hydrothermal solutions emanating from magmatic sources were responsible even for the concentration of iron and removal of silica. Structural control by faults, both normal and thrust, was considered by Guild to be very important in controlling movement of solutions and localization of ore bodies.

Park (1959) concluded that most iron ore bodies owe their origin either to supergene enrichment through normal weathering processes or to the migration and rearrangement of iron and silica during regional metamorphism, with ore bodies formed by weathering processes probably being more numerous and widespread. He cited as evidence for a supergene origin the tendency of the hard surficial ore of many deposits, including those of Itabira and Casa de Pedra in the Quadrilátero Ferrífero, to give way to soft, porous ore at depth. Supergene processes have also been cited by Edwards (1953), Krishnan (1952), Strauss (1952), and other authors as being responsible for the formation of hard ore bodies in itabirite or similar material.

Dorr and Barbosa (1963) discussed the entire problem of the origin of the high-grade hematite deposits, including slump structures, porosity, and thinning of the ore deposits. They proposed as a working hypothesis for the origin of the high-grade hematite ore the synmetamorphic metasomatic replacement of the silica of the itabirite by iron derived from the itabirite. Hypogene fluids probably related genetically to the granitic gneiss and channeled by zones of increased porosity in iron formation near fold axes were suggested as the means by which the iron and the quartz were transported. The greatly increased solubility of silica relative to iron under conditions of increasing temperature and the peculiarities of solubility of quartz just below the critical temperature of water are emphasized and cited as explanations for the existence of two or more generations of hematite in most ore bodies. The ore bodies were localized in the itabirite in zones of increased porosity and decreased pressure caused mainly by folds and local changes in the plunge of lineation.

The principal high-grade hematite ore deposits in the Monlevade and Rio Piracicaba quadrangles probably formed from the Cauê Itabirite through replacement of silica by iron, the origin suggested by Dorr and others (1952) and Dorr and Barbosa (1963) for most deposits of this type. There is no evidence that this type of ore formed by the simple removal of quartz. Removal of a large volume of quartz from itabirite without replacement almost certainly would have resulted in extremely high porosity or, under the stresses produced by the overlying rocks and by the deformation that caused the folding, a thinning to half or less than half of the original thickness. There is no indication of an unusually high porosity or of thinning in any of the known ore bodies in these quadrangles; on the contrary, the ore bodies are thicker than the adjacent itabirite. This thickening mainly results from structural thickening in the axial zones of folds but is apparently no less than would have occurred by folding a bed of uniform thickness.

Additional evidence for the hydrothermal replacement origin of the iron ore is provided by the occurrence of specularite in gneiss. Specularite was found in Monlevade Gneiss 200–500 meters stratigraphically below the Andrade ore deposit, in the mine railroad tunnel. The specularite occurs in coarse grains, both parallel to and crosscutting layering in the gneiss; it probably resulted from iron-rich solutions permeating the gneiss along fractures and layer boundaries.

All gradations exist from completely replaced ore to nearly unreplaced itabirite. Partially replaced enriched itabirite is commonly associated with ore and itabirite in the major deposits of these quadrangles and is especially conspicuous at the Morro da Água Limpa and Morro Agudo deposits. The enriched itabirite consists mostly of dark-blue-black hematite and quartz. The quartz is not distributed in distinct layers as in ordinary itabirite but occurs in lenses and irregular pods both parallel to and crosscutting the discernible original lamination.

The high-grade hematite bodies are enclosed in metamorphic rocks that, on the basis of their mineral assemblages, were formed at temperature-pressure conditions corresponding to those of the upper part of the amphibolite facies, about 500°–600°C. Evidence presented by Dorr and Barbosa (1963) from the Itabira district suggests that metamorphism and the formation of the high-grade hematite ore bodies in that district were contemporaneous. The chief evidence is as follows:

1. The lack of hard hematite in the overlying premetamorphic Itacolomí Formation. Hard hematite is more resistant than most of the material in the Minas Series and underlying rocks from which the Itacolomí was formed; if the ore bodies were of pre-Itacolomí age, certainly some of the high-grade hematite should have been preserved in Itacolomí rocks. None has ever been found, although pebbles and cobbles of much less resistant itabirite and schist are relatively common.
2. The hematite replaced itabirite that was complexly deformed at the beginning of the orogenic period with which the metamorphism was associated. The characteristic banding of the itabirite, in many places highly deformed, is often preserved in relict form in the high-grade hematite ore. This high-grade hematite ore is very hard, and it is unlikely that it woud have deformed in the same manner as the much less resistant itabirite.
3. Dikes that intruded the ore were not replaced by the iron, indicating that they were intruded after the replacement of the itabirite by iron; however, they are foliated, presumably by forces produced during the waning stages of metamorphism.
4. This same foliation cuts across minor structures (folds and crenulations) in the ore, further indicating that the ore must have been predike and synmetamorphic.

The ore bodies of the Monlevade and Rio Piracicaba quadrangles contain much of the same evidence, and thus one may also conclude that they formed contemporaneously with the metamorphism. Because data indicate the grade of metamorphism to be in the upper part of the amphibolite facies, the ore in these quadrangles must have formed at the temperatures under which the metamorphism took place.

The fluids that were responsible for the transportation of the iron and the metasomatic replacement and removal of the silica were probably derived from the sediments as they were being metamorphosed. Moreover, these fluids probably contained large quantities of water above its critical temperature and pressure. The fluids are postulated to have migrated along permeable strata and structures formed as a result of the orogeny—before the recrystallization of the sedimentary rocks to gneiss. Hematite was the principal mineral, in certain zones perhaps the only one, formed from preexisting hematite or ferriferous oxides or hydroxides. Some magnetite, however, formed locally in abundant quantities; from this evidence, it is inferred that the fluids were slightly reducing because under an oxygen pressure of 1 atmosphere, the temperature necessary to convert hematite to magnetite, through the following reaction

$$6Fe_2O_3 \rightarrow 4Fe_3O_4 + O_2$$

is about 1450°C, or more than two times the inferred temperature of metamorphism and formation of the ore deposits. The conversion temperature increases with increased oxygen pressure (Muan, 1955, p. 973).

The sequence of major events leading to the formation and modification of the high-grade hematite ore bodies is summarized as follows:

1. Deposition of the silica- and iron-rich sediments in the Quadrilátero Ferrífero basin.
2. Burial by sediments of the overlying Piracicaba Group accompanied by diagenesis and lithification.
3. Orogeny at the end of Minas time. Minor folding of the Minas Series sedimentary rocks and further lithification of the iron-formation, with the formation of hematite, if not already existing, and fine-grained chert and ferruginous chert. This deformation was probably not sufficiently intense to convert the oxide-facies iron-formation to itabirite.
4. Deposition of the Itacolomí Series and younger(?) sediments.

5. Orogeny at the end of the middle Precambrian (1350(?) million years) with intense deformation:
   a. Folding that, owing to the depth of burial, caused the rock to yield by plastic flow rather than by rupture. Locally, the rock failed, allowing thrust faults to form.
   b. Conversion of the cherty iron-formation (taconite) to itabirite.
   c. Rearrangement of the iron and silica both by fluids emanating from the sedimentary rocks undergoing anatexis and by fluids present in the iron-formation and adjacent formations.
   d. Formation of the paragneiss by a combination of isochemical recrystallization by heat and pressure and allochemical metasomatism by the fluids from the rocks undergoing anatexis and from deeper magmatic sources. Events may have taken place almost simultaneously.
6. Epeirogenic uplift and erosion that exposed the hematite deposits. Supergene weathering processes related to the present surface. These processes have modified the deposits, in places forming soft ore through solution along crystal boundaries and in other places forming a case hardening of the upper parts of the ore bodies.

CANGA

Canga [11] is lithified iron-rich material that forms blanket deposits at or near the surface as a weathering product of itabirite or high-grade hematite ore. It is chiefly a weathering product of the high-grade ore. Fragments of itabirite and hematite are cemented with hydrous iron oxides. With increasing alumina, from rocks other than itabirite or high-grade hematite ore, canga grades into iron-rich soil or laterite, and with decreasing iron oxide cement, it grades into rubble ore or itabirite talus. As fragments other than itabirite or hematite increase, canga grades into a normal clastic sedimentary rock, for example, a sandstone, arkose, or graywacke with an iron-oxide cement (Pettijohn, 1957, p. 651–652). Canga most commonly forms on dip slopes, generally less than 20° underlain by itabirite or hematite ore; it may extend outward over adjacent rocks at the bases of the slopes. Less commonly, it forms thin layers on the steeper inface slopes of the cuestas commonly formed by the resistant itabirite. Sections *B–B′* and *C–C′*, plate 6 show the relationship of canga to itabirite and adjacent rocks.

The cementing material of canga consists of hydrous oxides of iron, mainly goethite and lepidocrocite, and hematite; it may contain a few percent silica and alumina. Much of the cango in the Quadrilátero Ferrífero contains between 1 and 0.2 percent phosphorus.

Canga that contains a high percentage of iron, usually as fragments of high-grade hematite ore, is locally called canga rica (rich canga). Canga was used extensively in the early small furnaces and Catalan forges for the following reasons: (1) Its strength, which keeps it from breaking down into small fragments or powder and forming a dense, nonpermeable mass when charged into furnaces; (2) its light weight, which prevents compaction of the charcoal into a nonpermeable mass; and (3) its porosity, which makes it easily reducible. Some canga is still being used in the smaller iron-making operations in the Quadrilátero Ferrífero, but it has generally been supplanted by high-grade hematite ore or sinter made from such ore.

Canga is formed by the solution and redeposition of iron; it not only forms at the surface but also at the base of already deposited canga and at the soil-bedrock contact (Simmons, 1960; Pomerene, 1964). Unlike its close relative, laterite, which is formed from many rock types, canga in the Quadrilátero Ferrífero is formed only from itabirite and associated ore. According to Dorr and Barbosa (1963), canga observed on three continents is restricted to oxide-facies iron-formation. In addition to itabirite as a source of the iron, seasonal rainfall and a tropical or semitropical climate are considered by Dorr to be essential for the formation of canga. The formation of canga is directly affected by physiography, structure, and stratigraphy of the iron-formation and associated rocks and by the ground-water regimen.

Iron is taken into solution as Fe^{+2} or is transported as colloidal particles of hematite or magnetite; the iron-laden water travels downward through the porous itabirite and comes out at the base of the slope. As the water comes to the surface and evaporates, iron is precipitated as hydrous oxides or less commonly as the anhydrous form, hematite (Park, 1959, p. 580–582). On steep slopes most of the water runs off, leaving little to percolate down and later reappear to form canga. More rapid mechanical erosion on steep slopes likewise contributes to the lack of canga on them.

Extensive canga sheets mantle itabirite and adjacent rocks in the vicinity of Ponte Saraiva, and smaller canga deposits occur elsewhere in the Rio Piracicaba quadrangle. The largest canga deposit in the Monle-

[11] Park (1959) considered that the term "canga" is a useful one but that its usefulness is impaired because it has come to mean many things to many people. He advocated retention of Derby's (1910) definition, "a rock formed by the cementation of hematite of rubble ore into a hard ironstone conglomerate."

vade quadrangle is along the Rio Santa Bárbara, at the foot of the Andrade hematite deposit.

RUBBLE ORE

Rubble ore consists of pieces of hematite in the form of large, almost unbroken blocks; large angular fragments; and boulders, cobbles, and pebbles. The pieces may be mixed with soil and fragments of other rocks, or they may be relatively free of extraneous material; if the pieces are cemented by iron oxides, the resulting mass is termed canga.

Rubble ore is formed primarily by gravity concentration of pieces of hard hematite below outcrops of hard hematite ore bodies. Almost all hard hematite ore bodies at the tops or on the slopes of moderately steep hills have rubble ore deposits below them.

In the Monlevade quadrangle, extensive deposits of rubble ore occur along the south side of the Rio Santa Bárbara below the outcrops of hematite in the Cauê Itabirite. Several of these rubble deposits consist of large, virtually intact blocks as much as several hundred feet long and wide that have slid down the hill into the river or into tributary gullys as parts of extensive land slides. The largest deposit is the one below the Andrade ore body. It consists of boulders and irregular blocks as much as a meter in diameter, mixed with a small amount of itabirite, quartzite, and schist fragments; in places, the mass is cemented to form canga. The river gravels of the Rio Santa Bárbara contain a high proportion of hematite boulders and cobbles from the northwesternmost outcrop of Cauê Itabirite downstream to about a kilometer below the point on the river opposite the Andrade mine.

Rubble ore was an important source of iron ore, along with canga, for the early small furnaces in the Monlevade and Rio Piracicaba area, as well as in the Quadrilátero Ferrífero as a whole. None is known to have been used in present operations in the Monlevade and Rio Piracicaba quadrangles, although some was being mined and shipped from other areas of the Quadrilátero Ferrífero during the time of this study.

MANGANESE

Manganese occurs in the Monlevade and Rio Piracicaba quadrangles as manganiferous zones in the Cauê Itabirite and as beds, lenses, and small irregular bodies in manganiferous itabirite, itabirite, and clastic rocks of the Elefante Formation. In areas adjacent to the Quadrilátero Ferrífero, manganese deposits are known in rocks of the Rio das Velhas Series, but no deposits of the age are known in the Monlevade or Rio Piracicaba quadrangles or in the Quadrilátero Ferrífero.

MANGANIFEROUS ITABIRITE

Locally, within the Monlevade and Rio Piracicaba quadrangles, the upper part of the Cauê Itabirite contains zones of manganese-rich itabirite. These zones are generally of small areal extent. Most of the manganiferous itabirite is in the southwestern part of the Rio Piracicaba quadrangle, on the flanks of Serra do Elefante and southwestward to the Morro da Jacutinga. When the manganese content is low, on the order of a few percent, as is normal, manganese minerals are generally not apparent in hand specimen or under the microscope. Only when the manganese content is above about 5 percent are manganese minerals generally recognizable in individual grains. However, manganiferous itabirite may be distinguished from nonmanganiferous (below 1 percent Mn) by its general appearance, which is generally darker and duller.

The problems of the origin of manganiferous itabirite are similar to those of the origin of itabirite. The origin and the transportation of the manganese component present no special problems; because of its known geochemical behavior, manganese would be expected to go along with iron in the weathering, transportation, and concentration cycles (Krauskopf, 1957). The manganese content of the earth's crust is one-fiftieth that of iron (Mason, 1958, p. 22), and intermediate igneous rocks contain approximately 60 times as much iron as manganese (Nockolds, 1954, p. 1032). Because manganese compounds are generally more scarce and more soluble than those of iron; manganese takes much longer to concentrate in sufficient quantities to cause it to precipitate chemically with iron and silica. That it took time for it to concentrate in the Quadrilátero Ferrífero basin is suggested by the very small amount of manganese in the lower part of the Cauê Itabirite, and its relative concentration in the upper part of the formation and in the overlying Gandarela Formation in the western and central parts of the Quadrilátero Ferrífero as well as in the Elefante Formation in the eastern part of the Quadrilátero Ferrífero. A probable source of the iron and manganese in the Minas Series of the Quadrilátero Ferrífero was the volcanic rocks of the Nova Lima Group of the Rio das Velhas Series (Dorr and others, 1956).

The process of concentration during the long period of deposition of the Cauê Itabirite and overlying sediments does not explain the small areal distribution of the manganese. Local conditions—such as differences in the depth of the basin, changes in water circulation in the basin resulting from changes in bottom configuration, shifts in connections with the sea or in river channels, or other factors that affected the pH and Eh of the water in particular areas of the basin—may have been responsible for the local areal or stratigraphic precipitation of manganese. Manganese-precipitating bacteria are known and may have contributed to the formation of the manganese-rich rocks.

OTHER MANGANESE-RICH ROCKS

The Elefante Formation locally contains a higher than normal amount of manganese. Numerous thin beds of manganese oxides in the formation are associated with several beds of manganiferous itabirite, and a few chemical analyses indicate a high manganese content. The Elefante Formation was produced by an increase in clastic sedimentation, probably as a result of renewed crustal instability following the long period of stability during deposition of the Cauê Itabirite. This period of crustal instability may have commenced with a rise in sea level or a downwarping of the area, resulting in an invasion of the basin by ocean water. This invasion, coupled with uplift of source areas, changed the sedimentation from the chemically or biochemically precipitated iron, silica, and, later manganese to the deposition of calcareous and clastic sediments. Locally, the equilibrium in the basin was not sufficiently disturbed, and deposition of itabirite, sometimes dolomitic, continued. In some areas, calcareous and fine clastic material were deposited together, subsequently forming a dolomitic shale or shaly dolomite that was later metamorphosed to amphibolite. In some places, manganese and iron were deposited with the carbonate rocks, shaly dolomite, and fine-grained clastic rocks. Several times during this period, conditions in the source area and the basin must have become sufficiently stable to permit the deposition of the thin but extensive and locally manganiferous itabirite members.

MANGANESE ORE

Manganese ore is associated with manganiferous itabirite of the Cauê Itabirite and with manganiferous itabirite and manganese-rich metasedimentary rocks of the overlying Elefante Formation. In these quadrangles the only known deposit of sufficient size and grade to be exploited, that at the Água Limpa manganese mine, is in the Cauê Itabirite. The manganese oxides are concentrated in unusually porous or permeable zones and along fractures in the itabirite and along joints or fractures and in permeable beds in the schist or gneiss. Some have been deposited at or near the surface as manganese-rich canga. Most of the larger occurrences are in structurally complex areas.

Four possible origins have been considered by previous students of the deposits; syngenetic, hydrothermal, supergene concentration during an erosion cycle prior to the post-Minas folding, and supergene concentration related to the present erosion surface. More recently the origin of the manganese ore deposits in the Quadrilátero Ferrífero and adjacent areas has been discussed in detail by Dorr, Coelho, and Horen (1956), Dorr, Horen, and Coelho (1958), and Park and others (1951); according to them, only the last-named origin is supported by evidence from the major districts in this area. The deposits are shallow and the ore bodies decrease in grade and size with increasing depth, contrary to what would be expected if they were of syngenetic or hydrothermal origin.

Several factors are required for the formation of manganese oxide deposits; chief among them are a source of manganese and the proper structural or physiographic setting for the deposition of manganese minerals. Additionally, the proper physico-chemical conditions, mainly those of Eh and pH, are necessary for the solution, transport, and precipitation of the manganese.

Whatever the original source, the immediate sources of the manganese in the Rio Piracicaba quadrangle are primarily the manganiferous itabirite of the Cauê and secondarily the manganese-rich itabirite and other metasedimentary rocks of the Elefante Formation. The manganese minerals of the protore are taken into solution by reduction of the manganese from Mn^{+4} to Mn^{+2} or by the breakdown of the minerals by weathering. The reduction of the protore oxide minerals is influenced by pH; the lower the pH, the higher the Eh at which the reduction of manganese can take place (Garrels, 1960). In the silicate minerals, the manganese is mostly in the manganous state, and breakdown in a high-pH, moderate-Eh environment would inhibit oxidation and thus facilitate transportation.

As weathering progresses and low pH solutions migrate downward from the surface into the relatively porous manganiferous itabirite, manganese and iron are reduced and taken into solution. The solutions may migrate either down the dip of the formation or laterally to porous zones or structurally favorable areas such as the troughs of synclines. As these solutions react with the unweathered itabirite or mingle with ground water of a higher pH, the Mn^{+2} is oxidized to Mn^{+4} and precipitated, along with iron that is oxidized to Fe^{+3}, and along with other elements in the solution such as potassium and barium. As erosion and weathering continue, the manganese from the surficial zone is continually leached and carried downward, and concentration continues until, if the site of deposition is large enough and the time sufficiently long, an ore body is formed.

GOLD PLACER DEPOSITS

Gold placers occur along the two major streams, the Rios Piracicaba and Santa Bárbara, and several of their tributaries. It was the discovery of these gold placers by the early explorers near the present town of Rio Piracicaba that led to the first mining activity in the area. Evidence still remains of the extensive placering—which was done by small hydraulic operations, ground sluicing, and much pick and shovel work by slaves—in the gullies northwest of Rio Piracicaba and in the canga between Rio Piracicaba and Ponte Saraiva. Gold placers were also mined in the gullies leading from the Andrade mine area to the Rio Santa Bárbara (Francisco José Pinto de Souza, oral commun., 1958). The gravels of the two major streams were also worked. Inhabitants of Rio Piracicaba and surrounding area still pan for gold in the gravels of the Piracicaba River during times of low water; however, the yield is reported to be small.

The source, or sources, of the placer deposits has not been definitely established. The nearest and most probable source of most of the coarse placer gold in the Rio Piracicaba and its tributaries is the gold veins near the town of Florália, about 6 kilometers west of the west border of the Rio Piracicaba quadrangle. These veins are probably in the Monlevade Gneiss; they extend to depths of only a few hundred meters. The area of these veins is drained by the Rio Maquiné, one of the principal tributaries, in this area, of the Rio Piracicaba. The Rios Maquiné and Piracicaba occupy subsequent valleys, formed by the erosion of relatively weak strata overlying the more resistant Cauê Itabirite. As the streams migrated down the dip of the itabirite, they left behind rich auriferous gravels. Some of these gravels were concentrated by later transverse streams (probably resequent), such as Córrego Talho Aberto; some of the gravel that remained on the slopes behind the migrating streams was partly or wholly cemented by iron-bearing solutions from the itabirite to form an auriferous conglomerate and, as an extreme end-product, an auriferous canga.

PEGMATITE DEPOSITS

Many small to medium-sized pegmatite bodies are exposed in the Monlevade and Rio Piracicaba quadrangles, and countless others probably are concealed by soil or jungle. Pegmatites occur with increasing frequency and size to the east and are concentrated in the Mica belt of eastern Minas Gerais (Pecora and others, 1950), 100 kilometers east of the Quadrilátero Ferrífero. Most of the pegmatites within these quadrangles contain either minerals for which there is little demand or minerals which are not up to accepted standards of size or purity, or they are too small to be economically operated. Only two pegmatites are known to have been operated; the Talho Aberto mine for phenacite and amazonite, and the Pé de Serra mine for mica. Both were in operation in 1961. Other mica-rich pegmatites are exposed along Jacuí Creek south of the Monlevade airport, in the vicinity of Monlevade, and in the area west of Rio Piracicaba and south of Talho Aberto.

The pegmatites of the Monlevade and Rio Piracicaba quadrangles are composed chiefly of quartz and potassium feldspar, but they contain minor amounts of mica. The potassium feldspar is chiefly microcline; some is the green microcline, amazonite. Locally, semiprecious gem stones such as beryl and phenacite occur. The pegmatites in these quadrangles are mainly irregular in form, although some of the smaller ones appear to be tabular or lenslike. They show both concordant and discordant relationships with the enclosing rock; the same body may be both concordant and discordant. However, concordant relations are far more numerous than discordant. The pegmatites occur in the Monlevade Gneiss and overlying Minas Series rocks. All the known bodies, including the deepest parts of those opened up by mining, show the effects of extensive weathering.

BUILDING STONE, CLAY, AND SAND AND GRAVEL

Building stone and clay are extensively used in all forms of construction in the area. Most of the building stone is obtained from the Monlevade Gneiss and from the Bicas Gneiss Member of the Elefante Formation. Although nearly two-thirds of the quadrangles is underlain by these two units, most outcrops are deeply weathered, and the rock is unsuitable for building purposes; thus it is difficult to locate an accessible source in many areas. Exposures of relatively unweathered gneiss suitable for building stone are widely scattered; quarries have been developed northwest of Monlevade, south of Carneirinhos, and south of Rio Piracicaba. Much of the gneiss exposed in roadcuts along BR–31 in the western part of the quadrangle and adjacent parts of the Saõ Gonçalo quadrangle to the west is suitable for building stone.

Deposits of clay suitable for making bricks, tiles, and other products occur in many of the valley bottoms. The principal deposits are in valleys underlain by gneiss. Most of the clay is probably residual, derived from the weathering of the feldspars of the gneiss, although some may have been carried in from adjacent areas. Most of it is not suitable for high-quality ceramic products; this fact, coupled with a scarcity of fuel and consequent reduced burning, leads to low-strength, relatively porous, permeable products.

Sand and gravel are not plentiful in these quadrangles and as a result are very little used. The broad river and creek valleys are mostly floored with fine sand and silt, and the narrow canyons are cut in bedrock stripped of most of the surficial cover. Only locally along the Rio Piracicaba are there deposits of material suitable for concrete aggregate or road metal, and no sustained sand and gravel operation exist. In these quadrangles and in the eastern Quadrilátero Ferrífero, most of the concrete aggregate and road metal used is produced by crushing and screening gneiss.

MINES, DEPOSITS, PROSPECTS, AND QUARRIES

IRON ORE MINES AND DEPOSITS

ANDRADE MINE AREA

The Andrade mine (pl. 1, No. 1) is on the northeast flank of the Pico do Andrade 8 kilometers northwest of Monlevade. This mine is linked to the Usina Monlevade by a 10-kilometer meter-gage electrified railroad completed late in 1944. A well-maintained gravel road connects the mine with Monlevade via Carneirinhos.

The massive hematite outcrops have probably been known for many years but were not developed by João Monlevade and other early iron producers in the area, as sufficient ore was available much nearer to the operation and in more easily accessible areas. The present operation at Monlevade was based initially on ore from the Tanque mine at Monlevade.

The Andrade deposit is on the Fazenda de Andrade, which along with several smaller fazendas was acquired by CSBM in 1921. The deposit was explored by the company from 1936 to 1940. During this time, 55 adits and tunnels totaling 3,640 meters in length were driven, and 130 pits aggregating 1,010 meters were sunk, making this the most thoroughly explored iron ore deposit in Brazil. At the time of the author's study in 1959, nearly all these early exploration works were inaccessible or had been obliterated by the opencut mining operations. However, data concerning the early exploration were available in the files of CSBM, and much use was made of them.

The Andrade mine was placed in production in 1946, about a year after completion of the railroad. Production to the end of 1958 totals 2,711,398 metric tons; annual production is given in table 5.

TABLE 5.—*Production, Andrade and Tanque mines, in metric tons*

[Data furnished by and published with permission of the CSBM]

	Tanque mine	Andrade mine		Tanque mine	Andrade mine
1937	18,751		1949		147,723
1938	48,415		1950		218,906
1939	80,815		1951		206,775
1940	103,122		1952		206,735
1941	60,845		1953		228,045
1942	47,334		1954		271,840
1943	25,239		1955		214,430
1944	61,400		1956		295,350
1945	39,431		1957		281,240
1946	44,116	73,556	1958		310,480
1947	3,345	132,407			
1948		123,911	Total	532,813	2,711,398

The deposit is mined by a series of benches extending from the top to the base of the Pico do Andrade. The working faces of the benches are 20 meters high. The benches are linked to each other and to the crushing plant by roads that have a maximum grade of 8 percent. The ore is delivered to a crushing plant, consisting of a 90 by 120 cm jaw crusher and two ARBED cone crushers. The ore is crushed to 8 cm and separated by screening into a <24-mm fraction and into a >24- to 55-mm fraction; the ore is then stored in bins from which it is discharged into railroad cars and hauled to Monlevade. The <24-mm fraction is further separated by screening into a <12-mm fraction and into a >12- to 24-mm fraction. The product ranging from >24 to 55 mm is used in the Siemens-Martins steel furnaces. The <24-mm material is used in the blast furnaces; it is screened again at the present sintering plant, and the fines are sintered. A new sintering plant is under construction adjacent to the crushing plant (fig. 24); when it is finished, only sinter will be used in the blast furnaces. Only a small amount of raw ore, for use as hard lump open-hearth ore, will then be hauled from the mine.

The Andrade iron deposit is in the trough of the tight northeast-plunging Andrade syncline. The Cauê Itabirite is well exposed in the trough of the syncline. Here, beds of itabirite and of hematite that has replaced the itabirite show minor folding, crumpling and squeezing, and a pronounced lineation (fig. 24). In the center of the syncline, the squeezing and buckling has produced a small anticline, forming a double-troughed syncline. The folding and accompanying interbed movements produced the normal subsidiary and drag folds, most of which clearly indicate the direction of movement, (fig. 25).

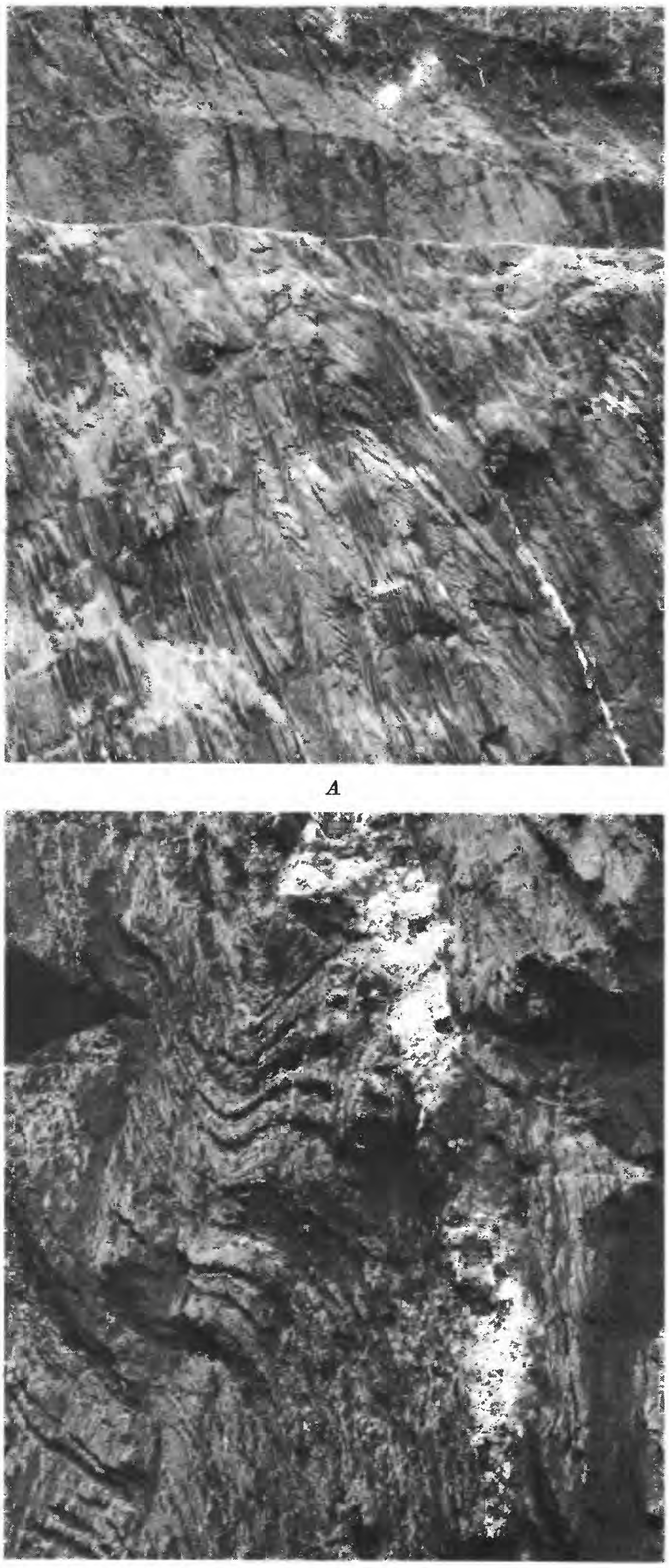
The ore occurs in the troughs of the syncline and for more than 1,000 meters along the east flank. The ore body as it crops out or is exposed in the opencut mining operations is arcuate, concave to the northeast. The body thins to the east, and the hematite grades into itabirite, although some small and a few extensive lenses of ore occur in the Cauê Itabirite between the Andrade and Tanque mines. To the north, the ore

FIGURE 24.—Andrade mine in 1958. View is southeast. The pronounced northeast lineation in the ore is clearly shown in the cuts above the benches. The crushing and sintering plant then under construction is in the foreground.

also grades into itabirite; in this direction, very little ore occurs in the itabirite north of the main ore body.

The hematite ore at the Andrade mine consists of all types and classes (discussed on p. E30–E37). The distribution of the various types of ore and itabirite is highly irregular, and it was not feasible to map them separately. Not uncommonly, alternations of equigranular and schistose material occur in bands, lenses, and irregular forms from a few tenths of a meter to several meters is size. These changes may take place both laterally and perpendicularly to stratification. In general, however, the itabirite occurs in distinct and persistent beds that are more prevalent near the stratigraphic base and on the flanks of the ore body than in its central part. Schistose ore is the most widespread, followed by rodded ore and equigranular ore in about equal proportions.

It is not possible to effectively and economically separate the various types of ores during mining, although zones in which either equigranular or schistose ore predominates can be selectively mined. An attempt has been made during the past several years to mine



A

B

FIGURE 25.—Highly deformed itabirite, northwestern limb of Andrade syncline, Andrade mine. *A*, View of cut made for construction purposes. Distance from top to bottom of photograph is approximatley 8 meters. *B*, Closeup of minor folds. White streak is veinlike quartz segregation, 7 centimeters wide. Width of field is approximately 1 meter.

from zones in which relatively hard ore (coarse equigranular or schistose) predominates (Peter Zwetkopf, oral commun., 1961).

The equigranular ore produces the highest proportion of hard to soft ore, and finely rodded ore produces the highest proportion of soft to hard ore.

The ore at the Andrade mine, whether hard or soft, is of unusually uniform composition. The weighted average, determined during the 1936-40 company exploration, of 44 million tons of hard ore, both compact and schistose, is 67.92 percent iron and 1.36 percent silica. The average grade of 33 million tons of intermediate to soft ore is 65.21 percent iron and 2.26 percent silica. The average grade of 77 million tons of high-grade hematite ore of all classes (hard, intermediate, and soft) is 66.73 percent iron and 1.88 percent silica. The ore body includes 22 million tons of rich itabirite and enriched itabirite that has an average grade of 47.4 percent iron and 29.6 percent silica. The average grade of the 99 million tons within the explored part of the ore body is 61.3 percent iron and 9.4 percent silica.

With selective mining to exclude itabirite, but without attempting to exclude soft ore, the average grade can be maintained at very near that determined for ore-grade material during the 1936–40 exploration. During 1959 and 1960 the yearly average (unweighted) of the monthly production averages was respectively 66.63 and 66.80 percent iron, 2.23 and 1.80 percent silica, 1.41 and 1.19 percent alumina, and 0.083 and 0.099 percent phosphorus. The average (unweighted) of the monthly averages of fines used in the production of sinter in 1961 was 66.62 percent iron, 1.67 percent silica, 1.34 percent alumina, and 0.137 percent phosphorus.

The median length of the ore body is approximately 2,100 meters, extending from the Pico do Andrade slightly north of east for about 1,500 meters and from the peak to the north about 600 meters. The average stratigraphic thickness is about 100 meters. Upward, the ore body comes to a point at the Pico do Andrade, at an elevation of 1114.9 meters. On the flanks, the lowest points at which ore crops out are 710 meters in the east and 840 meters in the north. On the basis of this configuration (pl. 4) and a projection down to the level of the Rio Santa Bárbara (570 m. or 140 m. below the lowest outcrop), the ore body contains 116 million cubic meters of ore and itabirite and enriched itabirite.

The data obtained during the extensive 1936–40 exploration indicate that about 25 percent of volume of the ore body is itabirite and that the remainder is almost evenly divided between hard and soft ore. Although the exploration data are used in computing the measured reserves of the explored part of the ore body, the calculations of the inferred reserves are based on the assumption that the configuration of the ore body, the character of the ore, and the proportions of itabirite and hard and soft ore do not change materially between the lowest outcrops and the river level. If calculations are based on these data and densities of 4.8 for hard ore in place, 4.5 for soft ore in place, and 3.8 for itabirite in place, the ore body is estimated to contain about 500 million metric tons of ore and itabirite (table 6). Measured and indicated reserves, those above the lowermost outcrops, total 147 million metric tons of hard ore, 130 million metric tons of soft ore, and 77 millions of tons of itabirite. Inferred reserves, those between the lowermost outcrops and the river level, are 62.5 million metric tons of hard ore, 57.5 million metric tons of soft ore, and 33 million metric tons of itabirite.

TANQUE MINE AREA

The Tanque mine (pl. 1, No. 2) is 6 kilometers southeast of the Andrade deposit and is less than 1 kilometer north-northwest of the northern part of the Usina Monlevade. The mine consists of several separate lenses of ore; these lenses occur on both sides of the present Monlevade-Carneirinhos road. The sintering plant is just east of the southeastern or Bonhote deposit. A railroad formerly connected the deposits with the blast furnaces, but it and all other mining and ore-handling installations have been removed.

During the most recent operation at Monlevade, by CSBM, production commenced in 1937 and was discontinued in 1947. In almost 11 years of operation, about 533,000 metric tons of high-grade hematite ore was produced (table 5) by open-pit mining.

The deposit and the surrounding area have also been explored by some 10 adits and a large number of pits. This work delimited the main ore body and revealed only small lenses of high-grade hematite ore surrounded by much larger areas of itabirite or enriched itabirite, and the mine was abandoned after development of the Andrade ore deposit.

Very little ore remains exposed; opening of several small faces to obtain fill for the soccer field and roads exposed a very soft, powdery hematite entirely unsuitable for direct charge into the blast furnaces but which would be suitable for sintering.

The Tanque deposit is in the trough of the northeast-plunging Tanque syncline. The Tanque syncline appears to be less tightly folded than the Andrade syncline, and the itabirite and the ore are less deformed. Itabirite in the trough of the Tanque syncline is well exposed opposite the mine on the north side of the Córrego do Carneirinhos in a roadcut on the Monlevade-Itabira road. Here, the itabirite is crumpled and contorted but has not been as intensely deformed as in the Andrade syncline. Within the mine area the syncline plunges from 10° to 15° NE.

All stratigraphic units from the Monlevade Gneiss to the Sítio Largo Amphibolite are exposed in the Tanque mine area. The ore was formed within the Cauê Itabirite. The contact between the Cauê Itabirite and the underlying Batatal Formation is well exposed in the Monlevade-Itabira roadcut. There, the contact is gradational; thin beds of itabirite are interlayered with quartz-mica schist, the proportion of schist decreasing upward. The lowermost itabirite bed is about 20 meters below the main itabirite bed.

MORRO AGUDO IRON ORE DEPOSIT

The Morro Agudo deposit (pl. 2, No. 3) is in the west-central part of the Rio Piracicaba quadrangle, about 5.5 kilometers west-northwest of the town of Rio Piracicaba. The deposit is reached by road from the Fazenda do Cururú in the Florália quadrangle, 1 kilometer west of the border between that quadrangle and the Rio Piracicaba quadrangle.

Morro Agudo is a sharp conical peak rising 1175 meters above sea level; it may be seen for many kilometers. The peak is the common corner of four properties; a westernmost pie-shaped segment belongs to a neighboring ranch. The remainder of the properties and most of the ore deposit were acquired by CSBM from the Brazilian Iron and Steel Co.

TABLE 6.—*Reserves of ore and itabirite in the Andrade ore body*

Type of material	Specific gravity	Average grade (percent Fe)	Measured (explored area)		Indicated (below explored area and above lowest outcrops)		Inferred (between lowest outcrops and river level)		Total	
			Cubic meters	Metric tons	Cubic meters	Metric tons	Cubic meters	Metric tons	Cubic meters	Metric tons
Itabirite	3.8	47.4	5,800,000	22,000,000	14,400,000	55,000,000	8,800,000	33,000,000	29,000,000	110,000,000
Hard ore	4.8	67.9	9,200,000	44,000,000	21,500,000	103,000,000	12,800,000	62,500,000	43,500,000	209,500,000
Soft ore	4.5	65.2	7,300,000	33,000,000	21,500,000	97,000,000	12,800,000	57,500,000	43,500,000	187,500,000
Total	4.4	61.3	22,300,000	99,000,000	57,400,000	255,000,000	34,400,000	153,000,000	116,000,000	507,000,000

The Morro Agudo ore deposit was studied by R. T. Chamberlin, E. C. Harder, and Harmon Lewis from 1910 to 1914. In 1914 Lewis mapped the deposit on a scale of 1:2,000 and accurately showed the contacts and hematite outcrops based on natural exposures and deep trenching. Their map has proved invaluable in this present study. A clearer understanding of the major structural and stratigraphic features, based on the regional mapping, aided in reinterpreting the structure of the deposit and enclosing rocks. This reinterpretation slightly increases the inferred size of the deposit.

In 1961 CSBM began exploration preparatory to exploiting the Morro Agudo deposit. This exploration, consisting of adits in the flanks of the deposit and diamond-drill holes in the axis of the syncline, confirmed the general shape of the deposit as deduced from surface data. The infolding in the axial zone of the upper ore body is deeper than indicated by surface evidence, and the syncline in the lower ore body is shallower than deduced. The exploration has not been completed at the time of the author's last visit to the property in early 1961.

The Morro Agudo deposit is in the trough of a southeastward-trending syncline, here named after the peak. The crest and southeast slope of Morro Agudo consist mostly of hard hematite ore that has replaced Cauê Itabirite; part of the slope is covered by canga, and some unreplaced itabirite crops out. The deposit is underlain by 50 meters of Caraça Group undivided, which is in turn underlain by Monlevade Gneiss.

The Morro Agudo deposit consists of two distinct ore bodies, separated by an inferred fault here called the Morro Agudo fault (pl. 5). The fault itself is not well exposed at the surface and has not been penetrated by subsurface exploration; however, its surface position may be established within a few meters. The principal evidence for its existence resulted from diamond drilling, which showed that, just west of the fault, the lower contact of the ore body is at an altitude of 700 meters. Immediately east of the fault, the lower contact crops out at an altitude of 870 meters (pl. 5, sec. *F–F′*). The total dip slip component of the fault is estimated at 300 meters based on a projection of the western ore body to the inferred fault position. There is no indication of strike slip. The fault is probably a reverse fault or perhaps a thrust fault; the eastern block was dragged westward and upward by left lateral movement on the Rio Piracicaba fault, which is inferred to cross the area immediately north of the deposit.

The western ore body is named the Pico and the eastern, the Espalhado. The Pico extends southeastward from the peak to the Córrego do Espalhado in the valley that follows the fault, and the Espalhado extends eastward from the creek.

The Pico ore body is 150–200 meters wide and about 750 meters long; it is well exposed through a vertical range of about 50 meters around the northwest, west, and south flanks of Morro Agudo peak and was further penetrated by several adits and diamond-drill holes. The maximum width, slightly over 200 meters, is through the peak of Morro Agudo. The maximum stratigraphic thickness, 190 meters, is at the eastern end of the ore body. Its average plunge is 17°.

The Espalhado ore body is triangular in plan, wedging out to the west, just east of the Córrego do Espalhado, and widening out to the east. It is at least 400 meters long, slightly over 400 meters wide, and as much as 40 meters thick. Its northern, western, and southwestern boundaries can be approximately located from the few existing outcrops, and its eastern boundary is placed 500 meters east of the creek (pl. 5), where it is inferred to plunge under the overlying Bicas Gneiss Member of the Elefante Formation.

The ore exposed at the surface of the Morro Agudo deposit is fine- to medium-grained hard hematite; no quartz could be detected when the ore was examined with the hand lens. The deposit was sampled by geologists of the Brazilian Iron and Steel Co., and one check sample was taken during the present study. Results of the sampling (table 7) attest to the purity of the ore. Most outcrops consist of compact and equigranular ore, but much of the ore found in underground exploration is schistose (fig. 21). The deposit contains lenses and layers of unreplaced itabirite or partly replaced enriched itabirite; these lenses and layers are more numerous and form a higher proportion of the total material in the eastern part of the Corpo do Pico ore body. The unreplaced or partly replaced itabirite is estimated to make up from ½ to ⅓ of the body. Incomplete exploration data indicate that about half of the high-grade hematite ore is hard or intermediate and that half is soft or intermediate soft.

The volume of the Pico ore body is about 12 million cubic meters and that of the Espalhado ore body, if based on an average thickness of 20 meters, is about 3 million cubic meters. If one calculates from these volumes and uses a specific gravity of 4.5 for high-grade hematite ore and 3.75 for itabirite (50 percent Fe content), reserves of the Morro Agudo deposit are 34.9 million tons of high-grade hematite ore and 28.5 million tons of itabirite (table 8).

TABLE 7.—*Analyses of Morro Agudo ore*

	Pico ore body								Espalhado ore body
	1	2	3	4	5	6	7	8	9
Fe	69.5	69.90	69.90	69.95	69.90	70.00	70.10	69.85	67.97
P	.0015	.007	.012	.006	.006	.003	.005	.004	.03
H_2O	----------	.43	.45	.38	.48	.45	.40	.49	.16
Mn	----------	nd	----------	.02	----------	----------	----------	----------	.02
SiO_2	----------	.11	.04	.07	.08	.06	.06	.06	1.87

1. Collected by R. T. Chamberlin, 1911; Arthur Houle, analyst.
2–8. Collected by R. T. Chamberlin, 1911; H. K. Shearer, analyst.
9. Collected by R. G. Reeves, 1959; analyzed in the laboratory of CSBM, Monlevade.

MORRO DA ÁGUA LIMPA IRON ORE DEPOSIT

The Morro da Água Limpa iron ore deposit (pl. 2, No. 4) is on Morro da Água Limpa, 7 kilometers west of the town of Rio Piracicaba and along the west edge of the Rio Piracicaba quadrangle. The deposit occupies most of the top of an east-trending ridge about 1.5 kilometers long. The 1,058-meter high Morro da Água Limpa is the highest point on this ridge. A road extends eastward from the Fazenda do Cururú (in the Florália quadrangle, 1 kilometer west of the Rio Piracicaba quadrangle) along the north slope of the Morro da Água Limpa at about 850 meters elevation. Several ephemeral trails lead from this road to the ridge crest.

The deposit was studied in 1912 by Harmon Lewis, geologist of the Brazilian Iron and Steel Co., who made a geologic sketch map and estimate of the ore reserves. Both the Brazilian Iron and Steel Co. and British interests, represented by an English mining engineer named Atherton, residing in Florália, were negotiating for the property in 1912. Records of the results of the negotiations are incomplete, but it appears that neither acquired rights to the property. CSBM acquired the property through the purchase of the Fazenda do Cururú for silvicultural purposes. In 1961, when this report was being completed, CSBM started exploration (a program consisting of trenching, tunneling, and drilling). This had not been concluded at the time of the author's last visit to the deposit in December 1961.

TABLE 8.—*Ore reserves of the Morro Agudo deposit, in metric tons*

	Ore			Itabirite	Total
	Hard	Soft	Total		
Pica ore body (indicated)	14,000,000	13,500,000	27,500,000	22,500,000	50,000,000
Espalhado ore body (inferred)	3,800,000	3,600,000	7,400,000	6,000,000	13,400,000
Total deposit	17,800,000	17,100,000	34,900,000	28,500,000	63,400,000

The Morro da Agua Limpa deposit is in the trough of the Água Limpa syncline. The lithologic units exposed at the deposit are the Monlevade Gneiss, the Caraça Group undivided, and the Cauê Itabirite. Units above the Cauê Itabirite have been removed by erosion. The Caraça Group consists of about 40 meters of quartzite and quartz-mica schist. The Cauê Itabirite consists of at least 160 meters of itabirite, enriched itabirite, and various types of hematite ore.

At the Água Limpa deposit, the syncline trends east in the vicinity of the deposit, swinging to the northeast less than a kilometer east of the east end of the deposit. Where exposed at the extreme west end of the deposit, the syncline plunges about 20° E. Farther to the east, the syncline is nearly horizontal (section *A–A′*, pl. 6) and is contorted by minor cross folds. The beds at the west end of the deposit are dropped down by a fault that is tentatively considered to be the northward extension of the Água Limpa fault. Displacement down the dip of the fault is about 80 meters; there is no indication of strike slip.

The shape and extent of the Morro da Água Limpa deposit as inferred from surface data and company exploration (Dr. James Büchi, oral commun., 1962) indicate that the body extends in an east-west direction for approximately 1,000 meters. Its maximum width is estimated to be 400 meters, and the maximum thickness, about 165 meters. If one estimates on the basis of the inferred shape and extent, the deposit contains about 30 million cubic meters of itabirite, enriched itabirite, and hematite ore. The high-grade hematite ore is scattered in small lenses throughout the deposit, and it is doubtful that ore comprises one-fourth of the body. Owing to the irregular distribution of the ore and the lack of sufficient data either from surface exposures or subsurface exploration, no attempt is made to compute reserves for this deposit.

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PÉ DE SERRA IRON ORE DEPOSIT

The Pé de Serra iron ore deposit (pl. 2, No. 5) is on the Fazenda do Pé de Serra of Francisco A. de Barros. The property is 3 kilometers north-northwest of the town of Rio Piracicaba and is reached over 3.5 kilometers of steep unimproved dirt road, impassable as of 1959 during wet weather even with 4-wheel-drive vehicles. The deposit was worked in the early 1900's to provide ore for a small Catalan furnace on the Fazenda do Pé de Serra and the neighboring Fazenda do Talho Aberto. Francisco de Barros recommended mining in late 1959; ore was trucked to Rio Piracicaba, from where it was shipped by rail to Belo Horizonte and other destinations.

The deposit consists of a lens of hard hematite enclosed in Cauê Itabirite. It is on the overturned northwest limb of the Talho Aberto anticline. Here, the strata strike N. 60° E. and dip from 40° to 60° SE. Both the Cauê Itabirite and overlying Elefante Formation rocks show the effects of strong deformation, including conspicuous drag folding and extensive recrystallization of quartz and iron minerals. The ore contains from 68 to 70 percent iron and virtually no impurities other than a very small amount of silica. The extent of the ore deposit is concealed by soil and dense woods, but the deposit may be continuous with hematite ore exposed in a small creek 800 meters to the northeast. The thickness as indicated in the old pit is about 30 meters, and ore of this thickness is exposed over a length of about 50 meters.

MANGANESE MINES AND PROSPECTS

ÁGUA LIMPA MANGANESE MINE

The Água Limpa manganese mine (pl. 2, No. 6) is on the Morro da Jacutinga, an 821-meter-high conical hill about 0.75 kilometer north of the Rio Valéria. The mine is 3 kilometers west-northwest of the junction of the Rios Valéria and Piracicaba and 8 kilometers west-southwest of the town of Rio Piracicaba. It is on the main Belo Horizonte-Nova Era line of the Estrada de Ferro Central do Brasil, and passenger service and ore loading facilities are available at Pantame Station and siding, 2 kilometers east-southeast of the mine. The mine is also accessible over 12 kilometers of unimproved road from Rio Piracicaba, and over 22 kilometers of unimproved road from Santa Bárbara via Florália. The Água Limpa manganese mine is 2 kilometers south of the iron deposit of the same name on the Morro da Água Limpa.

The first recorded discovery of manganese was by Dr. James Büchi, geologist of CSBM, in 1953 when he discovered eluvial manganese-bearing material on the flanks of the Morro da Jacutinga. On a revisit to the area in late October 1953, he discovered an outcrop of manganese oxides 10 meters long and 1.5 meters thick, 20 meters below the peak of the Morro da Jacutinga. This discovery was the result of a systematic regional prospecting campaign carried out by CSBM.

Exploration of the deposit began in November 1953 and continued until May 1958. During this period the deposit was explored by six adits and crosscuts from them, totaling about 500 meters, and by about 100 cuts and trenches.

Mining commenced in 1956 in an opencut that followed the outcrop downward from the northwest flank of the peak. Surface mining ceased early in 1959 when the waste to ore ratio became too high for economic operation. Smaller amounts of ore were mined from two of the adits driven in to the northeast limb of the syncline; production continued from those after the opencut operations ended. Production, in metric tons, and grade of ore from 1956 to 1958 are as follows:

Production and ore grade at Água Limpa mine

	Production (metric tons)	Ore grade (percent)		
		Mn	Fe	SiO_2
1956	1,545	32.20	25.61	8.08
1957	4,030	35.42	20.91	8.50
1958	1,470	34.21	21.82	8.47

All mining in both the opencut and adits was by hand; this included drilling, sorting, stockpiling, and loading of ore into trucks for the haul to the railroad loading point at Pantame Station. The ore was mostly broken by pick and sledge hammer. At places, drilling and blasting was necessary. The ore was sorted into two fractions by forks with tines about 10 centimeters apart; a coarse fraction remains on the fork and a fine fraction passes through the tines. The coarse fraction was generally used in the blast and openhearth furnaces of CSBM at Monlevade and Sabará. The fine fraction was used in the sintering plant at Monlevade, where it was mixed with iron-ore fines, and with limestone and charcoal to produce a manganiferous self-fluxing sinter.

The mine area is underlain by Minas Series metasedimentary rocks (pl. 7). The lowermost unit is Caraça Group, overlain by Cauê Itabirite and manganiferous itabirite. Quartz-muscovite schist and intercalated itabirite of the Pantame Member overlie the Cauê Itabirite.

At the Água Limpa manganese mine, the Cauê Itabirite is separated into an upper and lower part by a manganese-bearing bed about 100 meters above the base of the formation. The lower part of the formation is characterized by well-formed crystals, mostly dodecahedrons of magnetite 0.05–2.0 mm in diameter. Many of the crystals are only slightly magnetic, probably resulting from their alteration to martite. These magnetite-martite crystals are the only iron oxide minerals in some specimens; in others, specularite is abundant and may exceed magnetite. In the upper part of the formation above the manganese bed, the iron oxide is mostly specularite in small thin crystals. The thickness of the crystals is 0.02–0.05 mm, and the diameter, 0.05–0.2 mm; most of the crystals are between 0.05 and 0.1 mm in diameter. Quartz occurs throughout the itabirite as stubby subhedral prisms 0.1–0.5 mm in diameter and in length.

In the mine area the strata are folded into an overturned isoclinal syncline plunging 40°–60° SE., to which the name Morro da Jacutinga has been given. The overturned northeast limb dips 70° NE. The upright southweast limb dips 40°–60° NE. The southwest limb includes subsidiary folds that produce complex arcuate outcrops. The axis of the syncline is sinuous but trends generally southeast from the Morro da Jacutinga.

Isoclinal folding has produced structural thickening of the metasedimentary strata. Immediately west of the mine area, along the Água Limpa-Florália road, the Cauê Itabirite is 80 meters thick. Where well exposed in a creek about 1.5 kilometers east of the mine, this formation is about 120 meters thick. Within the mine area, its thickness ranges from about 150 meters on the flanks of the fold to slightly more than 200 meters in the axial zone. A stratigraphic thickness of at least 100 meters of quartz-muscovite schist of the Caraça Group is exposed between the Água Limpa fault and the base of the Itabira Group. Although it is difficult to ascertain the normal thickness of the schist owing to the lack of a definite break between it and the underlying quartzite, the schist within the mine area appears to correspond to the upper 25 or 30 meters of the Caraça Group. Apparently the structural thickening in the schist is relatively greater than that in the itabirite, and the schist may be up to four times normal thickness.

The intense folding has also produced a pronounced lineation in the itabirite. This lineation is especially apparent in the upper part of the Cauê Itabirite; it is caused by a segregation of quartz and hematite (specularite) into rods or pencils. The trend of the lineation is nearly parallel to the altitude of the fold axis (40°–60° SE.).

Minor folds having their axes parallel to the axis of the syncline are common in the Cauê Itabirite and overlying Pantame Member quartz-muscovite schist.

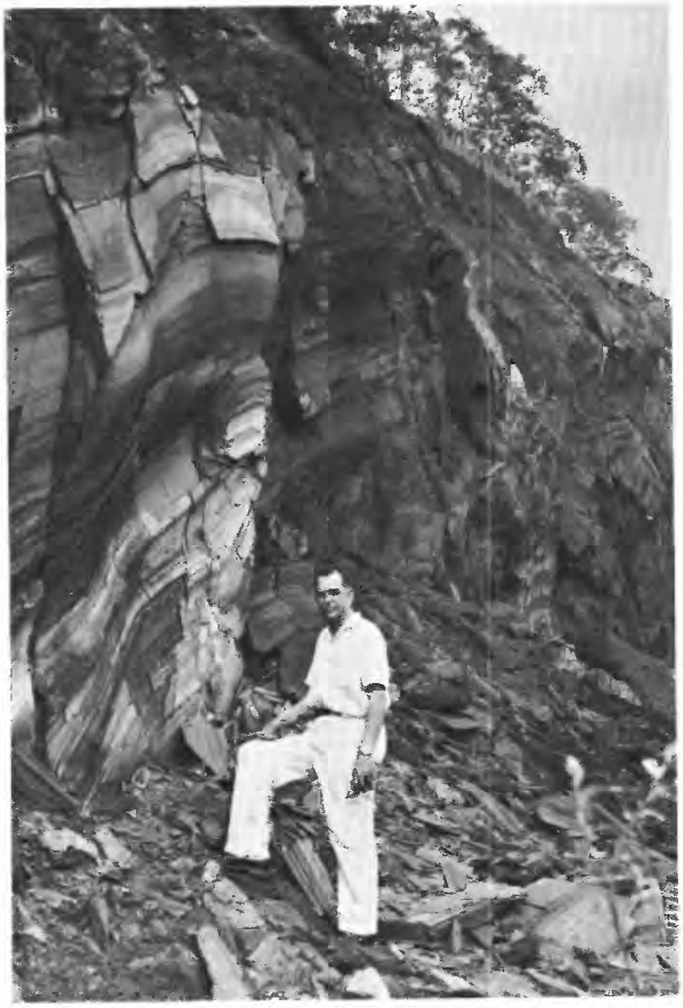

FIGURE 26.—Drag-folded manganiferous itabirite on the northeast (overturned) flank of the Morro da Jacutinga syncline, Água Limpa manganese mine.

These are best exposed on the northeast flank of the Morro da Jacutinga syncline (fig. 26).

The manganese ore ranges from 0.5 to 2 meters thick and averages 1 meter. Locally, the thickness changes greatly in short lateral distances. The ore consists of a mixture of earthy manganese oxides, euhedral magnetite crystals, and fine-grained crystalline hematite. The manganese oxides have been identified by X-ray [12] as chiefly cryptomelane and pyrolusite. Braunite may be present in small amounts, but its peaks were mostly masked by those of the other oxides.

The magnetite crystals are almost without exception in the form of perfect octahedrons that range in size from about 1 to 12 mm along the edges of the faces (fig. 27). A chemical analysis of crystals removed

[12] Analyses made at Zurich Univ., Switzerland, James Büchi, oral commun., 1959; analyses made in the laboratories of the U.S. Geological Survey, Elliot Morris, analyst; and analyses by the author and Profs. M. L. M. Formosa and Mauricio Ribeiro of the Rio Grande do Sul Univ.

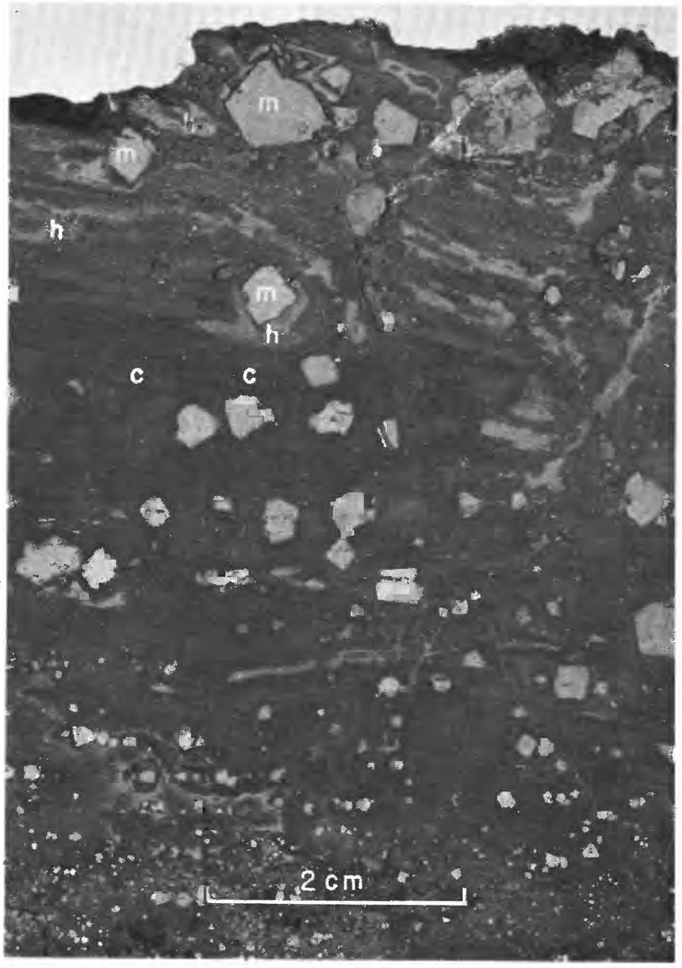

FIGURE 27.—Manganese ore from the Água Limpa manganese mine; contains magnetite (light gray, m) set in a matrix of cryptomelane (dark gray, c). Light-gray streaks are mostly fine grained hematite (h).

from the matrix and thoroughly cleaned showed the following chemical composition, in percent (James Büchi, written commun., 1959):

FeO	20.25	MgO	Trace
Fe_2O_3	71.11	CaO	Trace
Fe	(65.56)	Al_2O_3	0.71
Mn_3O_4	7.34	SiO_2	.44
Mn	(5.31)	Total	99.85
P_2O_5	Trace		

Comparison of this chemical composition with those given by Palache, Berman, and Frondel (1944, p. 700), in addition to the high magnetism (jacobsite is only weakly magnetic) indicates that the mineral is manganoan magnetite rather than the Mn-Mg-Fe member of the magnetite series, jacobsite. Results of X-ray studies of the manganoan magnetite by Elliot Morris, U.S. Geological Survey, indicate a cell length of 8.4 A.

The hematite occurs as fine crystalline grains in streaks and agglomerations in a cryptomelane-pyrolusite-braunite(?) matrix.

The manganese ore of the Água Limpa manganese mine probably formed through supergene enrichment of preexisting manganiferous itabirite, as previously discussed (p. E38), by manganese-bearing solutions migrating into the trough of the Morro da Jacutinga syncline.

The association of magnetite with the manganese ore at the Água Limpa manganese mine permits the use of the dip needle and other geophysical instruments to discover concealed deposits. At the Água Limpa mine, the itabirite is sufficiently magnetic to affect a handheld dip needle. However, the magnetite-bearing manganese layers are much more magnetic and exert a much greater effect on the dip needle. Dip-needle traverses across the itabirite bed disclosed several magnetic zones in addition to the main zone. It was likewise possible to follow the main zone several hundred meters southwest of its last exposure along the Rio Piracicaba-Florália road.

The shape of the manganese ore body is controlled by the folding of the enclosing rocks. The principal ore body is within the Morro da Jacutinga syncline; it is U-shaped in section, with the distances between the arms of the U ranging from 150 to 225 meters. The length of the ore body, from the level at which mining ceased in 1959 (800-meter) to the lowermost workings (adit 1), is 350 meters. The maximum depth to the base of the U, based on an average projected plunge of 30°, is 200 meters (normal to the plunge), and the average depth is 150 meters. If the amount of manganese-bearing material is calculated on the basis of the above shape and size and an average thickness of 1 meter, the part of the deposit within the Morro da Jacutinga syncline contains approximately 100,000 cubic meters of this material. The manganese-bearing material on the contorted southwest limb of the syncline and adjacent anticline is not considered, as its thickness is much less (0.3 meter) and its manganese content, lower. If calculated on the basis of a specific gravity of 3.5, the amount of material is 350,000 tons. However, owing to economic conditions obtaining at the time of this report and predicted for the foreseeable future, most of this material is not manganese ore.

MANGANESE PROSPECTS

In addition to the Água Limpa deposit, a number of manganese occurrences were found during the systematic prospecting campaign by CSBM in the mid 1950's. Six of the most promising, the Espigão das Cobras, Espigão do Elefante, Espigão do Raimundo João, Espigão da Venda, Pantame, and Sítio Largo, were explored by trenches, pits or shallow shafts, short adits, or combinations of these methods. The prospecting and the exploration were under the direction of Dr. James Büchi; data and geologic information of workings that were inaccessible during the time of this study were kindly made available by CSBM.

Three of the prospects, the Espigão do Raimundo João, Espigão da Venda, and Pantame are associated with manganiferous itabirite of the Cauê Itabirite east of the Água Limpa manganese mine. The Espigão das Cobras, Espigão do Elefante, and Sítio Largo are associated with manganiferous beds or zones in the Elefante Formation. Manganese ore in commercial quantities was not found in these prospects, and all exploration activities on them ceased in 1958.

The Espigão das Cobras manganese prospect (pl. 2, No. 7) is 4.5 kilometers west of the town of Rio Piracicaba and 2 kilometers southeast of Morro Agudo. It is reached over a trail about 3 kilometers long that leaves the Rio Piracicaba-Água Limpa-Florália road at Fundão de Cima, 3 kilometers (by road) southwest of Rio Piracicaba. It was explored by a 62-meter tunnel and several trenches.

The prospect is in the Pantame Member of the Elefante Formation, on the north limb of Morro da Água Limpa syncline. Within the tunnel, the beds strike northward and dip eastward; however, beds at an outcrop about 75 meters southwest of the tunnel strike northeast and dip northwest. The area is near the keel of the syncline, and evidence points to minor folding; some of the folds have an amplitude of several tens of meters in the keel zone, and as a result of these folds the beds change strike and reverse dip.

The manganese occurs in a 4-meter thick bed of itabirite and manganiferous itabirite. Most of the dark-colored layers of the itabirite consist mainly of fine-grained specularite, but in some, manganese oxide minerals predominate over specularite.

The Espigão do Elefante prospect (pl. 2, No. 8) is on the south bank of the Córrego do Elefante, about 1.5 kilometers northeast of the crest of the Serra do Elefante and 3 kilometers west of the town of Rio Piracicaba. It is reached by a trail about 2 kilometers long that leaves the Rio Piracicaba-Florália road 3 kilometers southwest of Rio Piracicaba. The prospect was explored by one adit, one tunnel, and nine test pits. Ore was not found in sufficient quantity to warrant exploitation, and there has been no production from this property.

The manganese occurs in the Bicas Gneiss Member of the Elefante Formation, in thin lenses, conformable with layering in the gneiss. The lenses are 5–15 cm thick and several meters to several tens of meters long. The Bicas Gneiss Member host rock is a garnetiferous quartz-biotite gneiss; the only exposures were in badly weathered gneiss saprolite.

The Espigão do Raimundo João manganese prospect (pl. 2, No. 9) is about 400 meters northwest of Pantame Station, from which it is reached by trail. Exploration consisted of several opencuts and a 30-meter adit.

Manganese occurs as thin and discontinuous layers near the top of the Cauê Itabirite. The dip of the itabirite is nearly vertical; the strike is extremely variable owing to minor folds, although the general trend is east. The main manganese bed is mostly between 0.3 and 0.4 meters thick, although at one place in a tight fold, the thickness is 1.5 meters. A sample from the trench at the Espigão do Raimundo João manganese prospect assayed, in percent:

Mn	25.71	Al_2O_3	2.34
Fe	32.00	P_2O_5	.250
SiO_2	8.66		

The main manganese bed was exposed for 60 meters in the trench and was cut at 18 meters from the portal of the adit about 20 meters below the trench. A second smaller manganese bed found in the trench was not cut at its projected location in the adit; this fact suggests that the beds are lenticular.

The Espigão da Venda manganese prospect (pl. 2, No. 10) is about 6 kilometers southwest of the town of Rio Piracicaba and about 0.75 kilometers northeast of Pantame Station.

Manganese, mainly as pyrolusite and psilomelane, occurs in a bed intercalated with manganiferous itabirite of the Cauê Itabirite. The manganese bed is 0.4–0.6 meter thick in the western end of the upper adit, but it decreases to about 0.1 meter in the eastern part of the upper adit and in the lower adit. The manganese bed is about 60 meters above the base of the Cauê Itabirite, which is here about 70 meters thick. The upper third of the formation is manganiferous. The formation has been deformed; it contains drag folds whose axes plunge 10°–20° SSE. Quartz is segregated into lenses 2–15 cm long and 1–10 cm thick that both parallel and crosscut bedding at low low angles.

Three samples of ore from an opencut along the outcrop of the manganese bed at the Espigão da Venda manganese prospect assayed as follows:

No.	Mn	Fe	SiO_2	Al_2O_3	P_2O_5
1	33.22	25.42	4.86	3.34	0.25
2	26.41	23.70	13.04	6.01	.25
3	36.80	18.95	8.08	3.84	.18

NOTE.—Analyses by and published with permission of CSBM.

1. Broken ore from bottom of opencut, below lower adit.
2. Broken ore from top of cut, near portal of upper adit.
3. Hard blue ore from upper part of cut.

The Pantame prospect (pl. 2, No. 11) is about 300 meters north of Pantame Station, from which it is reached by a steep trail. A small pile of ore from a prospect pit dating from World War I showed a fair tenor of manganese (sample 1). This pit was cleared out to enable sampling of ore in place (samples 2, 3). The three samples assayed as follows:

No.	Mn	Fe	SiO_2	Al_2O_3
1	24.37	35.80	1.72	1.29
2	27.37	34.00	1.00	1.00
3	29.71	31.32	1.34	.91

NOTE.—Information furnished by and published with permission of CSBM.

The ore consists of three thin beds of manganese oxides interbedded with manganiferous itabirite near the top of the Cauê Itabirite. Here, the beds strike east and dip 80° S. The drag folds and deformation that exist at the neighboring prospects (Espigão do Raimundo João and Espigão da Venda) are not apparent here.

The Sítio Largo manganese prospect (pl. 2, No. 12) is in the northeast corner of the Rio Piracicaba quadrangle, on the east bank of the Rio Piracicaba about 3.5 kilometers northeast of the village of Ponte Saraiva. It is along the east bank of the Rio Piracicaba on a road that extends from the town of Rio Piracicaba through Ponte Saraiva to Ponte Torta (1 km east of the Rio Piracicaba quadrangle).

At the prospect, manganese oxide minerals occur as filling in north-trending fractures in Sítio Largo Amphibolite. The Sítio Largo Amphibolite is folded into closely spaced northeast-plunging minor anticlines and synclines, and deformation at the prospect appears to be more intense than normal for the immediately surrounding area. The Cauê Itabirite, particularly the upper part, the Sítio Largo Amphibolite, and the overlying Elefante Formation contain small amounts of manganese; it is probable that the Sítio Largo prospect is a supergene concentration of manganese in a structurally favorable area.

OTHER MINES AND QUARRIES

In addition to the iron and manganese deposits that have been or were being mined, two pegmatites have been worked for mica and semiprecious gems and several quarries have been opened to provide building stone for Rio Piracicaba and Monlevade. The two pegmatites are the Pé da Serra and Talho Aberto, and the principal quarries in operation at the time of this study (1957–59) were the Jacuí, Monlevade, and Rio Piracicaba.

PÉ DE SERRA PEGMATITE MINE

The Pé de Serra pegmatite mine (pl. 2, No. 13) is 1 kilometer west-southwest of the Talho Aberto reservoir and 3.5 kilometers north-northwest of the town of Rio Piracicaba, from which it is reached over 4.5 kilometers of unimproved steep, narrow dirt road and 0.5 kilometers of trail leading from the end of the road. The deposit was discovered in late 1958 by Francisco A. de Barros and at the time of the author's visit in August 1959 was being operated by him. The principal product, mica, is hauled by mule to a loading point on the road, about 0.75 kilometer from the mine. Here, the mica is sorted, and the saleable sheets loaded on 4-wheel-drive pickup trucks for the haul to trimming stations. The mine workings consist of the following: An opencut 25 meters long; two adits, each about 5 meters long, at 12 and 16 meters from the mouth of the cut; and three short adits on various levels at the end of the cut (fig. 28).

The deposit consist of a pegmatite 1–4 meters wide in the Bicas Gneiss Member of the Elefante Formation, about 25 meters stratigraphically above the contact with the underlying Pantame Member of the Elefante Formation. The pegmatite trends about east and dips from 70° N. to vertical. The gneiss strikes N. 55° E. and dips 30° SE. The contact between the pegmatite and gneiss is irregular, and it shows both crosscutting and concordant relationships (fig. 28).

The workings are all in the weathered zone, and no fresh pegmatite is exposed in them or elsewhere. The pegmatite is a mixture of pure white to dark-brown clay, glassy vein quartz, and muscovite. No quartz crystals were apparent, but the glassy vein quartz is scattered throughout the pegmatite. A large mass of the quartz occurs along the south wall of the cut. The muscovite occurs as large, thick books having random orientation. The books, which are scattered throughout the pegmatite, range from 25 cm to about 1 meter in diameter and from 10 to 30 cm in thickness; in general, the distance between books is from 30 to 50 cm.

The muscovite appears to be fairly clear to slightly stained and reasonably free of cracks or other imperfections. According to the owner, it was of high quality, which would justify its laborious extraction and transport by mule and truck to the trimming station. The quality and grade of muscovite observed in the faces of the adits at the end of the opencut and in a small pile at the owner's house probably corresponded to ASTM visual qualities V–3 or V–4 of the "Visual classification of muscovite block mica" and to ASTM grades 1 or 2 of the "ASTM grades (sizes) of muscovite block and film mica" as given by Skow (1960, tables 1 and 2, p. 524–525).

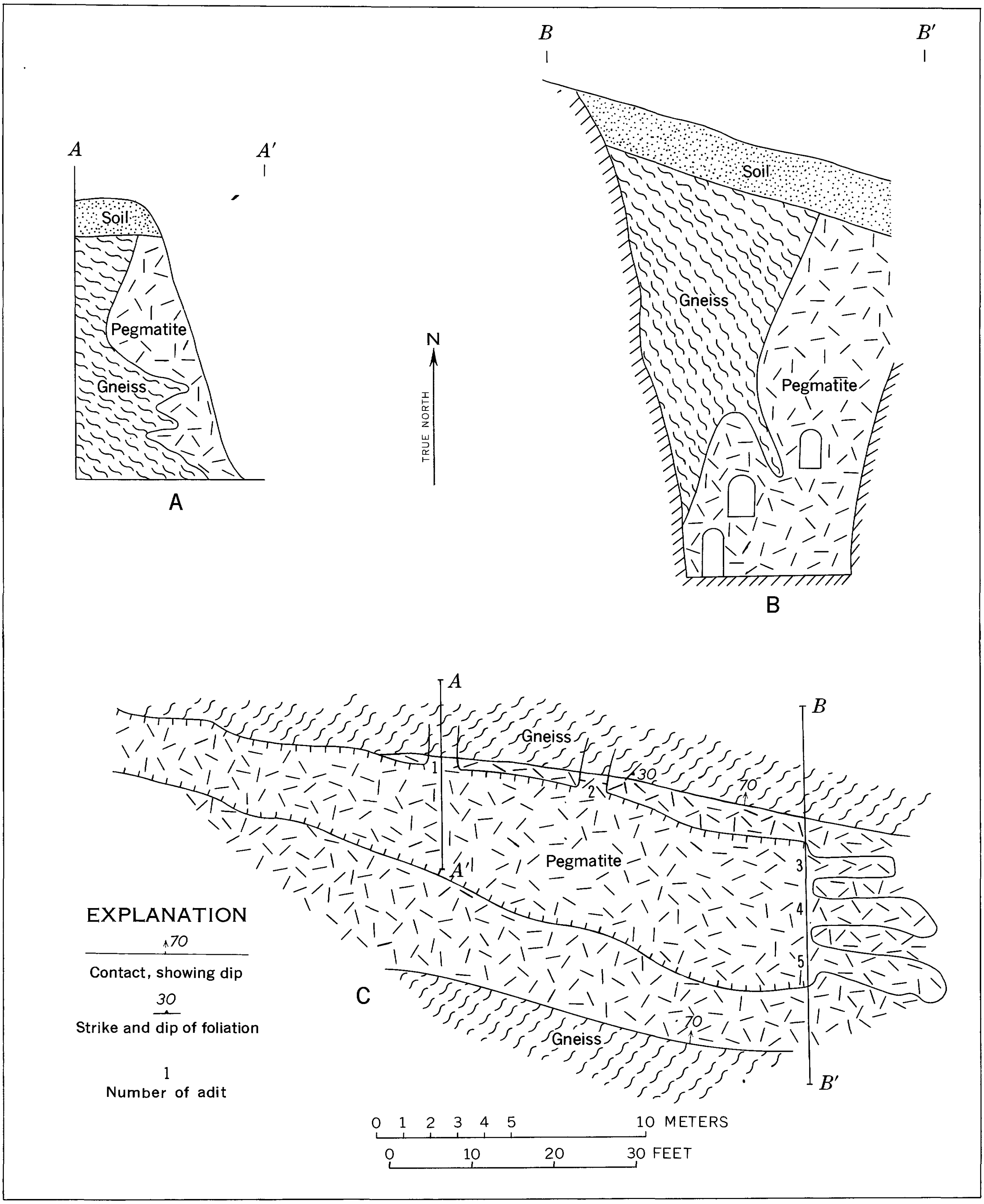

FIGURE 28.—Geologic map and sections of the Pé de Serra pegmatite mine.

TALHO ABERTO PEGMATITE MINE

The Talho Aberto pegmatite mine (pl. 2, No. 14) is at the north end of the Talho Aberto reservoir, about 4 kilometers north of the town of Rio Piracicaba. The mine is accessible by 4-wheel-drive vehicles over a steep, narrow road that leads north from Rio Piracicaba. The pegmatite was first discovered about 1900 and has been intermittently operated until the time of the author's examination in 1959. This pegmatite is famed for its exceptional phenacite crystals (Ford, 1932, p. 603), which have been studied by a number of mineralogists (Hussák, 1909 and 1917; Goldschmidt and Schroeder, 1909; Slavik, 1909; Buttgenbach, 1924; Rosicky, 1927; Saldanha, 1938). The Talho Aberto pegmatite also contains large amazonite (green microcline) crystals. The mine workings consist of an upper adit, now abandoned and partly caved; a 20 meter long lower adit about 10 meters vertically below the upper adit and a slightly inclined downward adit on the same level as the lower adit. This inclined adit was partly filled with water at the time of the examination. The mine was being intermittently operated, at the time of the author's last visit in early 1961, for amazonite which is cut for ashtrays and semiprecious gems. All the recent production has been from the lower adit.

The deposit consists of a N. 50° E.-trending pegmatite body in the Bicas Gneiss Member of the Elefante Formation. The body averages about 1 meter wide, although it varies from several meters down to 0.5 meter. The dip is 45° SE. The pegmatite shows both conformable and crosscutting relationships with the gneiss.

The pegmatite as seen in the present workings consists predominatly of quartz, potash feldspar, and muscovite. According to Hussak (1917), the pegmatite contained in addition to the phenacite, hyaline quartz, crystals (as long as 50 cm) of beautifully colored amazonite, dirty-green mica with inclusions of limonite, sparse black tourmaline in prismatic crystals, and rare monazite, zircon, columbite, xenotime, pyrite, and red almandite garnet. The phenacite occurs as well-formed crystals as much as 6 cm in size exhibiting rhomboid faces. The larger crystals contained inclusions of green mica. Many of the crystals were clear and colorless, but some were milky. The smaller crystals (less than 1 cm in diameter) were generally clear and transparent, and according to Hussak, "when cut were very beautiful owing to their high index of refraction." Crystals of intermediate size (2–3 cm) were "numerous and in their great majority almost opaque, milky white in color, and rich in fluid inclusions, and with corrosion 'figures' on all their faces" (Hussak, 1917). The quartz exposed in the workings occurs both as large, randomly oriented crystals as much as 60 cm long and as vein fillings surrounding the other constituents. The potassium feldspar is mostly amazonite; some is white to slightly pink microcline. The amazonite occurs in large nearly-perfect crystals showing random orientation; at the time of the author's visit, a large crystal 120 cm long and 24 cm in diameter and the end of another 30 cm on each side were exposed on the face of the adit. The microcline crystals are in general smaller than the amazonite crystals, and none more than 20 cm long were observed. The muscovite occurs in well-formed books, also randomly oriented, up to 40 cm in diameter and 10 cm thick.

No other beryllium minerals common to Minas Gerais pegmatite mines were found or have been reported; their "notable" absence was referred to by Hussak (1917).

JACUÍ QUARRY

The Jacuí quarry (pl. 1, No. 15) is about 3 kilometers south of Carneirinhos and 200 meters north of the new Belo Horizonte-Monlevade highway. The quarry is at the base of a bluff along the north side of Jacuí Creek. Rock is broken by blasting (blast holes are drilled by hand). The largest blocks are further broken by secondary blasting, and the remainder is broken and trimmed by hand. Most of the material produced is used for paving blocks and other building stone in Carneirinhos and vicinity.

The quarry is in the Monlevade Gneiss, in the core of the Carneirinhos anticline. The gneiss is medium grained and light gray. It has a distinct layered appearance produced by lenticular layers of quartz and feldspars, separated by discontinuous biotite laminae. It is only slightly weathered; some of the feldspars have been partly kaolinized, and biotite is bleached along joints. The gneiss is cut by nearly-vertical joints spaced from a few tenths to several meters apart, striking north-northwest.

MONLEVADE QUARRY

The Monlevade quarry (pl. 1, No. 16) is 2.5 kilometers northwest of the main part of Monlevade and 3 kilometers east of Carneirinhos. It is the base of a 100-meter-high bluff along the north side of Carneirinhos creek, on land belonging to CSBM. At the time of this study, the quarry was intermittently operated by lessors under contract, and as many as 15 men were employed during times of greatest demand. The rock is broken by blasting and handwork as described for the Jacuí quarry. Much of the production is used by CSBM for paving and construction in Monlevade.

The quarry is in the Monlevade Gneiss, on the limb between the Carneirinhos anticline and the Tanque syncline. The gneiss is medium to coarse grained and consists of segregations of coarse-grained quartz and feldspars, separated by biotite laminae. A specimen from about 75 meters below the surface and 50 meters in from the edge of the bluff shows minor weathering effects, principally alteration of the feldspar. The rock is jointed and has nearly vertically joints trending northeast and northwest. The joints and the tendency of the rock to split parallel to the biotite laminae aid in quarrying and working the rock into paving blocks and other shapes.

RIO PIRACICABA QUARRY

The Rio Piracicaba quarry (pl. 2, No. 17) is 2 kilometers west-southwest of the town of Rio Piracicaba, a few hundred meters north of the Rio Piracicaba-Água Limpa road. It is on the side of a steep hill along the northern edge of the valley of the Rio Piracicaba. The quarry furnishes most of the paving blocks and building stone used in the town of Rio Piracicaba. Most of the stone is shipped in rough or semifinished form and later trimmed in Rio Piracicaba. The rock in place is broken by blasting. Blast holes are drilled, and the smaller broken blocks are further reduced by hand.

The quarry is in the Bicas Gneiss Member of the Elefante Formation. The gneiss is light to medium gray and fine grained. It consists of quartz-feldspar layers from a few tenths of a millimeter to a millimeter thick, separated by very thin biotite laminae. The rock locally contains drag folds and other minor folds, segregations of dark hornblende-biotite-rich and silica-rich layers, and other evidence of intense deformation and metamorphism. The gneiss is cut by joints from a few tenths of a meter to several meters apart; most are steeply dipping to the southeast and trend northeast.

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