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Geology and Mineral Resources of the Congonhas District Minas Gerais, Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 290

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

Geology and Mineral Resources of the Congonhas District Minas Gerais, Brazil

By PHILIP W. GUILD

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A study of pre-Cambrian sedimentary iron formation and associated deposits of hematite and manganese ores.—Prepared in cooperation with the Departamento Nacional da Produção Mineral of Brazil under the auspices of the International Cooperation Administration of the United States Department of State

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[Plates in pocket]

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By Philip W. Guild

ABSTRACT

A thick pre-Cambrian sedimentary iron formation containing local concentrations of high-grade hematite ore occurs in an area of about 7,000 square kilometers in the "quadrilátero ferrífero" of central Minas Gerais, Brazil. Highly deformed, metamorphosed sedimentary rocks resting on a basement complex of gneiss and granite are cut by ultramafic, basic, and intermediate to acid intrusive rocks. Two sedimentary series, separated by an angular unconformity, have been mapped in the Congonhas district. The lower one, known as the Minas series, is divided by the writer into three parts: (1) a lower group of nearly iron-free quartzite and mica schist; (2) a middle group of iron formation (itabirite) and dolomite; and (3) an upper group of phyllite and subordinate quartzite, ferruginous quartzite, iron formation, dolomite, graywacke, and volcanic rocks. A thick series of green schist containing phyllite, graywacke, tuff, and thin lenses of iron formation underlies the Congonhas lowland. This series probably is, in part at least, equivalent to the typical Minas series rocks and represents an offshore, deeper water facies deposited during deep subsidence of a geosynclinal trough. The overlying Itacolumí series is composed predominantly of micaceous quartzite, but has numerous conglomerate beds containing pebbles and cobbles of vein quartz, quartzite, and itabirite, plus minor phyllite, ferruginous quartzite, and itabirite.

Ultramafic rocks, which intrude the green-schist sequence, are altered to steatite, talc schist, and serpentine. Batholiths, stocks, and dikes of granodiorite cut the green schist, steatite, and typical Minas series rocks; they are probably of post-Itacolumí age. Dark dike rocks with gabbroic affinities cut all the others. Quartz veins are abundant in many rocks of the district.

A weak orogeny in post-Minas time gently folded and lifted the rocks of the Minas series, permitting erosion and deposition of the coarse clastic sediments of the overlying Itacolumí series. A strong post-Itacolumí orogeny folded the sedimentary rocks, imposed one or more cleavages upon them, and culminated in thrusting which superposed several fault slices in the Congonhas district, where the northward- and eastward-trending structures of the quadrilateral meet at right angles. Prominent linear structures trend predominately eastward throughout the ferriferous region and with few exceptions plunge gently to steeply in that direction. An extensive transverse fault crosses most of the district and separates the typical rocks of the Minas and Itacolumí series from the green-schist sequence and its associated intrusive rocks.

Low- to medium-grade regional metamorphism which accompanied the diastrophism converted the argillaceous rocks to quartz-sericite-chlorite schist and phyllite. Tremolite-actinolite, talc, specularite, magnetite and in places spessartite, albite-oligoclase, biotite, chloritoid, almandine(?) and kyanite were formed. The metamorphic grade increases southeastward. However, aureoles of thermal metamorphism around the granodiorite intrusions complicate and obscure the picture. Sillimanite, staurolite, and other high-temperature minerals were developed locally.

Post-Mesozoic uplift and erosion has virtually destroyed an old peneplain and given rise to the present-day topographic relief of the area. The major streams are antecedent and cut through the principal ranges in deep water gaps, but most tributaries are subsequent and well adjusted to the bedrock. Remnants of several old levels in the highlands and of terraces in the lowlands indicate that uplift has been intermittent, and tilted upper Tertiary lacustrine deposits north of the Congonhas district suggest that some of it has been accomplished by block faulting.

Deep weathering has extensively altered some of the near-surface rocks, giving rise to sheets of canga (limonite-cemented detritus) and laterite over areas of itabirite and replacing some dolomite with alumina-, iron-, and manganese-rich materials. Alluvial deposits occur along streams and on a few terrace remnants.

Iron ores of the Congonhas district are of three major types: (1) unweathered or relatively unaltered itabirite; (2) hematite ores composed of nearly pure iron oxide; and (3) surficial ores. With minor exceptions all are closely associated with the middle group of the Minas series.

The principal itabirite zone ranges in thickness from 70 to more than 600 meters. The average grade is estimated to be about 40 percent iron, chiefly as specular hematite but also as subordinate magnetite. Much near-surface material has been enriched to 55 percent or more of iron by the leaching of gangue minerals (quartz and dolomite) and by redeposition of iron as limonite.

It is postulated that these unusual ferruginous sediments were deposited as chemical precipitates of iron oxide, colloidal silica, and alkaline earth carbonates brought into a restricted marine basin by one or more large rivers. The landmass was low; hence little or no clastic material was introduced. Somewhat acid conditions inhibited the precipitation of carbonates during most of the period of deposition. An offshore volcanic arc probably cut off circulation between the basin and the open ocean, and volcanic emanations may have aided in lowering the pH of waters in the basin below the "limestone fence." Regional metamorphism produced specularite and quartz from the siliceous-ferruginous precipitates, and magnetite, dolomite, and quartz from the carbonate-bearing sediments. Platy specularite was partly oriented to form an incipient cleavage.

High-grade (67–70 percent iron) hematite ore masses ranging from a ton or less to many millions of tons occur locally in

the itabirite. Sedimentary and structural features identical with those of the itabirite and associated dolomite indicate an origin through post-deformational replacement of quartz and carbonate by new specularite which probably was derived from the iron formation itself by hydrothermal solutions moving along breccia zones caused by thrust faulting. Preexisting bedding, cleavage, and breccia structures were preserved by fine-grained (average 0.01 mm), unoriented, interlocking hematite grains that contrast sharply with the unreplaced platy specularite of the original formation. Magnetite octahedra, some a centimeter across, were partly or completely altered to hematite. Both proximity to faults and variations in the carbonate content of the sedimentary rocks localized replacement; the largest known deposit of the district occurs where dolomitic itabirite was overridden by a thrust block.

Surficial leaching has dissolved minor quantities of iron from some hematite ores, destroying the intergranular cohesion and producing friable or powdery material. Mosaic-textured ore with interlocking, sutured grain boundaries resists this leaching better than ore with tabular, oriented specularite grains; and weathering therefore exhumes structures that were preserved during metamorphism and replacement.

Surficial ores have been derived mechanically from itabirite ("chapinha" or "little plate" ores) and from hematite deposits (rubble ores); and chemically by the leaching of gangue minerals and hydration of anhydrous iron oxides (laterite) and by recementation by limonite (canga).

Substantial mining of iron ore for shipment out of the district began only a few decades ago, although some metal was smelted locally in the early 19th century. Production to date is estimated at 5,000,000 tons, a minute fraction of the total ore available. Reserves of high-grade hematite are placed, in round figures, at 150,000,000 tons; of surficial ores of shipping grade at 100,000,000 tons. The quantity of itabirite above a depth of 1,000 meters is calculated as 39,000,000,000 tons containing 20,000,000,000 tons of hematite or 15,000,000,000 tons of metallic iron. Of this vast amount about 7,500,000,000 tons lie within 100 meters of the surface and might be extracted by opencut. Some of this material is sufficiently softened by leaching to be easily minable and can be concentrated by simple beneficiation to more than 60 percent iron.

Most of the present production of the district comes from the Casa de Pedra mine of the Companhia Siderúrgica Nacional and is shipped to the steel mill at Volta Redonda.

Manganese ores are widespread and were formerly mined extensively. Total production has probably been more than 500,000 tons, largely from the Miguel Burnier (São Julião) area. The principal deposits are concentrations of psilomelane and pyrolusite in favorable dolomitic zones in the middle group of the Minas series. Manganese oxides replacing phyllite and filling fractures in quartzite form much smaller deposits which have yielded a relatively small production. Oxidation of gondite (manganese silicate rock) has not been sufficient to form economic deposits in the Congonhas district. The grade of ores mined has ranged from 55 to 30 percent manganese. Known reserves of commercial ore are small, although large quantities of low-grade wad (10–20 percent manganese) may be used at some future date.

Minor mineral commodities produced at one time or another in the district include ocher, steatite, talc, metallurgical-grade dolomite, marble, and quartz crystals. Gold associated with the granodiorite intrusions and found in stream gravels first attracted settlers to the area, but the deposits were virtually exhausted more than a century ago. Deposits of bauxite may possibly be discovered in the future.

INTRODUCTION

It has long been known that Brazil has very large reserves of high-grade iron ores, but because these deposits were remote from world markets and because abundant reserves were more accessible elsewhere in the world, they were largely ignored until 1910, when Derby (1910) brought them to the attention of the geologic and mining professions at the International Geologic Congress in Stockholm. Since that time many investigations have been made by governmental agencies and by private groups. No comprehensive study was undertaken, however, and much of the literature is vague or contradictory. The existing geologic maps are either on very small scales, or are fragmentary, dealing only with small areas on inadequate base maps.

The enormous increase in consumption of iron ores throughout the world and the rate of depletion of other sources led to a joint undertaking in 1946 by the U. S. Geological Survey and its Brazilian counterpart, the Departamento Nacional da Produção Mineral, for the investigation of the most important of the Brazilian iron deposits, those occurring in the central part of the state of Minas Gerais (fig. 1). The study was initiated under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation, United States Department of State, and later incorporated into the point 4 program.

IRON REGION OF CENTRAL MINAS GERAIS

Minas Gerais, one of the larger states of the United States of Brazil, has an area of 593,810 square kilometers (about 229,00 square miles) and more than 7,000,000 inhabitants. Only São Paulo outranks it in population. As the name implies, mining, particularly for gold and diamonds, first attracted settlers to the country. Agriculture is now the principal livelihood of the people, however. Gold and diamond mining continues on a reduced scale, but iron ores give promise of restoring the state to its former prominence as a mineral producer.

In the south-central part of the state a rich iron formation crops out in long ridges within an area of about 7,000 square kilometers, and isolated remnants occur to the east and north. The dashed line of figure 1 shows the general outline of the region, although the geologic boundaries do not follow the rectangular limits of the quadrangles. Relatively large deposits of very high grade specular hematite, some of them standing as spectacular peaks high above the surrounding country, occur at several places along the formation. The iron region lies in the Central Highlands, near the head-

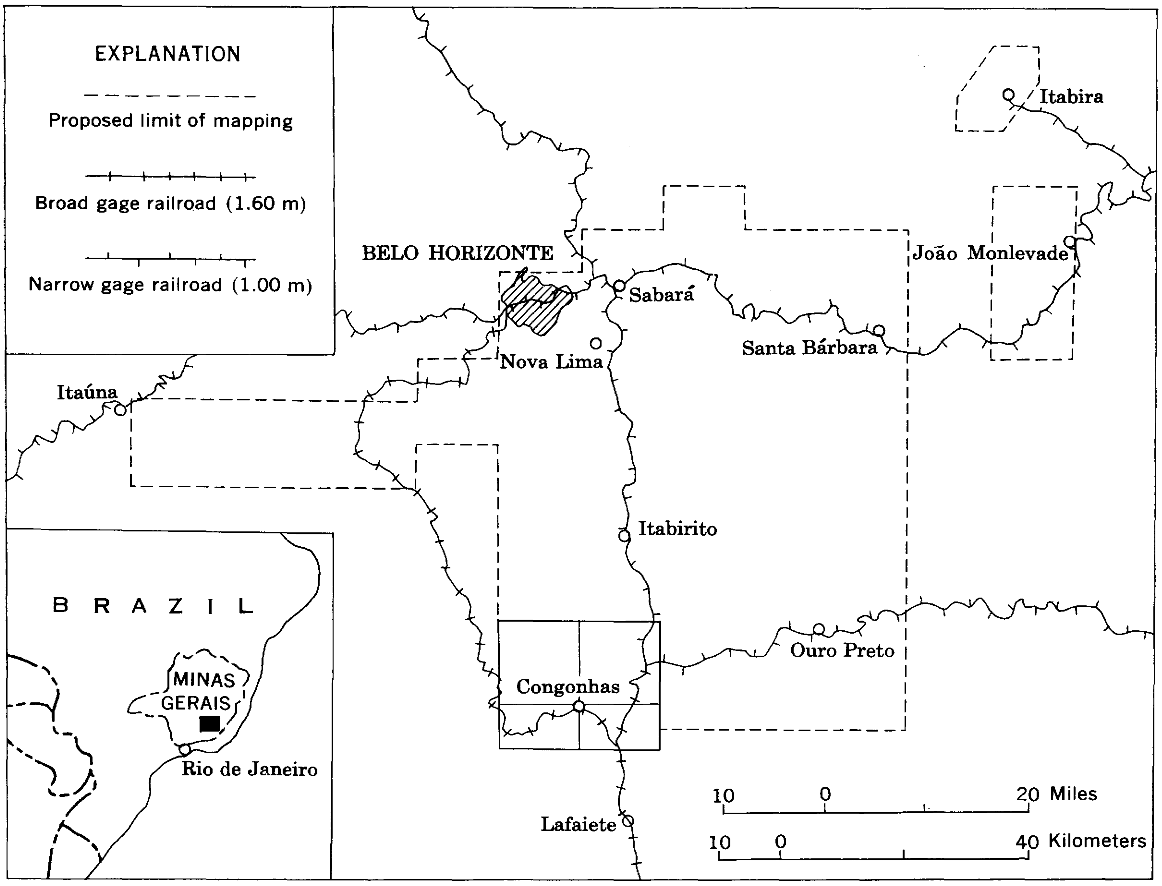

FIGURE 1.—Index map of central Minas Gerais, Brazil.

waters of two large rivers, the Rio São Francisco and the Rio Doce. The São Francisco flows northward for about 1,200 kilometers before turning eastward to the Atlantic; the Doce drains directly eastward to the ocean. The altitude within the region ranges from about 600 to 2,100 meters (1,800 to 6,400 feet), and the mountains are rugged. Although referred to in general reports as the Serra do Espinhaço (Backbone Range), many ranges exist, and local usage gives individual names to parts of single continuous ridges. The rivers, which have many rapids and falls, are deeply entrenched in the mountains. Three prominent water gaps through major ranges indicate rejuvenation of old rivers that had probably reached maturity on a relatively low peneplain before uplift in early Tertiary(?) time. Many partly dissected surfaces at different altitudes are evidence of intermittent elevation totaling many hundred meters.

The region has many small towns, most of which date back to the early gold-mining days. Ouro Preto was the capital of Minas Gerais for nearly two centuries, until a new city was built in 1897 on a site just north of the mountains where there was adequate room for expansion. This new city, Belo Horizonte, now has a population of more than 300,000 and is growing rapidly. It is modern, progressive, and well suited to be capital of a state about as large and populous as Texas.

The Estrada de Ferro Central do Brasil (Brazilian Central Railways) connects Belo Horizonte with Rio de Janeiro, about 340 kilometers (210 miles) south-southeast. Other railroads connect it with points east, north, and west. Belo Horizonte is also a highway hub, although the roads are poor by modern standards, the best are gravel surfaced. Because the railroads and roads are tortuous through the mountains, the distance to Rio de Janeiro is nearly doubled, being about 640 kilometers by rail and 600 kilometers by road. There is a modern airport at Belo Horizonte and excellent air service to all the major cities of Brazil.

The climate of the region is temperate because of the altitude, even though it is situated within the tropics between latitude 19°30′ S. and 20°45′ S. The temperature varies little from the annual mean of about 70°F, and the annual rainfall averages about 58 inches. There are essentially two seasons, the wet summer from November to February, and dry winter from April through September, with short transition periods between. The rains are not continuous, however, and dry spells of

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several weeks sometimes occur in summer. Infrequent rains occur even in mid-winter. Violent hailstorms are not uncommon, but snow is unknown.

Vegetation is not dense, except on the east edge of the region. Brazilians distinguish two regions, the "zona da mata," heavily forested country east of the São Francisco–Rio Doce divide where the precipitation is much greater, and the "zona do campo," relatively open country in the drier interior. The boundary is indistinct, however, particularly as the heavy cutting for lumber, firewood, and charcoal has denuded much of the country. Higher parts of the area generally are open or less heavily covered, principally because the soils are poor or lacking, whereas the valleys have a more luxuriant growth. The soils directly reflect the nature of the underlying rocks, as is the rule for tropical regions, and hence vegetation is often a useful guide to geologic mapping.

CONGONHAS DISTRICT

LOCATION, CULTURE, AND COMMUNICATIONS

The quadrangles covered by this report are the Casa de Pedra and São Julião full 7½-minute sheets and the Jeceaba and Congonhas half-sheets. As shown in figure 2, they lie between latitude 20°22′30″ S. and

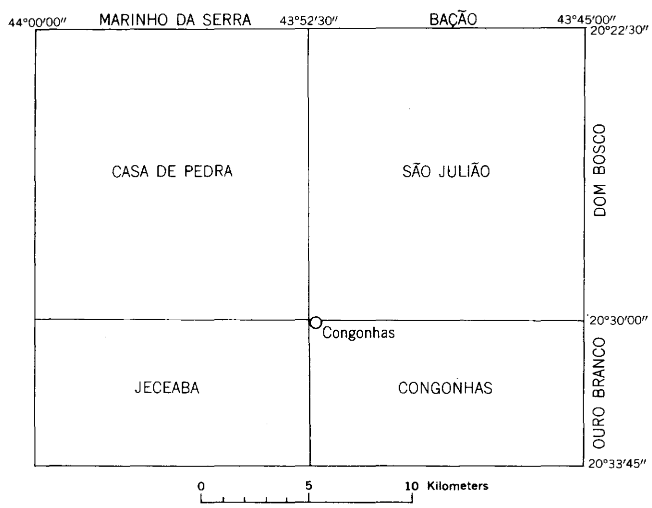

FIGURE 2.—Index map of the quadrangles of the Congonhas district.

20°33′45″ S., and longitude 43°45′ W. and 44° W. The area is about 600 square kilometers (232 square miles). It lies within the Itabirito quadrangle, Folha No. 34, of the Commissão Geographica e Geologica de Minas Geraes (now called the Departamento Geográfico de Minas Gerais). This quadrangle, one of a series mapped by the state at 1 : 100,000, was published in 1929.

The principal town is Congonhas (formerly Congonhas do Campo), originally a gold-mining camp that was founded early in the 18th Century when rich alluvial and eluvial deposits were discovered in the vicinity. The gold was virtually exhausted by the early 1800's, and the town has remained largely unchanged since that time. Its population is a few thousand; the best known feature of the town is the fine old colonial church with it unusual steatite statues of the Old Testament prophets that is one of the national shrines of Brazil. The main line of the railroad reached Congonhas in 1912, and since then the town has enjoyed a modest revival as a commercial center for the surrounding agricultural area and a shipping point for iron and manganese ores, dolomite, talc, and other mineral commodities. Congonhas is the seat of government for the município (roughly a county) of the same name.

The second town of the district is São Julião (formerly Miguel Burnier), center of a once important manganese mining industry and site of a small charcoal blast furnace. Casa de Pedra is a company-owned town devoted entirely to the mining of iron ore, and Jeceaba (formerly Camapuán) is a railroad town and chief outlet for a prosperous agricultural region lying to the south and west. Alto Maranhão, Santa Quitéria, and Lobo Leite are old gold-mining towns that have lost their main source of income.

The district is unusually well situated for railroad facilities, compared with the norm for this part of Brazil, inasmuch as the main line of the Estrada de Ferro Central do Brasil (Central Brazil Railways) extends directly through it and a branch line follows along the east edge. The main line is broad gage, 1.60 meters or 5 feet, 3 inches. It connects Rio de Janeiro with Belo Horizonte. By rail Congonhas is 487 kilometers (303 miles) from Rio de Janeiro and about 150 kilometers (93 miles) from Belo Horizonte. From João Murtinho, southeast of Congonhas, a branch line extends northward toward Itabirito and Belo Horizonte. As far as São Julião a three-rail line accommodates both the broad- and narrow-gage (1.00 m) traffic. From São Julião northward it is narrow gage only, although plans have been made to extend the third rail to Itabirito and a few kilometers have been laid. From São Julião another narrow-gage branch extends eastward to Ouro Preto and Ponte Nova.

Future communications may be still better because plans have been laid to build a broad-gage line from Belo Horizonte through Itabirito and the Congonhas district that will bypass a proposed dam on the Rio Paraopeba at Fecho do Funil, southwest of Belo Horizonte.

The district is also easily accessible by highway, and secondary roads within the district are reasonably adequate. The old Rio-Belo highway, graveled and passable in all seasons, parallels the narrow-gage railroad along the eastern border, and a spur extends to Congonhas. A new highway under construction in 1951 now links Congonhas with Belo Horizonte. The latter follows the eastern flank of the Serra da Moeda and enters the district northwest of Fábrica.

Congonhas and São Julião have post offices, plus telegraph and telephone service.

TOPOGRAPHIC FEATURES

The Congonhas district lies in the basin of the upper Rio São Francisco near the headwaters of two of its major tributaries, the Rio das Velhas and the Rio Paraopeba. About 80 square kilometers of the district drain to the Rio das Velhas, the rest lies within the basin of the Rio Paraopeba. The Rio das Velhas proper is farther north; one of its tributaries, the Riberão Mata Porcos, flows through the northern part of the São Julião quadrangle. The Rio Paraopeba enters the Jeceaba quadrangle from the south, flows westward and northward to Salto, where it cuts through a sharp ridge, and then follows the west edge of the district northward. A major tributary, the Rio Camapuán, joins it at Jeceaba, and another, the Rio Maranhão, joins just east of Caetano Lopes near the middle of the Jeceaba quadrangle. The greater part of the district, and particularly of the ferriferous areas within it, is drained by the Rio Maranhão and its tributaries. The main line of the railroad follows the Maranhão and Paraopeba valleys; the narrow-gage line crosses the divide at São Julião and descends to the Rio das Velhas.

Total relief within the district is 830 meters, from 800 meters above sea level where the Rio Paraopeba leaves the west edge of the Casa de Pedra quadrangle to 1,630 meters in the Pico da Bandeira (or Alto da Casa de Pedra), highest point in the Serra do Mascate near the center of the same quadrangle. The district is sharply divided into highlands and lowlands. The highlands, generally more than 1,000 meters in altitude, comprise most of the eastern two-thirds of the Casa de Pedra quadrangle and the northern two-thirds of the São Julião quadrangle. The rest of the district is lowlands, ranging in altitude from 800 to a little more than 1,000 meters. These so-called lowlands are, however, sharply incised, and have virtually no level areas except along the narrow alluviated flood plains of the major streams. Indeed some of the most nearly level terrain is in the highland valleys.

The most prominent topographic feature of the district is the westernmost mountain range, the Serra da Bôa Vista—Serra das Almas.[1] It forms the eastern rim of the Paraopeba valley from Salto north, being cut through by only two small streams. Southwest of Salto, this range gradually blends with the rest of the hills and dies out a few kilometers beyond the border of the Jeceaba quadrangle. To the east two ranges, the Serra do Batateiro and Serra do Mascate, are higher than the Serra da Bôa Vista-das Almas but are not as prominent because they do not rise so far above the surrounding country. Other peaks and ranges have been given names, as shown on the maps (pls. 1–4), but topographically they are hardly more notable than many unnamed hills. Exceptions are the Pico do Engenho and Morro Santo Antônio, which are situated along the scarp separating the highlands from the lowlands and have prominent steep faces several hundred meters high.

PREVIOUS GEOLOGIC INVESTIGATIONS

The iron region with its rich mineral deposits has been studied geologically by many men, and an extensive literature has been built up over a period of more than a century and a half. Freyberg (1932) lists a bibliography of 976 titles; the number now exceeds 1,000. Of these the majority are concerned with mining or with mineral species; relatively few are geologic reports in the modern sense. In spite of this great volume the region is still imperfectly known, because it was not mapped on any adequate scale during these studies.

Von Eschwege (1822 and 1833) was one of the first to describe the geology of the area. Among other things he divided the rocks of the Ouro Preto district into the same general units that are recognized today, although the mode of origin he proposed is not in accord with present-day concepts. The modern period may be said to begin with Derby, an American generally considered the founder of Brazilian geology, and Gorceix, a Frenchman who was the first director of the School of Mines at Ouro Preto. Derby published many papers from 1874 to 1912, and Gorceix from 1877 to 1891, of which only a few of the more important ones are cited in the bibliography. An English mining geologist, Scott, spent many years in Brazil at the turn of the century and described many aspects of the geology and mines. About 1910 a group of American geologists headed by Leith, Harder, and Chamberlin began investigations of the iron deposits and the regional geology which resulted in several important scientific papers and many private mine reports. During the late twenties and early thirties Freyberg traveled extensively through Minas Gerais, making numerous observations and compiling a reconnaissance geologic map. He not only did much original work but searched the literature thoroughly, so that his two principal works (Frey-

[1] Local place names are prevalent in this part of Brazil. Many mountain ranges change names every few kilometers. The writer has eliminated some names but has retained the ones that seem to be most firmly established in local usage.

berg 1932, 1934), one on general geology and the other on mineral resources, are still the most comprehensive accounts of the region.

Although the men cited above were not Brazilian, and the literature thus has an international flavor, the Brazilian geologists have also been very active. During the last half century, and particularly during the last 25 years, the number of papers published by Brazilian geologists has steadily increased. Of the many who have made contributions, perhaps the most important are L. J. de Moraes, D. Guimarães, and O. Barbosa, but a complete list would include several times as many names. In 1934 Guimarães and Barbosa published a geologic map of the state on a scale of 1:1,000,000 that incorporated all information available at that time. A. I. Erichsen[2] and colleagues of the Departamento Nacional da Produção Mineral prepared geologic maps (unpublished) of the Belo Horizonte and Itabirito quadrangles, using as base maps the 1:100,000 topographic sheets of the Commissão Geographica e Geologica de Minas Geraes (now the Departamento Geográfico de Minas Gerais).

Few papers have dealt specifically with the geology of the Congonhas district. Scott (1900) described the manganese mines of Miguel Burnier (São Julião), giving a number of geologic cross sections. Freyberg (1927, p. 438–441; and 1932, p. 95–103, with sketch map, and p. 238–239) gave brief accounts of some features. Grösse and others (1946) published the results of an extensive exploration program at Fábrica from 1937 to 1940. Barbosa's description (1949) of the geology of the Congonhas region is one of the most detailed areal studies in central Minas Gerais that has been published to date. The present writer concurs in many of the ideas presented in it, although he differs in some details.

PRESENT INVESTIGATION

Field work in the Congonhas district was done by the writer from 1947 to 1951. During much of the time he worked alone, or in company with Aristides Nogueira da Cunha, geologist of the Departmento Nacional da Produção Mineral, whose knowledge of the country and people was very helpful. For the last 6 months of the field work, Joel B. Pomerene of the United States Geological Survey assisted the completion of the mapping, particularly that in the eastern part of the São Julião quadrangle.

The lack of adequate base maps was a severe handicap throughout the course of the field work. Topographers of the Geological Survey mapped about 60 square kilometers of the Casa de Pedra quadrangle by plane table in 1947. The rest of the geologic mapping was done on aerial photographs, scale, about 1:10,000, furnished in 1949 by the Divisão das Aguas of the D.N.P.M. In 1950 the compilation by multiplex methods of maps of these and adjacent quadrangles was contracted for with a Brazilian firm, the Serviços Aerofotogramétricos Cruzeiro do Sul, S. A., but the final maps were not delivered until after the writer returned to the United States, so that all field information was still on the photographs until it was too late for further field checking. The Casa de Pedra mine area was mapped by the writer with the plane table.

[2] Erichsen, A. I., and others, Geologia e recursos minerais da zona de Itabirito, and Geologia e recursos minerais da zona de Belo Horizonte: Unpublished geologic maps, scale 1:100,000. In files of Departamento Nacional da Produção Mineral.

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The writer is indebted to many persons and organizations for their assistance in furthering the progress of the work. Foremost among them is the Departamento Nacional da Produção Mineral, which cooperated with both money and personnel, providing the aerial photographs mentioned above, a diamond drill and crew to operate it, chemical analyses, thin and polished sections, transportation on certain occasions, and the services of a geologist, rodmen, and field assistants. Dr. Alberto I. Erichsen, head of the Divisão de Fomento during the period when the field work was done, and Dr. José Alves, chief of the Belo Horizonte office of the D.N.P.M., generously offered advice and assistance, and the other members of the organization were unfailingly helpful. The writer is also indebted to Dr. Djalma Guimarães of the Instituto de Technologia Indústrial de Minas Gerais for advice and for many thin sections, and to Dr. Luciano Jacques de Moraes and Dr. Octavio Barbosa for the time and effort they spent in orienting him in the geologic problems of the region.

Thanks are due to the Companhia Siderúrgica Nacional and its personnel for assistance freely given at Casa de Pedra, headquarters for much of the field work. Capt. Schatz of the Companhia de Mineração de Ferro e Carvão at Fábrica was always hospitable and helpful, as was also Dr. Gil Guatimosim of the Companhia de Mineração Usina Wigg at São Julião. To all these and many others, too numerous to mention by name, the writer is grateful for making his sojourn in Brazil pleasant and profitable.

The project was under the general supervision of J. V. N. Dorr 2d, in charge of the geologic investigations in Brazil, and W. D. Johnston, Jr., chief of the Foreign Geology Branch, Washington, D. C. Much of the report was prepared at the Geology Department of the Johns Hopkins University in Baltimore, which kindly provided office space and other facilities.

GEOLOGIC SETTING

GENERAL FEATURES

REGIONAL SETTING

The Central Highlands of Brazil consist geologically of highly deformed, metamorphosed sedimentary rocks that rest on a basement of gneiss and granite and are cut by ultramafic, basic, and intermediate to acid intrusive rocks. These rocks have traditionally been assigned to the pre-Cambrian (Oliveira and Leonardos, 1943, and many others) because they are more deformed and metamorphosed than an overlying series of the Paleozoic (table 1).

TABLE 1.—*Pre-Cambrian and older Paleozoic rocks of Minas Gerais, Brazil*

System	Name	Description
Silurian(?)	Bambuí (or São Francisco) series	Phyllite and limestone.
	—Unconformity—	
Pre-Cambrian	Lavras series	Diamantiferous conglomerates, tillite, quartzite, and phyllite
	—Unconformity—	
	Itacolumí series	Quartzite, conglomerate, phyllite, and minor iron formation.
	—Unconformity—	
	Minas series (1)	Quartzite, schist, iron formation, dolomite, phyllite, and volcanic rocks.
	—Unconformity—	
	"Complexo fundamental"	Gneiss, granite, schist, and amphibolite.

[1] Barbosa, O., (1954), and Rynearson, Pomerene, and Dorr (1954) insert a new series here, unconformable under the Minas series and above the "Complexo fundamental."

Only the "Complexo fundamental," Minas series, and Itacolumí series, plus rocks intrusive into them, are present in the ferriferous region under discussion. Attempts to subdivide and correlate these rocks have been made by many geologists. Some of the more important divisions are given in figure 3. In spite of the general agreement on many details, several major points of difference remain that can only be resolved after detailed mapping has progressed considerably farther than it has at present. One of these is the problem of the Caraça quartzite, called basal Minas series by Harder and Chamberlin, included with the Itacolumí series by Guimarães and most Brazilian geologists, including the Federal Survey, and recently assigned once more to the lower Minas series by Barbosa (1954). Another problem is that of the thick green-schist sequence named "Barbacena" by Barbosa, and tentatively called Minas series equivalent in this report. Lacourt's (1936) lower Minas ferruginous phyllite and biotite schist almost certainly correspond in part to this group of rocks. The problem will be discussed more fully in a later section.

The Minas series is the most important group economically, for it contains nearly all the iron and much of the manganese and gold of the region. The iron-bearing member is generally resistant to erosion; hence it crops out boldly in prominent mountain ranges that have attracted attention from the earliest times. In plan these ranges roughly form a rectangle (the "quadrilátero ferrífero" of Brazilian writers), with a westward prolongation and isolated outliers to the east and northeast (fig. 4). Harder and Chamberlin (1915, p. 346) pointed out that "the characteristic deformation of the rocks of central Minas Gerais has been thrust faulting and accompanying folding;" they offered as evidence of the faulting the V-shaped branchings of the formations at several places.

The most prominent features of the regional geology are the following:

1. A western range, the Serra da Moeda and its southern continuation (which has several local names), directly overlies the basement rocks in normal sequence and dips steeply eastward (fig. 4).

2. A northeastward trending range (known by several local names, but perhaps best described as the Serra do Curral d'El Rei or simply the Serra do Curral) extends from a point near Itaúna to the Serra da Piedade near Caeté. It cuts off the Moeda structure almost at right angles. Dips are steep to moderate southward; evidence indicates that the beds are overturned so that the upper part of the sequence rests on the underlying crystalline complex.

3. What appears to be an overturned syncline extends southwestward from Barão de Cocais, partly filling the gap between the Serra do Curral and the Serra do Caraça. The writer has little data on this part of the region, however, and the structure may be different.

4. Generally eastward-dipping beds along the flank of the Serra do Caraça and in the Serra do Antônio Pereira outline the main eastern limit of the ferriferous area, although some outlying patches are known. The thickening of the iron formation in the sharply concave bend at the Fazenda da Alegria, west-northwest of Santa Rita Durão, is very prominent—here Harder and Chamberlin measured an apparent stratigraphic thickness of more than 1,200 meters, although only 3.7 kilometers to the east the formation is only "a few score" meters thick.

5. Northwest of Mariana the rocks of the Minas series swing sharply westward around the nose of a plunging anticline and trend westward along the southern flank of the Serra de Ouro Preto. This structure does out or

Derby, 1906	Harder and Chamberlain, 1915	Guimarães, 1931	Lacourt, 1936 (Ouro Preto)	Barbosa, 1954	Guild, this report (Congonhas)
Minas series: Schist, quartzite, dolomite, and iron formation	Minas series: Itacolumí quartzite	Itacolumí series: Quartzite, conglomerate, and phyllite (includes most of Caraça quartzite)	Itacolumí series: Upper: Quartzite; Middle: Phyllite; Lower: Quartzite conglomerate	Itacolumí series: Quartzite, conglomerate, phyllite, and itabirite lenses	Itacolumí series: Micaceous quartzite, conglomerate, ferruginous quartzite, iron formation, and phyllite, "Santo Antônio facies" of Itacolumí series
		Unconformity	Unconformity	Unconformity	Unconformity
	Piracicaba schist and quartzite	Minas series: Phyllite with quartzite, dolomite, and itabirite lenses	Minas series: Upper: Diabase (amphibolite) and basalt (talc schist); Ferruginous phyllite, "limestone" and "sandstone"	Minas series: Piracicaba formation: Phyllite and quartzite, dolomite, and itabirite	Minas series: Upper: Phyllite with quartzite, thin iron formation, dolomite, and tuff(?)
	Itabira iron formation	Dolomite, phyllite, itabirite, and manganiferous beds	Middle: Itabirite and dolomite	Itabira formation: Dolomite, ferruginous dolomite, and itabirite	Middle: Dolomite, ferruginous dolomite, and itabirite — Green schist, graywacke, thin iron formation, tuff(?). In part or entirely equivalent to Minas series? Equals deep geosynclinal facies, intruded by ultramafic and granodioritic rocks
	Batatal schist		Phyllite	Schist	
	Caraça quartzite	Micaceous quartzite and schist	Quartzite	Caraça formation: Quartzite and minor conglomerate	Lower: Mica schist, phyllite, and quartzite
Unconformity	Unconformity	Unconformity	Lower: Ferruginous phyllite biotite schist, and talc schist	Unconformity	Unconformity
			Unconformity	Barbacena series: Green schist, steatite, partly granitized	Unconformity
Gneiss and mica schist	Gneiss, granite, and mica schist	Gneiss and mica schist	Granodiorite intrusions: Gneiss, migmatite, and mica schist	Unconformity — Mantiqueira series: gneiss and granite	Gneiss and granite

FIGURE 3.—Summary of divisions proposed for the pre-Cambrian sedimentary rocks of the iron region.

is cut off by the large batholith extending from the vicinity of Cachoeira do Campo to Itabirito, but what is probably its continuation appears a few kilometers north of São Julião, bends northward around the batholith, and forms an interior range than continues nearly to the Serra do Curral.

6. Another east-west trending structure passes through São Julião to Fábrica, north-northwest of Congonhas, where it abuts a mass of arcuate, generally north-south structures that are interpreted as thrust sheets in this report.

The intensity of deformation and the grade of metamorphism increase eastward across the area. Metamorphic zones cannot be accurately defined, however, because post-deformational granodioritic intrusions imposed a thermal metamorphism on the regional metamorphism. Deformation and recrystallization generally were not great enough to destroy bedding planes, although in places a strong cleavage greatly obscures them. Perhaps the most prominent, and certainly the most uniform structural element of the rocks is a lineation that trends about east and plunges moderately to steeply in that direction. Pebbles in conglomeratic beds are almost invariably elongated parallel to this lineation, strongly suggesting plastic deformation. Axial ratios in the bedding plane are about 2:1 in the west and south but increase to about 10:1 near Camargos, the easternmost point where pebbles have been observed. At the Camargos locality they were apparently smeared out to thin films, perhaps one-tenth of their original thickness, assuming that they were originally more or less equidimensional. Such deformation graphically demonstrates the intensity of the forces to which these rocks were subjected and suggests the uncertainties involved in measuring stratigraphic thicknesses.

Small-scale aerial photograph compilations reveal some straight linear features that extend intermittently for many kilometers, although ordinarily they are not recognizable on single pictures and are usually overlooked entirely in the field. Three of the "lineaments" coincide with small offsets in the beds of the Minas series along the Serra da Moeda structure and extend well out into the underlying gneiss. They unquestionably are deep seated, nearly vertical fault zones, and apparently have relatively small displacements.

The reader should be warned that the foregoing summary of the regional geology is for the most part based on small-scale reconnaissance maps of other geologists and somewhat on meager personal observations. Past investigations show that detailed mapping invariably reveals greater complexities; hence the picture will undoubtedly be modified as work progresses.

CONGONHAS DISTRICT

The Congonhas district lies in the southwest corner of the quadrilateral where the northward- and eastward-trending structures meet. The geology of the area is extremely complex, as shown on the maps (pls. 1-4). Gneiss of the basement complex forms the west edge. Rocks of the Minas series crop out in the Serra

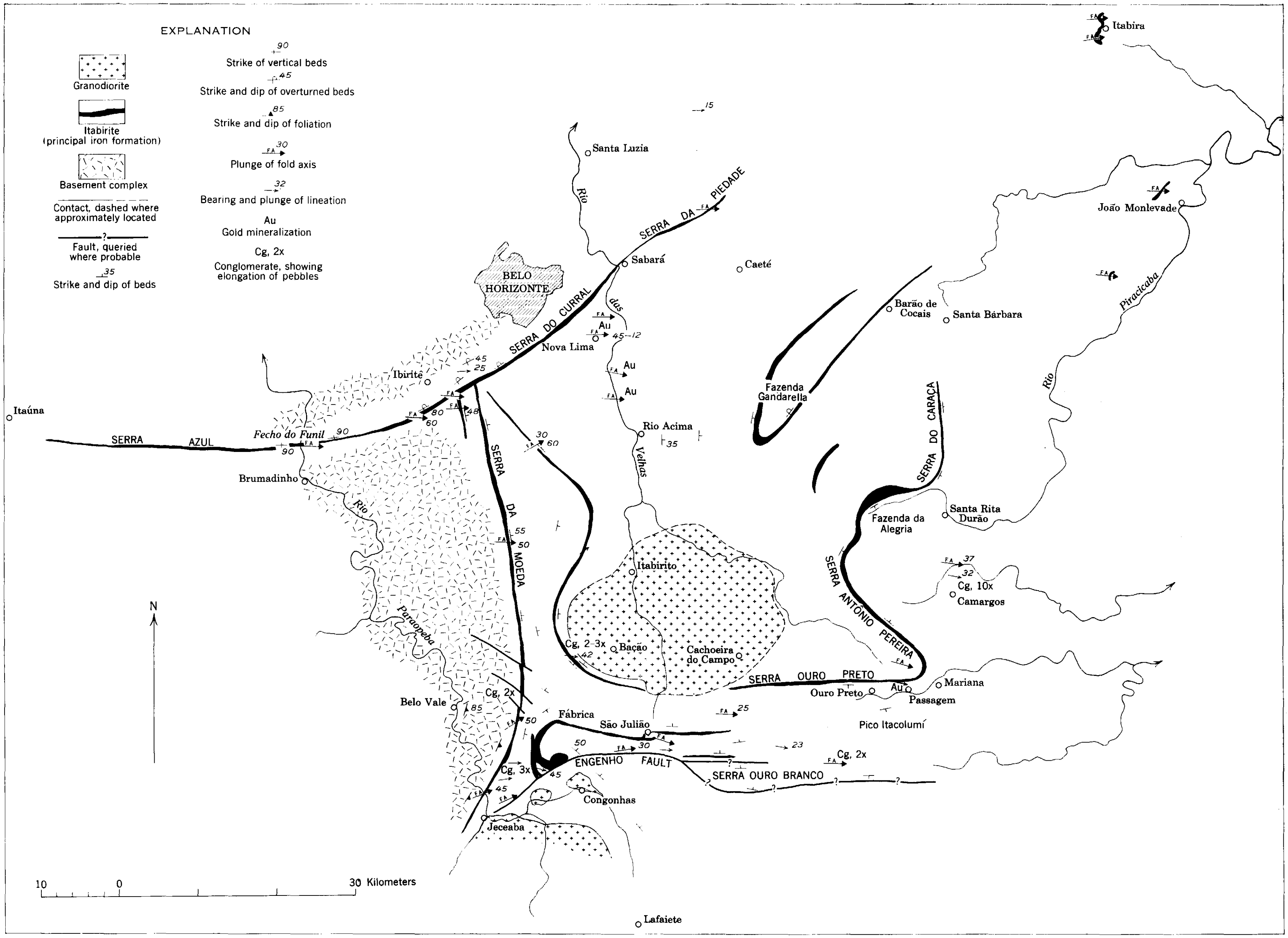

FIGURE 4.—Sketch map of the "quadrilátero ferrífero" of Minas Gerais, Brazil, showing the outcrop pattern of the major belts of iron formation.

da Bôa Vista-das Almas, and the iron formation extends a short distance beyond the western border of the Jeceaba quadrangle before pinching out. This western range is arcuate and convex to the east. Two en echelon ranges, convex to the west, and a third almost circular mass are interpreted as having thrust relationships to the western range and to each other. The eastward-trending belt of iron formation and associated rocks that extends from Fábrica through the middle of the São Julião quadrangle is essentially anticlinal. This belt is faulted against the iron formation of the Serra do Mascate. To the north a broad synclinal belt of phyllite extends almost to the north edge of the district, where lenses of iron formation reappear in the contact zone of the large batholith. A synclinal area of rocks of the Itacolumí series occupies much of the space between the Serra do Mascate and the Fábrica-São Julião structural belt. A somewhat arcuate fault zone trends northeastward from a point near Jeceaba in the southwest corner of the district to the eastern border of the mapped area and probably continues for some distance to the east. It limits the areas of quartzite and iron formation, bringing them into contact with the green-schist sequence and its abundant intrusive rocks.

BASEMENT ROCKS

A "crystalline complex" of gneiss and acid igneous rocks underlies the valley of the Rio Paraopeba from Salto, 2 kilometers north of Jeceaba, to Fecho do Funil, north of Brumadinho (fig. 4). About 7 square kilometers in the northwest corner of the Jeceaba quadrangle and about 73 square kilometers, roughly the western third, of the Casa de Pedra quadrangle are underlain by these rocks. As they constitute the basement on which the iron-bearing sediments and associated rocks were deposited and have no other apparent relationship to the ore deposits, they were not studied in detail nor was an attempt made to distinguish the rock types during mapping. In general they are light-colored medium-grained rocks composed of quartz, plagioclase and microcline feldspars, and biotite, plus subordinate quantities of muscovite and minor constituents.

Most of the rocks show a well-developed gneissic foliation of lighter and darker laminae ranging in thickness from about a millimeter to perhaps a centimeter. In thin section they are composed of moderately strained quartz, plagioclase (in the oligoclase range), and deeply pleochroic biotite in ragged flakes and aggregates more or less oriented parallel to the foliation, plus a greater or smaller quantity of microcline porphyroblasts ordinarily concentrated along certain layers or crosscutting the foliation at moderate angles. The composition as well as the color and general appearance change abruptly from layer to layer. Some biotite-rich layers are dark-speckled gray; others with more microcline are more nearly salmon colored. The range of composition is, in general, 30–50 percent quartz, 30–60 percent feldspar, 5–15 percent biotite, and as much as 5 percent muscovite with epidote, titanite, and other minor constituents in some places. Either plagioclase or microcline may predominate. The grains are always anhedral. Plagioclase is usually somewhat sericitized, and the twin lamellae may be a little twisted. Potash feldspar is fresher and appears younger. It is ordinarily associated with relatively coarse-grained quartz. The general appearance is that of metamorphosed sedimentary rocks which have been "migmatized" by the introduction or mobilization of potash.

The microcline-quartz streaks are sharply lenticular in places and give the gneiss and "augen" appearance. As the size and number of these lenses increase the gneiss grades to a more massive granitic rock. Some masses have no foliation and are truly igneous in aspect, having the composition of granite or quartz monzonite. Point count analyses of thin sections gave the results shown in table 2.

TABLE 2.—*Modal composition of two igneous rocks from the basement complex*

	Percent	
	(1)	(2)
Quartz	17	30
Microcline [a]	45	31
Oligoclase	32	36
Biotite	3. 4	1. 5
Muscovite	2. 4	1
Accessory minerals	. 3	. 5

[a] Includes some perthite and orthoclase(?).
1. Pinkish granitoid intrusive(?) rock exposed below lowest Minas series quartzite on western slope of the Serra das Almas, 2.2 km south of the north edge of the Casa de Pedra quadrangle.
2. Nonfoliated mass intrusive into gneiss at the lower falls of the Rio Paraopeba, 0.4 km south of the north edge of the Jeceaba quadrangle.

The gneissic foliation has a very regular attitude within the area mapped. It strikes northeast to north along the Serra da Bôa Vista–das Almas front and dips 35°–70°E. conformably with the bedding of the overlying Minas series. This parallelism is rigorous in the railroad cut at Salto and on the trail west of Batateiros (Casa de Pedra quadrangle). Few measurements were made away from the contact, but the general conformability probably extends for several kilometers. West of Salto the foliation maintains a regular attitude for 900 meters or more. In the vicinity of Belo Vale, however, just west of the Casa de Pedra quadrangle, exposures in railroad cuts show wide divergences. Strikes swing from north-south to east-west in short distances, and dips range from gentle to steep to the east, north, and west.

This conformability is difficult to explain and raises doubts that the old classification assigning the basement complex to the "Archean" and the metamorphosed sedimentary rocks to the "Proterozoic" is correct. The problem is not a local one, for similar conformability between gneiss and sedimentary rocks has been pointed out by other geologists from many places in Brazil. Pecora and others (1950, p. 229–232) discuss the lack of angular unconformity between the Complexo fundamental and sedimentary rocks in the mica belt of eastern Minas Gerais. Freyberg (1932, p. 21–23) noted this concordance not only along the Moeda structure but also in the vicinity of Belo Horizonte, but was unable to explain it to his own satisfaction. Oliveira and Leonardos (1943, p. 154–155) describe the contact in the state of Goiaz as being conformable and gradational over an interval of several dozen meters. Even at Salto where the contact appears sharp because of the abrupt appearance of bedding in the quartzite (fig. 5),

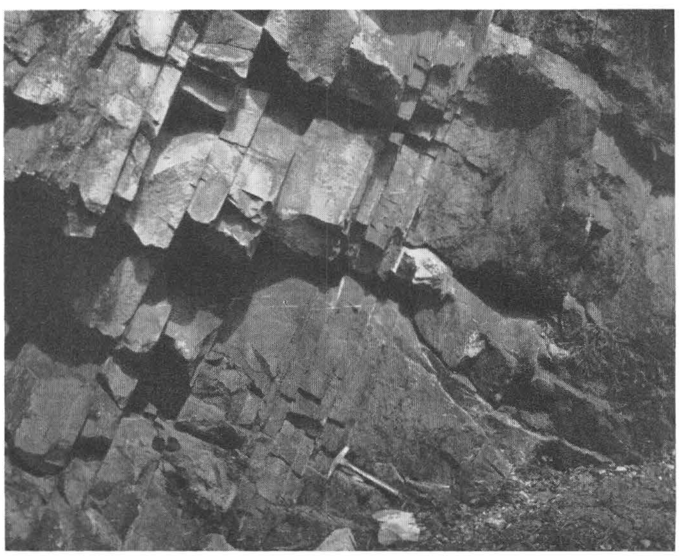

FIGURE 5.—Basal contact of the Minas series. Bedded quartzite lies on nonfoliated granite at this point. Railroad cut at Salto do Paraopeba, Jeceaba quadrangle.

the uppermost "gneiss" is unusually quartzitic and differs from the overlying rocks chiefly in containing coarser grained quartz and muscovite. Where exposures are less good this may cause some uncertainty as to the exact location of the contact. This gradational contact may represent an ancient weathered zone (regolith) composed predominantly of residual quartz, on which the first sediments of the Minas series were deposited shortly after submersion. This will not explain the conformability of the foliation and bedding, however, unless the gneissic structure was formed in a horizontal plane before the deposition of the Minas, and folding of the gneiss and overlying rocks then occurred contemporaneously.

Further uncertainty of the age-relationship is introduced by narrow felsic dikes with coarse-grained to pegmatitic textures that cut both the gneiss and the basal member of the Minas series. These dikes consist of about two-thirds feldspar, chiefly microcline and subordinate oligoclase, 20 percent quartz, muscovite, and minor dark constitutents, generally biotite, but in some a deeply pleochroic hornblende. Some dikes contain tourmaline.

To summarize, the evidence indicates at least two periods of igneous activity, one prior to deposition of the Minas series sediments and the other post-Minas and perhaps contemporaneous with the granodiorite intrusions (p. 26).

Rocks of the basement complex are less resistant to erosion than the siliceous members of the metamorphosed sedimentary series and form relative lowlands. They have a local relief of several hundred meters, however, and crop out in many bare, rounded summits. The foliation is too weak to have any control on drainage or weathering; in consequence there is no pattern to the topography, which has been likened by several writers to the billowing waves of the ocean.

METAMORPHOSED SEDIMENTARY ROCKS

MINAS SERIES

The writer divides the rocks of the Congonhas district that unquestionably belong to the Minas series into three groups—a lower one of clean quartzite and quartz-mica schist or phyllite, a middle group consisting of the iron formation and associated carbonate rocks, and an upper group of phyllite and subordinate quartzite, ferruginous quartzite, iron formation, dolomite, graywacke, and volcanic rocks. This division is based chiefly on the section in the Serra da Bôa-Vista–das Almas, where the structural complications are at a minimum. The only horizon that appears to be reasonably well defined is the base of the principal iron formation. Quartzitic and argillaceous members of the lower and upper groups cannot be positively distinguished from one another, but in general the lower group is almost iron free whereas the rocks of the upper group are ferruginous in many places.

LOWER GROUP

Quartzite.—The quartzitic members of the lower group are hard white rocks composed chiefly of fine- to medium-grained quartz and minor amounts of white mica. They are well bedded for the most part, the planes of stratification ordinarily being marked by thin mica-rich laminae that weather rapidly. The bedding planes are even and parallel in most places (fig. 5) but crossbedding occurs in a few spots. The crossbedding is of the current-formed type and has long straight laminae of coarser and finer material making angles of as much as 20° with the gross bedding. Ripple marks were not observed.

In hand specimen some of the quartzite appears homogeneous in grain size whereas other beds are composed of distinctly larger, usually rounded grains set in a matrix of finer grained sugary quartz and mica. The larger grains range from less than a millimeter to a few millimeters across in most places where they are present, but up to a few centimeters in a few places, forming thin conglomerates. They range in color from clear glassy quartz through milky, pinkish and bluish varieties to grains that are almost jet black. Other minerals that occur at least locally are a bright green mica, tourmaline, minute brown zircons, and scattered magnetite octahedra or in places minute plates of specularite. Nodular bluish-gray masses as much as a few centimeters across are composed principally of very fine grained sericite(?) and probably represent mud balls.

In thin section the quartzite is seen to have a cataclastic texture. The larger grains show severe undulatory extinction and many also display good lamellae. Minute inclusions are common; they cause the variations in color noted above. Overgrowths of clear quartz are present on some grains. The finer grained interstitial quartz ranges in size from 0.5 to 0.01 millimeter or so, most of it being less than 0.1 millimeter. It commonly is less strained than the large grains and some shows no evidence of crushing. Much of the fine-grained quartz resulted from the crushing of larger grains, with or without recrystallization, but some was probably deposited as fine sand or may even be crystallized cherty silica originally present as cement between the clastic grains. Small flakes and clusters of colorless mica, muscovite or sericite, are oriented parallel to the bedding planes, which are also the planes of a poorly developed flow cleavage. They wrap around the larger grains or around eyes of fine-grained quartz that probably was formed by crushing of larger single grains. Minute flakes only a few microns long, enclosed in some of the finest grained quartz, suggest that this material may have been derived from an impure colloidal gel.

The tourmaline, which occurs near pegmatites and quartz veins in the lower beds of the group, is a magnesia-rich type belonging to the variety dravite. It forms slender needles from a few hundredths to a few tenths of a millimeter in diameter and several times as long, both disseminated through the quartzite and concentrated as narrow dark zones composed almost entirely of tourmaline. The disseminated grains are very pale and only slightly pleochroic from pale yellow to brownish yellow in the thickest fragments ($\pm$0.5mm), but those in the compact zones are dark green to black in hand specimen and pleochroic from yellow to brown, or in places pale pinkish to green, in thin sections of standard thickness. The index of refraction increases from N_E1.620 for the palest variety to nearly 1.630 for the dark type, indicating an increase in the iron (schorlite) molecule. The tourmaline evidently resulted from the metasomatic addition of boron by emanations or solutions from post-Minas granitic rocks.

A green mica, which also occurs in the lowermost quartzite beds, may be a variety of fuchsite, as Gorceix (1883, p. 10–12) reported that an emerald-green mica from quartzite near Ouro Preto contained 0.9 percent chromium sesquioxide. Like the tourmaline, it indicates metasomatic action.

Kyanite occurs sparingly as ragged unoriented grains as much as 1 millimeter across. It grows along minute fractures and probably had a hydrothermal rather than a metamorphic origin.

The quartzite is generally resistant to erosion and crops out boldly in long linear exposures, although with increasing mica content it weathers more readily and tends to produce sandy, infertile soils. The quartzite forms either the crests of ridges where it is the thickest and most resistant rock present, or prominent shoulders on ridges underlain by iron formation, where the latter is thick and holds up the crests.

Schist.—The argillaceous rocks of the lower group are composed predominantly of muscovite or sericite with varying quantities of fine-grained quartz. Minor amounts of chlorite may be present, and tourmaline is not uncommon. The mica ranges from very fine grained sericite to moderately coarse grained plates and sheaves as much as several millimeters across in the more schistose varieties. The maximum size of the quartz grains is only a few tenths and usually only a few hundredths of a millimeter. The mica is oriented roughly parallel to the bedding, where this can be determined. Coarser plates and aggregates are ordinarily contorted. Flattened dark-blue "knots", composed of very fine grained sericite containing abundant minute inclusions, probably were derived from clay balls. Float of very coarse grained kyanite, in radiating bladed aggregates many centimeters across, is found along the western slope of the Serra da Bôa Vista and apparently came from veins in the schist.

The schists are poorly exposed in most places. Where the chlorite content is appreciable they are a grayish-green color which turns to rusty red on weathering. A small content of very finely divided graphite gives some of the schist a dark-gray color; these slaty-appearing beds are much more resistant to erosion and form good outcrops.

These argillaceous rocks represent mud and clay interstratified with the cleaner sand. The rock types grade laterally and vertically into each other in some places and are sharply separated in others. The lower schist members, particularly near the contact with the gneiss, are coarser grained and more schistose. Farther from the gneiss the rocks are finer grained and phyllitic.

Distribution.—The best and most continuous exposures of the rocks of the lower group are in the Serra da Bôa Vista-das Almas. Quartzite overlies the gneiss along the western slope except for one short interval where poorly exposed schist seems to be the lowest member. Quartzite forms the crest of the southern part of the range, but in the Casa de Pedra quadrangle itabirite is the most resistant formation and the quartzite and schist of the lower group lie on the western slope.

The same sequence of east-dipping quartzite, phyllite, and itabirite forms the Serra do Batateiro, lying just east of the Serra da Bôa Vista in the Casa de Pedra quadrangle. The lower two members are correlated with the rocks which have a similar stratigraphic and topographic position in the western range and probably are thrust over rocks of the upper group exposed in the valley between the two ridges.

A belt of lenticular quartzites and schist along the northern border of the São Julião quadrangle, between the railroad and Riberão Mata Porcos, also belong to the lower group. As these rocks are more regular and better exposed in the quadrangles to the north, mapping of the Bação and Marinho da Serra quadrangles may necessitate some revision of the structural and stratigraphic interpretations given in this report. Similarly, the determination of the structural and age relationships of the quartzite and schist that enter the east edge of the São Julião quadrangle 2.5 kilometers south of Usina must await further study of the geology of the Serra do Ouro Branco. The writer tentatively correlates these latter beds with the lower group.

Thickness.—The lower group thickens from about 100 meters at the west edge of the Jeceaba quadrangle to 650 meters at the north edge of the Casa de Pedra quadrangle. To the southwest of Jeceaba it thins and disappears within a few kilometers. In the railroad cut at Salto, which affords the best and most continuous exposure of the lower and middle groups, the section shown in table 3 was measured.

TABLE 3.—*Stratigraphic section of the lower group of the Minas series at Salto do Paraopeba, Jeceaba quadrangle*

	Thickness (meters)	Cumulative from base (meters)
Lowest itabirite outcrop.		
Schist, outcrops throughout river gorge; not exposed in railroad cut	32. 5	135. 2
Quartz-muscovite schist with minor chlorite, coarse-grained. Weathers grayish green. Bedding not prominent, parallels cleavage	14. 0	102. 7
Sharply gradational normal contact.		
Quartzite, well-bedded, clean, with minor sericite. Beds range from nearly a meter to a few centimeters thick, generally thinner downward. Break into angular blocks on 2 joint sets. A 10-cm pegmatite bed at 16.30 (52.80 m above base of group) is highest intrusive rock exposed	52. 2	88. 7
Sericitic quartzite, thin-bedded, indistinct. A 2-4 cm quartz-tourmaline vein 8.50 m above base of member, a 5-cm pegmatite dike 8 m above base	12. 7	36. 5
Quartz-mica schist, predominantly dark green to brown, bedding indistinct, cleavage parallel to bedding. A 50-cm pegmatite sill 6.50 m above base of member, thinner ones at 0.5, 2.7, and 3.8 m	12. 8	23. 8
Quartzite in thick, regular beds; sericite partings to a few mm thick spaced 5–40 cm apart, average 10 cm. Quartz-muscovite schist, 30 cm thick, 5.5 m above base, 60 cm of similar schist 8 m above base. Beds break into angular blocks on strike joint set dipping about 20° NW. Kaolinized pegmatites, 10 cm thick, parallel bedding 3.7 and 9.2 m above base	11. 0	11. 0
Base of Minas series.		
Biotite gneiss intruded by granite and pegmatite.		

The thickness remains relatively uniform for about 7 kilometers to the north, and then increases rapidly, as shown in table 4.

TABLE 4.—*Stratigraphic sections of the lower group of the Minas series on the western slope of the Serra da Bôa Vista–das Almas, Casa de Pedra quadrangle*

	Thickness, in meters, of section at indicated distance, in kilometers, north of Salto do Paraopeba				
	E–E′	*D–D′*	*C–C′*	*B–B′*	*A–A′*
	3. 5	5. 7	8. 5	11. 6	15. 6
Itabirite	-------	-------	-------	-------	-------
Schist	40	65	50	30	40
Quartzite	40	30	55	75	105
Schist	30	2	105	120	[a] 270
Quartzite	30	38	65	65	200
Total	140	135	275	290	615
Gneiss	-------	-------	-------	-------	-------

[a] Includes two thin (10- and 15-m) quartzite lenses.

Inspection of the map indicates a transgressive overlap southwestward, and only the two highest members are present at Salto. Furthermore, the lensing and pinching is such that the various members do not correspond as precisely as the sections of table 4 suggest. The uppermost schist member is an exception to this and extends across the two quadrangles with a remarkably constant thickness.

The rapid thickening between sections *B–B′* and *A–A′* continues at least to the north edge of the Casa de Pedra quadrangle, 600 meters north of section *A–A′*, where the lower group totals 650 meters. It is not known whether or how much the lower group may thicken on the adjacent quadrangle, but 22 kilometers to the north the writer (Park and others, 1951, fig. 3) measured a section of 190 meters of quartzite and 185 meters of dark phyllite between the underlying gneiss and overlying itabirite. Reconnaissance observations show that the same general pattern continues throughout the length of the Serra da Moeda.

The section is considerably thicker in the Serra do Batateiro (table 5).

TABLE 5.—*Stratigraphic sections of the lower group(?) of the Minas series on the western slope of the Serra do Batateiro, Casa de Pedra quadrangle*

	Thickness of section, in meters	
	D–D′	*E–E′*
Itabirite	---------	---------
Phyllite	300	180
Quartzite	600	ca 600
Thrust fault(?)	---------	---------
Total	900	780

If, as believed, the base of this section is a thrust fault, the members present may not represent the entire thickness of the group.

The rocks of the lower group exposed along the north edge of the São Julião quadrangle and in the adjacent Bação quadrangle to the north are extremely lenticular, in contrast to the fairly regular sequence in the Serra da Bôa Vista–das Almas. They lie in the metamorphic aureole of the batholith which enters the edge of the northeast corner of the district and cuts through the lower and middle groups. What appear to be the lowest beds are garnetiferous schists, highly contact-metamorphosed, that may not belong to the Minas series, though they are so considered in this report, as there is no evidence to the contrary within the mapped area. The itabirite is also very lenticular, so that it is difficult to divide the series into lower and middle groups in this area. The units become more uniform and continuous to the northwest. Evidence suggests that the combined lower and middle groups are about 1,000 meters thick here; of this perhaps one-half, or 500 meters should be assigned to the lower group.

MIDDLE GROUP

The rocks of the middle group differ from the underlying and overlying rocks in that they were derived predominantly from chemical precipitates rather than from clastic sediments. They are composed almost entirely of recrystallized chert, iron oxides, and dolomite in varying proportions, and include minor amounts of amphibole, chlorite, talc, and other silicates in some places. All gradations exist between the two principal types, itabirite and dolomite.

Itabirite.—The term "itabirite" seems to have been introduced into the geologic literature by von Eschwege (1822), who adapted it from an aboriginal word meaning "whetstone." It has been used in several ways by different authors—to designate high-grade hematite ore by von Eschwege, siliceous iron formation containing less than 50 percent iron by Harder and Chamberlin (1915), and hard ore and iron formation (as opposed to the soft varieties) by Freyberg (1932). Freyberg gives an admirable summary of the history and changing significance of the word, which has by now passed into the general international vocabulary, although he ends by proposing to define it by its present physical state, a secondary characteristic that depends chiefly on the amount and nature of the surface leaching the rock has undergone. The most widely accepted present-day usage, and the one that seems to have the most logical genetic basis, restricts the term to laminated rocks containing iron oxides and visible quartz and other light-colored constituents. This excludes the ferruginous quartzite and conglomerate beds, which are not laminated; the high-grade ores, which do not contain visible quartz in layers; and the somewhat ferruginous dolomite containing scattered magnetite octahedra.

Most itabirite has a simple mineralogic composition, consisting of specular hematite flakes and granular quartz in alternating layers. The separation is not complete, but sufficient to give the rock a conspicuously banded appearance (fig. 6). The laminae range in thickness from less than 0.1 millimeter to perhaps 2 centimeters and commonly occur in groups of predominantly lighter and darker layers that give the appearance of coarser bedding. Individual laminae can ordinarily be traced for meters across a large exposure, maintaining a remarkably constant thickness.

Although itabirite is generally resistant to erosion and is the principal ridge-forming member of the Minas

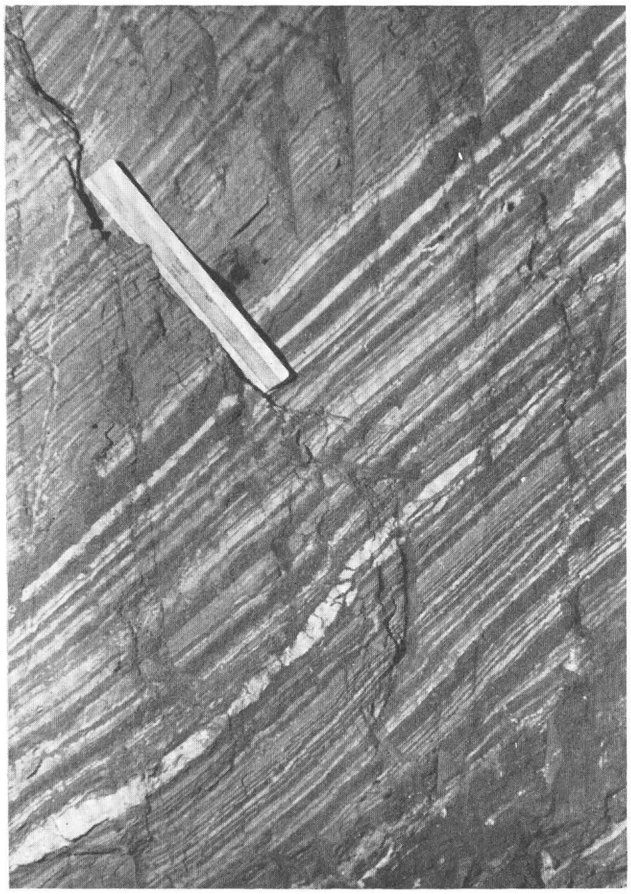

FIGURE 6.—Itabirite. The dark material is hematite, the light is quartz. A thin quartz veinlet cuts the bedding at a high angle near left edge, and the prominent white band almost parallel to bedding near the center is also vein quartz. Adit 6, Serra do Batateiro, left wall, 28 meters. Scale 20 centimeters long.

series, only a relatively small part is completely unweathered at the surface. Much of it has no cohesion because the leaching action of surface waters has softened it; elsewhere the more ferriferous laminae remain hard whereas the siliceous layers disintegrate. Extensive alteration to, and replacement by, limonite has formed a capping which preserves original structures and protects the underlying powdery material from erosion.

In thin section the rock consists of an aggregate of mosaic-textured quartz in interlocking grains about 0.01 to 0.1 millimeter across and hematite in tabular plates or irregular grains ranging from 0.001 millimeter or less to about 0.05 millimeter across. The smaller plates are translucent, blood red in transmitted light. In siliceous laminae the hematite grains are separate and distinct, either enclosed within individual quartz grains or crossing the borders between adjacent grains in a regular fashion that is not controlled by the texture of the quartz. In more ferriferous layers the hematite apparently has coalesced to form irregular aggregates, and the quartz is interstitial to it.

Dolomite is a common mineral in some beds of the iron formation, although in the past itabirite usually has been considered to consist only of the simple quartz-hematite type. The dolomite occurs as rhombohedra and irregular grains as much as a few tenths of a millimeter across that are ordinarily concentrated into laminae like the quartz and iron oxide. Talc is frequently present with the dolomite, and chlorite and amphibole also occur. The dolomite and iron usually are associated, as the carbonate layers are relatively more ferriferous than the intervening siliceous layers. The iron oxide in the carbonate-bearing itabirite is ordinarily magnetite rather than hematite. Exposures of dolomitic itabirite are rare, but numerous zones of leached magnetic itabirite, in many places containing conspicuous amounts of talc along the laminae probably indicate its former presence and suggest that a considerable portion of the formation contains carbonate. No deep exposures below the water table exist in the Congonhas district, but workings and drilling at the Passagem gold mine 30 kilometers to the east show that the formation is almost entirely dolomitic and magnetic at that point (Guimarães, 1935, p. 22–25). Available evidence points to lateral variations in the carbonate content of the formation with dolomite increasing eastward.

Some zones are composed of alternating layers of magnetite and tremolite, with or without accessory dolomite and quartz. The tremolite occurs as clusters of fibers as much as a centimeter or more long, radiating from closely spaced nuclei to form an interlacing mass that encloses the magnetite laminae. Limonite frequently replaces the amphibole in the surface zone, making a rusty rock that preserves the original texture. At the railroad bend east of São Julião, between kilometers 499 and 500, a very coarse grained amphibole schist crops out that is almost entirely limonite pseudomorphous after amphibole blades as much as 10 centimeters or more in length. This material closely resembles coarse chips of wood. Such magnetite-amphibole schist zones make excellent key beds for tracing minor structures but apparently do not occur at a particular horizon in the formation and hence cannot be used for determining major structures. Only the thicker and more continuous ones have been distinguished on the maps.

Dolomite.—The dolomite of the district consists of several types, ranging in composition from impure ferruginous and siliceous material to almost pure white rock that is extensively quarried for metallurgical use. The impure types contain magnetite octahedra from less than a millimeter to about a centimeter across, either in irregular laminae or scattered grains; quartz in individual grains and aggregates, in places more or less parallel to the gross bedding; and various silicate minerals. The silicates, which commonly form thin partings separating beds of more massive dolomite, include talc, chlorite, and amphibole (either anthophyllite or tremolite). Individual partings ordinarily consist entirely or predominantly of one of these minerals. Other minerals occasionally present in the impure dolomite are muscovite, specular hematite, and pyrite, but pyrite has not been observed in association with the iron oxides. Microscopic needles of rutile are abundant in some of the chlorite. The rock is white, gray, reddish, greenish, or varicolored, depending on the amount and nature of the impurities. Bedding ranges in thickness from the closely spaced laminae of the itabiritic types to nearly massive layers in the purer rock. Natural outcrops are not common, as the rock normally weathers deeply, but numerous road and railroad cuts near São Julião afford good exposures. Quarries also afford excellent exposures; those where marble is being quarried are particularly good. Figure 7 is of a face cut by a wire saw that strikingly shows the alternation of lighter and darker colored beds.

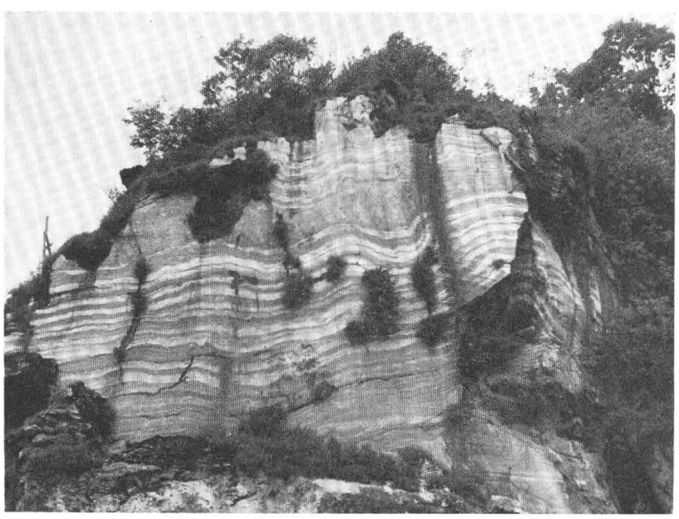

FIGURE 7.—Thick-bedded, folded dolomite. Face cut by wire saw at Cumbí marble quarry, 7 kilometers east-northeast of São Julião. View looking eastward in the direction of the fold axes and lineation.

Some zones have a breccia structure formed by angular fragments of fine-grained sugary quartz and more rounded pieces of pure white dolomite set in a matrix of the impure magnetite-bearing siliceous dolomite (fig. 8). The fragments range in size from less than 1 to about 20 centimeters—most fragments are a few centimeters across. This rock is evidently an intraformational breccia conglomerate, formed by the breaking up of thin siliceous beds, no doubt cherts, and carbonate beds soon after deposition, with attendant mixing in a paste of the ordinary impure material. The writer does not know whether these breccia conglomerates mark a single horizon in the group, as ex-

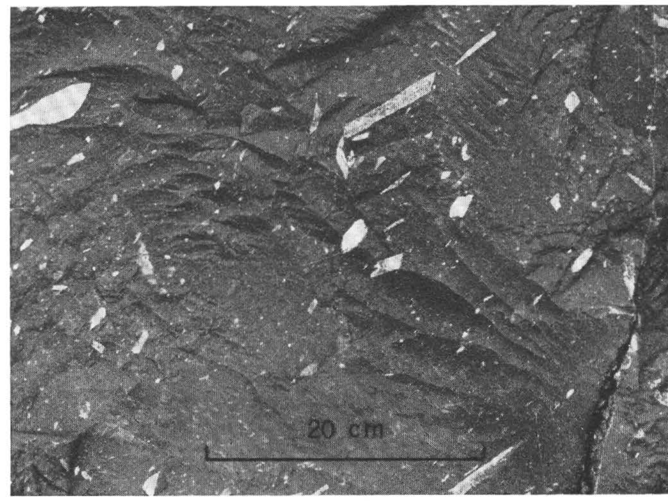

FIGURE 8.—Dolomite breccia conglomerate. Fragments composed of fine-grained quartz, recrystallized from chert(?), and pure dolomite, in matrix of siliceous dolomite, with abundant fine magnetite octahedra. Occurs 500 meters south of railroad station at São Julião. Scale 20 centimeters long.

posures are not sufficiently good for such correlations, but he thinks that several such zones are present.

The purer dolomite occurs as thick-bedded to massive lenses and zones at several points, particularly in the eastern part of the São Julião quadrangle. It ranges from white or light buff to pale salmon. The rock is very fine grained and dense except for infrequent thin partings of micaceous minerals. A thin section of a specimen from the large quarry at the Fazenda do Vigia, on the Pires-São Julião road, shows that there the dolomite is composed chiefly of equigranular carbonate grains averaging 0.03 millimeter across, with a few angular quartz grains and oriented mica flakes of about the same size. An analysis given by Freyberg (1932, p. 31) of rock from this quarry indicates that the composition of the carbonate is almost identical with that of the mineral dolomite, ($CaMg(CO_3)_2$), (table 6). The slight deficiency in CO_2 (loss on ignition) and excess of MgO suggest that some talc was present in the sample. Other analyses show considerable variation in the ratio of CaO to MgO, but in general the carbonate rocks of the Minas series in the Congonhas district and elsewhere in the ferriferous area are dolomitic.

Secondary concentrations of manganese oxides are widespread in the sedimentary rocks of the district, as will be discussed on page 62, and the presence of manganese shown by analyses 5 and 6, table 6, is of interest because these analyses may indicate the original localization of this element.

Dolomite weathers to several peculiar end products which have no apparent similarity to the original rock. These are (1) compact white or variegated clay, (2) spongy or cellular ocherous masses of limonite and silica, and (3) soft black wadlike manganiferous ma-

TABLE 6.—*Analyses of carbonate rocks from the Minas series, in percent*

	1	2	3	4	5	6
SiO_2	1.06			0.18	2.13	13.80
Al_2O_3	1.48			1.00	2.70	.90
Fe_2O_3					Tr.	5.85
FeO					4.95	5.71
MnO					1.45	1.40
CaO	29.64	30.2	30.4	44.42	28.49	26.40
MgO	21.23	21.8	21.7	9.17	19.50	13.87
Loss on ignition	46.60	47.8	47.9	45.00		

1. Dolomite, Fazenda do Vigia, after Freyberg (1932).
2. Analysis 1 recalculated after subtracting SiO_2 and $Al_2O_3+Fe_2O_3$.
3. Theoretical composition of dolomite.
4. Carbonate rock from Miguel Burnier (=São Julião), published by Serviço Geológico in Bol. 10, 1925, p. 25.
5. "White limestone," Miguel Burnier (Scott, 1900, p. 184).
6. "Gray limestone," Miguel Burnier (Scott, 1900, p. 185).

terial. They will be discussed fully in the section on weathering (p. 41) and are mentioned here because the widespread distribution of dolomite in the district could be mapped only by recognition of the nature and origin of these weathering products.[3]

Distribution.—In the Jeceaba quadrangle rocks of of the middle group are exposed only along the eastern slope of the Serra da Bôa Vista, where they conformably overlie the quartzite and schist that hold up the crest of the ridge. Along the continuation of this range in the Casa de Pedra quadrangle the middle group forms the ridge from section *E–E′* northward. The itabirite facies predominates along this western range, for the only dolomite known is a lens extending between section *D–D′* and *E–E′*, Casa de Pedra quadrangle; but as the upper part of the section is for the most part heavily covered with iron formation detritus, other dolomitic zones may also be present. In the section exposed by the Rio Paraopeba and the railroad cut at Salto some dolomitic amphibole-magnetite rocks occur near the top of the group, and it is probable that certain lower zones were also dolomitic (table 7).

In the Casa de Pedra quadrangle the Serra do Batateiro, Serra do Mascate, and Pico do Engenho are also underlain by the resistant itabirite member of the middle group. Indirect evidence suggests the presence of dolomite in these areas, but the dolomite does not crop out and probably occurs in only subordinate amounts. The upper part of the group is poorly exposed or completely covered in these ranges, however, so that there may be more carbonate members than appear.

From the vicinity of Fábrica, near the east edge of the Casa de Pedra quadrangle, a poorly exposed belt of rocks of the middle group extends eastward across the São Julião quadrangle and continues into the adjacent area. As the belt is apparently a faulted anticlinal structure flanked by rocks of the upper group, it is probable that only the upper members of the middle group are exposed, and these are considerably more dolomitic than the rocks of the ranges to the west and southwest. Dolomite weathering products extend along both sides of the belt at Fábrica, overlying itabirite in the center (p. 77 and pl. 9). From the Fazenda do Vigia eastward the proportion of dolomite increases rapidly, so that near São Julião the highly ferriferous members are subordinate to the carbonate-rich rocks. There are structural indications that a thrust fault may have telescoped the belt and emphasized the lateral facies change by superimposing beds deposited some distance apart, but exposures are not sufficient to prove this. The most uncertain factor in this apparent facies change relates to the fact that whereas the lower part of the section is better exposed in the western ranges, the upper part is better exposed in the east, where the base of the middle group is not known.

Both itabirite and dolomite occur in the belt along the north edge of the São Julião quadrangle, but the units are lenticular, and the distinctions between the lower, middle, and upper groups are not as clearcut as elsewhere. Schist and quartzite occur with the itabirite, and abundant itabirite lenses are enclosed in phyllite, so that the section is extremely irregular. Itabirite predominates over dolomite.

A belt of dolomite, much of it pure and massive, with minor zones of chlorite schist and dolomite breccia conglomerate, enters the east edge of the São Julião quadrangle 2.2 kilometers south of Usina. No itabirite occurs in association with this dolomite within the area mapped, but at Rodeio, a few kilometers to the east, a considerable thickness of iron formation is present, and these rocks are therefore assigned to the middle group rather than considered as a lens in the upper group.

Thickness.—The middle group varies greatly in thickness, being in general thinner in the southwest and thickening northward and eastward. The apparent extremes within the Congonhas district are about 70 meters in the Serra da Bôa Vista near the north edge of the Jeceaba quadrangle and 1,050 meters near São Julião, but complicating structural factors undoubtedly exist which cast doubt on any such variations in the thickness of the original sediments.

One of the best-exposed sections is at Salto, where a thickness of about 175 meters is indicated (table 7).

The thickness of the group at several places in the Casa de Pedra quadrangle is shown in table 8.

At the north edge of the quadrangle, 600 meters north of section *A–A′*, the itabirite of the Serra das Almas is about 700 meters thick, and 22 kilometers

[3] Pomerene, while mapping the area near São Julião, first recognized and demonstrated that these peculiar weathering products were derived from dolomite and thus deserves full credit for discovering an important key to the interpretation of the geology of the entire ferriferous region.

TABLE 7.—*Stratigraphic section of the middle group of the Minas series at Salto do Paraopeba, Jeceaba quadrangle*

	Thickness (meters)	Cumulative from base (meters)
Phyllite of the upper group of the Minas series:		
Covered	21	-------
Last itabirite outcrop.		
Itabirite, resistant, siliceous, thin-bedded	6. 5	175. 0
Covered	7. 7	168. 5
Actinolite and magnetite-bearing siliceous dolomite, well-bedded	8. 0	160. 8
Covered	25. 0	152. 8
End of outcrop in the railroad cut.		
Itabirite, magnetic, soft, thin-bedded, very siliceous	7. 3	127. 8
Magnetic rock, resistant, siliceous, with a brown amphibole in fine blades along bedding planes. A few zones have weathered more deeply, are soft, but appear to be of same type. More dolomitic?	13. 6	120. 5
Soft brown material containing abundant fine magnetite and stringers of fresh talc. Resembles weathered dolomite	1. 4	106. 9
Itabirite, low-grade, siliceous, including some clayey beds	3. 0	105. 5
Itabirite, moderately magnetic, thin-bedded, very siliceous	9. 4	102. 5
Ocherous material, soft brown with a little iron oxide left. A few thin magnetite beds present. Weathering product of a ferruginous dolomite	23. 0	93. 1
Itabirite, nonfolded, regular, thin-bedded	3. 5	70. 1
Two gouge zones 20 cm thick with severely dragged beds between them. Axes of drag folds plunge steeply NE and SW. These are essentially bedding plane faults on which the east side moved up.		
Itabirite, thin-bedded, severely drag folded	6. 8	66. 6
Itabirite, nonmagnetic, regular, thin-bedded (1 mm to a few mm), siliceous	12. 5	59. 8
Itabirite, hard, magnetic to very magnetic, moderately thick bedded	5. 2	47. 3
Itabirite, finely laminated, magnetic. The less ferruginous beds weather to a yellow ocher	3. 5	42. 1
Itabirite, finely laminated but thick-bedded, compact, siliceous, nonmagnetic	1. 0	38. 6
Itabirite, thin-bedded, siliceous, moderately magnetic	21. 5	37. 6
Itabirite, medium- to thin-bedded, magnetism decreases upward in section	8. 0	16. 1
Compact, magnetic itabirite that although finely laminated breaks along bedding planes spaced several cm apart	3. 3	8. 1
Itabirite, thin-bedded (1 mm or less), sandy, magnetic. At 3.0 m a 10-cm bed of moderately magnetic material containing an amphibole	4. 4	4. 8
Lowest itabirite exposed, limonite, and clay, beds slumped?	. 4	. 4
Base not exposed in railroad cut, but was observed elsewhere to overlie schist of lower group conformably.		

TABLE 8.—*Apparent thicknesses, in meters, of the middle group of the Minas series in the Casa de Pedra quadrangle*

Section	Serra Bôa Vista-das Almas	Serra Batateiro	Serra Mascate
E–E′	110	[a] 200	----------
D–D′	[b] 700	[c] 350	([d])
C–C′	320	[e] 200+	700
B–B′	525	----------	[f] 500(?)
A–A′	600	----------	----------

[a] Plus a fault slice which strikes nearly parallel to the section.
[b] Doubled or tripled by structural complications(?).
[c] Top not exposed.
[d] 1,500 m in the Serra do Mascate, but structures are nearly parallel to the section.
[e] Fault slide(?), part of original thickness faulted out(?).
[f] Structurally complex fault slice.

north in the section measured near Lagôa Grande (Park and others, 1951, pl. 3) at least 450 meters of itabirite is present.

As the base of the group is not exposed in the Fábrica–São Julião belt, the true thickness cannot be determined but structure sections based on the data available indicate that at least 250 meters of the upper part of the group is exposed in the outcrops and exploration adits at Fábrica (pl. 9). Near São Julião the indicated thickness is about 1,050 meters (section *C–C′*). This estimate, however, may not be correct for several reasons. First, the section lies on the nose of a plunging fold where thickening by plastic flow and other complex structural features may indicate too great an estimate for the thickness. Second, the section is interpreted as thrust-faulted so that an unknown amount of the total stratigraphic section may have been cut out. Approximately the upper two-thirds is dolomitic at this point.

The thickness of the rocks assigned to the middle group in the belt along the north edge of the São Julião quadrange may be about 500 meters. The dolomite in the belt south of Usina may be about 200 meters thick, but as this also may have fault contacts along one or both sides, the true stratigraphic thickness cannot be estimated.

UPPER GROUP

Lithologic features.—The upper group of the Minas series is composed chiefly of sericitic phyllite with variable percentages of very fine grained quartz. As exposures are relatively poor and the rocks have weathered deeply, their exact composition in the unweathered state cannot always be determined, but the prevalence of purple, red, yellow, and brown in the zone of weathering indicates ferriferous minerals such as chlorites, finely divided hematite, and pyrite. Dark-gray to black graphitic zones are also common. The phyllite is for the most part extremely fine grained, so that the weathered rock feels unctuous or only slightly gritty between the fingers, but some beds contain visible quartz grains that reach a maximum of several millimeters in diameter. In a few places the presence of angular light-colored blebs in a paste of purplish micaceous minerals is reminiscent of a graywacke texture.

The few specimens collected that were fresh enough to yield thin sections confirm the deductions made from the weathered zone. The thin sections show varying proportions of quartz in grains ranging from less than 0.01 to about 0.05 millimeter across and sericite in extremely fine grained aggregates, plus some chlorite, minute rolled zircons, flakes of specularite, small magnetite octahedra, and fine graphite dust. The fresher rocks are grayish green to yellowish green.

Bedding is usually revealed by compositional and textural variations from layer to layer. Small differences have been emphasized by weathering, and in large exposures such as new road cuts the variegated colors are conspicuous. Beds range in thickness from about a millimeter to a few centimeters. The fine-grained micaceous minerals are commonly oriented to form a cleavage which is in many places, but not everywhere, parallel to the bedding. One or more fracture cleavages are also ordinarily present; their chief visible effect is to cause a puckering of the flow-cleavage planes.

Quartzite beds and lenses are common in the upper phyllite. They are composed chiefly of fine- to medium-grained quartz with subordinate sericite or muscovite, and resemble the lower quartzites so closely in many places that the two cannot always be distinguished on the basis of single specimens or outcrops. Many of the upper quartzite beds are, however, slightly to moderately ferruginous, containing hematite, magnetite, or both. In this feature they contrast with the almost iron-free lower quartzites. Conglomeratic beds are more common, and crossbedding is also more frequently observed (fig. 9), but the most notable difference seems to be the lenticular character of the upper quartzites as opposed to the more regular alternation of quartzite and schist in the lower group.

Bedding is distinctly developed, marked by thin partings of micaceous material, darker ferruginous sands, or differences in grain size. The quartzite is ordinarily more resistant to erosion than the enclosing phyllite beds and commonly crops out boldly, holding up minor ridges or forming bluffs along the slopes of higher hills capped by other rocks. The lenses range in size from single beds in phyllite to masses more than 100 meters thick and several kilometers long.

Lenses of itabirite are interbedded with the phyllite. They range from less than a meter to a few meters in thickness and from a few hundred meters to more than a kilometer in length. Even very thin itabirite beds crop out if they occur in areas not covered by laterite or canga, and float from them is scattered for considerable distances downslope, so that they are easily recognized in mapping.

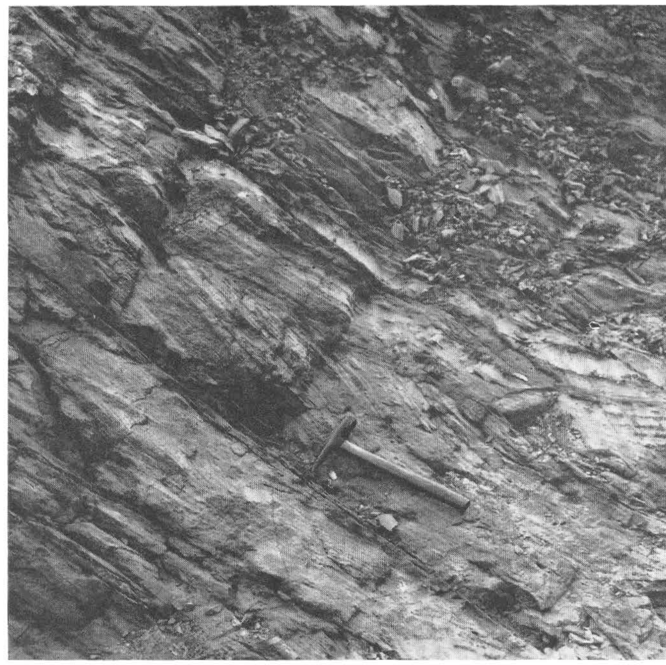

FIGURE 9.—Crossbedding in a quartzite lens of the upper group of the Minas series. Road cut 3 kilometers southwest of Casa de Pedra.

Some dolomitic zones entirely enclosed in phyllite and not associated with itabirite are considered lenses in the upper group rather than members of the middle group. They include pure, massive dolomite of metallurgical grade in the eastern part of the São Julião quadrangle and manganiferous weathering products in two thin belts near Cruzul, at the west edge of the quadrangle. Although they were not observed elsewhere in the Congonhas district, several lenses are known at Córrego do Eixo and along the Riberão Mata Porcos, a short distance north of the Casa de Pedra quadrangle.

A bed containing spessartite garnet partly altered to manganese oxides was observed in the phyllite of the upper group in a railroad cut 0.5 kilometer south of Salto, Jeceaba quadrangle. In thin section this rock consists of about 25 percent of garnet in grains 0.2–0.5 millimeter across, surrounded by very fine grained quartz and some coarse-grained mica that is moderately pleochroic in shades of brown. The only similar rocks known in the district occur in the green-schist sequence southeast of Alto Maranhão, Congonhas quadrangle.

Several geologists, in particular Guimarães (1951), have called attention to volcanic materials in the Minas series. Much of this material is thought to have been contributed as ash and mixed with the clastic sediments in such a manner that its presence has been largely masked. In the Congonhas district, although certain beds have a somewhat volcanic aspect, only one occurrence of recognizable volcanic rock is known in the area of typical Minas series rocks. This is a lenticular mass about 10 meters thick and a few hundred meters long exposed just south of the village of Esmeril, Jeceaba quadrangle. In outcrop and hand specimen it is a gray to purplish-gray fine-grained rock containing abundant rounded bluish quartz grains 1–2 millimeters across. Small flattened blebs of limonite mark a faint foliation. Under the microscope the rock is seen to be composed largely of very fine grained oriented sericite flakes and cryptocrystalline quartz (?), plus minor amounts of still recognizable plagioclase and microcline. The large quartz grains are considerably strained, and the limonite gives no hint of the primary mineral. This rock may have been a tuff or an acid flow or sill rock, but metamorphism has obscured its original nature. Certain ill-defined outlines suggest fragments that are reminiscent of a welded crystal tuff.

Distribution and thickness.—The major part of the outcrop area of the Minas series is underlain by rocks of the upper group, which apparently have a stratigraphic thickness several times as great as that of the lower and middle groups. No definite estimate can be given, but if no strata are repeated along the line of section *E–E′*, Casa de Pedra quadrangle, a thickness of 2,300 meters or more is indicated.

The group overlies the itabirite along the eastern flank of the Serra da Bôa Vista–das Almas and continues with regular eastward dips to the foot of the Serra do Batateiro and Serra do Mascate. It also overlies the itabirite along the eastern flanks of these two ranges, except where cut out by faults. A broad belt of phyllite extends eastward around the north end of the Serra do Mascate to and beyond the east edge of the São Julião quadrangle, lying between the Fábrica-São Julião belt of itabirite and dolomite on the south and the unnamed belt of lower and middle Minas series rocks on the north edge of the district. Phyllite also lies south of the Fábrica-São Julião belt, and on both sides of the Serra do Pires.

South and southeast of the limit of the quartzite and itabirite of the typical Minas series, phyllite containing a few minor quartzite lenses grades into rocks of the green-schist sequence. No sharp boundary exists, and for reasons which will be brought out in the next section the writer believes that at least part of the schist of the Congonhas lowland is equivalent to the phyllite of the upper group.

GREEN-SCHIST SEQUENCE

An extensive area is underlain by rocks which the writer groups together as the "green-schist sequence." These rocks are deeply weathered, poorly exposed, and apparently devoid of any horizon markers that make possible the determination of the structure or the measurement of a stratigraphic section. They were derived from diverse types of sediments, pyroclastic material, and perhaps flow rocks which have undergone both regional and thermal metamorphism; hence the geologic history is long and complicated, and the relationship of the sequence to other sedimentary rocks of the region is not clear.

LITHOLOGY

The predominant rocks of the sequence may be loosely grouped together as schists of various compositions. Quartz is the only mineral common to all the types; it occurs as angular, usually strained grains from 0.01 to about 1 millimeter across. Other minerals which may be present in widely different proportions are plagioclase feldspar, calcite, biotite, chlorite, muscovite and sericite, and graphite. Pyrite, magnetite, apatite, ilmenite and leucoxene, garnet, epidote, and zircon are minor constituents in some schist. Other types are quartz-zoisite-hornblende schist or amphibolite, and rocks composed almost entirely of pale-grayish green tremolite in matted, interlocking fibers. In many places weathering has altered most of these rocks to soft brown or reddish decomposed masses in which little but quartz and remnants of micaceous minerals can be observed; elsewhere they resemble weathered outcrops of the Minas series phyllites. In the deeper road and railroad cuts, and at a few points in stream beds, the more resistant types provide fairly fresh specimens, but most of the material for study was obtained from the cores of some diamond-drill holes put down by the D.N.P.M.

Two holes drilled near the river bank 250 meters south-southwest of the railroad bridge over the Rio Maranhão just west of Congonhas show a progressive gradation from schist to igneous rock (fig. 10). The predominant schist here is a well-bedded gray to greenish-gray micaceous rock containing small flattened lenses, a few millimeters long, of light-colored minerals oriented in the plane of foliation. In thin section these lenses are seen to consist of single crystals or aggregates of strained quartz, albite or sodic oligoclase, and calcite, in a matrix of fine-grained quartz and sericite; coarser grained biotite partly altered to a pale chlorite; and muscovite. Graphite dust is a common constituent as minute inclusions in the micas. Grains and lenticular patches of pyrite, commonly distributed along the planes of schistosity, are present in much of the core. The proportion of feldspar ranges from about 25 percent to none; most is twinned on the albite law, and all of it, twinned and untwinned, is more or less sericitized. Variations in carbonate content are especially marked, as some beds have 50 percent or more of calcite whereas others have none. The micaceous minerals wrap around the coarser grains to pro-

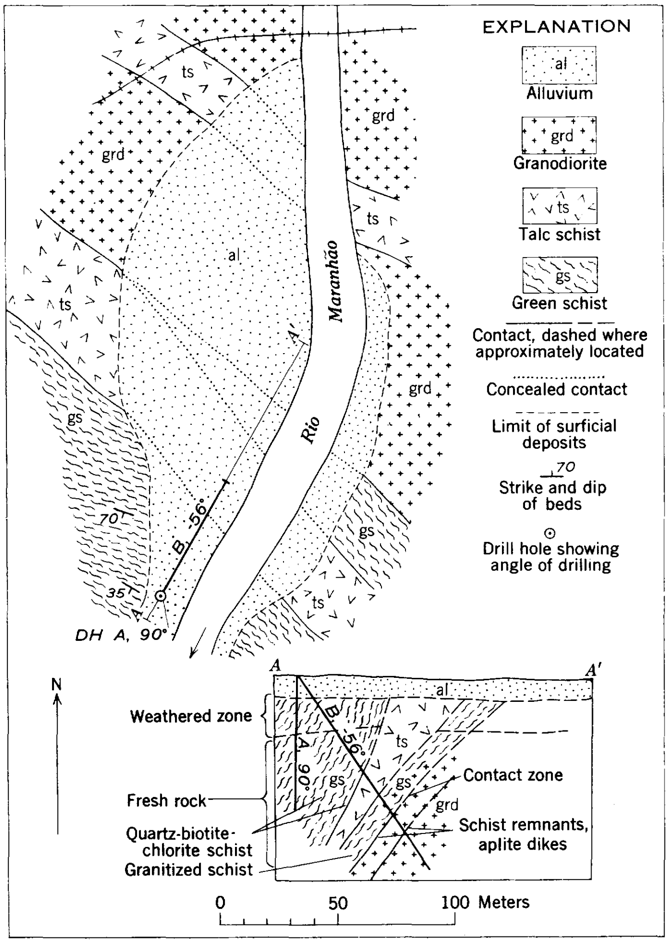

FIGURE 10.—Map and section of the area south of the railroad bridge over the Rio Maranhão, west of Congonhas, showing location and results of diamond-drill holes.

duce a microaugen texture. Interbedded with the coarser grained schist is dark-colored fine-grained graphitic phyllite composed largely of sericitic mica and subordinate quartz in grains a few hundredths of a millimeter across. Remnants of contorted beds (?) suggest severe drag folding of the less competent micaceous layers. A thin layer of biotite schist contains abundant grains of anhedral garnet about 0.1 millimeter across. Talc schist found in the drilling was undoubtedly derived from ultramafic rocks intruded into the sequence (page 25).

A thin sliver of sedimentary rocks between the talc schist and the large granodiorite mass to the north shows strong contact effects. The coarser quartz grains do not show appreciable strain, indicating that they have recrystallized, and irregular masses of very fine grained quartz have partly replaced the feldspar, older quartz, and micaceous minerals. The strong schistosity fades out as the mica and chlorite assume a matted fabric. Dikelets and irregular masses of granitic-looking material become progressively more common as the schist decreases to isolated remnants and dark schlieren in the light-colored igneous rock.

The outstanding difference between rocks mapped as phyllite and those called green schist is the partial or complete obliteration of the finer bedding planes in the schist. In many weathered outcrops only a weak cleavage can be distinguished which may or may not conform to the original stratification. Even the cleavage disappears in extreme cases, leaving a massive rock whose origin cannot be immediately determined, although examination of thin sections of unweathered specimens reveals a high proportion of quartz and indicates the sedimentary character of the material. A hole drilled in such a rock on the bank of the Riberão Santo Antônio 4 kilometers north of Congonhas, in the São Julião quadrangle, shows a quartz-chlorite-albite-epidote rock containing minor carbonate and biotite. The feldspar and epidote display a tendency toward elongation and orientation of the grains into a rude foliation, but the micaceous minerals are only slightly oriented. Quartz and carbonate veinlets are common, as are also very narrow veinlets of epidote or clinozoisite. This rock is closely associated with dikes of leucocratic quartz diorite.

Fine-grained dark rocks with limonitic weathering shells, apparently interbedded with the schist, are composed of roughly equal proportions of green hornblende, quartz, and zoisite or clinozoisite. Certain resistant grayish-green rocks are made up entirely of interlacing fibers of ferriferous tremolite, but amphibole-bearing rocks apparently comprise only a small part of the schist sequence.

Several beds of spessartite-quartz rock are intercalated in the schist about 2 kilometers east of Alto Maranhão, Congonhas quadrangle. They are about 60 percent garnet in euhedral grains averaging 0.05 millimeter in diameter, with interstitial quartz and a little pale amphibole. A thin crust of black manganese oxides has formed on the weathered surface.

Some well-bedded coarse-grained dark rocks were probably derived from water laid volcanic ash. Drilling 1.5 kilometers southwest of Congonhas, on the road to Santa Quitéria, provided unweathered material from such a zone. Thin sections show that untwinned albite in grains 0.05–0.5 millimeter across predominates over very fine grained quartz. Feldspar and quartz together generally are subordinate to micas, which include varying amounts of biotite, chlorite, and muscovite, both as fine flakes and aggregates and as unoriented porphyroblasts as much as several millimeters across. Very fine carbonaceous dust in the feldspar and the muscovite gives the rocks their characteristic dark tone.

Although small lenses in the schist were mapped as graywacke, microscopic examination shows that they do not differ materially from the green schist mineralogically or in appearance. These lenses are distinctive because they are more massive and more resistant to weathering. They consist of about 50 percent of moderately rounded grains of quartz and albite averaging a millimeter or so across set in a matrix of fine-grained quartz, sericite, biotite, and chlorite, with calcite, magnetite and pyrite as minor constituents in some places. Graphitic inclusions are abundant, particularly in the albite.

Lenses of low-grade siliceous iron formation occur intermittently along a narrow zone about 6.5 kilometers long in the schist and phyllite of the green-schist sequence, from 2 kilometers northeast of Congonhas to 1.8 kilometers north of Murtinho. Individual lenses range from 10 centimeters to a few meters in thickness; the more persistent ones may be traced for nearly a kilometer. These rocks resemble the itabirite of the Minas series in every way. They are fine-grained laminated quartz-iron oxide schists with crop out boldly or supply abundant float material to the soils.

DISTRIBUTION AND CORRELATION

The green schist and associated rocks underlie much of the Jeceaba and Congonhas quadrangles as well as the southeast corner and southern third of the Casa de Pedra and São Julião quadrangles, respectively. A combined pattern has been used to indicate areas in the eastern two quadrangles where dikes intrusive into the schist are so abundant that it was not feasible to distinguish them in mapping because of scale limitations and poor exposures. Along roads and railroads and in other places where exposures were sufficiently good an attempt has been made to show the actual distribution of the sedimentary and igneous rocks.

The schist areas have a local relief of 100 to 175 meters, but there is little pattern to the topography because significant lithologic variations are lacking in most of the sequence. Only in the belt of phyllite and itabirite crossing the Congonhas quadrangle northeast of the Rio Maranhão has bedding and differential resistance to erosion had a noticeable effect on the landscape and controlled the drainage pattern to a minor degree.

The thickness of the section and structural details cannot be determined because of the absence of recognizable stratigraphic horizons. However, even though many repetitions undoubtedly exist, the thickness must be very great—hardly less than several thousand meters.

The relationship of these rocks to others of the region is a major problem which has not been solved. These rocks have been called "Archean," pre-Minas "Proterozoic," and Minas series equivalent by various authors. The present writer is inclined to correlate them with the Minas series because (1) he can find no sharp break between recognizable Minas phyllite and rocks of the green-schist sequence along the line separating the two types; (2) contacts between quartzite and itabirite of the Minas series and the green schist are faulted in the Congonhas district and provide no concrete evidence for determining the relative ages of the two types; and (3) no essential differences exist between the rocks of the recognizable Minas and the green-schist sequence which cannot be attributed to lateral facies changes and the effects of thermal metamorphism caused by the large intrusive masses. Many aspects of the problem can only be discussed in relation to the structural and igneous history of the district and will therefore be deferred to a later section of this report (p. 39).

ITACOLUMÍ SERIES

A thick series of commonly coarse grained siliceous rocks overlying the Minas series in the Congonhas district is correlated on lithologic and stratigraphic grounds with the Itacolumí series. At the type section in Pico Itacolumí near Ouro Preto, 30 kilometers east of São Julião, the series was divided by Lacourt (1936) into three zones, a lower one of sericitic quartzite and interbedded conglomerate, a middle zone of phyllite, and an upper one of sericitic quartzite that is in part crossbedded. No such stratigraphic division is possible in the Congonhas district, but all these rocks, plus ferruginous quartzite and itabirite, are present in a succession of rapidly alternating types. Barbosa (1949) originally described these rocks as the Santo Antônio formation and placed them between the typical Minas and the Itacolumí, but he, as well as other geologists, now considers them to be equivalent to the latter series.

LITHOLOGY

The most abundant rock is a sericitic quartzite composed of moderately to well-rounded quartz grains that range in size from fine sand to coarse pebbles several millimeters in diameter, set in a matrix of coarse-grained sericite or muscovite. The mica wraps around the larger quartz grains. Kyanite in radiating clusters or individual blades oriented in the cleavage plane is common, although by no means universally present. The proportions of quartz to clay in the original sediment varied considerably, so that the rocks today range from compact hard quartzites to rather "dirty," barely coherent mixtures of sand and mica. A moderately well developed cleavage parallels the bedding in most places and serves to emphasize it, but at some points transects it at a high angle and almost obliterates all trace of the original stratification.

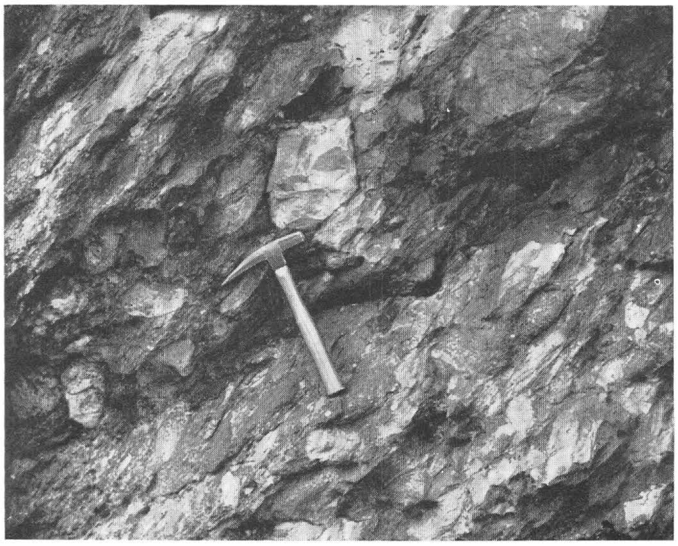

FIGURE 11.—Conglomerate of the Itacolumí series. East flank of the Serrote de João Pereira, 4 kilometers east-northeast of Casa de Pedra.

With increasing coarseness in the size of the pebbles the quartzite grades into conglomerate containing cobbles and boulders of vein quartz and recognizable fragments of rocks derived from the Minas series (fig. 11). Itabirite is the most conspicuous and readily identifiable component of the conglomerate; other rock types are quartzite and a few phyllite fragments. The size of the cobbles ranges from about 1 to 50 centimeters; the ratio of coarse- to fine-grained material and the

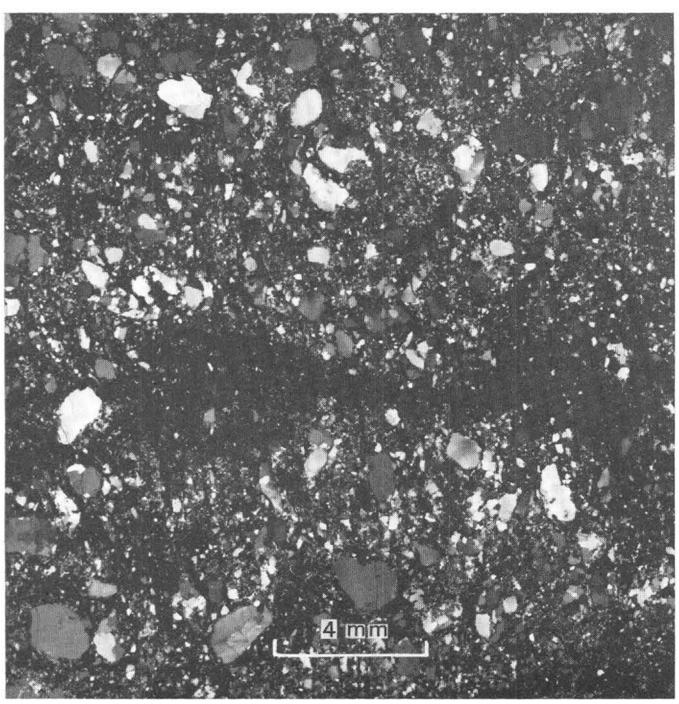

FIGURE 12.—Ferruginous grit from the Itacolumí series. Thin section, quartz pebbles and finer sand with abundant fine-grained hematite concentrated in layers parallel to the crossbedding. Partially crossed nicols, ×5.

composition of the components also vary within wide limits. The conglomerates form lenses or beds in the quartzite from a meter or less to at least a dozen meters thick and apparently are not restricted to any particular horizon. Certainly they are not "basal conglomerates."

Hematite is present to a greater or lesser extent in most of the quartzite and forms a major constituent of some beds. A few thin beds (less than 1 cm thick) are almost pure specularite. The hematite is interstitial to the larger quartz grains, which are obviously of clastic origin, and is probably clastic also, derived from the itabirite and deposited as black sands (fig. 12).

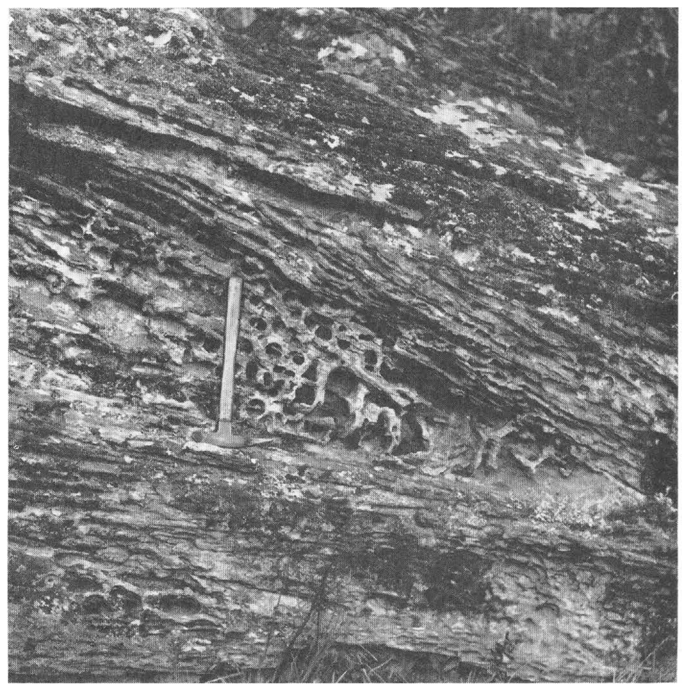

FIGURE 13.—Crossbedding in somewhat ferruginous quartzite of the Itacolumí series. The peculiar deep pitting, caused by differential resistance to erosion, is not diagnostic of any particular quartzite in the Congonhas district, 3 kilometers east-northeast of Casa de Pedra.

Small (less than 1 mm) octahedra of magnetite of metamorphic origin are sparingly present in some beds. Crossbedding is a common feature of the ferruginous quartzite (fig 13).

Finely laminated siliceous itabirite lenses that are similar to or indistinguishable from the itabirite of the Minas series occur as lenses in the Itacolumí rocks of the Congonhas district. Most of these lenses are thin, ranging from a few meters to a few dozen meters in thickness and a few hundred to about a thousand meters in length, but one has an apparent thickness of about 400 meters and a length of 6 kilometers. Points of difference between these itabirite lenses and the iron formation of the Minas series are (1) they are underlain and overlain by sericitic quartzites, rather than by argillaceous rocks as are the Minas itabirites, and have beds of clean quartzite within the lenses in some places; (2) no dolomitic zones are known, and no strongly magnetic zones were found in the Itacolumí itabirites; and (3) beds containing abundant angular pieces of fine-grained quartz, siliceous iron formation, and jasper-like pink to deep-red fragments are interbedded with the more normal itabirite. It is not always possible to distinguish between the ferruginous conglomerate and these zones of angular breccias, but the breccia zones have little or no mica and a much greater proportion of specular hematite than beds with well-rounded pebbles. Another structure which occurs sporadically in the itabirite of the Itacolumí series but has not been recognized in the Minas series is that illustrated in figure 14. Elongated lenticular masses of fine-grained quartz, some containing a little hematite in the cores and in concentric layers, are enclosed in darker, much more ferruginous material. They probably are nodules of recrystallized chert.

Argillaceous rocks are relatively rare in the Itacolumí series of the Congonhas district. Only a few scattered lenses of phyllite were interpreted as interbedded with the siliceous members, and some of these may belong to the Minas series and be in fault contact with the Itacolumí rocks. In outcrop they are nondescript gray- to brown-weathering, poorly exposed rocks. Most are very fine grained sericite-rich phyllite. In a few places porphyroblasts of clear muscovite to about 1 millimeter give the rock a spotted appearance. A chloritoid-garnet schist is exposed in the Córrego do Lagarto north of Poço Fundo, Casa de Pedra quadrangle. Porphyroblasts of chloritoid 1–2 millimeters across form resistant knots which stand in relief on weathered surfaces. In thin section the chloritoid is seen to have enclosed many tiny magnetite crystals, and fine bedding laminations remain preserved in the porphyroblasts. Garnet crystals 0.05–0.15 millimeters across, which also contain a few magnetite inclusions, are scattered sparsely throughout the rock. The groundmass is extremely fine grained quartz, sericite, and magnetite ranging from about 0.03 to less than 0.001 millimeter across. Kyanite is another common mineral in these rocks. One specimen is composed entirely of interlacing kyanite blades nearly 1 centimeter long containing finely disseminated specularite as the only other constituent.

DISTRIBUTION AND CORRELATION

The rocks of the Itacolumí series occur in two adjacent areas in the eastern part of the Casa de Pedra quadrangle and the west edge of the São Julião quadrangle. The larger one occupies the topographic basin lying north and east of Pico Engenho and southwest of

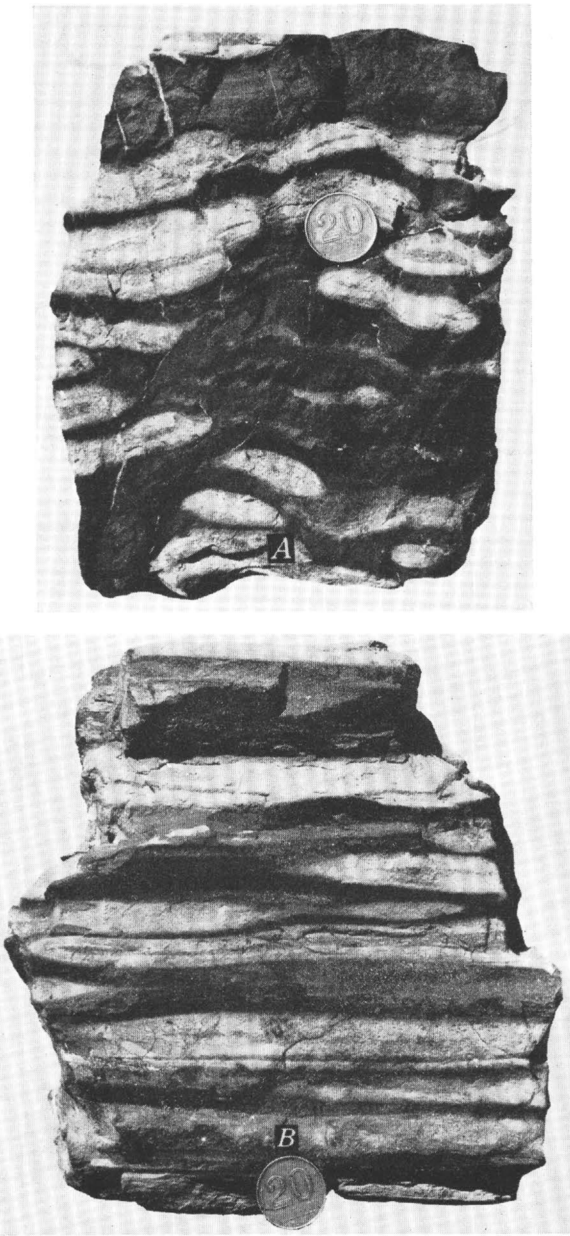

FIGURE 14.—Elongated nodular structures in itabirite. Light-colored material is finely granular quartz with a little specular hematite; dark is chiefly hematite. Thin quartz veinlets cut quartz and hematite. *A*, View parallel to the regional lineation. *B*, Same specimen from the side. Coin is 19 millimeters in diameter, the same size as a United States penny.

the Serra do Pires. It is composed chiefly of quartzite and conglomerate, with minor phyllitic and ferruginous members. This area is essentially downwarped into what Barbosa (1949) described as a plunging syncline, but has some faulting along the western border. Although the beds strike fairly consistently to the northwest over most of the area and dip moderately northeast, considerable repetition may have occurred, so that it is impossible to determine a stratigraphic thickness for the series. The minimum is, however, probably not less than 1,000 meters. The rocks are not well enough exposed to determine with certainty that an unconformity separates these rocks from the Minas series, but moderately folded pebbles in conglomerate derived from the underlying rocks suggest that at least some angular discordance must occur.

The second area is that of the Serra do Pires belt, occupied largely by ferruginous members of the series with subordinate quartzites. It is interpreted as being in thrust-fault relationship to the Minas series rocks on both sides of it, and is superposed on other Itacolumí rocks for a short distance southwest of Fábrica. The rocks in this fault slice dip gently to steeply northeast, and if not repeated they have a stratigraphic thickness of about 650 meters on section *A–A′*, São Julião quadrangle. A small area of conglomeratic quartzite east of the Riberão Goiabeira is also correlated with the Itacolumí series, and probably has fault relations to the surrounding rocks.

Barbosa (1949, 1954) has pointed out that the character of the sediments and their sporadic distribution indicates a Flysch or "Wildflysch" type of deposit—that is, one laid down in intermontane valleys and isolated basins contemporaneously with the initial stages of deformation and uplift of the older series. The character of the sedimentation suggests that these strata may not be strictly contemporaneous from one area to another, but in a general way they correspond to Itacolumí rocks of the type locality because they overlie the Minas series unconformably and contain somewhat deformed pebbles derived from the Minas series. The question of what constitutes the Itacolumí series has recently been reopened by Barbosa (1954), who suggests that the extensive quartzite beds of the area north of the "quadrilátero ferrífero," long considered as Itacolumí by Guimarães (1931) and others, are in fact lower Minas series as was formerly held by Harder and Chamberlin (1915). If true, the area of outcrop of the Itacolumí rocks would be severely restricted, and the Flysch sediments would be the characteristic, not the exceptional rock type of the series. Until these conflicting views have been resolved by more field work to the north and east, it seems best to consider these rocks of the Congonhas district as the "Santo Antônio facies" of the Itacolumí series.

INTRUSIVE ROCKS

Three distinct types of intrusive rocks occur in the Congonhas district: (1) an ultramafic suite of peridotite now altered to serpentine, steatite, and talc schist; (2) granodiorite and allied types; and (3) dike rocks of gabbroic affinities. Intrusive rocks are much more common in the green-schist sequence than in the typical Minas series; hence most of them occur in the southern part of the district, particularly in the Jeceaba and Congonhas quadrangles. They are not, however, restricted exclusively to these areas. Quartz veins are abundant in all the rocks of the district.

ULTRAMAFIC ROCKS

DESCRIPTION

The ultramafic rocks are greenish or grayish-green massive to schistose rocks composed largely of the ferromagnesian minerals talc, antigorite and other chlorite, and tremolite-actinolite, which in places contain accessory magnetite, dolomite-ankerite, and pyrite. Massive varieties in which talc predominates are steatite; serpentine has antigorite as the chief constituent. Although most of these rocks were mapped as steatite, detailed petrographic studies would undoubtedly reveal that the rocks in some areas should be called serpentine. Much of the steatite has a moderately well developed cleavage, particularly in smaller masses and along the borders of the larger masses, so that the distinction in mapping between steatite and talc schist is an arbitrary one, depending on the perfection of the cleavage. As these ultramafic rocks are relatively resistant to chemical alteration in the weathering zone they produce only thin, infertile soils and ordinarily crop out prominently.

Typical massive steatite of the district consists of white or light-green talc in aggregates of small, unoriented plates, with nearly equidimensional clots several millimeters across of dark-green, fine-grained chlorite. The overall texture is apparently pseudomorphous after that of a medium-grained equigranular peridotite, the talc presumably after the olivine and the chlorite after a pyroxene. Magnetite octahedra averaging about 0.1 millimeter are scattered throughout the rock as a minor constituent. Very fine grained magnetite dust arranged in straight lines and irregular networks apparently was localized by cleavages, fractures, and grain boundaries of the original silicates. A carbonate, which generally contains small pyrite blebs, occurs in irregular grains enclosing and replacing the silicate minerals at places in the steatite masses. Some grains are a centimeter or more across and are easily recognizable because of the reflection of light from their cleavage faces. The index of refraction of the ordinary ray is about 1.72, indicating that the carbonate is a moderately ferriferous ankerite, $CaO(Mg,Fe)\cdot O\cdot 2CO_2$. This rock is cut by veinlets of white carbonate which has an index of refraction of 1.69, corresponding to an ankerite with a very low iron content. Euhedral pyrite crystals as much as a centimeter or more across, displaying the cube, octahedron, and pyritohedron forms, are common in some steatite, particularly in areas where ankerite is prominent.

Types intermediate between steatite and serpentine contain both talc and antigorite, as well as a dark-green chlorite with anomalous blue and brown interference colors. Where talc is a minor constituent or absent, the rocks are true serpentine. The original texture is ordinarily preserved.

Light green nonpleochroic amphibole of the tremolite-actinolite series is a common constituent of the serpentine and steatite. It occurs both as anhedral, more or less equidimensional grains without orientation which may be pseudomorphous after original pyroxene, and as slender acicular crystals. A specimen consisting only of tremolite partly altered to a light-green chlorite has a medium-grained equigranular texture strongly reminiscent of a pyroxenite, although no pyroxene is present.

The talc schist is an extremely soft, unctuous, well-foliated rock composed of fine-grained parallel talc flakes and minor accessory magnetite. Actinolite needles, present in some places, ordinarily lie without orientation in the plane of schistosity, but may cross it at moderate to high angles.

Veins of talc, which occur sporadically in the steatite, lack the high degree of preferred orientation of the schist. Some are relatively fine grained and compact, in others the talc occurs as plates as much as several centimeters across. The veins reach a maximum of a few meters in width and perhaps a few dozen meters in length.

DISTRIBUTION AND GEOLOGIC RELATIONSHIP

The largest mass of ultramafic rocks in the district is apparently a sill which was intruded concordantly into the green-schist sequence, deformed and foliated during the orogeny which folded these rocks, and intruded by a later granodiorite. The steatite forms a border between the granodiorite and the green schist around most of the perimeter of the elongated stock extending about 7 kilometers southeasterly from the vicinity of Congonhas and also occurs as schistose inclusions or roof pendants in the nonfoliated acid rock. As Barbosa (1949) has pointed out, the sill largely controlled the emplacement of this granodiorite stock. Swarms of smaller lenses elsewhere, particularly in the itabirite-bearing zone northeast of the Rio Maranhão, resemble flows because they are rigidly parallel to the regional structure, but their composition and a few branching outlines indicate an intrusive rather than extrusive relationship.

Although ultramafic rocks are comparatively rare outside this principal belt, they occur sporadically throughout the area of the green-schist sequence. They have not, however, been positively identified from areas of typical Minas series rocks in the Congonhas district, a fact which has been used by some geologists, most recently by Barbosa (1954), to prove the pre-Minas age of the green schist.

More field work will be necessary before these ultramafic rocks can be dated accurately, because the criterion of their presence or absence in sedimentary strata has been used to date the sedimentary rocks. The writer believes that the ultramafic rocks are post-Minas because he tentatively correlates the green-schist sequence with the Minas series. However, recent work (Dorr and others, oral communication) casts serious doubt on this assumption, and a paper by Matheson [4] that has appeared since this report was completed dates the ultramafic rocks in the area north of the Congonhas region as pre-Minas.

GRANODIORITE

DESCRIPTION

Light-colored medium-grained holocrystalline intrusive rocks occur as batholiths, stocks, and dikes in the Congonhas district. They vary widely in composition, as shown in table 9, but two general types may be distinguished which grade into one another: (1) a hornblende-bearing muscovite-free rock close to quartz diorite in composition (analyses 1–3) and (2) a more felsic biotite-muscovite granodiorite (analyses 4–6). The plagioclase in the hornblendic variety generally occurs as hypidiomorphic zoned crystals several millimeters across that in places display more calcic rims over normally zoned sodic cores. The range is about An_{20} to An_{32}. The amphibole is a weakly pleochroic pale green hornblende. The felsic varieties have medium- to fine-grained granitoid textures and the plagioclase is not markedly zoned. In places the border zones of the felsic granodiorite masses are noticeably finer grained than the interiors.

Many leucocratic dikelets with gradational contacts cut both types. Microcline ordinarily predominates over plagioclase (table 9, analysis 7) but this is clearly due to residual potash enrichment of the late differentiates and not to the intrusion of new magma. The composition of the plagioclase falls on or near the albite-oligoclase boundary. The texture is generally medium grained granitoid, much like that of the typical granodiorite, but may also be partly or entirely coarse-grained pegmatitic.

The greater part of the granodiorite is massive, but along the borders of some of the larger masses there is a pronounced orientation of biotite flakes and segregation of biotite and hornblende into schlieren and lenticular or tabular masses oriented parallel to the contacts of the intrusions. Inclusions of foreign rocks are also relatively common, particularly in or near the

[4] Matheson, A. F., The St. John Del Ray Mining Co., Ltd., Minas Geraes, Brazil: Canadian Min. and Metall. Bull., v. 49, p. 37–43, 1956.

TABLE 9.—*Modal composition, in percent, of some rocks of the granodiorite suite*

	1	2	3	4	5	6	7
Quartz	13.7	18.3	21.7	28.7	25.1	25.6	26.0
Microcline [a]	6.4	10.9	7.8	16.6	11.7	11.3	44.5
Plagioclase [b]	47.3	50.2	45.7	47.6	53.5	41.1	28.5
Hornblende	6.2	3.7	1.7	------	------	------	------
Biotite	23.9	14.1	17.3	3.4	5.8	14.4	------
Muscovite	------	------	.4	2.7	3.9	7.3	.5
Accessory minerals (and alteration products) [c]	2.5	2.7	5.4	1.0	------	.3	.5

[a] Includes some orthoclase and perthite.
[b] Ranges from An_{10} to An_{32}, averages about An_{25}.
[c] Zircon, sphene, apatite, opaques, epidote, calcite, chlorite, and sericite.
1. Slightly gneissic intrusion from border zone of batholith, near Congonhas-Alto Maranhão road 3.5 km south of Congonhas.
2. Nonfoliated granodiorite, from road cut on east bank of river 1.5 km south of Jeceaba.
3. Granodiorite from railroad cut at km 500, west of Caetano Lopes, Jeceaba quadrangle.
4. Granodiorite from quarry west of Riberão Santo Antônio, 0.3 km northwest of Congonhas, São Julião quadrangle.
5. Granodiorite, road cut on Rio-Belo highway in northeast corner of São Julião quadrangle.
6. Slightly gneissic granodiorite from Riberão Sardinha, northeast corner of São Julião quadrangle, 0.5 km south of quadrangle border.
7. Felsic crosscutting dike from same specimen as analysis 6.

border zones. Steatite and talc schist, green schist, and quartz-muscovite schist all occur in the granodiorite near Congonhas as elongated masses which closely parallel the contacts of the intrusion. They may in part be roof pendants, engulfed in magma but retaining their original attitude, or they may all have been torn loose and oriented by laminar flow during emplacement.

Much of the granodiorite lacks any characteristic topographic expression. The more mafic varieties weather to a deep red soil and natural outcrops are rare except in the gneissic border zone. The felsic varieties weather to white clays that erode rapidly to gullies as deep as several dozen meters, producing an irregular broken topography superimposed on the rounded older slopes.

DISTRIBUTION AND RELATIONSHIP TO OTHER ROCKS

The largest intrusive mass within the district is a granodiorite batholith occupying the southern half of the Jeceaba quadrangle and the southwest corner of the Congonhas quadrangle. It extends a considerable distance to the south. The border zone is somewhat gneissic parallel to the contact, which cuts discordantly across the structures of the green-schist sequence in some places but is concordant in others. The rock is of the hornblendic type with zoned plagioclase (table 9, analyses 1–3).

Smaller intrusive bodies in the green schist area are almost certainly related genetically to the batholith, although they are more felsic (analysis 4). South and west of the itabirite-bearing phyllite zone trending northwest across the Congonhas and São Julião quadrangles these masses are distinct and usually of mappable size, but to the northeast granodiorite is so intimately mixed with the green schist that it was not found practicable to show them separately. The relative proportions of intrusive rock and green schist range from infrequent thin dikelets or sills in the schist and associated ultramafic rocks to large irregular masses of granodiorite with abundant inclusions and pendants of country rock. An attempt was made to distinguish the larger units along roads and railroads where artificial cuts made this possible, but in poorly exposed areas a combined pattern has been used to indicate schematically the nature of the bedrock.

The granodiorite in the extreme northeast corner of the São Julião quadrangle is the edge of a batholith about 20 by 30 kilometers across that extends northward to the vicinity of Itabirito. It has a weak to moderate foliation in the contact zone, but the attitude has no apparent relationship to the contact. The batholith intruded typical Minas series rocks, producing a well-defined aureole of contact metamorphism (p. 39). Dikes both of normal-textured granodiorite and tourmaline-bearing coarse-grained pegmatite are common in the schist of the contact zone.

These pegmatites resemble those in the lower quartzite at Salto and suggest that at least some of the intrusive rocks of the western area mapped as gneiss may be contemporaneous with the granodiorite suite. The rocks that intrude the gneiss are, however, decidedly more potassic (table 3) than the granodiorite of the Congonhas lowland in which only the late dikes have an excess of microcline over plagioclase, so any genetic relationship is doubtful.

Granitic dikes are not common in the typical Minas series rocks away from contacts with large masses of igneous rock, but a muscovite-bearing pegmatite that cuts itabirite was found in an exploration adit near Casa de Pedra, and other finer grained dikes may also be related to acid intrusive rocks. These latter dikes are thin crosscutting bodies which are so completely weathered where they are exposed at or near the surface that little is known of their original composition. Abundant zircon and tourmaline in washed concentrates of clay from these dikes, however, indicate that they have granitic affinities.

AGE

The granodiorite shows little sign of deformation. An exception occurs on the Pires road about 2 kilometers north of Congonhas, where the granodiorite is strongly sheeted along closely spaced fractures that were healed by the introduction of new unstrained quartz. However, as inclusions of country rock in the generally nondeformed granodiorite are characteristically schistose, the intrusion evidently followed the principal orogeny and regional metamorphism of the sediments. The northeastern batholith is post-Minas and almost certainly post-Itacolumí. The modal compositions (table 9) show that all the granodioritic rocks of the district are similar and probably related genetically. The writer therefore believes that they are all of post-Minas age, and calls on structural factors to explain the comparative scarcity of intrusive rocks in the typical Minas series rocks.

BASIC DIKE ROCKS

DESCRIPTION

Dikes of compact, tough dark-green to black rocks composed chiefly of ferromagnesian minerals and alteration products of calcic plagioclase occur at many places in the district. These rocks probably could be subdivided into several types, as the composition and texture vary, but no attempt was made to do so during the course of the field work and they are here referred to collectively as gabbro. This term is not strictly correct, however, as no augite or other pyroxene has been observed. Brazilian geologists (Guimarães, 1933, and others) call these rocks amphibolites, after the French usage, and the term "anfibolito diabasoide" is commonly applied to those with ophitic textures.

Ferromagnesian minerals, chiefly amphiboles, range from about 50 to nearly 100 percent of the rock. In some dikes the amphibole is a deeply pleochroic green hornblende, in others it is nonpleochroic actinolite. Chlorite, and in a few specimens biotite, is a common alteration product of the amphibole. Unaltered plagioclase feldspar, ranging from about An_{55} to An_{30}, is comparatively rare except in a few fine-grained dikes; most feldspar has been partly or completely saussuritized to zoisite, clinozoisite, and epidote, with secondary quartz and some albite. Ilmenite, titanite, and leucoxene occur in most of the dikes, in places forming 10 percent or more of the total mass. Apatite, magnetite, and various sulfides, including pyrrhotite, are accessory minerals. The basic dikes range in thickness from less than 10 to more more than 100 meters. Many cannot be traced beyond a single outcrop, but others extend for kilometers. Depending upon their texture and degree of alteration, and upon the comparative resistance to weathering of the dikes and country rock, these dikes either stand up in bold outcrops connected by trains of smooth limonite-coated boulders or lie in trenchlike depressions filled with dark-red soil.

DISTRIBUTION

Dark dike rocks cut the green-schist sequence, typical Minas series rocks, and the granodiorite in the Congonhas district. A coarse-grained variety containing deeply pleochroic hornblende prisms nearly a centimeter across, epidote, and abundant leucoxene is exposed in the railroad cut 600 meters north of Jeceaba. The dike is 100 meters wide and encloses a mass of quartzite from the upper group of the Minas series. Topographic evidence (prominent depressions in ridges and the alinement of lateral tributaries of streams crossing the area) indicates that this dike continues eastward about 5 kilometers. Deeply weathered outcrops and float in a sharply defined gully at Batateiro, 3 kilometers west of Casa de Pedra, reveal the presence of another coarse-grained basic dike some 50 meters thick. This dike also trends east-west and is vertical. A single outcrop of weathered basic dike rock was found along an east-west fault zone 1 kilometer south of Fazenda do Vigia, São Julião quadrangle. A prominent basic dike exposed at the east edge of this quadrangle extends eastward for many kilometers across the quartzite (lower Minas?) of the Serra do Ouro Branco.

Dikes that are in general medium to fine grained and frequently ophitic textured are relatively common in the green schist areas, particularly in the eastern part of the Congonhas quadrangle and the southeast corner of the São Julião quadrangle. Undoubtedly many which do not crop out prominently are present in the green schist-granodiorite areas, for their weathering products do not differ greatly from those of the schist. An extremely tough, fine-grained ophitic-textured dike cuts the contact zone of the batholith in the northeast corner of the São Julião quadrangle.

AGE

Guimarães (1933, p. 4) dates the "amphibolites" in the northern part of Minas Gerais as post-Itacolumí and pre-Bambuí (Silurian?). His descriptions indicate that these rocks are similar to, and probably identical with, at least part of the basic dikes of the Congonhas district, which are post-granodiorite and hence considerably later than the post-Itacolumí orogeny.

VEIN QUARTZ

Quartz veins, which are abundant in all the rocks of the district, may be divided into several types according to their occurrence and mineralogy. It is probable that the vein-forming solutions were of different origins and ages.

Simple quartz veins.—The majority of the veins are composed chiefly or entirely of cloudy white quartz. Veinlets found in drilling in the contact zone of a granodiorite stock contain a little finely divided pyrite, but veins in the sedimentary rocks show no trace of any gossan in the weathered zone and are essentially barren. They range in size from microscopic stringers to masses perhaps a dozen meters thick and several hundred meters long. The larger ones, where they occur in schist and other less resistant rocks, crop out and underlie small hills. Float from these veins covers extensive areas downslope.

Vugs containing crystals of slightly cloudy to limpid quartz are common in the milky quartz. The crystals are usually small, averaging less than a centimeter across and a few centimeters long; a few, however, are much larger.

Although many quartz veins disintegrate into blocky fragments at the surface, some have a very fine grained sugary texture in the weathered zone and closely resemble metamorphic quartzite. Careful observation usually reveals larger angular fragments of recognizable vein quartz, however. This feature and the lack of any of the micaceous minerals universally present in the quartzite of the district serve to identify the material. The texture probably resulted from partial solution of the quartz by surface or ground waters which penetrated along incipient fractures, such as planes of undulatory extinction, induced by tectonic stresses. Further study might show that the feature could be used for approximate dating of the veins, but no attempt to do so was made.

A group of closely spaced parallel quartz veins aggregating more than 20 meters in thickness follows the granodiorite-steatite contact west of Riberão Santo Antônio about a kilometer northwest of Congonhas. The contact appears to be offset sharply at this point, but as the veins do not extend much if any beyond the ends of the offset portion, the shearing was probably contemporaneous with the emplacement of the granodiorite and aided in localizing it. Vugs in the veins are filled with quartz crystals and a red fine-grained material that is composed of approximately equal parts of tiny white chlorite flakes and earthy hematite. This evidence suggests that the veins closely followed intrusion of the granodiorite, and that magnesia, iron oxide, and the other constituents of the vug fillings were probably derived from the ultramatic rocks, perhaps by the same solutions which caused the carbonatization of the steatite. The quartz of these veins has the fine sugary texture described above, which also suggests that the quartz veins are early.

QUARTZ-KYANITE-PYROPHYLLITE VEINS

Quartz veins with selvages of coarse kyanite blades are prominent features of the area underlain by the sericitic quartzite of the Itacolumí series. These veins range in thickness from about 10 centimeters to 1 meter, and many can be traced for hundreds of meters. The veins follow the direction of a joint system that strikes about N. 10°–30° E. and dips steeply northwest; hence they are essentially parallel to one another.

Zones of bladed kyanite that range from about 2 to 10 centimeters in thickness separate the vein quartz from the country rock. The zones are uniform in thickness for any one vein, and are symmetrically developed on each contact. The thicker quartz veins commonly have wider selvages. The blades are oriented at right angles to the plane of the vein, in a "cross-fiber" manner. Single kyanite crystals ordinarily extend completely across the zone from the vein quartz to the country rock, penetrating the quartz in a slightly irregular fashion but having a sharp outer contact, so that the selvage breaks cleanly away from the quartzite and adheres to the vein material. A few thicker veins also have a zone of kyanite extending down the center of the vein, and scattered blades may occur at any point within them. Narrow kyanite veins with the cross-fiber structure, but lacking the quartz cores, are apparently composed of only the selvages of the more common type.

Rosettes of bladed pyrophyllite crystals as much as a few millimeters long grow between the kyanite blades in a few veins. Pyrophyllite also occurs as rosettes on, and three-dimensional radiating clusters of blades within, coarse quartz crystals in a vein about 300 meters northeast of the switchback on the road to Poço Fundo, Casa de Pedra quadrangle.

The restriction of these veins to the impure Itacolumí quartzite and the characteristic occurrence of the kyanite in selvages suggest a derivation of the alumina from the country rock, apparently by some process of lateral secretion. The veins follow a prominent joint set, which indicates that they are younger than the post-Itacolumí orogeny. The sequence kyanite-pyrophyllite suggests a falling temperature, perhaps during the closing stages of the regional metamorphism after compressive stress had ceased. The pyrophyllite in the coarse quartz crystals must have formed from alumina picked up by the vein-forming solutions and deposited at a relatively low temperature.

QUARTZ-SPECULARITE VEINS

Coarsely crystalline specularite occurs in a few quartz veins, both as euhedral tabular crystals bounded by the basal faces and the rhombohedron and as irregular masses 30 centimeters or more across which show by the perfect basal cleavages that they are pieces of single crystals. The best locality known is a low knoll just south of the Côrrego do Logarto about 2 kilometers northeast of Casa de Pedra. The vein cuts quartzite of the Itacolumí series

Narrow veins in itabirite and ferruginous quartzite frequently have abundant flaky specularite in very thin brittle plates a few centimeters across that are commonly strongly curved. Hematite also occurs as extremely thin plates in coarse quartz crystals; a few are translucent and appear ruby-red by transmitted light.

The quartz-hematite veins seem to be restricted to the general vicinity of the iron formation. Presumably the iron was derived from the sedimentary rocks and redeposited.

"CLEAVAGE" QUARTZ

Coarse-grained vein quartz with several sets of closely spaced fracture planes reflect light evenly from large surfaces much as coarse-grained pegmatitic feldspar does from cleavage planes. Crystal faces have not formed in most of this "cleavage" quartz, so that the relationship between these planes and the crystallographic directions cannot be determined in hand specimen. In those crystals in which the faces can be identified, however, the fracture planes are at angles that do not correspond to the principal planes. Statistical studies with oriented thin sections would aid in solving the problems presented by this quartz, but they have not as yet been made.

"Cleavage" quartz veins are common in zones of manganiferous itabirite, where they ordinarily fill cross joints. Films and veinlets of crystalline manganese oxides cut them, and the veins themselves are sheathed in manganese oxides in some places, so that they are evidently related to ore-forming processes. Much of this quartz has an almost fibrous appearance, as well as the pseudocleavage, and columnar shapes extending perpendicularly from wall to wall of the vein. Remnants of a finely acicular amphibole, now largely altered to limonite, indicate that the columnar structure is pseudomorphous, but no amphibole veins of this type have been observed.

Terminated quartz crystals with a peculiar yellowish cast and a somewhat greasy luster are common in the weathering products of dolomite (p. 41). They are not known in the unaltered dolomite and probably formed in place from percolating ground waters. The crystals commonly fracture with a pseudocleavage like that of the vein quartz, and are also ordinarily associated with manganiferous material concentrated by supergene action.

The writer tentatively suggests that the "cleavage" quartz may have been formed, at least in part, by supergene waters at a recent date.

STRUCTURE

The rocks of the Congonhas district have been severely deformed. Deciphering of the resulting complex structure is unusually difficult because easily recognizable stratigraphic horizons are lacking, and the geologic column is itself based to some extent upon the structural interpretation. Thus a very real element of uncertainty must be admitted both for the stratigraphy and structure—a point which should be kept in mind by the readers and future users of this report. The writer believes that an interpretation based on extensive thrust faulting most adequately explains the observed minor structures and the overall distribution of the sedimentary formations. Lack of time has prevented the application of methods of modern petrofabric analysis to the problem; hence the discussion which follows deals largely with the megascopic features.

STRUCTURAL ELEMENTS OF THE METAMORPHIC ROCKS

PLANAR ELEMENTS

Bedding.—Bedding, made readily apparent in most outcrops by differences in texture and composition, is the most prominent single structural feature of nearly all the sedimentary rocks. Exceptions are certain massive quartzite and dolomite beds, and some phyllite in which one or more cleavages have partly obscured the planes of stratification. In much of the green-schist sequence bedding is difficult or impossible to distinguish on weathered outcrops, although cores from deep holes indicate that it is fairly definite below the weathered zone.

Most bedding surfaces are plane and parallel to one another. Graded bedding, which might assist in determining the normal or reversed attitude of the strata, was searched for but rarely observed. Ripple marks occur at only one place, in almost vertical ferruginous dolomite beds at the Usina railroad station east of São Julião, (Barbosa, 1949). Crossbedding of the current-formed type occurs sporadically in the quartzitic members of the Minas series. The long straight foreset beds make angles of 25° or less with the gross bedding, and in only a few outcrops can the top and bottom be unequivocably determined because of slight curvature or other features. In the rocks of the Itacolumí series both the straight current-formed and sharply curved eolian(?) types of crossbedding are present. The eolian(?) type provides excellent information on the original attitude of the strata but is so infrequently observed that it does not assist greatly.

Flow cleavage.—Most of the metamorphosed sedimentary rocks of the district contain platy minerals such as mica, talc, chlorite, or specularite which are usually oriented in one plane and give the rocks fissility. Chloritoid and kyanite are less frequently oriented. The amphiboles in some places have their long axes rigidly oriented in one plane, though generally without a preferred direction within the plane; elsewhere they show only a slight planar orientation or none at all. Minerals such as quartz and feldspar which have no inherent platy or acicular habit may occur as flattened lenticular grains or aggregates oriented more or less parallel to the preferred orientation of the micaceous minerals. Fissility due to the orientation of mineral grains will be called "flow cleavage" in this report. The perfection of this cleavage depends upon the relative abundance of micaceous minerals and the degree of preferred orientation.

Flow cleavage is parallel or nearly parallel to bedding in most of the rocks of the district, particularly where the beds strike north and dip east as in much of the Casa de Pedra quadrangle. Cleavage parallel to bedding has generally not been shown in areas where the bedding can readily be identified. In green schist areas, however, cleavage is commonly the only structure that can be determined; it may be parallel to the original stratification, but in the absence of sufficient evidence the predominant planar direction has been shown by the cleavage symbol.

Cleavage tends to be roughly parallel to the general stratigraphic trends, even in areas where bedding departs widely from the trend because of folding or faulting. For example, in the south end of the quartzite belt on the western flank of the Serra do Batateiro near the common boundary of the Casa de Pedra and Jeceaba quadrangles, the bedding is dragged from a north-south to an east-west direction adjacent to an extensive fault zone, but cleavage remains more nearly north-south with easterly dips. In the Poço Fundo area quartzitic and ferruginous beds of the Itacolumí series bend sharply west near the line of section *C–C′*, whereas the cleavage continues in a north-south direction and becomes more prominent than the bedding. The cleavage is relatively uniform in attitude in the broad phyllite area north of the Fábrica-São Julião structural belt, striking generally northward to northwestward and dipping eastward. This uniformity is, however, only relative to the extreme variability of the bedding. In many places in the eastern part of the district cleavage is largely controlled by stratification and parallels it regardless of its attitude.

Cleavage is best shown in the coarser micaceous schist. Infrequently two megascopic cleavages that intersect at low angles are visible. On the other hand the cleaner quartzite ordinarily shows little or no cleavage except in the micaceous partings. Flow cleavage in itabirite appears as a sheen due to light reflected from the minute specularite flakes. Specularite apparently is not as strongly oriented as mica, for most specimens reflect light from several directions, of which one is usually more pronounced. Itabirite of the Pico Engenho mass appears to be more coarsely crystalline and to have a better developed cleavage than the average for the district. In a few thin sections the specularite is oriented at moderate to high angles to bedding planes. Some of the green schist has coarse-grained muscovite, chlorite, and biotite plates with random orientations.

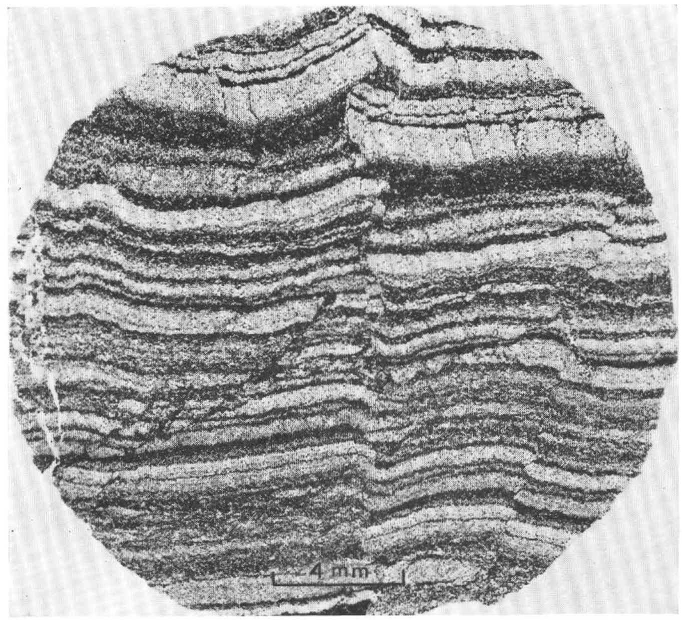

FIGURE 15.—Thin section of siliceous itabirite, × 4.7. Early deformation was plastic and preceded final crystallization of the original chert. Later fractures (without drag) localized a slight redistribution of iron.

Fracture cleavage.—Corrugation of flow-cleavage planes is a widespread phenomenon of the micaceous members of the Minas and Itacolumí series. In places it can be related to closely spaced fracture planes in the rock; elsewhere it is so elusive that it almost disappears under close examination with the hand lens. Similar corrugations in siliceous itabirite are related to microfaults which have been healed by recrystallization of the rock (fig. 15). The structure corresponds to what is commonly known as fracture cleavage.

The strike and dip of the fracture cleavage was measured only infrequently because of its indistinct nature, and no symbol has been shown for it on the maps. In general, however, it trends east-west and dips steeply. Fracture cleavage is one of the most important structural elements responsible for the pronounced lineation in the district.

LINEAR ELEMENTS

An eastward-trending lineation which with few exceptions plunges moderately to steeply eastward is universally present in the rocks of the Minas and Itacolumí series and may be found in some places in the greenschist sequence. This lineation is not only the most characteristic feature common to all the metamorphic rocks, but is far more uniform in attitude than the planar elements, inasmuch as it maintains its direction not only within the Congonhas district but throughout

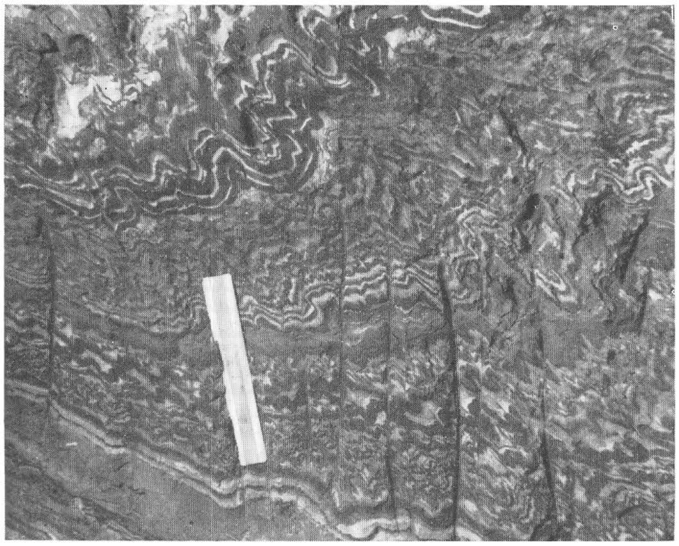

FIGURE 16.—Tightly folded itabirite. Adit 6, Serra do Batateiro (fig. 35), right wall, 23 meters from portal. A sample from 16 to 25 meters (table 13, analysis 1) gave 46.7 percent iron. The material is soft; note that scale, 20 centimeters long, has been pushed into it.

most or all of the "quadrilátero ferrífero" regardless of the trend of other structures.

Two general types of linear structure were distinguished during the course of mapping: fold axes and pencil structures due to other causes. They have been shown by different symbols. Where they both appear in a single outcrop, the two are parallel. Only a small proportion of the possible readings have been recorded on the quadrangle maps, but omitted symbols have the same general attitude.

Fold axes.—Minor crumpling and isoclinal folding are common in itabirite and high-grade hematite ores (figs. 16, 17, 23, and 26). Small folds are not frequently seen in other formations, perhaps in part because the formations were more competent at the time of deformation and in part because they lack the distinctions between adjacent fine laminae which would preserve the evidence of such deformation.

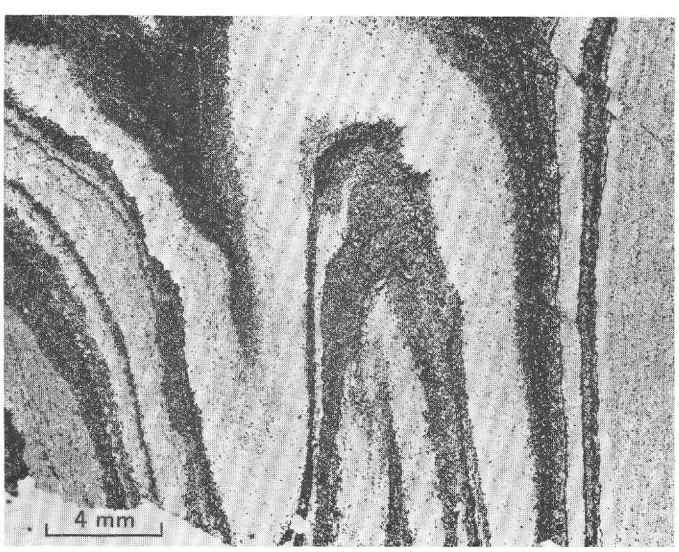

FIGURE 17.—Folded siliceous itabirite. White is quartz, black is specularite. Note slight redistribution of iron along fractures. Photographs of thin section, × 4.7, without analyzer.

Folds large enough to show at the map scale are not common in the western part of the district. The evidence even for those shown at Casa de Pedra, Serrote de João Pereira and Fábrica (pl. 5, *F–F′*) is somewhat weak, but the outcrop patterns and axes of minor crumpling suggest that the folds do exist, and that their axes plunge in the prevailing easterly direction. The pattern of the western part of the Fábrica-São Julião belt indicates many small, en echelon anticlines somewhat emphasized by faulting. Axes plunge gently, and at one point, 1.4 kilometers west of Fazenda do Vigia, plunge westward. From Fazenda do Vigia eastward the zone is crumpled on eastward-plunging axes. The scale of this deformation increases to a maximum near São Julião, where identifiable zones of magnetite-amphibole schist are severely folded and the middle group of the Minas series plunges eastward on the nose of a large faulted anticline. Quartzite lenses in the upper phyllite belt north of São Julião show a similar fold pattern.

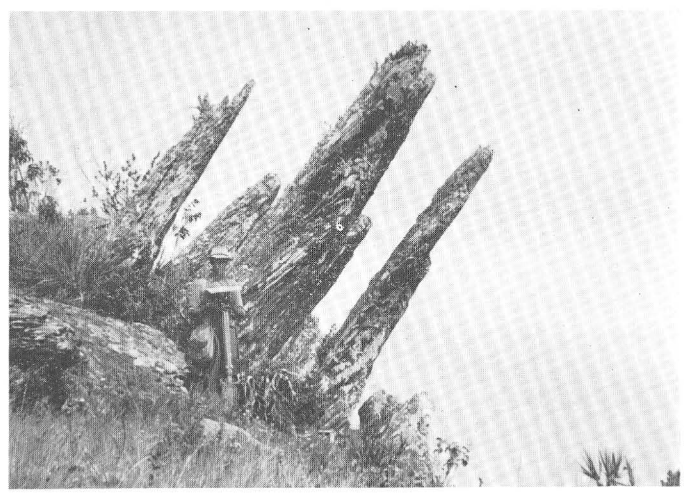

FIGURE 18.—Siliceous itabirite, showing elongated character of the outcrops, oriented with the regional lineation. West flank of Pico do Engenho.

Other linear elements.—The eastward-plunging linear pattern is expressed in many ways other than by the axes of visible folds. These have been combined on the map and shown by a single symbol.

The most conspicuous lineation is a "pencil structure" which causes the rocks to break into long, slender fragments, or in places to weather to prominent outcrops projecting to considerable heights (fig. 18). The outcrops are characteristic of the siliceous itabirite, although some quartzite also forms outcrops less prominently. The pencil structure is formed by the intersection of bedding and cleavage, or of flow and fracture cleavages. Even where the rocks do not break into elongated fragments the linear direction is shown in fine striations or faint corrugations on the most prominent planar element present, which is ordinarily bedding.

Lineation is also shown by the elongation of mineral grains and aggregates of grains, such as mica clusters partly wrapped around the large clastic fragments in quartzite. Talc forms elongated patches of minute flakes in itabirite and hematite. Conglomerate pebbles are commonly two to three times as long in one dimension as in the others; their long axes are oriented approximately parallel to the regional lineation, and as it is probable that most of them were originally about equidimensional, the presumption is strong that they were deformed during the orogeny. Greater deformation is indicated for elongated nodular structures in a few siliceous itabirites (fig. 14) which are believed to have been chert originally and thus considerably less rigid than the conglomerate pebbles at the time of deformation. Angular fragments in the dolomite breccia conglomerates commonly have a long axis, several times the length of the other two, oriented parallel to the regional lineation.

Some major hematite deposits not only of the Congonhas district but of the entire ferriferous area are elongate and oriented, but not enough is known about the shapes of all of them to assert that this rule holds true for every ore body. It may be pointed out that the great gold lode of the Morro Velho mine at Nova Lima trends due east and plunges moderately to gently in that direction. Other gold deposits of the area near Nova Lima also have this general attitude. Ore shoots within the bedding-plane vein at the Passagem gold mine east of Ouro Preto are also elongated in a direction somewhat south of east, although the vein itself dips southward along the south limb of an eastward plunging anticline. As the gold and hematite deposits are epigenetic, this elongate nature is consequent upon structural factors which prepared the sites for postorogenic mineralization.

JOINTS

As is to be expected in a terrain which has undergone severe deformation, joints are abundant in all the rocks of the district. One set is much more prominent than the others in the metamorphosed sedimentary rocks of the Minas and Itacolumí series. This set strikes approximately northward and dips steeply to moderately westward, forming angles of about 70°–90° to the lineation. In any one area these joints closely parallel each other and are ordinarily spaced from less than a meter to a few meters apart. They are particularly well-developed in quartzite and hard hematite ores, less so in the schist and phyllite. The quartz-kyanite veins follow these joints. Symbols representing joints have not been included on the quadrangle maps, but are shown on the large-scale map of the Casa de Pedra mine (pl. 6).

MAJOR STRUCTURAL FEATURES

FOLDS

Although thrust faults probably control the overall distribution of rock units in the western part of the highlands of the Congonhas district, preliminary folding, especially of the iron formation, preceded and prepared the way for them. The extent to which this folding may have affected the apparent stratigraphic thicknesses is well illustrated in a tunnel through the Serra da Rola Moca near Belo Horizonte, where repetition of beds is so frequent that even with continuous exposures for more than 1,000 meters it is impossible to estimate the true thickness. In addition to the repetition, plastic flow during folding has made the beds as much as 6 to 10 times as thick on the axial planes as along the limbs of certain folds. Exposures in the Congonhas district, though not as continuous as in this tunnel, show the same type of folding. The abrupt increase in apparent thickness of the iron formation in the Serra da Bôa Vista west of Batateiro (table 8, *D–D′*) can probably be attributed to deformation. The attitude of bedding planes in the northern part of the Serra do Mascate is commonly perpendicular to the trend of the range because of tight folding.

North and east of Pico Engenho and the Serra do Mascate folding probably controls the distribution of the formations, whereas faulting is subordinate to it, modifying or emphasizing the fold structures. Itacolumí rocks occupy what is apparently a downfolded area, the "Fábrica syncline" of Barbosa (1949). The fact that the fold axis must trend about southeastward at a considerable angle to the prevailing regional pattern casts doubt on this synclinal interpretation, however, and these rocks may be in fault relationship to the enclosing Minas series. The structure is cut off by faults at each end, and part of the southwestern border is probably faulted also.

The anticlinal Fábrica-São Julião belt brings up rocks of the middle group of the Minas series flanked by phyllite of the upper group. Faults greatly complicate this simple picture. The broad phyllite zone extending across most of the northern half of the São Julião quadrangle is essentially synclinal, though the detailed structure is complex. The middle and lower Minas series rocks at the north edge of the quadrangle apparently occupy the northern limb of this fold.

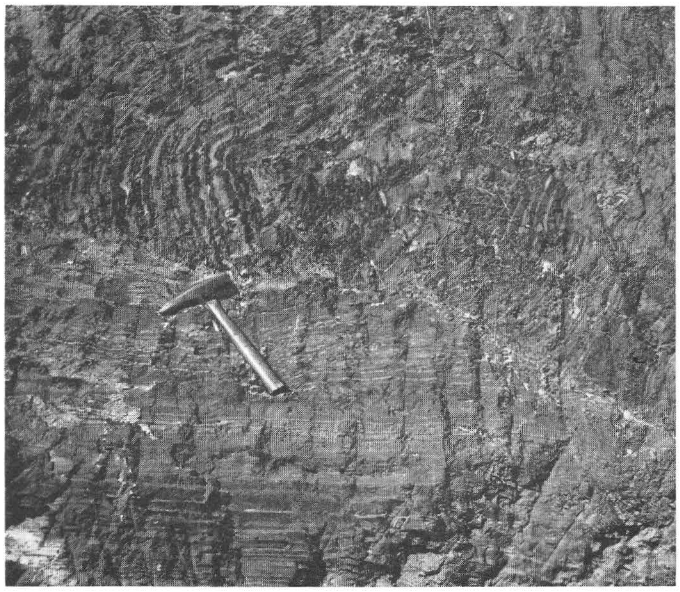

FIGURE 19.—Thrust fault in phyllite. The upper block crumpled and dragged; the lower block essentially undisturbed. Cut on irrigation ditch along east bank of the Riberão da Mata, 1.5 kilometers northeast of Pires.

THRUST FAULTS

EVIDENCE FOR THRUST FAULTING

Several lines of evidence indicate major thrust faults in the Congonhas district. Phyllite containing a minor itabirite lens caps a knoll on a quartzite ridge 3 kilometers southwest of Casa de Pedra (pl. 5, *E–E′* and *F–F′*). Both the phyllite and quartzite beds dip eastward at about the same angle. The contact, which can be traced completely around the knoll, is well exposed in a large outcrop on the eastern flank, where a fault plane dipping gently eastward and cemented by vein quartz separates the overlying phyllite from the quartzite. Another klippe (outlier) of phyllite overlies iron formation of the Itacolumí series on the boundary between the Casa de Pedra and São Julião quadrangles 1 kilometer south of Fábrica. The actual fault plane is not exposed, but the outcrop pattern suggests that the relationship is similar to that described above. Small thrust faults in phyllite are visible in the side of an irrigation ditch 1.5 kilometer northeast of Pires, São Julião quadrangle (fig. 19).

The stratigraphic sequence is repeated several times in the Casa de Pedra quadrangle. On the line of section *D–D′* the iron formation and other members of the Minas series crop out in four belts. Bedding dips eastward with no reversals, and although some evidence was seen for minor tight folding the general sequence does not indicate major overturning.

The outcrop areas have arcuate patterns. The Serra da Bôa Vista–das Almas belt is convex to the east, whereas the Serra do Batateiro and Serra do Mascate masses are convex to the west, so that the itabirite of the former range is separated by less than 1 kilometer from that of the western range at the point of closest approach, although 4 kilometers to the south they are about 4 kilometers apart. Bedding strikes swing around with the trends of these ranges. At the south end of the Serra do Batateiro they turn sharply eastward. On the north this range ends abruptly and a broad valley underlain by phyllite of the upper group continues on the strike of the ridge-forming lower and middle groups.

The Serra do Mascate is even more sharply convex to the west. Its iron formation overlaps on that of the Serra do Batateiro for a short interval west of Casa de Pedra, but rests on upper phyllite for most of the distance. On the line of section *B–B′* the itabirite and phyllite beds, exposed only a few meters apart, are nearly parallel but strike at right angles to the trend of the contact. From this point northward the trace of the contact is somewhat sinuous and strongly influenced by the topography, indicating that it has a fairly low dip. Two adits driven from points just west of the contact north and south of section *B–B′* cut only phyllite. The adits are caved, but the size of the dumps shows that they extended a considerable distance into the hill without entering iron formation. At the extreme north end of the range the trace of the contact swings to the east in such a manner as to suggest that the itabirite has virtually no downward extent.

The Pico do Engenho mass, nearly circular in outline, seems to be composed of two structural units. The western block consists of steep beds striking about west-northwest, the eastern block consists of beds that strike northeastward and dip southeastward. The boundary between these two units was not traced in detail. The entire mass has unconformable relation to the surrounding rocks. On the west it cuts across the dolomite on the east end of the Casa de Pedra ore body (pl. 6). Near Poço Fundo it overlies rocks of the Itacolumí series and elsewhere is in contact with phyllite of the upper group of the Minas series.

The axes of minor folding and the lineation are oriented at right angles to the general trend of the formations, a fact which does not accord with a fold hypothesis, for if the rocks were repeated by isoclinal folding the major axes should be north-south. Minor axes and lineation would then probably lie north-south also and the rocks would have the character of *b*-tectonites common to most folded terrains. Instead the relations suggest *a*-tectonites, in which linear structures are oriented parallel to the direction of transport. (In the absence of petrofabric studies, however, it cannot be stated positively that these rocks are *a*-tectonites.) In Scotland and Norway this deformational pattern is found in zones of major overthrusting. A strong lineation in the Bygdin conglomerate, Norway, which is expressed by stretching and folding of pebbles on axes parallel to the movement of the overriding Caledonian thrust sheet and by a prominent joint set perpendicular to the elongation, is attributed by Strand (1945) to triaxial deformation caused by forces exerted in the direction of transport (the *a*-petrofabric direction). He emphasizes that only one orogeny could be responsible for this lineation. Phillips (1937) explains the lineation developed near the Moine thrust in the Scottish Highlands by two orogenies acting from different directions at different times, but this conclusion has been disputed. The lineation is parallel to the direction of thrusting. For the purpose of the present report it seems sufficient to conclude that similar structural relationships in other severely deformed areas are associated with extensive thrust faulting; thus their presence in the Congonhas district confirms the other evidence for thrusting here.

THRUST FAULTS OF THE CASA DE PEDRA AREA

The area near Casa de Pedra is at the junction of the northward-trending structures of the western ranges extending toward Belo Horizonte and the eastward-trending structures which continue to the vicinity of Mariana (fig. 4). A severe combination of stresses caused an unknown amount of movement by thrust faulting. The western range is apparently autochthonous. With its arcuate shape, reinforced by the crystalline basement, it acted as a buttress. The Batateiro thrust slice moved westward across the argillaceous rocks of the upper group. At the south end the lower quartzite formed the sole of the thrust plate. Northward the thrust became shallower and cut through the lower schist and itabirite. The underlying rocks were only slightly disturbed. A somewhat brecciated zone exposed on the old railroad grade 200 meters north of the houses at Batateiro and a few discordant strikes and dips northward along the grade are the only signs of crushing. The thickening of the lower group between the Serra da Bôa Vista and the Serra do Batateiro suggests that the amount of displacement was considerable.

Isolated exposures between the north end of the Serra do Batateiro and the Serra do Mascate are apparently remnants of another fault slice. The bifurcate nature of the iron formation of the Serra do Batateiro suggests that these faults may extend the length of the range.

The Serra do Mascate thrust block rests on autochthonous phyllite of the upper Minas series as far south as Pico da Bandeira, then on phyllite and itabirite of the lower thrust sheets. Itabirite forms the sole of the thrust plate throughout most of its length. The structural discordance to the underlying rocks has already been discussed. The ore deposit at Casa de Pedra lies in this thrust sheet.

The Pico do Engenho mass may be parts of two sheets, as has been mentioned above. Thus a minimum of three, and perhaps five allochthonous "nappes" are superimposed on the western range in the vicinity of Casa de Pedra.

THRUST FAULTING OF THE ITACOLUMÍ SERIES

Rocks of the Itacolumí series are involved in thrust faulting in the Congonhas district. In the Poço Fundo area minor thrusts have modified the border of the "Fábrica syncline."

Extensive faults probably limit the Serra do Pires mass. Along the southwest border quartzite and iron formation are in contact with phyllite and dolomite(?) of the upper group of the Minas series and with Itacolumí quartzite. A coarse breccia is exposed in a cut made for manganese near the west edge of the São Julião quadrangle 2.5 kilometers northwest of Cruzul. On the northeastern flank of the range the contact of the phyllite overlying the Itacolumí iron formation appears to be conformable in some places, but evidence of faulting is seen in the cuts made for the new highway about 1.3 kilometers south-southwest of Fábrica and elsewhere. Crossbedding indicates overturning of part of the quartzite near Cruzul (Barbosa, 1949), and the general relations show that intense, probably isoclinal, folding preceded the faulting.

OTHER THRUST FAULTS

Although folding apparently predominated in the eastern part of the district, it is probable that thrust faulting also occurred. Interpretations made here are tentative, however, as solution of many of the problems of the eastern border must await completion of mapping in adjacent quadrangles. Scattered exposures suggest that the plunging fold at São Julião is thrust westward over itself. The abrupt lithologic variation from a predominantly ferruginous to a predominantly dolomitic facies may indicate considerable transport and telescoping (p. 18).

ENGENHO FAULT

The boundary between the typical rocks of the Minas series in the northern part of the district and the rocks called the green-schist sequence in this report is sharply defined and can be traced from a point a few kilometers northeast of Jeceaba in a northeasterly direction to the Casa de Pedra-São Julião border and eastward to the edge of the district. The quartzite and itabirite members are sharply cut off against phyllite in the Jeceaba quadrangle, where a southward-dipping fault plane is

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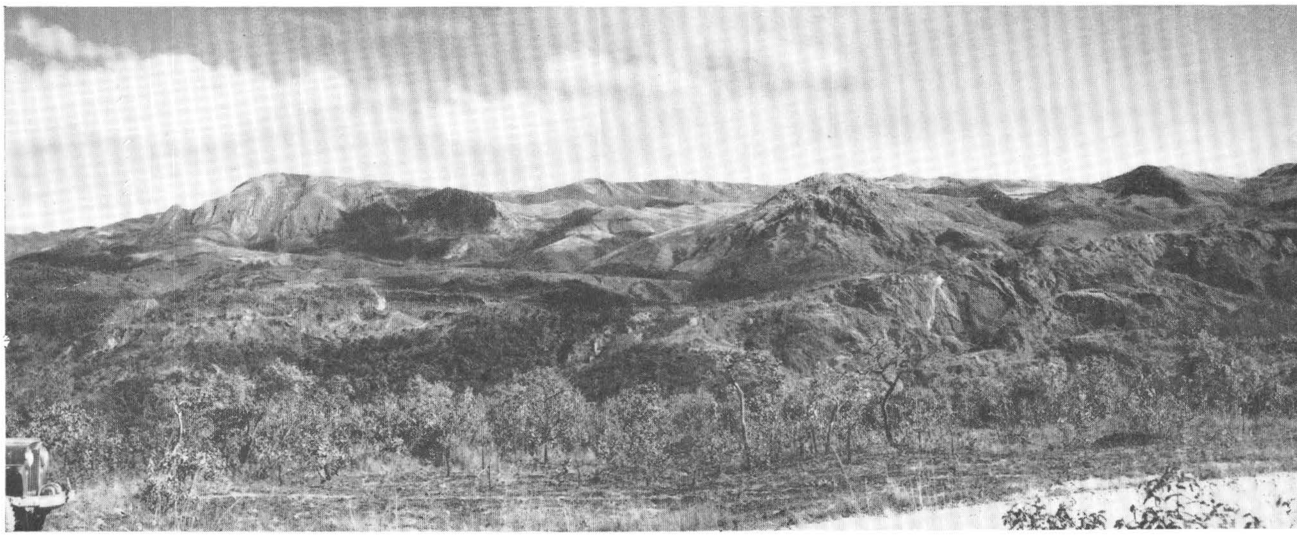

FIGURE 20.—The Engenho fault scarp from the Pires road, 4 kilometers north of Congonhas, looking west. Green schist and granodiorite form lowland in foreground, typical Minas series rocks form the highland beyond the fault. Pico Engenho on left, Morro Santo Antônio near center. The Serra do Mascate forms the distant skyline.

exposed in a few places. In the Serra do Batateiro a severely fractured zone about half a kilometer wide marks the south edge of the quartzite, which is displaced westward for almost a kilometer. Evidence shows that the fault zone is double in the southeast corner of the Casa de Pedra quadrangle, for the iron formation debris on the ridge north of Coelhos and the quartzite lenses south of Pico do Pilar indicate a gradational transition from typical rocks of the Minas series to those of the green schist sequence. The resistant rocks end on prominent topographic breaks, but no scarp is preserved and the offset is not apparent where the fault cuts argillaceous rocks, probably because they are less resistant and lack appreciable physical differences. The most prominent scarp is that of Pico do Engenho, whose southeast face drops about 300 meters at an average slope of nearly 45°. The south face of Morro Santo Antônio is also very steep (fig. 20).

From the vicinity of Cruzul eastward the scarp is less regular and less pronounced to the east edge of the district, though just beyond the boundary the south face of the Serra do Ouro Branco rises almost vertically for about 500 meters. The line marks the limit of green schist, and particularly of the abundant granodiorite bodies. Dolomite and quartzite lenses in the phyllite trend at slight angles to this line and are cut off by it. A quartzite breccia is exposed on the new highway where it crosses the trace of the fault. However, no direct evidence of faulting could be found on the Rio-Belo highway south of São Julião.

The writer interprets this structure as a complex fault zone along which repeated movements have taken place. Extensive displacement was not necessary to cut off the thrust sheets, which had no roots and probably wedged out not far to the south. The fault zone apparently dies out in the thick phyllite section on the eastern section flank of the Serra da Bôa Vista, as no trace of it was found in the vicinity of Jeceaba, where the westward curve of the range brings the strike of the bedding about parallel to the trend of the fault. The drag of the bedding in the thick quartzite zone of the Serra do Batateiro and in the Morro Santo Antônio suggests early movement while the rocks were still plastic and before the cleavage had formed, but the sharp delimitation of the granodiorite intrusions in the São Julião quadrangle indicates that displacement was postmagmatic, and hence postorogenic. Activity may have been renewed intermittently along a zone of weakness in the crust. The relative movement was apparently upward and westward for the southern block.

DEEP-FOCUS FAULTS

Study of aerial photographs reveals several nearly parallel structures in the gneiss of the basement complex west of the Serra da Bôa Vista-das Almas. They trend about N. 50°–60 W. A few coincide with minor offsets of the metamorphosed rocks of the Minas series. The northernmost one in the Casa de Pedra quadrangle has a breccia zone 5–10 meters thick in which fragments of various rocks are cemented in vein quartz which stands in relief as a pronounced wall above the surrounding gneiss. This zone branches into several parts a short distance west of the mountain front. The lack of topographic effect on the trend of the zones shows that they are essentially vertical planes. In the overlying sediments the zones are deflected somewhat to the south, probably because of refraction in the weaker materials, and they die out quickly, though the strongest ones apparently cause minor offsets in the itabirite of the Serra do Mascate.

A complex of nearly parallel fractures having minor offshoots can be traced intermittently across the São Julião quadrangle from the vicinity of the Serra do Ouro Branco to Fábrica, where it nearly coincides with the continuations of the most prominent basement fault. The presumption is strong that the fractures reflect a zone of weakness in the crust. A warm spring with a uniform flow and a year-round temperature of about 23°C is situated at the intersection of two faults of this zone 0.5 kilometer north-northeast of Pires. Breccia is exposed at several spots along the zone. Quartzite is cut off against a gabbroic dike 1 kilometer south of the Fazenda do Vigia, and against a fault only 200 meters north. The quartzite makes a sharp angle to the general trend of the area, as though it had been rotated. Faults of this system probably accentuate the limits of the Fábrica-São Julião structural belt, although the displacements probably are not great enough to account entirely for the distribution of the rocks. Available evidence indicates that they extend deep into the crystalline crust.

OTHER FAULTS

In addition to the major fault systems already described, many other faults are known and others have undoubtedly escaped attention. Most cannot be traced far and are relatively unimportant, except in causing local modifications in the outcrop pattern. An east-west set is probably one of the youngest systems, for it offsets the Engenho fault between Pico do Engenho and Pico do Pilar and is the locus of several gabbroic dikes. A fault of this set apparently limits the area of dolomite outcrop south of Usina. Faults trending almost east-west offset the dolomite lens at Fazenda do Vigia and the lower quartzite in the contact zone of the northern batholith.

STRUCTURE OF THE CONGONHAS LOWLAND

The foregoing discussion applies almost exclusively to the highland areas of the district. Relatively little is known about the structure of the lowland areas underlain by green schist and granodiorite. Southeastward from the Serra da Bôa Vista in the Jeceaba quadrangle bedding strikes essentially parallel to the range, and the stratigraphic sequence appears to be unbroken between the top of the itabirite and the granodiorite batholith, although if the Engenho fault continues it probably could not be detected. Steatite at the extreme west edge of the district may indicate that this fault has superimposed older rocks on the upper group of the Minas series. The writer, however, considers it more likely that no sharp break exists and that the green schist strata are equivalent to upper Minas series rocks in this area.

Eastward the attitude of bedding, and of cleavage where bedding is obscure, becomes more irregular. Many folds and faults must occur, but the absence of recognizable zones prevents determination of the details of the structure. Lineation continues into the phyllite areas south-east of the Engenho fault in the corner of the Casa de Pedra quadrangle, and here also no sharp break can be found between phyllite of the highland area and green schist.

From the vicinity of Pico Engenho a zone with fairly uniform strikes extends southeastward across the district and for some distance beyond. The zone probably marks the axis of a major fold structure, but whether it is a syncline or an anticline cannot be stated definitely because the stratigraphy is unknown. The structure of the eastern part of the lowland has a general southeasterly trend with local variations. Steatite and granodiorite intrusions also have this attitude, the former because they were present as sills(?) before deformation, the granodiorite bodies because they were largely controlled by preexisting structures. Rocks of the gabbroic suite crosscut the enclosing rocks.

METAMORPHISM

Rocks of the Congonhas district show evidence of two types of metamorphism, regional and thermal. Several periods of regional metamorphism may be involved (Guimarães and others describe the Minas series as polymetamorphic), but this writer does not attempt to distinguish between them. The effects of thermal metamorphism are best exemplified in the contact aureole of the batholith in the northeast corner of the São Julião quadrangle.

REGIONAL METAMORPHISM

HIGHLAND AREAS

The metamorphic grade of the rocks of the typical Minas series and Itacolumí series is low, corresponding for the most part to the muscovite-chlorite stage. Pelitic rocks are fine-grained quartz-sericite-chlorite phyllite, usually containing accessory magnetite or hematite. Spessartite garnet occurs in one thin manganiferous bed. Psammitic facies have cataclastic textures. Outlines of clastic grains are well preserved, though the grains are severely strained or crushed and surrounded by fine-grained recrystallized quartz and sericite or muscovite. Feldspar of the volcanic rock in the upper group (p. 20) has been almost completely sericitized. Carbonate facies contain dolomite and quartz, and ordinarily one or more of the silicate minerals chlorite, muscovite, talc, tremolite, or anthophyllite, plus magnetite, hematite, or rarely pyrite. Ferruginous sediments were metamorphosed to quartz-specularite, quartz-dolomite-magnetite, and quartz-dolomite-magnetite-actinolite or simply quartz-magnetite-actinolite schist, collectively called itabirite. The silica was probably chert, and thus more susceptible to metamorphism than clastic quartz. The formation of magnetite or hematite may have depended on the presence or absence of a reducing agent, perhaps organic carbon, in the sediment, or on the original ferrous or ferric state of the iron (p. 49).

These assemblages are indicative of the green-schist facies, but certain anomalies appear in restricted areas, as northeast of Poço Fundo, where kyanite, garnet, chloritoid, and muscovite porphyroblasts occur in very fine grained quartz-sericite-magnetite phyllite of the Itacolumí series. Although chloritoid is a possible constituent of the facies, kyanite and garnet seem out of place. The garnet crystals are too small (average 0.1 mm) to determine, and may be spessartite, but the association suggests they are probably almandine. Unusual local conditions are indicated, probably both of bulk composition and temperature. These rocks are situated close to the planes of suspected thrust faults; it may be that temperatures and pressures were raised for a short time during the movement. Sedimentary laminae preserved by inclusions in chloritoid are rotated. Kyanite also occurs sporadically in quartzite of the Minas and Itacolumí series as unoriented ragged grains along minute fractures and rosettes on bedding planes. The occurrence of kyanite probably can be attributed more to hydrothermal than to metamorphic agencies, and hence is related to the quartz-kyanite veins (p. 29) in mode of origin, if not in time. Turner (1948, p. 94) discusses the mobility of aluminum silicate in actively circulating solutions under conditions of low-grade regional metamorphism and cites occurrences of similar rocks elsewhere.

LOWLAND AREAS

The grade of regional metamorphism apparently increases southeastward from the Engenho fault, but the picture is obscured by deep weathering, lack of knowledge of the original rock types, and by the extensive intrusions of granodiorite. Phyllite in the area southeast of Pico Engenho apparently is of the same metamorphic grade as the Minas series phyllite to the northwest, and the rocks of the narrow phyllite zone that crosses most of the Congonhas quadrangle have the same general aspect, although no fresh material could be collected for thin sections. On the other hand, plagioclase-quartz-biotite and quartz-hornblende-zoisite schists are exposed in railroad cuts near Murtinho. If the criterion is valid that strong preferred orientation indicates crystallization under stress and hence that schistose assemblages are the product of regional metamorphism, the rocks cut by the drill holes near Congonhas (p. 20 and fig. 10) reached the biotite-almandine stage before intrusion of the granodiorite, though garnet is sparse and fine grained. The metamorphic grade may be stated as near the boundary between the green-schist and amphibolite facies.

THERMAL METAMORPHISM

Under thermal metamorphism the writer groups those effects believed due to the rise in temperature and increased mobility of aqueous solutions induced by the intrusion of the granodiorite masses. The distribution of rocks mapped as green schist shows a definite relationship to the areas of granodiorite and indicates that they were derived at least in part by thermal metamorphism of argillaceous sediments which had previously been regionally metamorphosed. Variations in original composition are also indicated. Some of these rocks may have been derived from basic flows, though none was definitely identified in the Congonhas district. The probable contributions of volcanic ash have already been discussed (p. 21). The zone of phyllite extending across the Congonhas quadrangle shows sedimentary as well as metamorphic facies differences, as evidenced by itabirite lenses. It is noteworthy, however, that no granodiorite invades this zone, although large and small intrusions are abundant to the northeast and southwest. Northwest along the strike in the São Julião and Casa de Pedra quadrangles where the granodiorite intrusions approach the itabirite-bearing zone more closely, the pelitic rocks are green schist. The lack of any significant alteration around much of the intrusive mass in the southeast corner of the Casa de Pedra quadrangle may be due to the concordant nature of the contact and the presence of relatively impermeable beds.

The chief effect noticeable in weathered outcrops is a blurring of the fine details of bedding and a less pronounced schistosity. The rocks weather deeply and give a dark-red soil. Cores of fresh rock from the Congonhas lowland contain quartz, albite or oligoclase, biotite, chlorite, muscovite, epidote or clinozoisite, calcite, ilmenite and leucoxene, magnetite and considerable late pyrite. There is a pronounced lessening of the degree of orientation of mica, and in places unoriented chlorite has replaced biotite. The general effect on the schist of the biotite-almandine zone seems to have been a retrograde metamorphism; on the contrary, the metamorphic grade of the sericite phyllite increased somewhat and the texture became coarser.

Two types of metamorphism affected the ultramafic rocks. The regional type imposed the strong foliation on the talc schist and the schistose borders of the larger masses, and probably altered any original pyrogenic silicates remaining to chlorite (antigorite) and amphibole. The thermal metamorphism, aided perhaps by solutions from the granodiorite, produced the massive steatite containing ankerite, vein talc, actinolite needles, amphibole asbestos, and pyrite.

The effects of contact metamorphism are more clearly visible in the aureole around the large northern batholith. The upper phyllite is altered to green schist which superficially, at least, is identical to the green schist near Congonhas. Fresh rock is not exposed, but in the railroad cuts west of Riberão Sardinha the phyllite can be traced into material that is progessively coarser grained and more massive. Bedding disappears gradually, until all traces are lost close to the main contact. Fragments of schist, some many meters long, are enclosed within the granodiorite. Many pegmatite dikes and quartz-tourmaline veins intrude the schist.

Float of coarse-grained skarnlike material occurs at several places in the zone, but no outcrops were observed. Some pieces contain garnet, staurolite, kyanite, sillimanite, cordierite, quartz, biotite, muscovite, and chlorite, indicating that high metamorphic grades were reached locally. Thin carbonate lenses in the upper group may have been especially susceptible to metamorphism and metasomatism. Reports that topaz occurs in the area—one hill is called Morro do Topázio—also indicate metasomatic activity. No topaz was found during the course of the field work, however. The quartzite in the contact zone is recrystallized to an extremely coarse grained rock which could be mistaken for vein quartz except for micaceous films preserving traces of the bedding. The argillaceous beds are coarse-grained muscovite schist. Some of the itabirite has been transformed to quartz-magnetite schist. Westward along the contact, just north of the limit of the quadrangle, gneiss containing quartz, calcic plagioclase, garnet, hornblende, sillimanite, and biotite separates the granodiorite from the normal rocks of the Minas series.

Temperatures in this aureole reached a high degree near the contact, but fell off sharply away from it. Although the batholith is many kilometers across, the zone of thermal metamorphism is not more than 500 meters wide in the São Julião quadrangle. This evidence suggests to the writer that intrusion took place at a relatively shallow depth where cooling was fairly rapid.

THE GREEN-SCHIST PROBLEM

It may be appropriate at this point to assemble the evidence bearing on the age of the green schist sequence and its associated rocks, particularly inasmuch as similar rocks elsewhere in the ferriferous area have recently received considerable attention. Field work by members of the mapping project in the area north of the Congonhas district has supported Barbosa's division of the sedimentary rocks overlying the basement complex into two series separated by a profound angular unconformity (Rynearson, Pomerene, and Dorr, 1954). The lower group of the Minas series is described as resting on schist of varying composition that contains thin zones of lean iron formation. Ultramafic, granodioritic, and gabbroic rocks intrude the schist. In the Ouro Preto district Lacourt (1936) recognized a group of schists underlying the quartzite and the schist here correlated with the lower group (fig. 3) but considered them as lower Minas series. He did not describe unconformable relations, nor did he realize that the large batholith underlying these rocks is of post-Minas age.

Within the Congonhas district the base of the Minas series is exposed only along the western slope of the Serra da Bôa Vista-das Almas, where the lower group directly overlies gneiss and granite referred to the basement complex. The highlands with unquestioned Minas series rocks are separated from the lowlands by the extensive Engenho fault system, except in the western part of the Jeceaba quadrangle, but although quartzite and itabirite members are scarce to the south, the argillaceous members show no detectable differences across the fault. On the contrary, the map pattern indicates that the green schist aspect of the argillaceous rocks is determined by the relative proximity to larger intrusive masses or to the innumerable swarms of smaller bodies. The writer can see no features of the sedimentary rocks that cannot be explained by facies changes, structural disturbance, and metamorphic effects.

The lithologic similarity between the phyllite of the green schist sequence and of the Minas series is marked. Individual specimens or outcrops are indistinguishable. Graywacke facies are more common in the lowland area but are also present in the upper group of the Minas series. Volcanic members also appear to be more prevalent in the green schist. Clean quartzite is common only near the fault zone, as in the area south of Pico Engenho, but quartzite inclusions in granodiorite near Congonhas resemble the rocks of the Minas series. The itabirite of the green schist sequence is identical in appearance to that found in the Minas series.

The phyllite south of the fault shows the same structural elements of cleavage, fracture cleavage, and lineation as the phyllite to the north. No additional evidence was noted to indicate an orogeny sufficiently strong to cause a sharp angular unconformity.

The grade of regional metamorphism does not increase abruptly across the fault but increases gradually to the southeast, if the effect of thermal metamorphism by intrusive rocks is discounted. For example, spessartite occurs both in the upper Minas phyllite near Salto and in green schist east of Alto Maranhão.

The writer believes the two groups of rocks are contemporaneous as evidenced by the batholith contact zone in the northeast corner of the district. This batholith, which intrudes typical Minas series rocks, extends far to the north and east and has produced a wide metamorphic aureole in rocks that have been described as pre-Minas. In composition and structure this granodiorite is similar to the granodiorite masses which intrude similar rocks in the Congonhas lowland. Furthermore, the metamorphic effects are similar. Elsewhere in the Congonhas district acid intrusive rocks are rare in the recognizable Minas series rocks.

The apparent absence of ultramafic rocks in the Minas series of the Congonhas district is perhaps the most cogent argument for considering the green schist to be older. One small mass of steatite occurs southwest of Jeceaba on the edge of the quadrangle, in rocks which correlate with the upper phyllite if no structural discordance is present. Others crop out just west of the quadrangle border. Thin talc schist zones in the Minas series, most of them closely associated with dolomite, may possibly be of igneous origin but can better be ascribed to metamorphism of sediments. However, ultramafic rocks are not found in unquestioned Minas rocks. If the two groups are contemporaneous, therefore, it seems necessary to rely on differences in geologic environment to explain their absence in one group. The writer suggests that the peridotites were restricted to the deeper, axial parts of the geosyncline, and that they were intruded during the opening stages of an intermittent, long continuing orogeny.

It has not been proved that the green schist and associated rocks of the Congonhas lowland are equivalent to the similar rocks to the north, but the presumption is strong that they are. For the present, the writer prefers to consider that at least part of the green schist is also equivalent in time to typical Minas series rocks, but that these sediments accumulated near the axis of a subsiding trough where they were buried more deeply and intruded more extensively than the shallow water, nearshore facies. Extensive movement along the Engenho fault zone juxtaposed the two facies. This movement may have been somewhat like that of a hinge, dying out westward.

The green-schist problem in many ways resembles the Glen Arm and related problems of the eastern United States, where differences in sedimentation, volcanism, metamorphism, and intrusive history have obscured the geologic history for many years in spite of a vast amount of work by many people. More work is required to resolve the problem in Brazil.

PHYSIOGRAPHIC DEVELOPMENT

There is general agreement that the Serra do Espinhaço has been emergent since the end of the pre-Cambrian. Freyberg (1932) considers that an extensive peneplain had formed by Late Cretaceous or early Tertiary time. As this peneplain must have been near sea level, the present altitudes of some 1,600 meters in the Congonhas district and more than 2,000 meters elsewhere must be largely due to post-Mesozoic uplift. Differential erosion has caused local relief of more than 800 meters, and the peneplain has been completely destroyed in the Congonhas district, although remnants may still exist in other parts of the ferriferous area.

The major streams, the Rio Paraopeba and the Rio das Velhas, are antecedent to the uplift and probably consequent on the old peneplain. They have maintained their courses and cut through the principal ranges in deep water gaps. Most of the smaller streams are subsequent and well adjusted to the bedrock. For example, the Riberão Mata Porcos, which enters the north edge of the Congonhas district, follows the upper phyllite zone around the arcuate structure of the sediments flanking the large batholith until, at a point where both the itabirite and quartzite are unusually thin, it cuts through these rocks into granodiorite. Tributaries of the Riberão Mato Porcos in the São Julião quadrangle are also adjusted to the local structure. Ridges between them have relatively gentle eastern slopes parallel to the dip of the beds and steeper back slopes opposed to the dip.

Only two small streams cut through the western range in its entire length of 50 kilometers. These are in the middle of the Casa de Pedra quadrangle at the point where the Serras do Batateiro and do Mascate approach most closely and block the way eastward. The Riberão do Esmeril and Côrrego dos Monjolos, encroaching from south and north, respectively, will eventually capture these streams, but they have relatively low gradients and some time will elapse before this happens.

Uplift has been intermittent. At Gandarela, 11 kilometers east of Rio Acima (fig. 4) and 40 kilometers north-northeast of São Julião, terrestrial deposits of sand, clay, and lignite were deposited in a local basin some 500 meters below the summits of the surrounding ranges (Freyberg, 1932). The Pliocene(?) age of the flora shows that local relief of 500 meters or more had formed before late Tertiary time. These deposits are now 500 meters higher than the local base level, and dip about 20° E. They were apparently uplifted and tilted by block faulting.

Evidence of intermittent uplift occurs also within the Congonhas district, although there is no way in which to date the movements or correlate with certainty the different physiographic features. The general conclusion, however, is that a long standstill was followed by renewed elevation and erosion. During this period the major distinction between highlands and lowlands was achieved. The green schist-granodiorite areas show mature topography with relatively low relief. Remnants of fairly mature topography are also found in upland areas. A notable example is the upper valley of the Côrrego do Lagarto northeastward from Casa de Pedra. It is relatively broad and gentle, falling about 30 meters in about 2.5 kilometers. In the next 2 kilometers it decends 130 meters in a precipitous narnow gorge. An extremely resistant ferruginous quartzite protects the upper reaches of the old valley from the rejuvenated stream. The massive hematite of the ore deposit is temporarily protecting the headwaters of this stream from capture by the Côrrego da Casa de Pedra, which flows southeastward with a steep gradient over phyllite. Other examples of relatively mature topography occur on the Serra do Mascate, the north end of the Serra do Batateiro, and in the gentle depression between them. At lower levels are the prominent bench on the west side of the Serra do Batateiro, the divides at the heads of the Riberão do Esmeril and the Côrrego dos Monjolos, and the Lagôa dos Porcos northwest of São Julião. Remnants of a pediment along the western slope of the Serra da Bôa Vista are preserved by a cover of iron formation rubble. Near the line of section *D–D′*, Casa de Pedra quadrangle, the scarp of the range probably rose not more than 200 meters above the surrounding area at the time of the standstill, whereas today its average relief is several times as great.

Barbosa (1949) found traces of three terraces in the lowlands of the Maranhão-Paraopeba valley. The higher ones are well dissected, may never have been perfectly developed, and require a certain amount of conjecture to reconstruct. The oldest terrace rises eastward from about 950 meters near Jeceaba to more than 1,000 meters at the east edge of the district. The second one has altitudes of about 880 meters near Jeceaba and 915 meters near the junction of the Rio Maranhão and Riberão Soledade in the Congonhas quadrangle. Remnants are covered with coarse gravel that was thoroughly worked for its gold content by the early settlers. The third terrace, which is narrow, is 10 meters or less above the present level of the stream. This terrace is being rapidly dissected, and the river is cutting bedrock at many points.

SURFICIAL DEPOSITS

Large areas are covered by materials derived from bedrock at a fairly recent date by weathering processes which are related to the present surface. These materials either occur more or less in place, having undergone only slight or moderate transportation downslope (eluvium), or have been carried by running water and redeposited at a distance from their source (alluvium). In either case they conceal the underlying geology. The usual weathering products of schist, quartzite, granodiorite, and other common rock types can ordinarily be recognized and thus they serve as reliable guides to the bedrock. They have not been mapped separately. On the contrary, the weathering products of iron formation persist for long periods, travel slowly downslope for considerable distances from the higher ridges, accumulate in thick blanket-like deposits, and effectively mask the underlying formations. They have potential value as iron ores. In order to present the geologic evidence more precisely and at the same time to serve as a guide to the distribution of surficial ores, these weathering products have been mapped separately. The result is essentially an outcrop map of the ferriferous areas. The approximate traces of concealed contacts and faults have been indicated on the basis of the available evidence and structural interpretation.

RESIDUAL DEPOSITS

LATERITE AND CANGA

The term "laterite" is used in this report to refer to uncemented iron formation debris, talus, and deep-red ferruginous soil. By contrast, canga is composed of rubble derived mechanically from the iron formation and firmly cemented by hard limonite deposited from ground-water solutions. The term is a local one derived by contraction from an indigenous word. Laterite may, of course, be cemented at depth, and conceivably canga may overlie uncemented material, so the distinction on the map refers only to the state of the surface material.

Canga is resistant to erosion and is largely responsible for the preservation of older surfaces. Canga sheets of several ages are known, but their dating and correlation present the same problems met in deciphering the physiographic history of the region.

Details of the origin, distribution, thickness and composition of laterite and canga will be deferred to a later section (p. 58).

WEATHERING PRODUCTS OF DOLOMITE

Several peculiar weathering products of dolomite which occur in the district need much more study, not only to solve the scientific aspects of the transformation of carbonate rocks by tropical ground waters but because some of them have potential economic importance. Two general types, which probably grade into one another, can be distinguished: (1) material preserving original bedrock structures, at least to a minor degree, and (2) massive materials having no trace of sedimentary or metamorphic structures. The source of the first type can be identified with certainty, but that of the second, massive type has only been established by indirect evidence. The symbols "Md?" and "d?" have been used on the maps to distinguish areas in which no unaltered dolomite remains in the outcrops.

This alteration of dolomite is best exposed in the railroad cut on the north side of the tracks opposite the station at Usina, 2 kilometers east of São Julião. Bedded white dolomite passes into soft brown material in which bedding is perfectly preserved. The contact is sharp, but irregular, and a karst type of surface has formed on the fresh rock. Specimens were collected from the same bed immediately above and below the contact. The fresh rock contains a few percent of quartz in angular grains averaging about 0.05 millimeter across, plus a little talc or muscovite and chlorite. The micaceous minerals are largely confined to thin partings. A very little pyrite is present as minute grains chiefly concentrated in the micaceous partings.

The altered material is a dark-yellowish brown. The micaceous partings extend unbroken into it; otherwise it bears little resemblance to the dolomite. If struck with a pick, the point sinks in to the shaft almost without resistance, and muddy water spurts out with considerable force. (This has led to the useful, if informal, name of "splash rock" for the material.) A small fragment feels almost dry to the touch, and can easily be cut to any desired shape with a pen knife. If squeezed between the thumb and forefinger, it resists pressure for a moment without any of the plasticity of a clay, then collapses suddenly to a little muddy water that has a faintly gritty feel.

Some simple laboratory tests carried out at Usina Wigg (São Julião) explain the reason for this behavior. Cubes were cut as carefully as possible to exact dimensions, weighed, dried at 100° C. to constant weight and reweighed. Loss of weight (moisture) was 70.2–70.5 percent. The specific gravity for saturated material averaged 1.35, for dried material 0.37. Tests showed that the saturated material has a crushing strength of between 750 and 1,000 grams per square centimeter (10.7–14.3 lb./in.^{2}). Rough calculations indicate a porosity of about seven-eighths, which explains why this "rock" collapses to muddy water when its strength is exceeded.

The dried residue was analyzed, and the results shown in analysis 1, table 10. Under high heat the yellowish material turns brick red, and in the reducing flame becomes black and magnetic. Microscopic examination shows angular quartz grains like those in the dolomite,

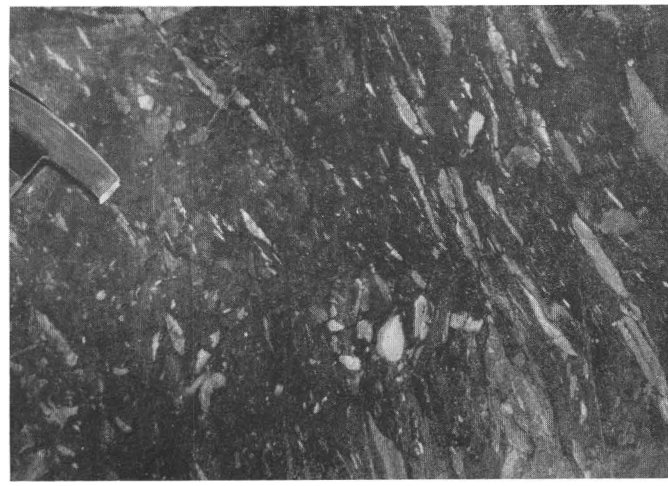

FIGURE 21.—Weathered dolomite breccia conglomerate. The light fragments are finely granular quartz, the matrix a mixture of limonite and quartz grains like the "splash rock." Cut beside Pires road, 1.2 kilometers southwest of São Julião.

micaceous minerals, and amorphous iron hydroxide. The 30 percent silica is equivalent to about 4 percent quartz in the original dolomite, approximately the amount observed in the thin section. Finely cellular limonite has preserved the volume and structures of the dolomite although it actually replaces only a small quantity of the original material. The process may be one of deposition of thin films of limonite on intergranular boundaries and subsequent leaching of the bulk of the carbonate.

Although specimens allowed to dry slowly in air remain firm, they disintegrate upon being immersed in water. Undisturbed material gains and loses moisture with the season, however, and the specific gravity is variable. Calculations indicate that the material should support its own weight to a depth of 5 or more meters even if completely saturated. Thin zones interbedded with and partly supported by itabirite have been recognized in exploration adits at greater depths.

The material described above was derived from a relatively pure dolomite. Siliceous dolomite beds naturally yield products containing greater amounts of quartz. Angular aggregates of finely granular white quartz in the porous material (fig. 21) preserve the structure of the dolomite breccia and by the lack of slump or compaction afford additional evidence that replacement occurred, and that the change was not due solely to the leaching of carbonate and residual downward enrichment of the less soluble components.

The "splash rock" apparently acts as a sponge, taking up elements present in the ground water and losing its excessive porosity, for it is closely associated in space with aluminous and manganiferous clay and wad. Two major trends of alteration occur, one toward nearly pure white kaolinitic clay and eventually baux-

TABLE 10—*Analyses of dolomite alterations products, in percent*

[Analyses 2–7 by Cassio Pinto in D.N.P.M. laboratory, Belo Horizonte]

	1	2	3	4	5	6	7
SiO_2	30.80	36.4	33.5	19.3	36.2	44.1	45.2
Al_2O_3	.12	7.2	13.1	19.6	32.9	38.9	39.2
Fe_2O_3	54.20	----	----	----	----	----	----
Fe	(37.9)	27.8	21.7	19.9	12.3	1.8	.7
Mn	2.15	1.6	1.6	8.4	----	----	----
P	----	.06	.14	.05	.05	.04	.05
Loss on ignition	7.66	3.0	8.8	12.0	12.4	13.5	13.4

1. Solid residue of weathered dolomite from outcrop opposite Usina railroad station, analyzed by chemist of Companhia Mineração e Usina Wigg, S. A. The natural sample yielded 70.5 percent water at 100°C.
2. Sample from lens of black, friable material exposed on Rio-Belo highway south of km 99, São Julião quadrangle.
3. Thin bed of wadlike material enclosed in phyllite, cropping out at side of Rio-Belo highway near km 98, São Julião quadrangle.
4. Bed of black wadlike material exposed in new highway cut 2 km west of Fábrica fazenda house, Casa de Pedra quadrangle.
5. Dark-red compact clay, outcrop on road 1 km east of Cumbí marble quarry, about 7 km east-northeast of São Julião.
6. White clay from same locality as No. 5.
7. White clay from opencut 1.2 km southwest of São Julião on road to Pires.

ite, and the other toward black mixtures of manganese and iron hydroxides. Table 10 gives analyses of specimens of these weathering products, arranged in the order of increasing alumina and decreasing iron, but it must be emphasized that these specimens were taken from several places and do not represent the progressive alteration of identical original material. For example, much of the iron of analysis 2 is anhydrous and probably was derived unaltered from a ferruginous bed. The trend toward manganese-rich material shown by analyses 1–4 continues, but a more complete discussion of origin, grade, and reserves will be deferred to the sections dealing with ore deposits.

The aluminous clays range from brick- to purplish-red massive-appearing material, in which only disseminated quartz grains can be identified, to white kaolinitic clay, also containing the quartz. Many are mottled because of variations in the iron content. A characteristic mode of occurrence is shown in figure 22.

View *A* illustrates the massive, jointed character of the dark-red material (no. 5) which has lost all trace of any bedded character. No soil forms over the barren and hummocky outcrop. The white streaks shown in view *B* are tubular "pipes" from which the iron has been leached (no. 6), apparently by downward percolating waters. Similar material at the west end of the Casa de Pedra mine is cut by many veinlike bodies of glassy brown limonite which probably was leached and redeposited by ground water. Analysis 7 represents material from a deposit of uniformly white clay which has been mined for foundry use at Usina Wigg. It grades abruptly into weathered dolomite breccia (fig. 21), suggesting that the clay is a final alteration product of dolomite.

Elsewhere in the Congonhas district evidence of the original material is less direct, but sufficient to leave little doubt that the "splash rock," manganiferous wad, and clay are derived from dolomite and can be used

FIGURE 22.—Compact clay, derived by weathering from dolomite(?). *A*, View of barren surface and shallow cut. The dark material is brick red, with appreciable iron cabinet, the white is virtually iron free (table 10, analyses 5 and 6). Note that the clay is not plastic, but breaks with a conchoidal fracture. *B*, View looking down on ends of tubular pipes, same outcrop. About 1 kilometer east of Fazenda Cumbí and 8 kilometers east-northeast of São Julião.

for mapping purposes. These deposits occur at definite stratigraphic horizons, are chiefly associated with rocks of the middle group of the Minas Series, and often crop out along the strike continuation of unweathered dolomite. In places, at least, they extend to considerable depths, for a vertical drill hole at the west end of the Casa de Pedra mine (DH 8, pl. 6) stayed in mottled limonitic clay for 60 meters, and elsewhere the clays are deeply eroded in gullies.

ALLUVIUM

Sand, gravel, and transported clay occupy small areas along the major streams and some tributaries in the lowlands and occur at a few spots in the highlands where resistant rocks have protected them from the rapid erosion of the rejuvenated streams. Even in the lowlands they are being removed from most spots and carried downstream at a rapid rate. Areas large enough to be mappable have been shown.

Gravels remaining on uneroded bits of higher terraces have not been mapped.

The alluvium consists for the most part of vein quartz containing a considerable admixture of black sands. Coarser iron ore fragments have also been carried long distances. The gravels are (or were) auriferous, and have been worked for their gold content.

GEOLOGY OF THE MINERAL DEPOSITS

IRON

Iron ores of the Congonhas district are of three major types: (1) itabirite ores, consisting of unaltered itabirite and therefore ordinarily containing quartz and any other rock-forming minerals present in the iron formation; (2) hematite ores composed of nearly pure iron oxide; and (3) surficial ores. Types 2 and 3 are closely associated with the iron formation and are derived from it by processes which have concentrated the iron.

ITABIRITE

CHEMICAL AND PHYSICAL NATURE

Most itabirite is of simple mineralogic composition, consisting of hematite and quartz, or hematite (in places magnetite), quartz, and dolomite in laminae which are alternately iron rich and iron poor. Leaching, hydration, and redistribution in the surface zone have commonly altered the original proportions, however, so that relatively little is known of the exact nature and grade of typical unweathered itabirite. No mine openings in the Congonhas district extended below the leached zone.

Hematite, Fe_2O_3, contains 69.94 percent iron and in its crystalline form specularite, typical for itabirite, has a specific gravity of about 5.20. Magnetite, Fe_3O_4 or $FeO \cdot Fe_2O_3$, contains 72.4 percent iron and has a specific gravity of about 5.17. Quartz, SiO_2, and dolomite, $CaMg(CO_3)_2$, have specific gravities of about 2.65 and 2.85 respectively. The disparity in specific volumes between the ore and gangue minerals makes the latter appear very prominent relative to their actual weight percentages, or in other words causes the itabirite to appear considerably leaner than it actually is. For example, material with equal volumes of hematite and quartz contains about 46 percent iron. The theoretical weight-volume relationships for quartz-hematite rock are summarized in table 11. Partial or complete substitution of dolomite and magnetite for quartz and hematite would not affect these ratios appreciably.

TABLE 11.—*Weight-volume relationship of siliceous itabirite*

Fe (percent)	Percent by weight		Percent by volume		Specific gravity
	Hematite	Quartz	Hematite	Quartz	
70	100	0	100	0	5. 20
60	85. 8	14. 2	75. 5	24. 5	4. 60
50	71. 5	28. 5	56. 2	43. 8	4. 10
46.3	66. 2	33. 8	50. 0	50. 0	3. 93
40	57. 2	42. 8	40. 0	60. 0	3. 67
30	42. 9	57. 1	27. 5	72. 5	3. 38
20	28. 6	71. 4	17. 0	83. 0	3. 10
10	14. 3	85. 7	7. 8	92. 2	2. 86
0	0	100	0	100	2. 65

It is probable that all gradations exist between silica rock, dolomite, and pure hematite, but the writer and his colleagues (Dorr, Guild, and Barbosa, 1952) consider that most material containing more than 66 percent iron (about 95 percent hematite) resulted from enrichment of the iron formation. In this report the upper limit for itabirite is placed at 66 percent iron. No lower limit can be assigned, although material with less than about 15 percent iron contains so little hematite that it would probably not be called itabirite because it would not appear laminated.

Sampling of itabirite in exploration adits and visual estimation of the proportions of hematite and quartz exposed in the workings indicate that most itabirite contains at least 35 percent iron. Most authors, including the present writer, agree that the average iron content of the formation may be between 40 and 45 percent. Some analyses are given in table 12.

Recalculation of the iron as Fe_2O_3 shows that some of the analyses lack several percent of totaling 100, and suggest that the analyses may not be too accurate, inasmuch as the low water content refutes the possibility of any considerable content of alumina, and no other constituent should be present to this amount. The values for silica may be slightly low. The small but uniform phosphorus content is noteworthy. No phosphate minerals have ever been identified, as far as is known to the writer. The low manganese content is characteristic of nearly all itabirite, although a few beds have appreciably more (see p. 61).

Analyses of ferruginous carbonate rocks are rare, as the only ones exposed that have not been leached are too low grade to have any economic importance for iron and contain too much iron to be valuable as dolomite. One magnetite-bearing siliceous dolomite containing a small amount of amphibole from Usina was analyzed by the company chemist at Usina Wigg with the following results:

Constituent	*Percent*
SiO_2	37.40
FeO	15.00
Al_2O_3	1.19
CaO	17.36
MgO	9.08
MnO	.19
Loss on calcination	19.50
	99.72

Disregarding the minor constituents, and calculating all the iron as magnetite, this is equivalent to about 16 percent magnetite, 35 percent quartz, and 45 percent lime-magnesia carbonate.

Completely unweathered itabirite is a hard, tough rock which would require drilling, blasting, crushing, and fine grinding to liberate the ore minerals from gangue. Individual specularite grains range in size from less than 0.001 to about 0.05 millimeter in the average material, and although aggregates of grains are much larger, unweathered itabirite is a fine-grained ore. Its economic utilization would entail problems of mining and beneficiation similar to those of the taconites of the Lake Superior district.

Some siliceous itabirite is fresh and hard at the outcrop. Much of the itabirite has been softened by weathering, however, even where there has apparently been no significant change in the bulk composition. The softening is caused by loosening of the bonds between individual grains, which results in partial or complete disaggregation or loss of cohesion. In general, the more ferruginous laminae and beds are less affected and remain relatively hard whereas the iron-poor laminae become a gritty, loosely cemented material much like soft sandstone or are altered to an incoherent fine sand. In places the ferruginous material is also leached to an incoherent hematite powder. This weathering greatly reduces the difficulty of extraction and beneficiation. Some itabirite is so soft that it can easily be picked, shoveled, or even cut with the fingernails. (For example, the boxwood scale in figs. 6 and 16 has been pushed slightly into the wall of the adit to hold it from falling.) Material of this sort could of course be mined directly with a power shovel. Harder beds or lenses would probably have to be loosened by blasting, but drilling would not be difficult.

Beneficiation of weathered itabirite is also relatively simple. Screening eliminates much of the silica from material in which the ferruginous layers are still relatively firm and the siliceous layers are soft. This process yields ore containing 62 percent iron from average itabirite in the Serra do Batateiro 1.5 kilometers southwest of Casa de Pedra. To treat itabirite in which both the silica and iron are disaggregated, gravity methods of concentration will be required. Tests have shown that Humphrey spirals will give a product containing 67–69 percent iron from such material (Whitehead and Dorr, 1950).

Weathering effects probably extend to the water table, and therefore are deep in the higher ridges. No completely unweathered itabirite occurs in the tunnel through the Serra da Rola Moça, for, although it is 220 meters below the surface at the point under the crest of the ridge, the water table is still deeper. Most of the samples analyzed (table 12) came from the weathered zone at depths of some 15 to 30 meters.

The simple leaching described above apparently takes place without any significant introduction of new material. In addition, considerable hydration of the iron oxides, leaching of quartz, and cementation by limonite occurs in the zone immediately adjacent to the surface and at greater depths where surface waters descend freely in open fractures. Limonite is used here as a comprehensive term for ferric hydroxide ($Fe_2O_3 \cdot nH_2O$). It is a dark-brown to yellow, noncrystalline mineral with a dull to glassy luster and a characteristic yellowish-brown streak which distinguishes

TABLE 12.—*Analyses of itabirite, in percent*

Analyses 1–3, 6, and 7 by Maria Yelda Esteves Ramos in the Laboratorio da Producão Mineral, Rio de Janeiro. Nos. 10–14 quoted from Grosse (1946, p. 114).]

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	7.24	8.0	28.60	32.30	37.30	41.50	42.70	43.11	24.50	43.74	38.30	24.29
Al_2O_3				.60	.46					.73		
Fe	63.8	60.4	47.1	46.5	42.7	39.1	38.1	35.91	51.86	38.48	40.28	49.95
Mn	Tr.	Tr.	Tr.	.18	.16	Tr.	Tr.					
P	.024	0.29	.015	.011	.017	.022	.017	.06	.07	.06	.07	.11
H_2O	.10	.14	.06	.39	.46	.07	.05					

1. Itabirite from east flank of Serra do Mascate, 2 km north-northwest of Casa de Pedra.
2. Chip sample, adit 6, Serra do Batateiro (pl. 8), 28.5–31.9 m.
3. Adit 6, 31.9–39.0 m.
4. Itabirite, quoted from Scheibe (1932, p. 37).
5. Itabirite, quoted from Scheibe (1932, p. 37).
6. Adit 6, 39.0–43.5 m.
7. Adit 6, 25.0–28.5 m.
8. Fabricá (pl. 9), adit 3 about 90 m from portal.
9. Fabricá, adit 1, about 230 m from portal.
10. Fabricá, adit 18, about 135 m from portal.
11. Fabricá, adit 6, about 60 m from portal.
12. Fabricá, adit 2, about 80 m from portal.

it from the brick-red streak of hematite. Limonite is not only formed in place by the hydration of hematite, but is deposited from solution in favorable spots as cement around partly altered itabirite grains, in cavities left by removal of other minerals, and as vein fillings in open fissures. Aluminous material, probably both clay and hydroxide, is also introduced in small quantity, no doubt largely by concentration of the minor amounts present in the original rock. In many places the phosphorus content is appreciably higher than in unweathered itabirite.

Analyses of partly hydrated itabirite samples are given in table 13. The water contents of samples 1–5 are higher than those shown in table 12, but are still fairly low, indicating that only part of the iron is present as limonite.

TABLE 13.—*Analyses of partly hydrated itabirite, in percent*

[Analyses 1–2 by Maria Yelda Esteves Ramos; nos. 3–5 by Oswaldo Ericksen de Oliveira, both of the Laboratório da Produção Mineral, Rio de Janeiro; no. 6 by Cassio Pinto, DNPM Laboratory, Belo Horizonte]

	1	2	3	4	5	6
SiO_2	29.63	1.95	1.1	0.3	0.5	1.1
Fe	46.7	60.2	55.1	61.2	64.7	56.3
Mn	Tr.	.1	Tr.	-------	Tr.	-------
P	.028	.32	.32	.14	.09	.07
H_2O	1.62	.78	2.9	2.2	1.1	10.9

1. Chip sample, adit 6, Serra do Batateiro (pl. 8), 16.0–25.0 m.
2. Chip sample, exploration adit on east flank of Serra do Batateiro, 2 km southwest of Casa de Pedra, 1–6 m inside portal.
3. Chip sample, adit 3, Serra do Batateiro (pl. 8), 5 m from portal.
4. Adit 3, 12.3–13.3 m.
5. Adit 3, 24.0–25.0 m.
6. Grab sample, outcrop 450 m west southwest of head of aerial tramway, Casa de Pedra.

Itabirite grades into canga as more and more of the iron is present as limonite. The writer has used the term "enriched itabirite" for material like that represented by analysis 6, which is surface material almost or completely altered in place to limonite, and has mapped it as bedrock, wherever bedding and other structures can be definitely identified. From the miner's viewpoint, and for metallurgical practice, much of this material is canga to a depth of a few meters.

ORIGIN

The development of the iron formations can be divided into three distinct stages: (1) sedimentation; (2) deformation and metamorphism; and (3) weathering of the near-surface part.

SEDIMENTATION

The similarities of itabirite to less metamorphosed cherty iron formation have been pointed out by several authors (Tyler, 1948; Barbosa, 1949; Dorr, Guild, and Barbosa, 1952; and others). The present writer has presented some aspects of the problem elsewhere (Guild, 1953). Chert and cherty iron formation have been widely discussed for generations by geologists of many countries, for these rocks have worldwide distribution in the pre-Cambrian and occur sparingly in the younger systems as well. The problem of their origin resolves itself into several parts: (1) the source of the vast quantities of iron and silica; (2) the mode of transportation; (3) conditions which permitted their selective concentration and the exclusion of other materials; and (4) the rhythmic layering of the formations.

There is now general agreement that iron formations are chemical precipitates of iron compounds, silica, and carbonates, containing minor amounts of alumina, manganese, phosphorus and other constituents. An estimate of the quantity of iron and silica deposited in the itabirite member of the Minas series throughout the area of the "quadrilátero ferrífero" can be made from the following data: area, 10,000 square kilometers; average thickness, 300 meters; average grade, 40 percent iron; specific gravity, 3.67. Ignoring the carbonate content, these figures indicate 4.4×10^{12} tons of iron and 4.7×10^{12} tons of silica as the proper order of magnitude. Volcanic sources have been proposed by some writers for such vast amounts of iron and silica, but Gruner (1922), among others, disagrees, citing data to show the very great difficulties in this hypothesis. He believes that weathering of a preexisting land mass is capable of furnishing the iron and silica required. Although streams carry very low concentrations of these substances, Gruner states that the Amazon River transports enough to produce the Biwabik iron-formation of Minnesota, calculated to contain 1.9×10^{12} tons of iron, in 176,000 years. Experimental work has demonstrated that iron and silica can be carried either as stabilized colloids or in true solution, and that they will be precipitated soon after contact with normal sea water (Moore and Maynard, 1929; Castaño and Garrels, 1950). Thus, neither the source nor mode of transportation of the materials present insurmountable obstacles, and the crux of the iron formation problem lies in the selective and rhythmic precipitation of iron and silica in deposits relatively uncontaminated by the more common sediments.

James (1951b) has pointed out that in the Lake Superior district four facies of iron formation can be distinguished according to the nature of the iron minerals present. They are the oxide, with hematite and magnetite; carbonate, with siderite; sulfide, with pyrite; and silicate, with various ferrous silicate minerals. He shows that the particular facies formed depends upon the environmental conditions of deposition. Itabirite corresponds to the oxide facies. Krumbein and Garrels (1952) and more recently Huber and Garrels (1953) have discussed these environmental conditions in physicochemical terms of acidity and oxidation-reduction potential (pH and Eh). For the oxide facies the conditions are a positive Eh and a pH of 7.0–7.8, considerably more acid than normal sea water. Oxidizing conditions are necessary to keep the iron in the ferric state, and a low pH to inhibit the precipitation of carbonates which otherwise would mask the iron and silica by their volume, normally on the order of 100 times as great. Clastic traps to remove detrital material are easily postulated, though the mechanical load of the streams may not have been large.

The critical factor is a pH value low enough to keep most of the carbonate in solution. A restricted environment is essential. Sakamoto (1950) has proposed that iron formation was deposited in paralic lakes or lagoons where the pH could fluctuate widely with seasonal changes in rainfall and hence of the volume and acidity of water entering them, but it does not seem likely that such conditions would account for the widespread itabirite of Minas Gerais with its great thickness. The suggestion made by James (1951b) that the Lake Superior iron formations are related to the development of the Huronian geosyncline and deposited in closed or restricted basins behind rising offshore swells or island arcs agrees much better with the geologic setting of the itabirite of the Congonhas district. Large volumes of slightly acid river water pouring into such basins could be expected to reduce materially the normal marine pH of about 8.0, and might bring it below 7.8, the "limestone fence" of Krumbein and Garrels.

Although volcanic materials are associated with many iron formations of the world, attempts to show that the iron and silica were supplied directly from volcanic sources have not been successful. James believes that in the Lake Superior districts the only relationship is a mechanical one—that the volcanoes of the offshore arc assisted in blocking off normal marine circulation. The writer, however, suggests that volcanic emanations may have contributed acids to the water and thus aided directly in lowering the pH of the system. He sees no reason why they may not also have contributed some iron and silica which, added to the terrigenous materials, may help to explain the frequency, size, and richness of the pre-Cambrian iron formations.

In brief, relatively acid conditions are the prime requisite; volcanic activity may have assisted in producing these conditions but was not necessary; and although most of the material was probably derived from preexisting land masses, no doubt under tropical conditions of weathering, some iron and silica may have been contributed directly from juvenile sources.

Several theories have been advanced to explain the rhythmic layering so characteristic of the iron formations of the world. The advocates of volcanic sources for the iron and silica usually postulate repeated eruptions to supply new contributions, each of which forms a pair of layers because of more rapid precipitation of the iron. It is, however, beyond all possibility that hundreds of thousands of separate eruptions or regular pulsations could each have contributed roughly the same quantities to the system, and this is, perhaps, the strongest argument against a volcanic source for the materials.

To those who call upon dilute solutions of iron and silica in river waters to furnish the materials for the formations, the variation in solubilities of these substances in acid and alkaline environments affords the most logical explanation for the rhythmic banding. Iron is most soluble in acid solution, silica in alkaline. Sakamoto (1950) has probably advanced this theory most fully, postulating seasonal variations ranging from a pH of 5 to a pH of 9, with iron compounds precipitated during dry periods of high alkalinity and silica deposited when the pendulum swung to the acid side during the wet season. To the writer such repeated and regular variations seem extreme in a basin the size of that in which the itabirite of Minas Gerais was deposited.

It is essential to remember that the precipitation of iron and silica is not dependent upon the concentration of the substances, as for an evaporite assemblage. The extremely low content of these substances in sea water shows that they are constantly being precipitated. Experiments performed by Moore and Maynard (1929) demonstrated, however, that iron precipitates more rapidly than silica. Periodic additions of weak mixtures of stabilized colloids to saline solutions produced rhythmically layered deposits in which the ferruginous laminae represented the early-settled part of each addition. This experiment suggests that the layering of the itabirite is due to periodic fluctuations in the volume of water added to the basin and that the fluctuation may probably be attributed to seasonal variations. Thicker and thinner "varves" may be due to variations in rainfall from year to year. Exceptionally dry years or prolonged droughts might cause the pH to cross the "limestone fence" and permit the precipitation of carbonates.

If the laminae represent annual accumulations it is possible to make an estimate of the time required to deposit the iron formation. They average perhaps 1 millimeter per pair, or 1,000 per meter. The average thickness of the formation of 300 (?) meters suggests 300,000 years for its deposition, which is of the same order of magnitude as Gruner's figure of 176,000 years for the Amazon River to carry sufficient iron and silica to produce the somewhat smaller Biwabik iron formation.

The writer believes that the deposition of the Minas and Itacolumí series, and particularly of the iron formations, took place as outlined below: Sedimentation began with nearly iron free sands and clays, laid down at the border of a slowly subsiding trough (geosyncline). The surrounding lands, fairly high at the beginning of this period, gradually were reduced to a low peneplain, so that the last clastic sediments of the lower group were fine muds. Rising offshore swells cut off most or all the circulation with the open sea, producing a shallow isolated basin into which one or more large river systems brought the products of dominantly chemical weathering of the low-lying landmass. Any coarse clastic material was deposited in lagoons or brackish estuaries. The iron and silica were precipitated by the electrolytes of the sea water, but the relative acidity of the great volume of river water lowered the pH of the system below the "limestone fence" so that carbonates were held in solution. Volcanic emanations from the offshore arc may have aided in raising the hydrogen ion concentration, and may also have contributed iron and silica.

Fluctuations in the volume of river water, probably due both to seasonal and longer period climatic variations, controlled the quantities of material introduced into the system. Rapid precipitation of ferric oxide or hydroxide was followed by more leisurely sinking of gelatinous silica, giving rise to the finely laminated ferruginous-siliceous sediment. Sharply defined laminae probably represent periods when seasonal rainfall variations were pronounced; the indefinite layers in which considerable mixing of hematite and silica occur may represent periods of year-round rainfall and a constant addition of new material to the basin of deposition.

Four factors could conceivably control the pH of the basin. One, the acidity of the river water probably fluctuated with seasonal changes, as postulated by Sakamoto. The volume of water should also have an effect on the pH of the basin, and as the river waters probably became most alkaline at the same time that the volume was lowest, these factors could give rise to considerable variations. Examination of the relatively few fresh carbonate-bearing itabirite specimens available indicates that the carbonate layers are more ferruginous than the siliceous ones. This suggests that iron oxides and calcium-magnesium carbonate precipitated together when the system was relatively alkaline, and Sakamoto's proposal thus apparently has some application to the formation of this type of itabirite, though the writer cannot agree that the pH fluctuations were very great. In the eastern part of the Congonhas district, and particularly at Passagem, where Guimarães (1935) reports dolomite throughout the itabirite section, the pH apparently remained near 7.8 throughout the period of deposition. The eastward facies change toward more carbonate may reflect increasing distance from the source of the river waters and an increasing proportion of normal sea water.

The writer suggests that the relatively uniform dissemination of iron and silica across the basin—rather than a rapid dumping near the river mouth or mouths—could be accomplished in the following manner: Fresh water is lighter than salt water and floats on it for some time in sheltered areas before mixing thoroughly. For example, the Amazon waters flow out hundreds of miles across the ocean before losing their identity and can be distinguished readily from the deep blue marine water by their muddy brown color. The line of demarcation is sharp at any one time, but presumably must advance and recede with the stage of the river. Fresh supplies of iron and silica could thus be suspended as colloids or held in solution for some time and spread evenly across part or all of the basin before slow convection or diffusion mixed them with electrolytes or otherwise caused them to precipitate. Relatively rapid thinning, such as that of the iron formation in the Serra da Bôa Vista-das Almas, would then be due to thinning of the fresh water layer, or to its advance and retreat. Distance from source could also explain the rapid thinning of the quartzite members of the lower group (p. 13) which contrasts with the rather uniform thickness of the uppermost schist member. The fine clastic particles which compose the latter would have been held in suspension longer and distributed more evenly over the basin before settling occurred.

Fluctuations in volcanic activity might change the hydrogen ion concentration of the water, if this suggestion has any validity, and the most important factor would be renewal of circulation with the open sea. The beds and lenses of massive dolomite probably were precipitated rapidly from somewhat concentrated solutions at times when the pH increased markedly for some reason, probably because of the temporary incursion of sea water. (The dolomite may be the result of later magnesian metasomatism of limestone.) Incomplete exposures suggest a gradational lower contract for at least some of the dolomite zones, with alternating iron- and carbonate-rich beds succeeded by purer dolomite. In at least two places the pure dolomite beds are overlain by a meter or more of green chlorite schist containing extremely fine needles of rutile, and the chlorite schist is in turn overlain by normal itabirite. This suggests to the writer that a heavy ash fall terminated the carbonate precipitation and that more acid conditions resulted from the volcanism.

The association of magnetite and carbonate rocks indicates either mildly reducing conditions under which some ferrous iron precipitated, or the incorporation in the sediments of materials, probably organic, which were capable of reducing part of the ferric iron during diagenesis or metamorphism. Perhaps the organisms of that time were more tolerant of a mildly alkaline environment and flourished only when carbonate was precipitating. Although finely divided graphite is common in some phyllite, the writer has not observed it in iron formation, and the correct explanation of this association may be entirely different. More study is required to solve the problem.

During the period of chemical sedimentation the trough subsided slowly. The lack of facies other than the oxide indicates shallow, well-aerated waters, and the very regular lamination shows that the waters were calm and not affected by severe oceanic storms. The wave-ripple marks at Usina are restricted to a few thin beds of ferruginous dolomite and have not been found elsewhere. The dolomite breccias were doubtless produced by storm action that stirred up the sediments on the shallow bottom, but dolomite was probably precipitated at times of more open circulation, when ocean storm waves could reach into the depositional basin. The angular character of the fragments shows that the silica hardened quickly.

At the close of this period the geosynclinal trough deepened and began to fill with terrigenous sediments. Some volcanic materials were also mixed in; their relative abundance depends on whether the "greenschist sequence" is contemporaneous with the normal Minas series rocks or belongs to an earlier epoch. If the sedimentary rocks of the Congonhas lowland are Minas series equivalent, much of the tuff and graywacke was probably derived from the postulated offshore arc. The adjacent continental lands probably began to rise, for quartzite is common north of the Engenho fault. Some quartzite is crossbedded, indicating that the waters remained shallow, or even that the area was temporarily emergent. Clastic hematite, presumably derived from the main itabirite formation, was incorporated in ferruginous quartzite beds. Local isolated basins permitted recurrent deposition of chemically precipitated itabirite.

DEFORMATION AND METAMORPHISM

At the time of deposition the laminated chemical sediments contained abundant water. Some data on the properties of gelatinous silica quoted by Aldrich (1929, p. 145) show that the water content may originally be as high as 98 percent and is still 75 percent when the silica is brittle. A volume change of about 50 times occurs in the transition to chert. Moderate pressures, up to about 140 kilograms per square centimeter, suffice to reduce to water content to 50 percent, at which point the gel occupies about one-thirtieth of its original volume. Tremendous pressures are required to remove the remaining water and reduce the volume another one-third. It is probable that the remaining dehydration and conversion to quartz took place only under orogenic stress with attendant deep burial and elevated temperature (regional metamorphism).

The silica gel remained fairly weak in the geologic sense for a long time. Although called brittle from a laboratory viewpoint with 75 percent of water, and thus able to break when subjected to wave action to produce the breccias, it was incapable of resisting long-continued stress and behaved as an incompetent material under strong deformation. Moore (1946, p. 46) has suggested that this explains the intricate folding so common in many pre-Cambrian iron formations.

Elongation of nodules in the Itacolumní series (fig. 12) shows the plasticity of chert relative to quartz, for the nodules are drawn out at least 10 times and probably much more, whereas vein quartz pebbles in the conglomerates are elongated only 2 or 3 times. Flattening from the weight of overlying sediments must have emphasized the laminae, particularly of the Minas series, and has completely obscured any nodules which may originally have been present in this series. As carbonate-rich beds were not so susceptible to compression, they should have remained thicker than the siliceous laminae. The writer believes that this is true, although the point is a difficult one to prove or disprove.

The weak folding in itabirite pebbles of the Itacolumí conglomerate beds indicates that deformation had not been intense at the time these beds were deposited. There is no evidence in the Congonhas district to show how long the break between the two series may have been, or if any break occurred, for the uplift of the border of the geosyncline suggested for upper Minas time may have continued, intensified, and migrated toward the axis of the trough as Itacolumí time went on. Schneider (1951) has proposed that lateral facies changes and variations in the type of reaction to tectonic stress by different lithologic units have completely confused the study of the later pre-Cambrian rocks of the Brazilian shield. He does not believe that a division of the rocks into a "Minas" and "Itacolumí" series separated in time is justified, but suggests that unstable belts sank, filled with sediments, and deformed through a prolonged time interval, so that similar rock types and stress pattern cannot be correlated exactly over wide areas of the Serra do Espinhaço. The present writer believes that this broad picture, whose details have not as yet been filled in, may be the proper interpretation.

Whatever the long-range correlations may be, Minas series rocks in or near the Congonhas district were being eroded in Itacolumí time and deposited as poorly sorted gravel, sand, and clay in one or more local basins. Some of the pebbles more nearly resemble jasper than itabirite and suggest that the iron formation was still a ferruginous chert at that time. As deformation continued, or was renewed, the iron formation was intricately folded, chert crystallized to granular quartz, and the iron minerals took on their present forms of specularite and magnetite. In places, most notably in the Pico Engenho mass, an incipient cleavage developed through the orientation of specularite plates at angles to the bedding. Elsewhere specularite plates are parallel to bedding even in tightly folded itabirite. In much of the itabirite, however, the hematite is not particularly tabular in habit, and the slight preferred orientation that is parallel to bedding may have resulted from "load metamorphism" imposed before deforming stresses were strong. The iron formation owes much of its transformation to anhydrous crystalline minerals to the metamorphism which accompanied deformation.

In the closing stages of the orogeny tight flexure was no longer possible and relief of stress was accomplished by fracturing and faulting.

WEATHERING

Weathering affects itabirite in two ways, softening it where the principal action is solution and leaching of some of the constituents, and hardening it where hydration and cementation occur. The processes of hydration and cementation generally are restricted to the surface zone and to open fractures; geologically and economically the cemented material is closely allied to canga and further discussion of it will be deferred to a latter section (p. 59).

The nature of this leaching is not understood, though it must be some process that dissolves small quantities of material from the grain boundaries. Inasmuch as iron is more soluble in acid solutions, and silica in alkaline, the presence or absence of carbonates should play an important role in influencing the pH of the descending surface waters and hence the relative amounts of the substances leached. Thus differences in the original composition of the formation no doubt affect the amount and type of solution, and it seems logical to assume that the carbonate content of the itabirite was a controlling factor. In some areas where the leached material is highly magnetic it may be that removal of the carbonate has been the principal change. Where the iron is in the form of hematite and there is no evidence of pore space due to the removal of entire mineral grains, the formal presence of appreciable amounts of dolomite is doubtful, and it seems more likely that the silica was partly dissolved. No evidence of slump and distortion of original structures has been observed; on the contrary the leached material preserves bedding, folds, and joints perfectly until disturbed by erosion or mining operations. This does not preclude an overall settling and compaction of the entire mass.

HEMATITE ORES

Masses of nearly pure hematite in the itabirite have attracted attention from the earliest time because of their dark color, unusual weight, and resistance to erosion, which causes a few of the larger bodies to stand high above the surrounding country as veritable "mountains of iron." The hard ores are excellent for use in open-hearth furnaces, command a premium price, and have accounted for nearly all the iron ore exported to date.

DEPOSITS

The hematite deposits occur almost exclusively in the rocks of the middle group of the Minas series; the only known exceptions are small masses in itabirite of the upper group and ferruginous rocks of the Itacolumí series. Dimensions range from centimeters to hundreds of meters. Many small and some large masses are tabular and parallel to the bedding of the enclosing sedimentary rocks, but others are crosscutting both in detail and in their major relationship. The overall shapes are imperfectly known, but insofar as can be determined from surface exposures most of the deposits are irregular pods elongated parallel to the regional lineation.

MINERALOGIC AND CHEMICAL NATURE

The mineralogy of the ore is simple. Most of it consists almost entirely of fine-grained specular hematite. Magnetite is not uncommon, however, and some ores are moderately to strongly magnetic. Isolated quartz grains are present in some ore. The most common silicate is talc. A small part of the ore contains as much as several percent of this mineral in aggregates of minute flakes or as plates a few millimeters across, distributed evenly with a planar orientation. In other ore talc lines elongated open cavities or forms thin films resembling schlieren in igneous rocks. Pyrophyllite in tiny radiating clusters of bladed crystals has been found in a few places, but is rare. Small white patches or blebs, which are apparently a kaolin type mineral after some unknown silicate, occur sparingly. Most of the ore does not have any talc or other visible impurities. No sulfide or phosphate minerals have been seen.

The composition of a high-grade ore specimen is shown in table 14. Other less complete analyses (table 15) show that ore of the grade represented by the picked specimen, although somewhat richer than the overall average, is not rare.

TABLE 14.—*Analysis of a picked specimen of hard massive hematite ore, 1246-meter level, Casa de Pedra mine*

[Analyzed in U. S. Geological Survey laboratory, Washington, D. C.]

SiO_2	0. 15
Al_2O_3*	. 18
Fe_2O_3	98. 84
FeO [a]	. 50
MgO*	. 031
MnO*	. 049
Cr_2O_3*	. 002
P_2O_5	. 05
SO_3	Tr.
	99. 802
Fe	69. 52
Mn	. 038
P	. 02

[a] Corresponds to 1.6 percent magnetite, if all ferrous iron is present as magnetite.
*Determined as elements by quantitative spectrographic analysis and recalculated as oxides. Looked for spectrographically but not found: Cu, Ag, Au, Hg, Pt, Mo, W, Re, Ge, Sn, Pb, As, Sb, Bi, Zn, Cd, Tl, In, Co, Ni, Ga, V, Sc, Y, La, Ti, Th, Nb, Ta, U, Be, Ca, Sr, Ba, B.

STRUCTURE AND TEXTURE

Several distinct structures are present in the ores. Bedding is nearly always visible on weathered surfaces (figs. 23 and 24) and on some unweathered fractures and polished faces (figs. 25 and 26). In most places it is a thin, regular lamination, like that of the itabirite and it also resembles itabirite in that it is commonly folded. Some ores have relatively thick beds, however, that range from centimeters to perhaps a meter in thickness; individual blocks may show no sign of lamination, either on unweathered or weathered surfaces. These are the so-called massive ores.

Study of polished specimens reveals a marked difference in the texture of the massive and the thin-bedded

FIGURE 23.—Weathered outcrop of hard hematite ore. Thin beds in the middle were folded and somewhat sheared between more competent beds. Casa de Pedra deposit.

TABLE 15.—*Analyses of hematite ores, in percent*

Analyses 1–8 by Aida Espinola; no. 9 by Maria Yeldes Esteves Ramos in the Laboratorio da Producão Mineral, Rio de Janiero. Nos. 10–14 quoted from Grösse (1946, p. 114). Nos. 15–16 are averages of analyses made by the Cia Siderúrgica Nacional]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	0. 2	0. 1	0. 1	0. 02	0. 1	0. 2	0. 3	0. 5	0. 13	0. 30	0. 70	0. 51	0. 24	1. 22	0. 43	0. 37
Al_2O_3	----	----	----	----	----	----	----	----	----	----	----	----	. 61	----	1. 20	. 17
Fe	67. 6	69. 9	68. 7	68. 7	68. 2	68. 8	67. 4	69. 2	68. 3	68. 87	68. 85	68. 41	66. 80	68. 30	67. 10	68. 79
Mn	([a])	([a])	([a])	([a])	([a])	([a])	([a])	([a])	None	----	----	----	. 99	----	----	----
P	. 006	None	<. 005	<. 005	<. 005	<. 005	<. 01	<. 01	. 011	. 07	. 09	. 07	. 09	. 02	. 087	. 046
H_2O	. 3	. 2	. 3	. 3	. 2	. 1	. 6	. 1	. 47	----	----	----	----	----	----	----

[a] Trace.
1. Weakly magnetic hard hematite, adit 1, Batateiro deposits (pl. 8, fig. 35), 5.0–6.0 m from portal.
2. "Medium soft" ore, adit 1, left wall, 22 m from portal.
3. Micaceous hematite, adit 1, left wall, 28.6 m from portal.
4. Gritty hematite containing small lumps of hard ore, adit 1, face of first crosscut.
5. Thin-bedded, soft, very magnetic ore, adit 1, second crosscut.
6. Picked sample of hard hematite from adit 1, 90–100 m from portal.
7. Weakly magnetic, medium soft, thin-bedded ore, adit 3, Batateiro deposits, 27.0–29.0 m from portal.
8. Moderately magnetic soft ore, adit 4, Batateiro deposits, 17.4 m from portal.
9. Soft ore, adit 6, Batateiro deposits, right wall, 4–11.2 m from portal.
10. Massive hematite, Fábrica (pl. 9), adit 1, 80 m from portal.
11. Medium hard ore, adit 1.
12. Medium hard ore, Fábrica, adit 16.
13. Near-surface soft ore. Fábrica, adit 15, about 5 m from portal.
14. Residual ore in clay. Fábrica, adit 17, about 20 m from portal.
15. Unweighted average of 81,485 tons of run-of-mine ore, destined for blast-furnace use, representing part of the Casa de Pedra production between July 1947 and January 1948. Individual lots range from 66.14 to 67.51 percent iron.
16. Unweighted average of 6,115 tons of picked ore, destined for open-hearth use, representing part of the Casa de Pedra production from July 1947 to January 1948. Individual lots range from 68.38 to 69.06 percent iron.

ores, and between the individual laminae of the bedded ores. Massive ores are composed of anhedral, nonoriented, roughly equidimensional grains with an interlocking mosaic texture (fig. 27). Many laminae of the thin-bedded ores are composed of tabular, closely packed grains that have a strong preferred orientation which may be either parallel or at an angle to the bedding planes. Alternate laminae may have oriented and unoriented fabrics (fig. 28). Differences in reflectivity from adjacent laminae thus making the bedding and other structures easily visible with the inclined incident light. Laminae and massive ores with isotropic fabrics also take a higher polish, stand in slight relief, and resist etching and weathering to a greater degree than ores having a high proportion of oriented euhedral grains. Some ores contain oriented tabular specularite grains in a groundmass of unoriented anhedral specularite and cannot be classified rigidly. It is probable that all gradations exist from completely oriented to isotropic fabrics.

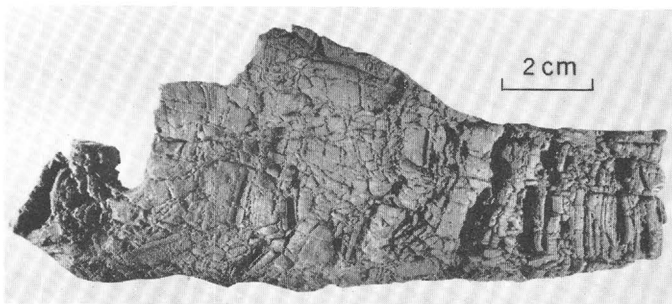

FIGURE 24.—Weathered face of hard hematite ore, showing bedding, relict cleavage, and incipient brecciation.

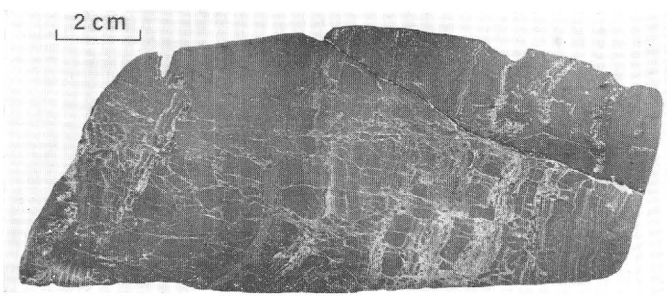

FIGURE 25.—Polished, etched, and repolished face of same specimen as figure 24, showing incipient brecciation preserved during replacement. All hematite, white is polishing powder filling crevices and pores opened by acid etch.

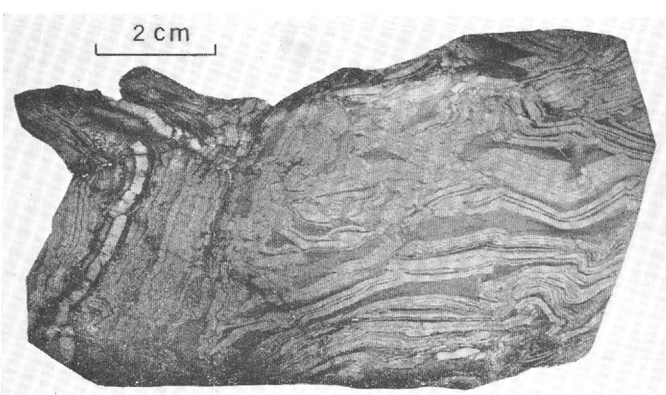

FIGURE 26.—Thin-bedded, folded hard hematite ore. Specimen is entirely hematite, laminations visible because of microscopic differences in texture. The bright laminae have mosaic texture, the dull ones an oriented, euhedral texture (fig. 27). Polished face, etched in cold HCl, reflected light.

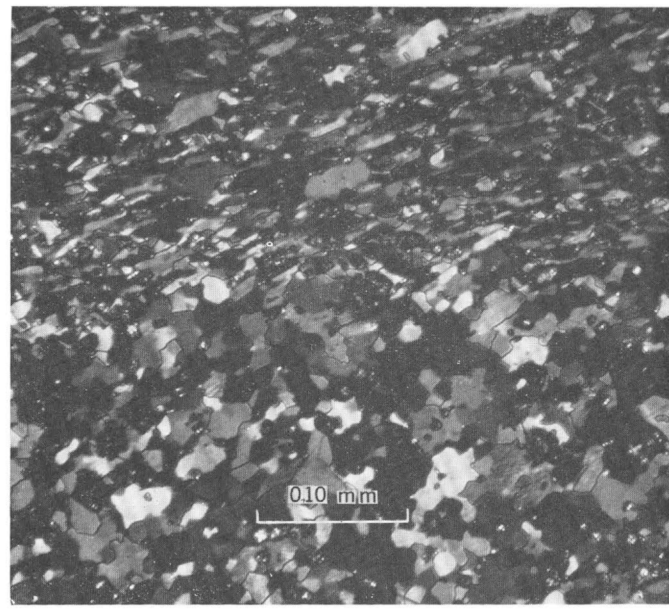

FIGURE 27.—Hematite ore textures. Isotropic mosaic texture below, oriented tabular grains above. Polished section, cross nicols. From specimen shown in figure 26.

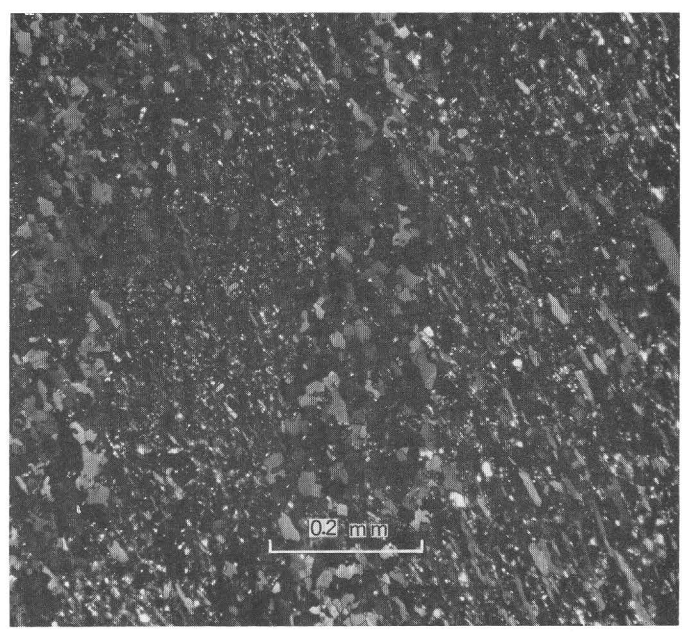

FIGURE 28.—Alternating laminae of mosaic-textured and oriented, euhedral hematite. Note that the cleavage makes an angle to the bedding. Same specimen as figure 27. Polished section, nicols.

As might be expected from the foregoing discussion of oriented and unoriented fabrics, some ores have a strong cleavage and others do not. In severely folded ores such as that shown in figure 27 the cleavage is not through-going, however, but bends sharply and remains close to the plane of the bedding.

The grain size of the textural types described above is fairly uniform at about 0.005–0.1 millimeter. Specularite also occurs as tabular plates 0.1–1 millimeter or more across in very thin veinlets that cut across the other textures and are evidently later. Most plates are oriented in the planes of the veinlets, but a few have random orientation (fig. 29). The direction of these veinlets in the specimen shown is about perpendicular to the bedding. Differential weathering forms crevices and apparently exhumes a close-spaced fracture system which controlled the formation of these veinlets (figs. 24 and 25).

Many ore specimens show a well-developed breccia structure. Figure 25 shows the incipient stage of brecciation of a laminated ore. Other specimens, not illustrated, are mylonites, although they may appear massive until examined on polished surfaces with reflected light.

Another structure, found at only one place in the Casa de Pedra deposit, is illustrated in figure 30. The material is massive hematite in which angular fragments have different textures and hence different resistance to polishing, weathering, and etching. There is no hint of the lamination characteristic of the iron formation.

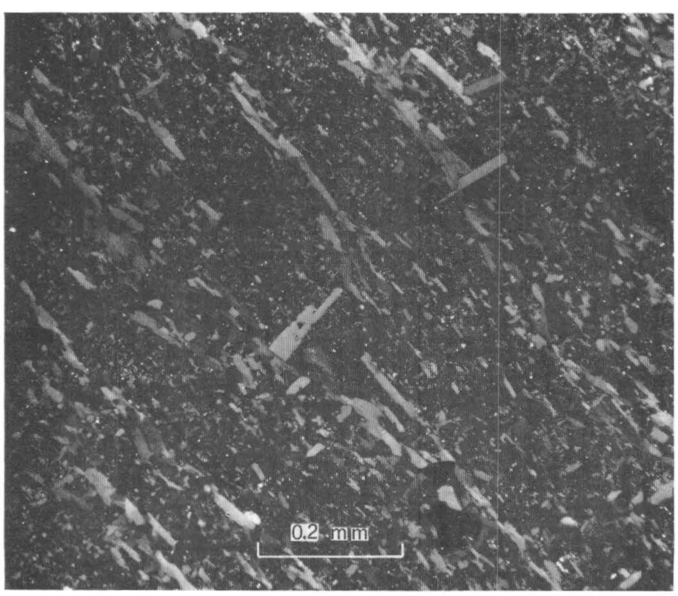

FIGURE 29.—Late veinlets of tabular hematite in fine-grained hematite and magnetite. Some plates grow across the veinlets and replace the groundmass. Polished section from specimen shown in figures 24 and 25. The veinlets oriented in the direction of the cleavage, nearly perpendicular to the bedding. Cross nicols.

The distribution of magnetite is variable, but the more magnetic zones generally follow planes of bedding. Octahedra are easily visible to the naked eye in some ores, as in figure 31, where they reach 1 centimeter or more. In a few places the octahedra are closely packed and make up nearly all the ore. Elsewhere the magnetite can be seen only under the microscope. Much of the ore contains very little or no magnetite. Polished sections reveal that hematite has

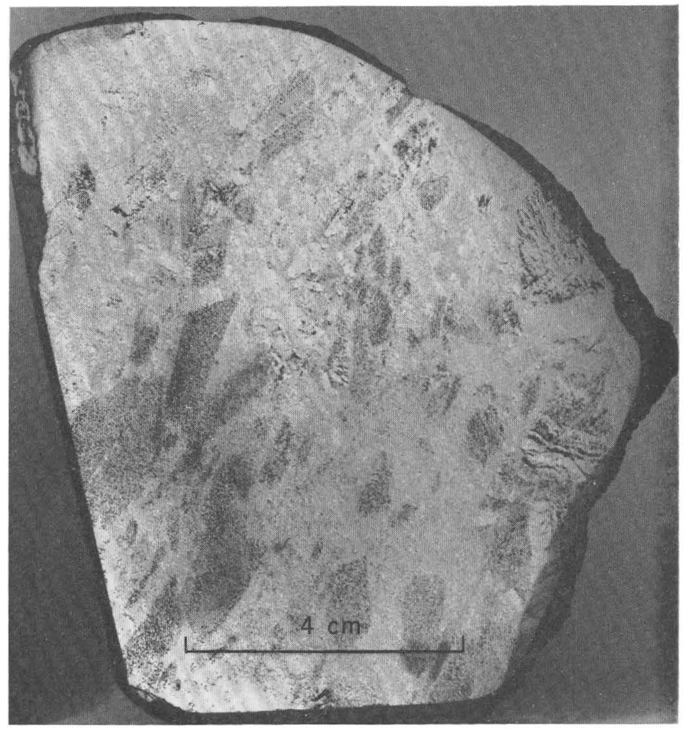

FIGURE 30.—Hard hematite ore with the structure of the dolomite breccia conglomerate. Polished, etched face. The structure is preserved by variations in the texture and porosity of the ore.

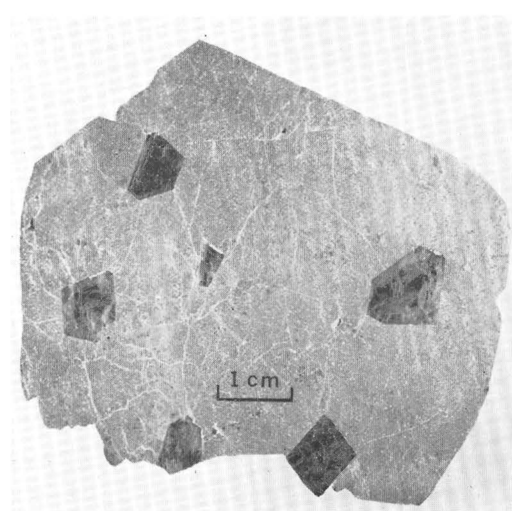

FIGURE 31.—Martite octahedra in fine-grained massive hematite. Numerous unreplaced magnetite remnants appear slightly darker than the coarse hematite. Polished face.

replaced much or all of the magnetite, so that the octahedra are for the most part martite (hematite pseudomorphous after magnetite), with or without unreplaced remnants of the original mineral. One, or at most a few specularite individuals replace the entire octahedron, and this feature sharply distinguishes martite from the groundmass specularite in polished section (fig. 32). Commonly the different quadrants

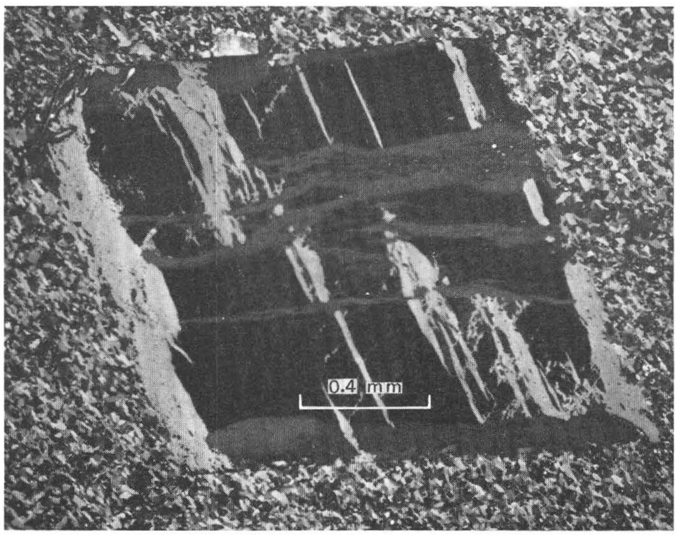

FIGURE 32.—Martite octahedron, showing the contrast between the coarse, interpenetrating hematite individuals controlled by crystal lattice of the replaced magnetite and the fine-grained mosaic-textured hematite of the groundmass. Black is unreplaced magnetite. Polished section, cross nicols.

of the section are composed of different individuals, as though replacement began at the corners of the octahedra; in some crystals replacement seems to have begun along the faces, in others replacement was controlled by the octahedral planes of the magnetite and the individuals extinguish uniformly across the grain to give a three-directional grid pattern. Some magnetite-rich ores show little or no evidence that the magnetite was ever euhedral. Most grains are ragged and irregular, set in a matrix of fine-grained unoriented specularite. A few fragments ordinarily show penetration and replacement by specularite, however, and indicate that the magnetite was the original mineral. No evidence of magnetite replacing hematite has been observed.

The linear structure so prominent in the area is expressed by the fold axes, elongated talc blebs, and a tendency for the ore to break in elongated blocks. A joint set nearly perpendicular to the lineation is especially well developed in the more massive ores, and the longest dimensions of many of the deposits apparently follow the lineation.

PHYSICAL PROPERTIES

Specularite has a hardness on Moh's scale of about 6.5, slightly less than that of quartz, but it is more resistant and on polished surfaces stands in relief above both quartz and magnetite. Most compact ores are difficult to drill either with percussion or rotary machines. In a demonstration at Casa de Pedra three jackhammer steels were completely blunted in drilling 5 centimeters into a block of specularite ore. In normal mining operation such extremely hard blocks can usually be avoided. Exploration by diamond core-drilling proved costly and unsatisfactory.

Only a relatively small proportion of the ore is completely hard and compact, however, and much of it is porous and softened. The ores range from material which rings under the hammer and breaks with a clean conchoidal fracture across bedding planes, through material composed of alternate hard and soft laminae, to incoherent fine-grained powdery material that disintegrates between the fingers. The writer and his colleagues (Dorr, Guild, and Barbosa, 1952) distinguished several categories of ore according to their physical properties. A fourfold classification of hard, medium hard, medium soft, and soft, and a threefold division into hard, intermediate, and soft have been used. The intermediate types are made up in part of hard ore and powdery ore too closely mixed to differentiate in mapping, and in part of material which is softened sufficiently to break on handling and yield a considerable proportion of fines.

The softer ores display the same structure observed in the hard varieties until they disintegrate. The writer believes that the thinner bedded types more often fall into the softer categories and that a greater percentage of the competent ores are thick bedded or massive. There are many exceptions, however.

Specularite has a calculated specific gravity of 5.256, and magnetite of 5.20. A fragment of a single crystal from the coarse-grained-quartz specularite vein near Poço Fundo (p. 29) had a specific gravity of 5.253. Determinations made on fine-grained ore fragments show a range in specific gravity, due to the degree of porosity, from about 5.0 to 5.3, but most hard-ore fragments range from 5.12 to 5.19. A factor of 5 metric tons (2,205 pounds) per cubic meter has been used for reserve estimates.

ORIGIN

EVIDENCE FOR A REPLACEMENT ORIGIN

The hematite ores were called syngenetic by Harder and Chamberlin (1915), who attributed them to the accumulation of unusually pure lenses of iron oxide or hydroxide in the sediments. Most other workers followed this assumption, but Sanders (1933) and Grösse and others (1946) have described the hematite ores as epigenetic and due to enrichment of the iron formation. The writer and his colleagues consider that the latter explanation is correct.

Evidenced for an epigenetic, rather than syngenetic, origin is of several kinds:

1. The martite clearly shows that hematite replaced preexisting magnetite. Gruner (1926, p. 641) states that "martite . . . seems to be of thermal origin in most cases," a statement with which the present writer agrees, for no evidence has been noted of alteration of magnetite to martite in the deeply weathered itabirite in the Congonhas district. On the contrary, the surface materials seem to be somewhat more magnetic than the bedrock, suggesting a certain amount of reduction.

2. The tight folds in much of the ore are similar to those in itabirite, indicating similar competency at the time of deformation.

3. The hard ores could not have been contorted in their present state, but on the other hand they could hardly have preserved fine-bedding structures through the orogeny had they been powdery ores which were later hardened by some process.

4. The textural variations from layer to layers in the ore of uniform mineralogic composition (figs. 26, 27, and 28) suggest that mineralogic variations must have existed at the time of deformation.

5. The breccia ores are completely healed. Many rotated fragments have isotropic mosaic fabrics, others have oriented platy fabrics which must have been imposed before brecciation.

6. The structure shown in figure 30 is that of the dolomite breccia conglomerate.

7. One specimen contains an angular fragment of fine-grained quartz enclosed in hard hematite ore (fig. 33). The texture and shape of the fragment are identical with those of fragments in the dolomite breccia conglomerate believed to be recrystallized from original chert.

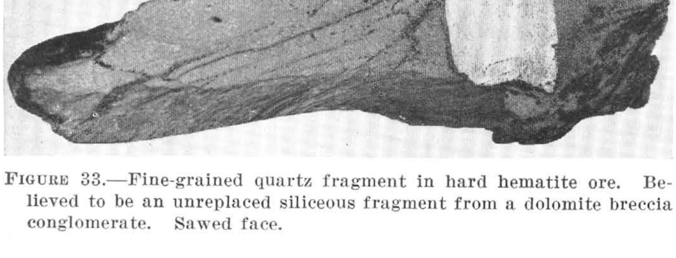

FIGURE 33.—Fine-grained quartz fragment in hard hematite ore. Believed to be an unreplaced siliceous fragment from a dolomite breccia conglomerate. Sawed face.

8. No hematite boulders have been found in the conglomerate of the Itacolumí series, although itabirite is common. Ore fragments are abundant in present-day streams draining iron-formation areas, and their absence in the conglomerate suggests that hematite ores as we know them today did not exist in Itacolumí time.

9. A thin hematite bed in the Itacolumí series preserves the structure of a conglomerate (fig. 34). Rounded pebbles with the fine lamination of itabirite

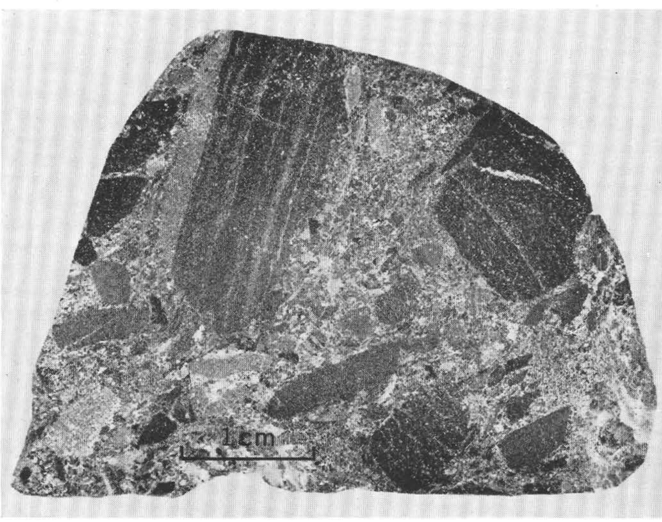

FIGURE 34.—Hard hematite with conglomerate structure, from the Itacolumí series. Both matrix and pebbles are now hematite, except for a few quartz grains in the matrix and a very little pyrophyllite. Polished face, reflected light.

are enclosed in a matrix of hematite. The mass is now composed entirely of fine-grained specularite except for a little pyrophyllite and a few coarse grains of quartz in the material interstitial to the pebbles. Near the pyrophyllite, partly replacing it and the quartz grains, the specularite has a coarser unoriented platy texture.

10. Coarsely crystalline specularite occurs in a few quartz veins that cut Minas and Itacolumí rocks, proving that iron was mobile to some extent in post-Itacolumí time.

GENESIS OF THE ORE

The writer offers the following hypothesis to explain the features of the hematite deposits of the Congonhas district: Deformation and recrystallization of the iron formation during the post-Itacolumí orogeny caused severe folding and the development of an incipient cleavage shown by the orientation of specularite plates in the ferruginous layers of siliceous itabirite. For some reason the iron of the dolomitic zones ordinarily crystallized to magnetite octahedra. Chert and carbonate recrystallized to finely granular mosaic-textured rocks. At the culmination of diastrophism, when the rocks could no longer yield easily by bending, extensive thrust faulting caused the brecciation of parts of the iron formation.

This brecciation opened channelways for solutions of unknown source and character which produced the widespread replacement of silica and carbonate by hematite. Details of bedding, incipient cleavage in the itabirite, breccia structures, and breccia conglomerate were all preserved. Even the microscopic textures may be in part at least pseudomorphous after itabirite and dolomite textures, just as the martite is controlled by the crystal lattice of the magnetite. The metamorphic specularite of the itabirite probably controlled the orientation of the metasomatically introduced hematite in such a manner as to preserve and emphasize the incipient cleavage. Thin-bedded itabirite was converted to thin-bedded, laminated ore. The thicker bedded rocks gave rise to the more massive ores with isotropic textures and little or no visible cleavage. Magnetite was less susceptible to replacement than the surrounding material, which presumably was a carbonate mineral. The darkest fragments with the densest texture in the specimen shown in figure 30 are apparently after fragments of pure carbonate rock such as are found in the unaltered dolomite breccia conglomerate (p. 16). The groundmass is less dense, reflecting the impure nature of the original material, and the angular, porous areas represent the siliceous fragments of recrystallized chert. The siliceous fragment shown in figure 33 resisted replacement.

The talc in many ores is probably residual from the dolomitic members of the formation. It is commonly associated with martite and seems to be more abundant in the massive than in the thin-bedded ores. Talc is common in the surface zone of leaching and recementation and apparently withstands reactions that completely alter iron minerals.

Evidence suggests that the mineralization followed soon after the faulting. The closely spaced fractures noted in some ore (figs. 24 and 25) cut ore having both isotropic and oriented fabrics and are healed with coarse-grained platy specularite that is not rigorously oriented, although it is generally alined parallel to the fractures (fig. 29). Continuing movement and low-grade stress probably fractured the ore slightly and provided passageways for circulating solutions which redistributed a small amount of hematite without causing a recrystallization of the mass of the ore. The cross joints may date from this same period, here considered as belonging to the closing stages as the same orogeny, although perhaps to be correlated with a later, less severe deformation.

The pyrophyllite in the ore is apparently related to a late stage of hydrothermal activity, perhaps contemporaneous with the quartz-kyanite-pyrophyllite and quartz-specularite veins in the Itacolumí series, which follow the cross-joint system. Veinlike masses of coarse-grained specularite in curved micaceous plates as much as several centimeters across (p. 29) are also late hydrothermal products.

SOURCE OF THE ORE-FORMING SOLUTIONS

The restriction of the hematite ores to the middle group of the Minas series suggests that the iron was derived from the itabirite formation and redistributed. Furthermore, the elements in the ores are those found in the unenriched formation; no new constituents have been introduced. The ratio of ore to the total volume of itabirite is so small that the loss of the necessary iron from other parts of the formation could not be detected.

The agent that accomplished the concentration of iron and removal of other minerals must have been heated water. Gruner's experiments (1926) showed that the alteration of magnetite to martite proceeds rapidly in air at temperatures of 150°–200°C but very slowly in water and various salt solutions at 100°. On the contrary, further experiments (Gruner, 1930) showed that water or steam at a temperature of about 250° will oxidize magnetite readily, and such heated waters will dissolve relatively great quantities of silica, even in the form of quartz. Gilbert (1925) expresses his conviction that hematite is nearly always hypogene and that platy (micaceous) hematite is never supergene. The absence of any high-temperature skarn-type minerals in the ore and in the dolomite of the area (except near known intrusive masses) suggests that the temperature of the water was moderate.

Although the granodiorite stocks seem to afford a likely source for the solutions, several facts argue against any genetic relationship between the ores and the intrusive bodies. No spatial relationship is apparent between the ore and the igneous rocks. Hematite deposits have not been found along the belt of itabirite in the contact zone of the large batholith in the northeast corner of the district. On the contrary, at least one itabirite lens is an unenriched, severely contorted quartz-magnetite schist in which hematite may have been reduced to magnetite. At the Passagem gold mine east of the Congonhas district a persistent bedding-plane vein having sodic-pegmatite affinities (Barbosa and others, 1948) follows the lower contact of the itabirite, but, although the formation is very dolomitic, no hematite ores were produced and the magnetite shows no sign of alteration to martite. The only apparent change was the formation of sodic pyroxene, glaucophane, cummingtonite, garnet, and tourmaline in the itabirite adjacent to the vein.

Although dikes cut both itabirite and ore in the

Congonhas district, no evidence has been found that the replacement was in any way related to them. In itabirite they contain inclusions of unaltered iron formation; in ore they enclose hematite fragments. Determination of the character of the dikes is greatly hampered by their decomposition to all depths encountered in mining. Study of the heavy residues from a few fine-grained dikes show tourmaline and zircon as the chief constitutents other than iron oxides derived from inclusions. A narrow granite pegmatite dike containing kaolin and coarse-grained muscovite mica cuts soft hematite ore in adit 6, Serra do Batateiro (pl. 8). These dikes probably were intruded after the time of formation of the hematite deposits.

The source and nature of the solutions are major problems. The solutions may have been ground water, heated by deep circulation or by proximity to magmatic intrusions, as has been suggested by Gruner (1937) for the Lake Superior ores, or perhaps connate water driven off from the sediments during deep burial and metamorphism. The chert originally contained a vast amount of water (p. 49) but it should have been expelled before deformation reached the intensity necessary for thrust faulting. The relative plasticity of chert probably restricted tectonic brecciation to the latest stages of the orogeny when most or all the silica had recrystallized to quartz.

Lateral movement of solutions toward the fault zones, which would afford channels for relief of pressure, may be the most acceptable hypothesis. This would account for the absence of elements such as sulfur that are not present in the itabirite, but would not explain how such solutions could leach silica, with which they should already be saturated. Future investigations should provide answers to these problems.

DISTRIBUTION AND LOCALIZATION OF THE DEPOSITS

Although the exact nature of the ore-forming processes is in doubt, mapping indicates a relationship between the deposits, thrust faults, and carbonate-rich zones of the iron formation. The principal Casa de Pedra deposit, largest known ore body in the district, lies between two overlapping faults near the intersection with the upper, carbonate-rich part of the formation. No dolomite is exposed, but drilling revealed the presence of dolomite weathering products in the wall rock. Most of the other deposits of the Casa de Pedra quadrangle are in the Serras do Batateiro and do Mascate, which general relationships indicate to be thrust slices. Deposits in the Serra do Batateiro lie near the trace of the fault in which the Mascate block is thrust onto the underlying Batateiros block. Deposits in the northern part of the Serra do Mascate lie for the most part near the trace of the underlying fault. The western range, in which the rocks lie in normal, generally unfaulted succession on the basement complex, has only small isolated hematite bodies, both within the Congonhas district and in its extension to the north.

Deposits in the central and eastern part of the Fábrica property occur in the upper part of the middle group on the flanks of an anticlinal structure. Several hematite masses are surrounded by dolomite weathering products. The Fábrica–São Julião belt contains relatively little hematite ore, but the few deposits are close to known or suspected dolomite zones. No hematite deposits have been reported from the Ouro Preto–Passagem–Mariana district, where the formation is very dolomitic but apparently is not thrust faulted.

The writer believes that structural control was the most important factor in the localization of replacement and that the chemical nature of the formation played a secondary role. He has not observed strongly brecciated but unenriched itabirite, although brecciation is a common feature of the hematite ores. On the contrary, every minor offset observed in material fresh enough to section is the locus of a minute specularite veinlet which has healed the fracture (fig. 17). Most veinlets are extremely short, extending only millimeters from the ferruginous layers, so that the hematite was apparently derived locally and redistributed. The bulk chemical composition must also have controlled the localization of ore, however, for hematite deposits do not occur in quartzite, schist, and other nonferruginous rocks of the district even where these rocks are severely fractured, and the siliceous itabirite of Pico Engenho and the Serra do Pires have no known ore deposits even though the geologic relationships indicate extensive faulting.

ORIGIN OF INTERMEDIATE AND SOFT HEMATITE ORES

Hematite ores are softened, or more specifically disaggregated, by the leaching action of ground water. The process is apparently one of intergranular solution that loosens the bond between individual crystals, yielding as the end product an incoherent powder of specular hematite. Ores that have oriented, euhedral textures are more susceptible to leaching than the dense, mosaic-textured and more massive ores, probably because of differences in the degree of interlocking of the grains. Where the two types occur in alternate laminae, differential weathering produces intermediate ores with strong relief on natural outcrops. Under prolonged solution even the most massive ores will become softened, however, producing nonbedded powdery ore.

Angular blocks of soft powdery hematite enclosed in clay below some outcrops show that this softening process is a present-day weathering phenomenon.

Grösse and others (1946) observed them at Fábrica, and good examples were formerly exposed along the southern slope of the Casa de Pedra deposit. The blocks could not have fallen in their present state without collapsing to powder. Furthermore, some grade inward imperceptibly from soft rims that can be scratched with the fingernail to cores of the hardest massive ore. The process is related to moisture, for where the ore is continually wet, as in the blocks enclosed in clay, the softening is common. Exposures in a small prospect adit at Casa de Pedra demonstrate this very well. A clayey laterite containing abundant ore fragments is cut by several hard glassy-appearing limonite veins. Individual hematite fragments are hard and unweathered where partly enclosed by the limonite, but completely soft where they project into the uncemented laterite. Bold outcrops, intermittently wet by rains and then dried, show only a pitting on the surface where the rainwater stands. That the hard ores crop out is a natural consequence of their resistance to softening, but loose blocks from such exposures eventually soften when enclosed in moist clay. Hard ore fragments on the surface, or those enclosed in canga, do not.

Analyses of powdery ore show that the softening process is one of leaching and not hydration, for the material left behind is nearly pure hematite (table 14, analysis 2). Some soft ore is very magnetic; it undoubtedly formed from magnetite-bearing hard ore and shows that no oxidation accompanied the leaching.

Weathering of the ore is of economic significance and importance, for if the softening is related to the present surface, as it seems to be, it should decrease downward and probably cease at the water table. Deep ores should be uniformly hard, and the problem of disposing of the fines that are produced near the surface should gradually disappear as the depth of mining increases.

The surface zone above the softer laminated ore is commonly hydrated and cemented to a depth of a few meters, and limonite veins may follow open fissures downward from the surface for considerable distances. This limonitic material has a relatively high phosphorus content, and care must be taken to exclude it from the highest grade ores during mining operations.

SURFICIAL IRON DEPOSITS

Surficial deposits of iron-bearing material cover large areas of the district over and in the vicinity of the iron formations. These materials are economically important and for several reasons are being used more widely by local industry than the itabirite and hematite ores from which they were derived. (1) They occur at the surface, thus are easily extracted by simple mining methods. (2) Most of them are enriched by removal of undesirable gangue minerals. (3) Some are more amenable to treatment in the customary charcoal blast furnaces than deeper, less weathered material. They may be divided geologically into materials derived by mechanical processes and by chemical processes.

RESIDUAL DEPOSITS FORMED BY MECHANICAL PROCESSES

From itabirite (chapinha).—The mechanical removal of granular quartz from leached itabirite which has not been cemented by the introduction of limonite in the surface zone leaves a deposit of thin iron-rich fragments if they have retained enough cohesion to be relatively strong. Large areas are covered to depths of several meters by residual deposits of these fragments mixed with soil. The Portuguese word "chapinha," meaning "little plate," is commonly applied to this material, which is sought not only because it can be easily screened from the enclosing soil by hand methods but because the plates are commonly porous and easily reduced in the last furnace. Screened material may average as much as 64 percent iron, with low silica, alumina, and phosphorus content.

From hematite (rubble ore).—Cobbles and blocks of hard hematite are common in many parts of the district, particularly downslope from ore deposits. Selective resistance to abrasion and solution increases the proportion of hard ore, so that much hematite float occurs on the flanks of itabirite ridges where no significant deposits crop out at present. Abundant hematite fragments in some chapinha ores raise the grade of this material. Cobbles are incorporated in coarse alluvium and carried considerable distances by streams.

Rubble ore has been mined because (1) the cobbles are often of a convenient size and require no drilling, blasting, or other breaking; (2) sound cobbles which have resisted weathering are of the highest grade; and (3) in places rubble ore has traveled so far down slope that it is more conveniently located near transportation than the deposits on the ridges from which it was derived.

DEPOSITS FORMED BY CHEMICAL PROCESSES

Surficial enrichment by chemical processes has produced many of the important ore deposits of the world, such as the lateritic iron and aluminum ores of tropical countries. The Mesabi iron ores and deposits of other Lake Superior ranges are usually assigned to this origin. Although the principal ore types of the Congonhas district are attributed to sedimentary and hydrothermal processes, they have been modified to a greater or lesser extent by weathering. Gathmann (1913) proposed that the hematite ores formed by surficial enrichment of itabirite, but Harder (1914) showed that his process could not account for their primary origin and was a relatively unimportant factor.

Much experimental work has been done on the solution and transportation of iron under weathering conditions by humic and organic acids. Harrar (1929, p. 61) states that "some of these supposedly weak organic acids dissolve remarkable quantities of iron and in natural solutions would be the most effective of all solvents," so that extensive weathering under tropical conditions is not surprising. Slight changes in acidity and pressure will cause the iron to precipitate as ferric hydroxide, the limonite of this report.

Large areas of itabirite are altered to or replaced by limonite, which forms resistant cappings several meters thick over most of the leached itabirite beds and preserves them from rapid erosion. In general only highly siliceous itabirite and hard hematite are unaltered on the older erosion surfaces; other types are composed of varying proportions of oxides and hydroxides of iron. Although for mapping purposes the writer places the contact between itabirite and canga at the point where original sedimentary features are no longer preserved, nearly all the surface material has been transported to some extent, and most outcrops should be called canga if considered mineralogically and metallurgically. The division between canga and laterite is also indefinite and artificial, for the gradations range from firmly cemented "canga" to the incoherent "laterite" of this report.

Limonite cements fragments of all sorts, shapes, and sizes, and most canga is therefore a mixture of itabirite, hematite, older canga fragments, and other mechanically derived rubble with a chemically precipitated binder. The types range from "canga rica," composed almost entirely of hard hematite blocks cemented by a minimum of limonite, to cellular limonite containing no fragmental material. Aluminum hydroxide is also generally present in varying amounts, so that canga and laterite grade toward bauxite (table 16).

Canga is not a uniform material to which an average grade can be assigned, but much of it contains from 55 to 60 percent iron and minor quantities of silica and alumina. The physical properties of canga make it a desirable ore for charcoal blast furnaces. The phosphorus content is commonly several tenths of 1 percent.

Laterite is at present only of value for the fragments of chapinha and hematite, and limonite concretions formed in place, which can be separated by screening. The proportion of such material ranges from nearly 100 percent to zero with increasing distance from the outcrops, so that laterite grades into normal soil above the adjacent formations.

Topographic, structural, and climatic factors apparently control the limonite cementation. Canga deposits are best developed and preserved on the slope toward which the formation dips, suggesting that downward percolating solutions moved most readily along bedding planes, as would be expected. On most back slopes canga is either thin or not present. In detail, however, many exceptions occur, and apparently no simple rules govern the localization of canga or laterite. Canga sheets ordinarily thicken downslope to as much as 10 meters or more, then break off sharply on steep cliffs where erosion on the softer phyllite or leached itabirite is undercutting them. Some laterite terrains in the valleys are being cemented at present to canga, but recent uplift has been so great that the net effect is now one of the destruction of older canga surfaces without compensating development of new ones.

TABLE 16.—*Analyses of canga and laterite (including bauxite), in percent*

[Analyses 1–2 by Maria Yelda Esteves Ramos; nos. 3–4 by Aida Espinola, both of the Laboratório da Produção Mineral in Rio de Janeiro; nos. 5–8 by Cassio Pinto, DNPM laboratory, Belo Horizonte]

	1	2	3	4	5	6	7	8
SiO_2	2.30	9.30	3.1	5.8	0.7	4.0	1.5	2.4
Al_2O_3	------	------	------	------	------	36.3	46.0	60.1
Fe	52.0	53.1	59.7	46.0	33.5	25.2	17.2	5.2
Mn	1.19	.12	.03	Tr.	.12	------	------	------
P	.053	.061	.04	.05	.11	.14	.08	.07
H_2O	1.32	2.92	1.1	2.0	17.3	22.3	27.4	29.8

1. Loose surface material 2.2 m thick, road cut at east end of Casa de Pedra mine. Hematite and limonite pebbles in ferruginous soil. Screening would raise grade.
2. Loose surface material, sample represents deposits from surface to 2 m. Cut on east bank of pond, 600 m north of Casa de Pedra deposit.
3. Partly consolidated rubble in deep, lateritic soil. Adit 5, Serra do Batateiro (pl. 8) 60 m from portal.
4. Dark red, soft to moderately hard (semiconsolidated) "laterite." Adit 5, 30 m from portal.
5. Cellular, brownish-red, moderately hard laterite without fragmental material, from trail about 170 m east-northeast of compressor house, Casa de Pedra.
6. Orange-colored compact laterite. Depression between Serras do Batateiro and Mascate, 2 kilometers northwest of Casa de Pedra.
7. Reddish aluminous laterite, eastern slope of Serra do Mascate, 2.5 kilometers northwest of Casa de Pedra.
8. Pinkish bauxite float, road cut about 250 m southwest of head of aerial tramway, Casa de Pedra.

MANGANESE

Manganese deposits have been known in Brazil since the early part of the 19th century, and a voluminous literature has accumulated since then. What are perhaps the most important papers on the deposits of Minas Gerais were written by Scott (1900), Derby (1899, 1901b, and 1908), Singewald and Miller (1917), Guimarães (1935), and Freyberg (1932, 1934). Park and others (1951), largely following earlier writers, divide the deposits into the following genetic types:

1. Original sedimentary beds (Morro do Urucum, Mato Grosso).
2. Deposits formed by weathering processes and surficial enrichment of manganese-bearing protore.
   a. Deposits derived from unknown manganese minerals, probably primary manganese oxides, in itabirite.
   b. Deposits formed by the oxidation of manganese silicate-carbonate-sulfide bodies.
   c. Deposits formed by the oxidation of other rocks that contain manganese.
   d. Deposits formed in nonmanganiferous rocks or soils by solutions transporting manganese from unknown sources.

Deposits of the Congonhas district fall into categories 2a, 2b, and 2d, but only those of 2a are of any significant importance. They have generally been known as the "Burnier type" from the town of Miguel Burnier, now called São Julião.

The present writer prefers to redefine the classification for the Congonhas district slightly to conform more closely with the deposits actually present there:

2a. Manganese oxides concentrated by supergene processes from small amounts of manganiferous material in original chemical precipitates (itabirite and dolomite).

2b. Manganese oxides formed by the weathering of gondite (manganese silicate rock).

2d. Manganese oxides from unknown sources deposited in clastic rocks.

The mineralogy of each type is similar. The ores consist principally of psilomelane-type minerals and minor pyrolusite, wad, and other oxides. No careful mineralogic study has been made during the course of the present work. The manganese content of the ores varies widely with the degree of concentration that has been achieved, as shown by the analyses in table 17. (See also table 10, analyses 1–4.)

Deposits derived from gondite.—Important manganese deposits occur in rocks of the "green schist sequence" in the Queluz or Lafaiete district south of Congonhas. However, although one of the largest deposits of the Western Hemisphere, the Morro da Mina, is only 7 kilometers from the edge of the Congonhas district and many fairly large ore bodies occur in the vicinity, the only deposits of this type within the Congonhas district are small and uneconomic. Three distinct beds of manganese oxides, 3, 3, and 0.5 meters thick, crop out within a distance of 15 meters on the trail 2 kilometers east-northeast of the church at Alto Maranhão (Congonhas quadrangle). Float ore from these deposits can be traced for a considerable distance. The depth and completeness of oxidation has been very slight, however, and abundant spessartite is visible both in hand specimen and thin section (p. 21). Float ore occurring about a kilometer away, approximately on the prolongation of these beds but within the granodiorite batholith, may be derived from an inclusion of gondite.

Deposits in the chemical precipitates.—Manganese oxides occur along definite zones in the chemical precipitates. In places they are unquestionably associated with dolomite and its weathering products, elsewhere the adjacent rocks are typical itabirite and the former presence or absence of dolomite cannot be proved. It has been shown that carbonates are abundant in the itabirite section, however, and the writer believes that most or all of the manganese was originally associated with dolomitic zones.

DEPOSITS IN DOLOMITE

The writer knows only one manganese deposit in fresh carbonate rock. This is a 30-centimeter vein of soft black coarsely bladed pyrolusite which cuts a somewhat ferruginous dolomite about 500 meters northeast of the fazenda house at Rodeio, 4 kilometers east of the São Julião quadrangle.

The evidence for relating most of the important deposits of the district to carbonate rocks lies in recognition of the dolomite weathering products (p. 41). Near São Julião, and particularly east of the highway, a continuous bedlike deposit of manganese oxides extends for about 8 kilometers, to a point outside the quadrangle. Active mining for many years showed that the ore continued to a depth of 150 meters or more. All the underground workings are now abandoned and inaccessible, however, so that most information concerning the deposits comes from Scott's description (1900)

TABLE 17.—*Analyses of manganese ores and protores, in percent*

[Analyses 1–2 by Maria Yelda Esteves Ramos in the Laboratório da Produção Mineral, Rio de Janeiro. Nos. 3–5, 6, 8, 11, and 12 by Cassio Pinto in DNPM laboratory, Belo Horizonte. No. 7 quoted from Grösse (1946, p. 114). Nos. 9–10 analyzed by the Cia. Siderúrgica Nacional. Nos. 13–15 quoted from Scott (1900)]

	1	2	3	4	5	6	7	8	9	10	11	12	13 [a]	14 [b]	15 [c]
SiO_2	4.30	1.80	3.4	27.0	1.0	7.4	2.46	4.2	0.44	0.49	2.7	8.3	5.11	14.48	1.27
Al_2O_3	------	------	------	2.8	4.8	3.2	5.56	8.7	1.01	1.00	.5	7.7	------	------	1.45
Fe	57.6	44.0	48.6	35.3	42.4	30.5	47.83	32.8	33.58	25.94	13.9	9.3	------	------	2.8
Mn	3.36	8.98	8.4	10.2	16.4	21.4	11.92	17.3	30.38	38.35	39.1	41.8	38.35	36.28	55.02
P	.023	.047	.10	.063	.11	.10	.12	.07	------	------	.35	.21	.20	------	.21
H_2O	1.94	5.17	7.2	6.9	11.1	[d] 14.9	------	12.1	------	------	[d] 11.8	[d] 14.7	------	------	4.74

[a] 2.54 percent Co reported.
[b] 2.11 percent Co and 2.25 percent Ni reported.
[c] 1.90 percent BaO and traces of lime, potash, and soda reported.
[d] Loss on calcination.

1. Manganiferous itabirite, road cut 60 m southeast of compressor house, Casa de Pedra deposit (pl. 6).
2. Manganiferous canga overlying itabirite of analysis 1.
3. Manganiferous wad containing specularite dust. Cut at charcoal-loading chute, old Fábrica road, 2 km northwest of Pires.
4. Wad, exploration adit west of Pires-São Julião road, 1.8 km southwest of São Julião.
5. Wad, adit 270 m S. 15° E. of benchmark 1195, at cattle guard on old Fábrica road, São Julião quadrangle.
6. Wad, prospect on west bank of Rib. da Mata, 1 km northeast of Pires.
7. Wad, adit 20, Fábrica, about 40 m from portal.
8. Wad, prospect 550 m southwest of switchback, Poço Fundo area.
9. "Ferromanganese" ore from Serra da Bôa Vista. Average of 780 tons from old stockpile, shipped in January 1948.
10. "Ferromanganese" ore from Serra da Bôa Vista. Average of 295 tons shipped from old stockpile in February 1948.
11. Sample from old ore pile at end of road 1 km north-northeast of hill 1366, west end of Fábrica. Replacement of itabirite? Ore came from one or more prospects to the north.
12. Sample from another pile at same place as no. 11. Replacement of phyllite(?)
13. Nodular concretions in weathered zone, Vigia.
14. Veins in surficial clay, Burnier.
15. Analysis of a shipload of ore despatched to England in 1899 from the Burnier district.

made when mining activity was at its height. His stratigraphic succession and cross sections aid in interpreting features observable only in weathered outcrops and abandoned opencuts at the present time. The immediate "wall rock" is brown to black earthy material, which Scott (1900) and Derby recognized as a weathering product of carbonate rocks, and incoherent specular hematite referred to as "jacutinga" or itabirite. Scott's analyses show that the earthy material, similar to the "splash rock" of this report, contains from 2–20 percent manganese oxides, 7–71 percent ferric oxide, and 4–78 percent insoluble siliceous residue. Only the alumina is uniform in content at 2.2–3.5 percent. Barium oxide ranges from 0 to 2.5 percent. Additional evidence that the manganiferous material was derived from dolomite is afforded by exposures in which the dolomite breccia structure is preserved by granular aggregates of white quartz surrounded by dark-brown to black earthy oxides which have replaced the original carbonate.

The manganese was probably derived from the same land surface that furnished the iron and silica, carried by streams to the basin, and precipitated under special conditions which separated it from the bulk of the iron. Analyses of fresh carbonate rock given in table 18 show a manganese content which, although small, is larger than the average for the rocks of the series. The mineralogic character of this manganese is not known. Although Scott and other writers have considered that it is probably present as the carbonate, Krumbein and Garrels (1952) indicate that manganese oxides will precipitate with calcite unless the system is strongly reducing ($Eh = -0.1$ or lower). The manganese may therefore have been precipitated as oxides or hydroxides in the same manner as the iron. Whatever its original nature, the manganese was precipitated at about the same time as the carbonates of calcium and magnesium. Rankama and Sahama (1950, p. 648) state that—

> the most favorable conditions for a non-reversible precipitation of manganese include oxidizing environments (relatively high redox potential) and the presence of small quantities of solid calcium carbonate (relatively high pH).

The earthy wads and commercial ores were formed by supergene enrichment of the minor quantities of manganese in the original sediments. Analyses of two cargoes shipped to England in the early days of mining (Scott, 1900, p. 205) show that the near-surface ore averaged 55 percent manganese, 2–3 percent iron, 1 percent silica, 0.02–0.03 percent phosphorus, and less than 5 percent water. Most of it was hard and crystalline in appearance. Ore from deeper levels contained 15 percent or more moisture and was relatively soft and pulverulent. This evidence suggests that enrichment is

TABLE 18.—*Manganese content of some dolomitic rocks, in percent*

	1	2	3
SiO_2	2. 13	13. 80	17. 2
Al_2O_3	2. 70	0. 90	--------
Fe	3. 85	8. 52	3. 06
Mn	1. 12	1. 08	1. 97
CaO	28. 49	26. 40	30. 6
MgO	19. 50	13. 87	8. 92
P	--------	--------	. 013
$BaSO_4$	--------	--------	1. 00
Loss on ignition	--------	--------	35. 40

1. "White limestone," underlies ore bed at Miguel Burnier (São Julião). Scott (1900, p. 184). Fe and Mn content recalculated from oxides.
2. "Gray limestone," overlies ore bed at Miguel Burnier (São Julião). Scott (1900, p. 185). Fe and Mn content recalculated from oxides.
3. Dolomite from middle group, associated with itabirite. Locality not specified. (Scheibe, 1932, p. 37).

related to the present erosion cycle, and that the deeper ores have not had time to dry out and expel loosely held water from the colloidal gels.

Prospects and shallow mine workings in the area west of the Fazenda do Vigia expose a zone, 3–5 meters wide, in the black wadlike earthy material that contains hard nodules and vuggy concretions. Small crystals of hard lustrous pyrolusite(?) with splendant faces line many cavities. The grade ranges from about 40 to more than 50 percent manganese, depending on the amount of sorting that has been done. These deposits and other small ones associated with earthy oxides in two narrow zones along the southern flank of the Serro do Pires are interpreted as having been derived from dolomitic lenses in the upper group of the Minas series. Exposures are poor, however, and the stratigraphic positions are not certain. The geologic relationships of some deposits at Poco Fundo, 2 kilometers northeast of Casa de Pedra, are even more obscure. Pockets of manganese oxides occur in black earthy wad, but without any apparent continuity as in other areas. Identifiable rocks are phyllite of the upper group of the Minas series and quartzite and itabirite, believed to belong to the Itacolumí series, which apparently overlie the Minas series rocks with a thrust-fault relationship. The wad may represent dolomitic zones in the overridden block.

DEPOSITS IN ITABIRITE

Manganese oxides occur in a few itabirite beds where evidence of former carbonate minerals is lacking. Psilomelane and some crystalline pyrolusite fill cracks in the weathered zone of the iron formation, replace certain beds, or even replace the itabirite across widths measured from centimeters to a few meters. This "Lagôa Grande type" (Park and others, 1951) results from downward enrichment of the iron formation. The material ranges in composition from hematite with minor manganese to manganese oxides with only minor limonite. The combined manganese and iron content commonly totals about 60 percent, and sorting will control the grade of the product to some extent, although the mixture is so intimate that from a practical standpoint the limits are about 45 percent manganese and 15 percent iron.

It is not certain that any genetic distinction can be made between deposits of the so-called Burnier and Lagôa Grande types. The black earthy dolomite weathering products occur in the general vicinity of a few manganese deposits in itabirite, but have not been identified at others. In general the Burnier type occurs in the eastern part of the district and the Lagôa Grande type in the western. Most deposits are in the upper, more dolomitic part of the section. Mapping shows that they are conformable with the enclosing rocks in their major relationship, although individual veinlets may be crosscutting. Veins of "cleavage quartz" (p. 30) are common in both types.

As manganese may theoretically be precipitated as either a carbonate or an oxide, and may be secondarily concentrated either in the same beds in which it was originally precipitate or in more favorable beds, present knowledge does not permit a detailed exposition of the mode of origin of these deposits.

DEPOSITS IN CLASTIC ROCKS

Manganese oxides occur in phyllite and quartzite as irregular narrow veins and as replacements of the country rock. Individual veinlets range from less than one to a few tens of centimeters across. They commonly show the very fine rhythmic layering typical of collodial gel deposits, and have botryoidal forms in open fractures. The deposits are secondary, the manganese being derived from unknown primary sources. Some deposits are near known chemical precipitates. Others are far from any evident source material, however, which indicates that solutions may have traveled a considerable distance. So far as is known all the deposits are shallow and related to the present surface.

Manganese is relatively common in the phyllite members of the upper group of the Minas series, but has not been found in the rocks of the lower group. It ordinarily occurs as a stockwork of psilomelane-type oxides enclosing a greater or lesser number of weathered but unreplaced rock fragments. Selective mining and careful hand cobbing yields a small proportion of ore averaging about 40 percent manganese and 10 percent or less iron. The largest known deposits are near Bocaina, about 1.5 kilometers west of Crockatt de Sá, São Julião quadrangle. Small isolated ore bodies occur in the phyllite north of the Fábrica-São Julião structural belt.

Veinlets of maganese oxides cut the impure sericitic quartzite of the Itacolumí series, forming small deposits that have been mined at many places. Like the deposits in phyllite, the material can be cobbed to yield a fair-grade product. The largest known deposits of this type in the district occur at Poço Fundo and along the west edge of the São Julião quadrangle 2 kilometers south of Fábrica. As each area is close to known or suspected thrust faults and therefore possibly to manganiferous sediments in the Minas series, the original source of the material may have been in these rocks.

OCHER

Irregular masses, nodules, and angular fragments of hard dark-red ferruginous material occur in soil and decomposed rock at several places in the district. Some are veinlike or concretionary, and have banded or concentric internal structure; others faintly preserve bedding and cleavage, and obviously resulted from the replacement of phyllite by iron oxide or hydroxide. An analysis of the latter type gave the following results:

SiO_2	11.9
Al_2O_3	8.7
Fe_2O_3	72.7
Loss on ignition	6.2
	99.5

The material is related to canga in its mode of origin, and must have formed under special conditions of ground-water circulation that resulted in a relative concentration of iron and removal of alumina. Most ocher is in phyllite near outcrops of iron formation, and the general geologic relationships of most of the deposits of the district suggest that structural disturbance facilitated their formation. Thus the principal mines are in the small klippe straddling the São Julião–Casa de Pedra border 1 kilometer south of Fábrica, and smaller deposits occur about 1 kilometer to the west-northwest. Both areas are interpreted as being near the sole of a thrust plate of upper Minas series phyllite lying on itabirite of the Itacolumí series. Two factors should favor increased circulation and interchange of material: (1) brecciation, and (2) superposition of different rock types along a surface that is not a bedding plane.

BAUXITE

No commercial deposits of bauxite are known in the Congonhas district, but a few scattered blocks were found beside the old railroad grade 250 kilometers southwest of the head of the aerial tramway at Casa de Pedra. An analysis of this material is given in table 15, analysis 8. Phyllite probably underlies the heavy cover of ferruginous laterite and rubble in this area, and the bauxite was presumably concentrated by residual weathering of the aluminous minerals of the phyllite. Grösse (1946) mentions bauxite concretions in aluminous clays at Fábrica. Lacourt (1936, p. 21) notes that other bauxites of the ferriferous region have formed under protective coverings of canga which retarded erosion and permitted long continued chemical weathering. It seems possible that exploration might discover considerable quantities of bauxite in areas where phyllite is overlain by old canga and ferruginous laterite. The depression between the north end of the Serra do Batateiro and the Serra do Mascate is perhaps the most favorable area. Analyses of surface materials from this area (table 15, analyses 6 and 7) show a fairly high alumina content.

STEATITE

The commercial value of steatite depends on its relative softness and its ease of working, combined with adequate mechanical strength and chemical inertness. Closely spaced joints and strongly developed cleavages destroy the usefulness of steatite in the thinner ultramafic masses and the border zones of the larger bodies. Harder minerals, such as serpentine, ankerite, and particularly actinolite, are undesirable constituents in parts of massive, otherwise satisfactory rock. Too much pyrite is deleterious because it oxidizes and stains the rock and also weakens it by the release of acid which attacks carbonate veinlets. Satisfactory material is therefore restricted to parts of the cores of larger ultramafic intrusions in the Congonhas lowland, but commercial-grade rock is available in sufficient quantity to meet any foreseeable demand. In quarrying operations, a surface zone of yellowish, oxidized or hydrated material as much as a few meters thick must be removed to expose fresh, grayish-green steatite.

TALC

Small talc deposits of sufficient purity to be commercially valuable have been found at several places in the Congonhas lowland. None of the mines were operating at the time of the field investigation, and little could be seen except the wall rock and discarded material on the dumps. Veins or narrow tabular bodies occur in steatite and in green schist near ultramafic intrusions. For the most part they are conformable to the enclosing rocks where these rocks are metamorphosed sediments, but a few apparently cut bedding at low angles. Three types of talc can be distinguished: (1) a schistose variety with extremely thin foliae puckered and distorted by a closely spaced system of fracture-cleavage planes, (2) comparatively massive fine-grained talc, and (3) coarse-grained flaky talc in flexible plates, several centimeters across, that are only partly oriented. The first type is probably equivalent to the talc schist of the border zones and represents altered ultramafic rock of unusually high talc content. The second and third types seem to have escaped the deformation imposed on the first and are presumably later. These types were probably deposited as hydrothermal veins, perhaps by solutions which originated in the granodiorite and derived magnesia from the ultramafic intrusive rocks.

Any appreciable amount of magnetite, pyrite, chlorite, or actinolite makes the talc useless for grinding purposes. Acicular crystals of light-green actinolite as much as several centimeters long occur in discarded material on dumps and in unmined rock in the opencuts, indicating that this mineral is the most common impurity in the massive vein talc.

GOLD

Gold, which was responsible for the founding of all the old towns of the district, has long since ceased to have any commercial importance. The old washings indicate that mineralization was related to the granodiorite intrusions and that the gold occurred in the contact zones near inclusions and wall rock. Apparently no commercial lode deposits were ever found, for all production came from the weathered zone where rock decomposition concentrated the gold by eluvial processes and from placer deposits in the stream terraces. The largest workings lie north and east of the town of Congonhas, where the kaolinized surface zone of the granodiorite stock was largely removed to a depth of several tens of meters in an area about 2.5 kilometers long and nearly a kilometer wide. Many other large "diggings" remain elsewhere. No attempt was made to mine gold in unaltered rock.

To the writer's knowledge, no auriferous "jacutinga" or other goldbearing iron formation has been discovered in the Congonhas district, although it has yielded considerable amounts of gold elsewhere in the "quadrilátero ferrífero."

Minute amounts of gold are panned from Recent alluvium by a few individuals. The average yield per man day is about three-fourths gram.

MINING

IRON

HISTORY AND PRODUCTION

The first mining and smelting of iron ores in the Congonhas district of which there is any record occurred at the Fábrica de Ferro (literally "factory of iron") in the second decade of the last century. The foundations of this primitive iron smelter can still be seen at Fábrica. Baron von Eschwege, a German of exceptional ability who was the foremost geologist and metallurgist of colonial Brazil, constructed and operated at a small plant for several years before abandoning it as unprofitable. Several Catalan forges used for smelting iron by the batch process were fueled with charcoal, and waterpower was used for the blast and to operate the hammer. In the last decade of the century, about 1893, a charcoal blast furnace with a rated capacity of about 18 tons per day was constructed at Miguel Burnier (São Julião). This furnace is still the only one in the district.

Except for the small quantities of iron ore used in the local forges and furnaces, no iron ores were mined until the railroad was constructed. The narrow-gage line reached Burnier about 1888; the broad-gage line dates from 1912. Although statistics are lacking, little iron ore was exported from the district until after the end of World War I. Between the wars considerable exploration, development work, and mining was done. Several companies were active, however A. Thun e Cia., Ltda., furnished the bulk of the production from its mine at Casa de Pedra. Most of the ore was exported to Germany, so that production, which had reached about 250,000 tons in 1938, the last full year before World War II, dipped somewhat when trade with that country was cut off. New commercial ties were soon made, and some ore was shipped during the war, but other factors restricted the vigorous development which the great resources of the district would seem to justify. Chief among these factors was the decision to create a domestic steel industry, to be supplied largely from the Congonhas district, and the limited transportation facilities of the one railroad. The properties of A. Thun e Cia. were purchased by the Companhia Siderúrgica Nacional (CSN) with the understanding that the ore would not be exported. The requirements of the CSN have first priority on the Estrada de Ferro Central do Brasil (E.F.C.B.), also nationally owned, so that little excess capacity remains for companies or individuals to ship ore for export.

Total production from the district has been about 5,000,000 tons, though exact figures are not available to the writer, and the present annual production may be about 400,000 tons.

OWNERS AND OPERATORS

The largest company operating in the district, and the one with the highest production record and probably the greatest reserves, is the Companhia Siderúrgica Nacional, the National Steel Mill of Brazil, owned in part by the government and in part by private stockholders. Headquarters are at Rio de Janeiro. The CSN mill at Volta Redonda, State of Rio de Janeiro, about 150 kilometers from the city, is the largest in South America. A 1,000-ton blast furnace was in operation during the period of the field work, and a second furnace was completed and put into operation early in 1954. A third furnace is planned for the future. Open-hearth furnaces, rolling mill, and fabricating plant are integral parts of the operation. The company owns iron, manganese, coal, and limestone and dolomite mines in several parts of the republic, from which it produces much of the necessary raw materials, but it also buys large quantities from other producers.

Headquarters for the CSN properties in central Minas Gerais are at Lafaiete, about 25 kilometers southeast of Congonhas on the E.F.C.B. The chief property in the district is Casa de Pedra, which includes not only the mine of this name but much of the area surrounding it.[4] Exclusive of a tongue reaching almost to Congonhas and another to the Rio Maranhão along the left bank of the Riberão do Figueiredo, the southern boundary of the main property extends from a point near the crossing of the pipeline and railroad in the southeast corner of the Casa de Pedra quadrangle westward and slightly north to the road east of the aerial tram, along the road to the junction with the road crossing the Serra do Batateiro, and westward across the Côrrego do Esmeril to the Serra da Bôa Vista. The boundary extends northward along the western slope of this range to the vicinity of the high point north of the Côrrego das Mares, eastward and somewhat southward to Pico da Bandeira and Poço Fundo, and continues southward to the road linking Casa de Pedra with Congonhas. The company also holds a large tract of land in the Serra das Almas, north and west of the Fazenda da Fábrica, and property containing dolomite quarries south of Usina on the east edge of the district.

The Companhia de Mineração de Ferro e Carvão owns the old Fazenda da Fábrica, site of von Eschwege's iron mill. This company, formerly a subsidiary of German steel interests, has head offices in Rio de Janeiro. Fábrica extends from Morro Redondo, a kilometer east of the fazenda house, to the north end of the Serra do Mascate. The company also owns land near Cachoeira do Salto in the Jeceaba quadrangle.

Usina Queiroz Júnior, Ltda., owns the old fazendas of Coelhos and Pinheiros that extend northward from the Rio Maranhão to the south edge of the Casa de Pedra property. The company ships ore from the

[4] No attempt was made during the course of the field investigation to locate property boundaries or determine owners or leasers of the deposits, and they are not shown on the quadrangle maps. Ownership dates back to grants made in colonial days and establishment of property boundaries is not readily accomplished. The limits described here in general terms have been summarized from sketch maps.

station of Coelhos, in the northeast corner of the Jeceaba quadrangle, to its 45-ton blast furnace at Gagé, on the E.F.C.B. a short distance south of Murtinho.

Mineração e Usina Wigg owns much of the land near São Julião, from the vicinity of Crockatt de Sá to kilometer 504 in the northeast corner of the quadrangle, and from the divide of the Serra da Bocaina and its continuation to the Riberão da Sardinha, plus a wide strip extending eastward on both sides of the Ouro Preto branch of the railroad beyond Usina.

Indústria e Comércio de Minérios (ICOMI), owner of many mineral properties in widely separated parts of the country, including the manganese deposits of the Territory of Amapá, produces rubble ore and chapinha at the Fazenda do Vigia and siliceous itabirite at Cruzul, both in the São Julião quadrangle.

Various individuals have been active from time to time, usually confining their operations to mining surface materials that were easily excavated, screened, or washed if necessary, and transported to the nearest railroad siding. Perhaps the most active of these has been Antônio Pacífico Homem, Jr., who has in the past shipped considerable ore from several places in the vicinity of Pires. Sr. Falabella of Congonhas also did similar mining a few years ago.

RESERVES

Far too little exploration has been done to enable precise estimates to be made of the reserves of the district, although geologic evidence leads to the conclusion that they are very large. The writer has divided the reserves into several types and has made separate estimates based on the information contained on the maps and sections. He has attempted to be conservative, taking the minimum probable dimensions and factors for each geologic unit. Methods of computation used and reasons for the decisions requiring individual judgment are given below.

ITABIRITE

The reserve estimate for the iron formation (table 19) is based upon the widespread distribution and the relatively uniform composition of the formation over long distances. The itabirite of the western range crops out continuously for 50 kilometers and must continue considerably farther downdip than the 1,000 meters used in the calculations. On the other hand the Serras do Bateiro, Mascate, and Pires, Pico do Engenho, and the east end of the Fábrica-São Julião belt probably rest on thrust faults which limit the downward extent of the iron formation. The probable average distances downdip to these supposed faults which were used in the computations are shown on table 19. Most calculations were based on the average thickness, length of the block, and dip length. A few areas, indicated by footnotes (table 19), were calculated as horizontal areas and vertical depths. Most of the Fábrica-São Julião belt is believed to be essentially an anticlinal crest from which the formation should extend downward and outward, and the depth figures used in this area are probably conservative.

No attempt has been made to allow for the present surface configuration. The column (table 19) showing reserves to a depth of 100 meters indicates material that could be extracted relatively easily by opencut. Much of this material should be partly weathered and perhaps somewhat enriched, making mining and beneficiation considerably simpler than the treatment of the unweathered formation.

The grade is estimated to be 40 percent iron. This grade seems to be the most probable overall figure for the formation exposed in outcrop and shallow exploratory workings. However, deep exploration is necessary to prove the grade at depth. Milling tests will be necessary to determine whether a usable product can be made from unweathered itabirite. A tonnage factor of 3.6 metric tons per cubic meter was used. This figure is slightly lower than the theoretical density for material of this grade (table 11). Pico do Engenho and the Serra do Pires, which contain relatively siliceous itabirite, were computed as 30 percent iron with a corresponding lower density.

The column showing the hematite content of the itabirite indicates the tonnage of concentrates obtainable by an ideal beneficiation. The figures for contained metallic iron are self evident.

HEMATITE

The irregular shapes of the hematite deposits, consequent upon their origins by local replacement of gangue minerals in the itabirite, prevent even approximate estimates of the total reserves. Ore cannot be projected far beyond the "limit of visibility." Reserve calculations must be determined largely on areas of surface outcrop, combined with whatever subsurface data are available, and conservative extrapolation is indicated. It can, however, be predicted that the total amount of hematite ore present in the district is much greater than the estimates given in table 21. Both extensions of known deposits and "blind" ore bodies will undoubtedly be found if and when large-scale mining is undertaken. The theory advanced here (p. 57) to explain the localization of the deposits suggests that the most favorable areas for future exploration are in the vicinity of the major thrust faults.

TABLE 19.—*Indicated and inferred itabirite reserves of the Congonhas district*

[Dimensions in meters, weight in metric tons, calculated at 40 percent Fe, 3.6 tons per cubic meter. Iron calculated as hematite, containing 70 percent Fe. All figures rounded off]

Locality	Length	Average thickness	[a] Area, (square meters)	Volume to 100-meter depth, (cubic meters)	Tons to 100-meter depth	Probable dip length	Total tons (above 1,000 meters)	[b] Tons of hematite	Tons of contained iron	Remarks
Casa de Pedra quadrangle:										
Serra da Bôa Vista-das Almas:										
South of *E-E'*	1,850	90	165,000	16,500,000	60,000,000	>1,000	600,000,000	340,000,000	240,000,000	
E-E'—C-C'	4,900	400(+?)	1,960,000	196,000,000	700,000,000	>1,000	7,000,000,000	4,000,000,000	2,800,000,000	
C-C'—B-B'	3,100	450±	1,395,000	139,000,000	500,000,000	>1,000	5,000,000,000	2,800,000,000	2,000,000,000	
B-B'-north edge of quadrangle	4,700	550+	2,600,000	260,000,000	900,000,000	>1,000	9,000,000,000	5,000,000,000	3,500,000,000	
Total, Serra da Bôa-Vista-das Almas.	14,550				2,160,000,000		21,600,000,000	11,140,000,000	8,540,000,000	
Serra do Batateiro:										
Southern part	1,600	200	320,000	32,000,000	115,000,000	600+	700,000,000	400,000,000	280,000,000	South of road along tributary to Cor. Casa de Pedra.
Northern part	3,800	300±	1,100,000	110,000,000	400,000,000	800+	3,200,000,000	1,800,000,000	1,250,000,000	North of road along tributary to Cor. Casa de Pedra.
Total Serra do Batateiro	5,400				515,000,000		3,900,000,000	2,200,000,000	1,530,000,000	
Serra do Mascate:										
Southwest of Casa de Pedra mine	1,000	400	400,000	40,000,000	140,000,000	[c] 200	280,000,000	160,000,000	110,000,000	Triangular area east of Serra do Batateiro.
Southern part, to Alto da Bandeira.	2,300	500?	1,150,000	115,000,000	400,000,000	[c] 500	2,000,000,000	1,100,000,000	800,000,000	
Central part, to *B-B'*	2,000	500?	1,000,000	100,000,000	360,000,000	[c] 400	1,400,000,000	800,000,000	560,000,000	
Northern part	2,600	[d] 1,000	[e] 2,600,000	260,000,000	900,000,000	[c] 200	1,000,000,000	1,000,000,000	700,000,000	
Total, Serra do Mascate					1,800,000,000		5,480,000,000	3,060,000,000	2,170,000,000	
Pico do Engenho			[f] 2,500,000	250,000,000	850,000,000	[g] 100	850,000,000	360,000,000	250,000,000	Calculated as 30 percent Fe, 3.38 specific gravity.
Fábrica area, west	1,700	[h] 400	680,000	68,000,000	[i] 240,000,000	250?	600,000,000	340,000,000	240,000,000	
Total, Casa de Pedra quadrangle					5,565,000,000		32,430,000,000	17,100,000,000	12,730,000,000	
São Julião quadrangle:										
Fábrica area, east, to *A-A'*	2,300	[h] 200	460,000	46,000,000	160,000,000	250?	400,000,000	230,000,000	160,000,000	
Fábrica-São Julião belt, *A-A'* to Vigia	[j] 4,800	[k] 200	960,000	96,000,000	350,000,000	250?	875,000,000	500,000,000	350,000,000	
Vigia to São Julião	[m] 4,000	[h] 300	1,200,000	120,000,000	430,000,000	500?	2,150,000,000	1,200,000,000	850,000,000	
São Julião to east edge of quadrangle	[p] 1,000	[q] 50+	50,000+	5,000,000+	20,000,000	200+	40,000,000	20,000,000	15,000,000	
Total Fábrica-São Julião belt					960,000,000		3,465,000,000	1,950,000,000	1,375,000,000	
Serra do Pires	3,600	300+	1,100,000	110,000,000	370,000,000	[g] 300	1,100,000,000	470,000,000	330,000,000	Exclusive of extension into Casa de Pedra quadrangle. Calculated as 30 percent Fe, 3.38 specific gravity.
Belt along north edge of quadrangle	4,000+	[q] 100+	400,000+	40,000,000+	150,000,000	300+	450,000,000	250,000,000	180,000,000	
Total, São Julião quadrangle					1,800,000,000		5,015,000,000	2,670,000,000	1,885,000,000	
Jeceaba quadrangle: Serra da Bôa Vista	4,500	100(+?)	450,000	45,000,000	160,000,000	>1,000	1,600,000,000	900,000,000	630,000,000	
Total Jeceaba quadrangle					160,000,000		1,600,000,000	900,000,000	630,000,000	
Grand total Congonhas district					7,525,000,000		39,045,000,000	20,670,000,000	15,245,000,000	

[a] Perpendicular to dip, unless otherwise specified.
[b] 40 percent Fe=57.2 percent hematite, by weight.
[c] Average depth above fault?
[d] Minimum horizontal width of outcrop.
[e] Horizontal area.
[f] Area measured with planimeter.
[g] Average thickness above fault.
[h] Combined width in axes of folds.
[i] Should subtract Grösse's estimates of 54,800,000 tons of ore (hematite) from this figure.
[j] Total distance—itabirite not at surface for entire distance.
[k] Approximate average width of outcrop, on axis of fold? May increase downward.
[m] Approximate length of outcrop measured around the bend.
[n] Apparent minimum total of stratigraphic thickness.
[p] Approximate length of exposures.
[q] Combined total of several itabirite zones.

Table 20.—*Measured and indicated reserves of hematite ore. Average 68 percent Fe. Specific gravity 5. Minor deposits omitted*

Locality	Dimensions			Tons per meter of depth	Depth (meters)	Volume (cubic meters)	Tons
	Length	Width	Area (square meters)				
Casa de Pedra (pl. 6):							
Eastern half	600	50–300				[a] 7,400,000	37,000,000
Western half	600	175	100,000	500,000	50	5,000,000	25,000,000
Total, Casa de Pedra							[b] 62,000,000
Serra do Batateiro (pl. 8):							
Deposit cut by adit 1			[c] 17,500	87,500	[d] 40	700,000	3,500,000
Deposit shown in northwest corner of pl. 8	400+		[c] 50,000	250,000	[e] 20	1,000,000	5,000,000
Deposit southeast of adit 4	200	30(?)	6,000	30,000	20(?)	120,000	600,000
Deposit at adit 6	200	25	5,000	25,000	[f] 40	200,000	1,000,000
Deposit southwest of adit 6 [e]	200	30+	6,000	[g] 15,000		100,000(?)	500,000
Total, Serra do Batateiro							10,600,000
Serra do Mascate:							
Deposit southeast of Alto da Bandeira	600	[h] 100+	[c] 75,000	375,000	[i] 20	1,500,000	7,500,000
Deposit forming Alto da Bandeira	200	100	20,000	100,000	20	[j] 130,000	650,000
Six small deposits near section *B–B′*			[k] 72,000	350,000	[e] 5	350,000	1,750,000
Deposit at north end of range, west of Fabrica	400+	100+	[c] 50,000	250,000	[m] 20	1,000,000	5,000,000
Total, Serra do Mascate							14,900,000
Fábrica [n]							
Western part (Casa de Pedra quadrangle)							54,800,000
Eastern part (São Julião quadrangle)							11,600,000
Total Fábrica							66,400,000
Total, Congonhas district							153,900,000

[a] Computed from cross sections. Described on p. 72.
[b] Probably conservative. Possibly several times as much, see p. 72.
[c] Area determined by planimeter.
[d] Average depth above adit 20 m.
[e] Probably conservative.
[f] Relief on outcrop 80 m.
[g] Poorly exposed, mixed ore and itabirite. One-half hematite?
[h] Average; 50–200 m; minor siliceous itabirite in outcrop.
[i] Conservative? Relief on outcrop 200 m, but deposit probably plunges eastward nearly parallel to slope.
[j] Roughly cone shaped, computed as one-third area × depth.
[k] Total area measured by planimeter.
[m] Relief on outcrop 100 m. Deposit probably plunges eastward about parallel to slope.
[n] Estimates made by Grösse (1946) used. See p. 79.

Most of the known deposits of the district are in or near the Serra do Batateiro and Serra do Mascate.

Calculations are based on length and width, or on outcrop areas measured with the planimeter. Tons per meter depth and what are probably conservative depth estimates are used for those deposits for which little or no subsurface information is available. A factor of 5 tons per cubic meter, based on determinations of the specific gravity, has been used. The writer cannot state what the proportion of lump ore to fines will be, and has made not attempt to divide the reserves into hard, medium hard, and soft ores. Grösse (1946) found, in his study at Fábrica, that about 57 percent of the near-surface material he measured will yield sizes above 5 millimeters, but only about 10 percent is "hard lump ore." As this writer has stated (p. 58), geologic evidence suggests that the proportion of hard ore may increase downward.

SURFICIAL ORES

Three types of surficial ore have been distinguished for purposes of estimating the ore reserve. They are enriched itabirite, canga, and rubble ores in laterite. The first two types are similar geologically and mineralogically, but the method used in mapping makes differentiation here advisable.

ENRICHED ITABIRITE

The leaching of quartz and redeposition of iron as limonite have raised the grade of the surface zone of the itabirite to 55 percent iron or more throughout wide areas where mechanical erosion has not been too rapid. The depth of this capping ranges from one to a few meters. Areas were measured with the planimeter, the average depth taken as 1 meter and a specific gravity of 3.5 used to calculate tonnage. Indicated reserves are given in table 21.

TABLE 21.—*Indicated reserves of enriched itabirite. Depth taken as 1 meter. Grade 55 percent +Fe. 3.5 tons per cubic meter*

Locality	Area ($m^2 \times 1 =$ volume) (cubic meters)	Tons
Casa de Pedra quadrangle:		
Serra da Bôa Vista-das Almas	1, 000, 000	3, 500, 000
Serra do Batateiro	750, 000	2, 600, 000
Serra do Mascate	2, 000, 000	7, 000, 000
Pico do Engenho	300, 000	1, 000, 000
Total		14, 100, 000
São Julião quadrangle	500, 000	1, 750, 000
Total, Congonhas district		15, 850, 000

CANGA

Areas mapped as canga were measured with the planimeter, multiplied by an estimated depth factor, and calculated at 3 tons per cubic meter (table 22). The thickness used for each area is shown and the approximate grade indicated. Although the best sections through the canga capping occur on the lower slopes where sapping and undercutting on weaker formations has caused large blocks to break away and leave vertical cliffs many meters high, the average thickness is considerably less. Canga rica, consisting almost entirely of hard hematite blocks, contains more than 60 percent iron and metallurgically is open-hearth ore. Enriched itabirite and canga require drilling and blasting.

TABLE 22.—*Indicated reserves of canga in the Congonhas district. Calculated at 3 tons per cubic meter, figures rounded off*

Locality	Approximate area (square meters)	Approximate thickness (meters)	Volume (cubic meters)	Tons	Approximate grade
Casa de Pedra quadrangle:					
Eastern flank of Serra das Almas on A–A′	2, 000, 000	3	6, 000, 000	18, 000, 000	50+
Smaller areas along Serra das Almas	750, 000	2	1, 500, 000	5, 000, 000	55?
Four small areas, Serra da Bôa Vista	310, 000	2	620, 000	1, 850, 000	55?
Serra do Batateiro:					
North end	130, 000	2	260, 000	800, 000	55?
Central (including eastern flank)	500, 000	3+	1, 500, 000	4, 500, 000	55+
Serra do Mascate:					
North end	360, 000	2	720, 000	2, 000, 000	55?
Central (including eastern flank)	1, 400, 000	3+	4, 200, 000	13, 000, 000	55+
Canga rica 0.5 km southwest of Alto da Bandeira	150, 000	3	450, 000	[a] 1, 600, 000	60+
Fábrica, west	450, 000	2	900, 000	2, 700, 000	55+
Total, Casa de Pedra quadrangle				49, 450, 000	
São Julião quadrangle:					
Fábrica, east	200, 000	2	400, 000	1, 200, 000	55+
Other areas in western half of quadrangle	700, 000	2	1, 400, 000	4, 200, 000	50+
Areas in eastern half of quadrangle	450, 000	1+(?)	500, 000	1, 500, 000	50+
Total, São Julião quadrangle				6, 900, 000	
Total, Congonhas district				56, 350, 000	

[a] Mainly hard hematite, calculated at nearly 4 tons per cubic meter.

LATERITE

Areas mapped as laterite contain fragments of "chapinha" (leached itabirite) and hematite in red ferruginous soil. Screening or washing ordinarily yields a relatively well-sized product containing 60 percent or more iron. The depth of the surface zone and the proportion of fragmental material vary greatly. Reserves have been estimated by measuring areas with the planimeter, taking the average depth as 1 meter, and assuming that a quarter of the volume is fragmental material which has a specific gravity of 4 (table 23).

Comparison of the results reached in this report by using "average" figures for depth, volume, and tonnage with those obtained at Fábrica by detailed exploration suggests that the reserves indicated here are of the right order of magnitude. Grösse (1946) dug several hundred test pits and measured many areas carefully. He arrived at a figure of 4,891,000 tons of surficial ore for the central and eastern parts of Fábrica, exclusive of the part west of adit 4 (pl. 9). This writer estimates 5,750,000 tons for the entire Fábrica area.

Summary.—Table 24 summarizes the reserves of iron ore of the Congonhas district. A major division is made between material which will require beneficiation and ore which can be shipped as mined or which requires only simple screening or washing. The Casa de

Pedra quadrangle contains about 83 percent of the total estimated reserves of itabirite and 87 percent of the shipping ore. All the remaining shipping ore and most of the itabirite are in the São Julião quadrangle. The Jeceaba quadrangle contains 4 percent of the itabirite reserves, and the Congonhas quadrangle has no reserves of iron ore worthy of mention.

Reserves of shipping ore are 0.6 percent of the total estimated reserves, and although exploration should raise this figure somewhat, it is evident that the future importance of the district lies in beneficiation of the iron formation. The total metallic iron of the district in deposits which may someday be commercially exploitable is probably in excess of 15,000,000,000 metric tons.

TABLE 23.—*Indicated reserves af chapinha and rubble ore in laterite. Average depth taken as 1 meter. Recoverable material as 25 percent of total volume, specific gravity as 4. Grade, 60 percent Fe*

Locality	Area ($m^2 \times 1$=volume) (cubic meters)	Volume of recoverable material	Tons
Casa de Pedra quadrangle:			
Laterite on western slope of Serra Bôa Vista	2, 000, 000	500, 000	2, 000, 000
Laterite on eastern slope of Serra Bôa-Vista-das Almas	3, 200, 000	800, 000	3, 200, 000
Laterite of Serra do Batateiro	3, 300, 000	825, 000	[a] 3, 300, 000
Serra do Mascate north of section *C–C′*	3, 000, 000	750, 000	3, 000, 000
Serra do Mascate, sections *C–C′* to *B–B′*	1, 700, 000	425, 000	1, 700, 000
Drainage basin Cor. da Casa de Pedra (east of Mascate fault)	1, 500, 000	375, 000	1, 500, 000
Flanks of Pico do Engenho	1, 700, 000	425, 000	1, 700, 000
Fábrica, west	1, 100, 000	275, 000	1, 100, 000
Total, Casa de Pedra quadrangle			17, 500, 000
São Julião quadrangle:			
Fábrica, east	750, 000	187, 500	750, 000
Remaining western half, to Vigia	8, 000, 000	2, 000, 000	8, 000, 000
Eastern half, including northern border	5, 500, 000	1, 375, 000	5, 500, 000
Total São Julião quadrangle			14, 250, 000
Total, Congonhas district			31, 750. 000

[a] Area of laterite south of the Engenho fault has been largely exhausted and is omitted here.

MINES AND POTENTIAL PRODUCING AREAS

CASA DE PEDRA

Location.—The Casa de Pedra deposit, the largest known hematite body in the district and the one which has been most actively exploited, is 6 kilometers west-northwest of Congonhas. A 12-kilometer graveled road connects the mine with the town, and branches lead to the main line of the railroad, 5 kilometers away and 350 meters lower. The deposit is on a low divide between the Côrrego do Lagarto and the Côrrego da Casa de Pedra. Pico do Engenho to the east and the Serra do Batateiro to the west rise well above the ore body, so that it does not crop out as spectacularly as some of the more famous deposits of the ferriferous area.

GEOLOGY

The quadrangle map (pl. 1) shows that the deposit is surrounded and partly covered by laterite and canga which effectively conceal its relationship with the neighboring belts of iron formation in the area. The writer considers that the ore body is part of the Mascate thrust plate and separated from the Batateiro and Engenho plates by major thrust faults. It is apparently localized on an anticlinal nose that swings southeastward from the main trend of the range in a manner similar to that of other fragments near the southern limits of the thrust slices. As the map shows, evidence that a dolomitic zone and phyllite of the upper group bend back sharply around the nose of the deposit is fragmentary and based almost entirely on weathering products of these rocks found in outcrops and diamond-drill holes.

The detailed map (pl. 6) shows the outcrops and mine faces as they appear in July 1947. The map shows the progress of an exploratory tunnel driven at the east end of the 1,206 level in May 1951, and diamond drilling which was done in 1949–50 has also been indicated.

TABLE 24.—*Measured, indicated, and inferred reserves of iron ore in the Congonhas district in metric tons*

Type	Grade (percent)	Quadrangles			Total for district
		Casa de Pedra	São Julião	Jeceaba	
Itabirite	40?	32, 430, 000, 000	5, 015, 000, 000	1, 600, 000, 000	39, 045, 000, 000
Shipping ore:					
Hematite	68	142, 300, 000	11, 600, 000		153, 900, 000
Surficial ore:					
Canga	50–60+	49, 450, 000	6, 900, 000		56, 350, 000
Enriched itabirite	55+	14, 100, 000	1, 750, 000		15, 850, 000
Rubble contained in laterite	60+	17, 500, 000	14, 250, 000		31, 750, 000
Total surficial ore		81, 050, 000	22, 900, 000		103, 950, 000
Total shipping-grade ore		223, 350, 000	34, 500, 000		257, 850, 000

The small cut in itabirite at the easternmost edge of the map was made in 1950 and added in 1951. The faces were remapped in November 1948 and June 1951, and their positions at those dates are indicated by dashed lines in the cross sections (pl. 6).

A few words of explanation about the detailed map (pl. 6) are in order. The same patterns for laterite and canga are used as elsewhere in this report to distinguish cemented from uncemented surface material. A combination of the canga and hematite patterns is used to show areas of outcrop where structures are preserved although the material is chiefly limonite. Physical character of the ore types according to the proportion of hard to soft material has been distinguished. This distinction, which is the weakest feature of the map, is in part subjective and open to errors of judgment, particularly where extensive limonitization has taken place. However, inasmuch as the physical character is important in determining the use to which the ore can be put, or even whether it can be used at all under present conditions, an attempt to show the ore types was considered necessary. No underground exploration has been done in the western part of the outcrop area, hence only surface indications could be used. It is by no means certain that areas shown as "medium-soft" ore altered to limonite are not itabirite rather than hematite at depth. On the one hand, drilling showed soft ore under laterite in drill holes 1A and 1B, section *C–C'*; on the other, a small lens of unenriched itabirite was discovered near the west end of the uppermost level at the time of the writer's last visit to the mine in 1951. Exploration is urgently needed, for the ultimate reserves of the deposit in large part depend on the western half of the area where no work has been done.

The exposed length of the deposit is 1,200 meters if the scattered outcrops at the west end are included as part of the main mass. The long axis trends N. 78° W. The width ranges from less than 100 meters at the east end of the exposure to about 300 meters in the center, and the outcrop area is an elongated oval. Bedding strikes about parallel to the long axis in most places where it can be observed, and dips steeply. However, in local areas the bedding departs from this regularity (pl. 6). Linear structures, manifested by fold axes and other features, trend and plunge eastward in most parts of the deposit, but also swing widely in some places. The attitudes of cross joints have been measured and recorded; they commonly lie within 20° of normal to the linear axes. In general the areas where lineation and fold axes plunge most steeply are also areas containing the hardest ore. Conversely, low plunges are found in areas of poor outcrops and strong alteration to limonite. Many exceptions to this rule occur, but the evidence suggests that the intensity and type of deformation influenced ore formation. Incipient axial plane cleavage was observed on several weathered outcrops and recorded, although examination of polished faces and sections throws some doubt on the true nature and significance of this feature (p. 53), which strikes from west-northwest to north and dips to the northeast and east.

Two areas where structures depart greatly from the average are worthy of mention. One is the low saddle just north of the west end of the uppermost mine bench, where bedding and linear structures swing sharply to the northeast, and for a distance of 20 meters are barely preserved. The outcrop is narrowest at this point. This zone may mark a fault, and may limit the extent of continuous hematite. The other area is near the west edge of the outcrop area, south of the road fork, where the structure is intricate and complex. Linear structures are steep and plunge in nearly every direction. The area contains better-than-average ore for this part of the deposit.

Nothing but ore and surficial cover are exposed in the area of the deposit. Around the periphery, however, other rock types are exposed or indicated by their weathering products. Much of the information on the rocks surrounding the deposit was obtained from 11 diamond-drill holes put down by the DNPM under the technical direction of A. Castilho Coelho at spots selected by the writer. Great difficulty and expense were experienced with the first drill holes, 1A and 1B, which started in ore, and most subsequent holes were drilled in country rock toward the ore body in an attempt to delimit the contact. Graphic logs are presented in plate 7, and the general relationship in the cross sections (pl. 6). The poor core recovery and general reliability of the results are indicated for each hole. Sludge was saved and examined where water return was obtained, and dry-blocking was resorted to occasionally to obtain information where other methods failed. Only a small part of the deposit was outlined before the work ceased, and attempts to interest the operators in additional exploration of this type were not successful.

Itabirite is exposed in the road cut at the east end of the deposit and was cut in drill holes 4, 5, and 6. The sections indicate 30–60 meters of itabirite along the contact of the ore body. At least one bed is manganiferous (3.36 percent Mn) and canga overlying the zone has a greater percentage (8.98) of manganese. A 30-centimeter clay zone, which contains abundant fine tourmaline needles, cuts the bedding near the road bend and is probably a dike. Bedding swings to north-south and dips moderately east on the nose of the deposit. Drill hole 5 cut massive hematite at 40 meters, indicating that the ore body continues eastward into the hill.

A 4.5-meter pit 15 meters above the road on the line of section *B–B′* exposes the typical black wad derived from the alteration of dolomite elsewhere in the district. Drill hole 4 cut through 26 meters of this material, and drill hole 6 cut through nearly 40 meters before itabirite was found. The contact was apparently gradational.

Manganiferous canga extends about 100 meters toward section *C–C′* before passing under laterite. Drill holes 3A and 3B on section *C–C′* also cut through decomposed dolomite(?). The evidence indicates a stratigraphic unit of manganiferous dolomite at depth.

The south edge of the ore body was originally covered with a heavy blanket of rubble and canga 10–25 meters thick that increased in depth downslope. Extensive mining has not exposed the south contact, but ocherous material and variegated clays exposed in the westernmost adit on the 1206 level and in cuts along the old railroad grade to the west probably indicate a dolomitic zone. Drill hole 8 cut vertically through 60 meters of this material before reaching hematite, which may not have been the main ore body.

The writer interprets the structure as a sharp anticlinal fold plunging eastward, and believes that the contact swings abruptly westward as indicated on the map. The itabirite zone does not seem to be present along the south contact.

General relationships suggest that phyllite of the upper group should overlie the dolomite. Drill hole 2B apparently cut decomposed phyllite, for dry blocking brought up plastic yellow clay which, although the structure was almost destroyed by the friction of the bit, resembled phyllite more than any other rock of the district. The laterite near *B′* appears aluminous and has a relatively low iron content (Al_2O_3 was not determined, table 16, analysis 5), and bauxite was found south of drill hole 8 on the west end of the mine area (table 16, analysis 8). Although direct evidence is lacking, it is probable, therefore, that phyllite overlies the dolomite as shown.

The "canga rica" along the northeast edge of the map area between sections *B–B′* and *C–C′* is composed almost entirely of hard hematite in unoriented blocks, averaging perhaps 50 centimeters across, firmly cemented into a compact mass by a minimum amount of limonite. The Casa de Pedra ("house of stone") is a cave extending under this cemented rubble from the northeast side, and is used as dwelling quarters. Drilling showed that the rubble has no roots in an ore body, but is apparently underlain by phyllite.

Itabirite in the cut at the easternmost edge of the map area strikes east-west, at right angles to the itabirite in the road below. The structural trend is the same as that of the Pico do Engenho mass to the east, and the itabirite rests on the continuation of the dolomite and phyllite zones indicated by the drilling in a way that seems best explained by a fault relationship. The writer believes that a major thrust separates this itabirite from the other rocks of the mine area. The canga rica may be the remnants of an ore body formed along the sole of this thrust plane. The same general situation occurs in another canga rica mass southwest of Alto da Bandeira (p. 76).

GRADE AND CHARACTER OF THE ORE

The chemical composition of the ore is uniform. Mining practice distinguishes two grades of ore, "common" and "special," which refer principally to the physical character, although there is a small difference in content of iron and other elements brought about chiefly by the admixture of hydrated material in the run-of-mine ore. (See table 15, analyses 15 and 16.) The special grade, destined for use in the open-hearth furnaces at Volta Redonda, is hard lumpy steely-blue ore. A complete analysis of this ore is given in table 14. "Common hematite" is a mixture of partly leached ore that breaks easily into smaller fragments. Smaller chips of hard ore and anything else not obviously canga that can be picked up by the mining forks is shipped. Finer material, including many elongated fragments that fall through the tines of the forks, are classified as waste or are sent to a washing plant. As will be explained below the "waste" is put aside for future use. Analyses of two grab samples from waste piles demonstrate the wisdom of this practice, for these samples contained 67.2 and 67.9 percent iron.

The map indicates the relative abundance of physical ore types in the exposed part of the deposit. The greatest proportion of hard ore and the so-called intermediate ore, which consists of harder and softer parts too intermixed to map separately, is in the eastern part of the deposit. Recent word from Brazil indicates that much of the hard ore in the knob on section *E–E′*, and presumably elsewhere behind the mining face shown on plate 6 has now been removed. Comparatively little powdery ore has been found in the deposit, as most "soft" ores have a fairly large percentage of harder chips or masses that can be screened out and shipped. Nevertheless, probably not more than one-half or two-thirds of the material is usable as mined. The iron content of the fines assures that they will be utilized at some future date.

Mining methods.—Mining commenced on the southern flank of the deposit at the east end, where the ore was most accessible and contained the greatest concentration of hard ore suitable for export. The initial mining system has not been appreciably modified. All mining is by opencut, on three principal benches about 20 meters apart plus a few subsidiary benches. Many short adits extend into the faces. Most are connected to the bench above by raises, and are used as part of the ore-hauling system. Certain adits and their continuations past the raises were driven to explore the deposit. The easternmost adit on the 1,206 level, which apparently has no portal because it was begun after the face shown on the map had advanced, was being driven in 1951 for the dual purpose of exploring the east end of the deposit and tapping the water of the Côrrego do Lagarto if satsifactory progress could be maintained. The writer does not know whether the second purpose was achieved, but the information to be gained from such a long tunnel would obviously be of great value.

Hand-held pneumatic drills using Swedish steel bits, resharpened at the mine, were used at least until 1951. Air was supplied to the working faces from electrically driven compressors, and a diesel-powered compressor was also installed as a standby. Power for the compressors and other uses, including lighting, was supplied by two company-owned hydroelectric plants in the valley of the Côrrego da Casa de Pedra below the mine. Blasting was done by fuse, although simultaneous electric-cap blasting was used experimentally at least once to the writer's knowledge. Secondary blasting is done occasionally, although it is usually unnecessary as the ore breaks small enough that sledge hammers can be used. Most loading was done by hand. Several small power shovels were in use in 1951, particularly for handling the fines. Tramming to chutes or ore pockets was done largely by hand on rails which could be easily relaid, but some pneumatic-tired trucks were also used in conjunction with the shovels. Transfer from chute or pocket to the next descent was made by trains of cars pulled by small diesel locomotives on the 1,224 level and by diesel and a few wood-burning steam locomotives on the 1,206 level. Ore thus lowered by stages to the principal chutes was loaded by gravity into one-half ton buckets and sent by aerial tramway to the railroad at Estação Casa de Pedra. Two tramways were in operation in 1947, a third was constructed west of and parallel to the others about 1950. The tramways feed to ore bins along a spur siding of the railroad where 75-ton gondola cars are loaded by gravity for shipment to Volta Redonda.

Normal operation called for one 8-hour shift, 6 days a week except for special holidays, which occurred fairly often. The production was about 1,000 tons per day. As the tramways each have a capacity of 50–60 tons per hour, the production rate could be increased to several thousand tons per day by the use of two or three shifts and a greater degree of mechanization.

Beneficiation.—Beneficiation of the ore consists of removing fines to meet size specifications. Material under about half an inch or 1 centimeter generally is undesirable for blast-furnace use. Washing in trommels and dry separation on vibrating screens have been used, but a relatively small proportion of the total production was obtained in this way. Plans were under consideration for installation of a sintering plant at the mine, which would make total recovery of the ore nearly 100 percent. The stock of fines in the waste piles would be the first feed for such a plant, after screening to recover the considerable proportion of coarser fragments.

Past production.—The writer does not have complete production statistics for the mine, but data from several sources indicate that about 1,250,000 metric tons were shipped by A. Thun e Cia. before the CSN acquired ownership. This ore was presumably all exported. CSN probably mined more than 1,500,000 tons by the end of 1953, but total production from the inception of mining to 1947, when the map was made, was about 1,500,000 tons. Top production for any one year has been about 250,000 tons.

Reserves.—The reserve estimate (table 21) is based on what is probably a conservative interpretation of the available data. All evidence points to a continuous ore deposit extending from the road on the east to the low saddle at the west end of the mine workings. It is assumed that ore extends 50 meters below the lowest exposure on each cross section. Areas of sections were measured, the mean of adjacent sections multiplied by the distance between them, and the resultant volumes converted to tonnage. The deposit was extrapolated 80 meters east of section A–A', giving the eastern half a length of 600 meters. The northeast contact was taken as a vertical plane passing through the limit of outcrop, although drilling and the shallow pit near the road northwest of F' indicate that soft ore underlies the laterite in this area. By including this area in the deposit a figure of 48,000,000 tons is indicated.

Only surface data are available for the western half of the deposit, which may not be a continuous ore body. In the absence of evidence to the contrary, however, reserves of this part have been estimated by the area and an assumed depth of 50 meters. The figure of 25,000,000 tons may be high. The writer believes that the ore extends downward to the lower thrust plane; it may connect with the outcrops east of the office, about 500 meters from the easternmost exposure of the ore body proper; and the westernmost outcrop may not mark the limit in that direction, as abundant float ore and isolated outcrops make a western extension possible. It is probable that a modest exploration program might substantially increase the reserves.

Although the Casa de Pedra deposit may be very large, it is well to consider other factors and point out that reserves of hard ore above the main haulage level, 1,206, may be much less and may be insufficient to support more than a few years of production without extensive alterations to the present mining system. Assured reserves of hard ore that can be extracted by opencut and lowered to the head of the aerial tram are only a small fraction of the total. Thus exploration is urgently needed both for immediate and long-term planning.

SERRA DO BATATEIRO

The Serra do Batateiro, in the south central part of the Casa de Pedra quadrangle, is one of the more accessible areas of the district which has important reserves of iron ore. The southern part extends northward about 3 kilometers from the vicinity of Coelhos (in the Jeceaba quadrangle), and adequate roads connect it with the ore bin and railroad siding at this point. The northern part of the range lies within 2 or 3 kilometers of the head of the aerial tram at Casa de Pedra. A. Thun e Cia. constructed a narrow-gage railroad on a steady low grade from the 1,206 level of the Casa de Pedra mine around the south end of the high ridge of the range, then northward around the head of the valley of the Riberão do Esmeril and southwest to the vicinity of some manganese mines near the village of Batateiro. The railroad was abandoned and the rails removed, but the grade was passable by jeep until 1950, and could easily be restored for truck traffic. CSN has converted the grade into a road as far as Grota dos Indios, 1.2 kilometers airline southwest of Casa de Pedra, where weathered itabirite was being mined in 1951. Branch roads in need of repair reach into other parts of the range. A road from Fábrica to Belo Vale, on the railroad west of the quadrangle border, was nearing completion in 1951. It skirts the north end of the range. Another road leads west through the Casa de Pedra mine area to the eastern flank of the range.

The exposed part of the Serra do Batateiro mass is cut off by the Engenho fault, but the topography and heavy float suggest that an offset block of itabirite extends another 500 meters southward to the second of the two parallel faults. Strikes and dips in the range are uniformly north-south and east, with only a slight tendency toward convexity, except in the slice swinging southeast from the main mass near section *E–E′*. By contrast most of the strikes in the Mascate block in the area southwest of Casa de Pedra are nearly east-west. The northern limit of the range is probably the intersection of the thrust plane with the present surface, hence the block extends only to a shallow depth in this area. The map and sections suggest, however, that the fault is considerably deeper in the central part where the iron formation is thickest.

SOUTHERN PART

No hematite deposits have been mapped in the part of the range south of the road which follows the tributary of Côrrego da Casa de Pedra, although abundant float ore in the debris mantling the slopes indicates the former presence of many small lenses. Usina Queiroz Júnior, Ltda. has stripped most of the float ore from the area between the railroad and the Engenho fault, washing it and shipping the concentrate to Gagé. A washing plant was producing two sizes, a plus-1 inch and a minus-1 inch, in 1947. The smaller size contained a considerable admixture of schist fragments and gave only 57.0 percent iron and 3.60 percent silica, but the coarser size appeared to be considerably richer. Production was 2,500–3,000 tons per month, and total production from the area had been a few hundred thousand tons. Most of the ore came from the part in the Jeceaba quadrangle. The remaining reserves are small, and the company has been producing most of its ore from the area north of the itabirite outcrops, where a thick mantle of rich residual ore extends southward from the road toward the crest of the range.

Little exploration or production of itabirite has taken place in the southern part of the Serra do Batateiro. An opencut was made on the eastern slope of the range at an altitude of about 1,080 meters, 200 meters north of the Engenho fault, and apparently some itabirite was mined and shipped, but all work had ceased by 1947. The itabirite is very magnetic, friable, and strongly contorted. The ferruginous layers are more coherent than the siliceous ones, so that screening probably raised the grade considerably. Three exploration adits have been driven into the northeastern slope of the high hill 1.7 kilometers south-southwest of the head of the aerial tram, for 3, 6, and 10 meters. The analysis of a sample taken in one adit is given in table 14, no. 2.

NORTHERN PART

The most important part of the Serra do Batateiro lies west of Casa de Pedra where the Mascate mass seems to be thrust faulted into juxtaposition with the itabirite of the former range. Plate 8 shows this area in detail. Outcrops of hematite are abundant on the eastern slope but have not been found west of the crest. Six exploratory adits were driven while A. Thun e Cia. owned the property, but nothing has been done in recent years. The geology and analyses of the ore and itabirite are shown on plates 8 and figure 35.

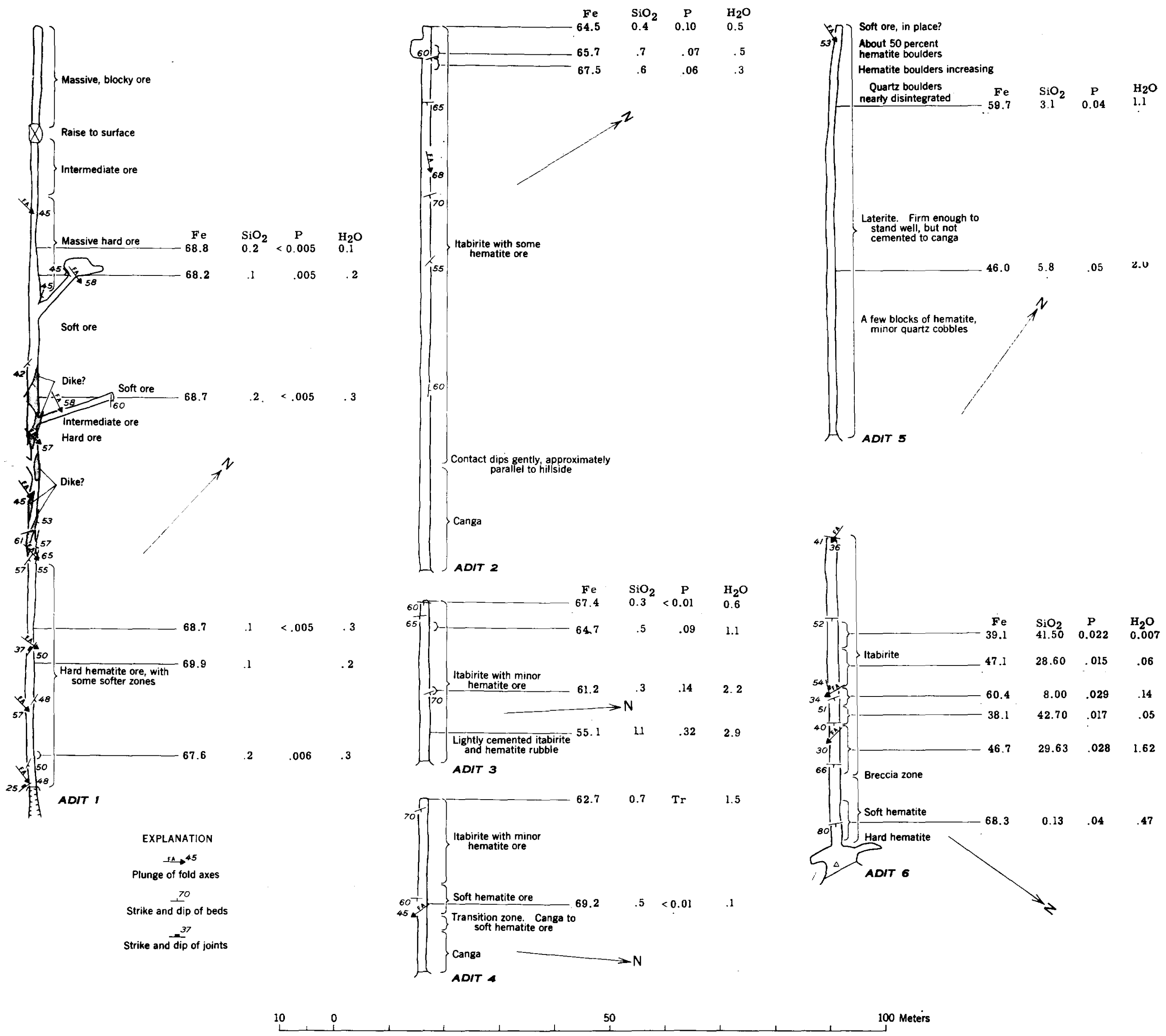

FIGURE 35.—Exploration adits in the Serra do Batateiro, Casa de Pedra quadrangle, Minas Gerais, Brazil.

Adit 1, which is 137 meters long, has two crosscuts and a raise to the surface 117 meters from the portal. This adit is driven almost entirely in hematite ore that ranges from soft to hard and blocky. A clay seam, exposed nearly parallel to the adit from 41 to 77 meters, is apparently an altered dike, as the heavy-mineral residue contains abundant zircon and some tourmaline. Bedding strikes about north and dips 45°–60° E. The outcrop area of the deposit is about 17,500 square meters. It may connect with the larger deposit to the northwest, but a thick canga mantle conceals the contacts on all sides. The small outcrop about 150 meters southeast is interpreted as being east of the trace of the fault. This area warrants further exploration.

The limits of the hematite deposit shown in the northwest corner of the map area are poorly defined, and some itabirite is also present. The hematite extends a short distance beyond the edge of the map. Only a rough estimate of the reserves can be made as no exploration has been done (table 20).

Much of the material cut in adit 2 is soft hematite ore, but as it does not crop out, no estimate can be made of possible reserves. The adit ends in rich itabirite, and a raise at 94 meters extends upward about 15 meters in soft ore and itabirite. Adits 3 and 4 also cut large amounts of soft ore and isolated blocks of hard hematite, although the overlying surface zones appear to be chiefly enriched itabirite. The canga along the entire slope contains much blocky hematite, confirming the assumption that the area is richer than average for the district.

Southeast of adit 4, hematite crops out for nearly 250 meters between the enriched itabirite of the crest of the range and the canga covering of the lower slope. This deposit may be only the end of a large ore body indicated by exposures in the adits, but the evidence is too weak to confirm this.

Adit 6 starts in a natural cave in a cliff of hard ore, cuts through 15 meters of soft ore, and continues 45 meters more in strongly contorted soft itabirite (fig. 16). Surface outcrops extend about 175 meters along the slope. The contact between the ore and itabirite shows evidence of thrust faulting nearly parallel to the bedding of the range, and several thin, deeply weathered pegmatite dikelets cut the formation. The ore body up the slope to the southwest is exposed in a shallow pit on the crest of the range and in scattered outcrops. The size and limits of the deposit are poorly defined.

The only hematite ore produced from this part of the Serra do Batateiro has come from the collection and dispatch of the rubble ore which lies in great profusion over much of the eastern slope of the range. Many thousands of tons have been trucked to the aerial tram from the vicinity of adit 1. Adit 5 was driven 75 meters into the mixture of laterite and rubble that had accumulated to a depth of about 20 meters. Bedrock was apparently reached in the floor of the adit near the face.

About 1950 a new mining operation was started near the south end of the area shown in plate 8, along the old railroad grade. The area is known locally as Grota dos Indios. Itabirite is mined by power shovel, screened, and trucked to the aerial tram. A new road was being constructed at a lower level in 1951 to enable gravity loading from chutes below the screening plant. A production of 600 tons per day was planned. One shipment reportedly assayed 62.12 percent iron, 2.60 percent silica, and about 2 percent alumina. Recovery was reported to be about 70 percent of the material treated. The decision to mine itabirite although high-grade hematite is available in a more accessible locality emphasizes one of the anomalies of iron production in Brazil. For blast-furnace use the hematite ores are too high-grade! The furnace practice at Volta Redonda is to use a mixture averaging 59 percent iron and 7 percent silica. The silica is necessary to maintain a proper slag burden and composition, as the sulfur content of the Brazilian coking coal is very high. At times quartzite and quartz cobbles have been used to provide the silica, but efforts were being made to find a natural ore with about the right composition. The mining and use of high-silica itabirite is discusssed on (p. 81).

The northernmost two kilometers of the range have not been explored by adits or pits. No hematite deposits of mappable size are known.

SERRA DA BÔA VISTA–DAS ALMAS

The western range, because of its lateral extent and the assumed vertical continuation of the iron formation, probably has the greatest itabirite reserves of the district (table 19). It contains no known hematite deposits of appreciable size and thus is at present the least important and least developed of all the ranges. It is not easily accessible except near the railroad at Salto in the northwest corner of the Jeceaba quadrangle. The old railroad grade from Casa de Pedra gives poor access to the eastern slope, and the Fábrica–Belo Vale road crosses the range in the water gap of the Côrrego da Bôa Vista. A road from Arrojado Lisbôa, a station on the railroad at the west edge of the Casa de Pedra quadrangle, reaches the western slope at the largest of the laterite areas. A recently constructed side road not shown on the map climbs to an altitude of 1,190 meters on the line of section *D–D′*. The rest of the range is inaccessible except by narrow trails passable only on foot or horse. The slopes are steep, in places even precipitous, and the country is devoid of human habitation except in the less rugged southern part.

The only exploitation of the iron has been a small operation for rubble ore in the higher part of the laterite-covered pediment near section *D–D′*. Ore is trucked to Arrojado Lisbôa, reportedly for shipment to São Paulo. A large proportion consists of hematite boulders, even though no sizable high-grade deposits are known. One small hematite deposit has been mapped near the line of section *D–D′*, however, and other isolated outcrops are present.

Most of the mine workings, opencuts, prospect pits, and adits shown on the map were operated for or explored manganese ores. The only exception appears to be the adit on the eastern slope of the Serra das Almas 400 meters north of section *B–B′*, which cuts about 65 meters of relatively soft, fairly rich itabirite. A lateral branch extends about 10 meters south of the adit 18 meters from the face.

PICO DO ENGENHO

Pico do Engenho and its satellite, Pico do Pilar, constitute an elliptical mass of itabirite which lies discordantly across members of both the Minas and Itacolumí series, and is probably the remmant of a thrust sheet. Its proximity to Casa de Pedra makes the western and northern flanks easily accessible, but the southeastern face falls away sharply for several hundred meters to the Congonhas lowland.

Much of the itabirite is hard and siliceous, particularly in the southeastern half which may be faulted against the northwestern half of the block (p. 34). Only on the western slope and in a small area on the relatively flat summit is the itabirite appreciably enriched. No sizable hematite deposits are known, although a few thin beds of high-grade ore occur in the siliceous iron formation. The only reserves of any importance at present are chapinha and detrital hematite in laterite, plus a small amount of canga, along the western and northern slopes. However, mining has been confined to the small cut in itabirite at the east end of the Casa de Pedra mine area (pl. 6) and to the production of a little highly siliceous itabirite from boulders on the northern flank at the end of the road to Poço Fundo.

Siliceous itabirite and angular breccia conglomerates (p. 24) of the Itacolumí series have also been mined in the Poço Fundo area. The material is trucked to Casa de Pedra. Production to 1951 had been very small and probably did not aggregate a thousand tons.

SERRA DO MASCATE

From a structural viewpoint the author considers that the Serra do Mascate includes everything from the Engenho fault southeast of Casa de Pedra to the northwest corner of the Fábrica property. The Casa de Pedra mine area itself has already been described p. 69), and the small bit within Fábrica will be described later (p. 78).

Area southwest of Casa de Pedra.—Scattered exposures, most of them along the old railroad grade, indicate that most of the triangular area between the Casa de Pedra deposit, the Serra do Batateiro, and an east-west line passing through the southernmost outcrops is occupied by itabirite. Strikes are nearly east-west, and the dips are steep. Most of the area is covered with laterite and canga. A few open cuts were made along the railroad grade while A. Thun e Cia. owned the property, and several thousand tons of weathered itabirite were mined. Only a small mass near the trace of the bounding fault was mapped as hematite, but the other canga-surrounded outcrops to the south apparently are rich and may be ore. This area is easily accessible and might well be suitable for testing large-scale mining and beneficiation. The block of itabirite tapers eastward in horizontal plan and westward in vertical section, if the writer's interpretation of the structure is correct.

Southern part.—The southern part of the Serra do Mascate proper consists principally of itabirite. A fairly level upland surface of enriched limonitic material is exposed continuously for more than a kilometer. A prominent rock outcrop near the south end, known locally as Pedra do Granito, is hard siliceous itabirite, but the rest is thin bedded and moderately rich. Some of the outcrops near the southwest end of the exposed area are hematite and more detailed mapping could probably outline one or more ore deposits. A thin hematite zone crops out for about 300 meters on the eastern slope south of section C–C′, and another zone projects through laterite on the nose of a ridge just north of this section line, but no reserves have been estimated for these deposits.

A large irregularly shaped hematite mass is exposed for about 600 meters on the southeastern face of Pico da Bandeira, and isolated outcrops lie to the southeast downslope. If the deposit has much depth it may be one of the larger ones of the district, but the eastward plunge of the linear structures is nearly parallel to the slope, which indicates that the ore may not project very far into the hill. The top of Pica da Bandeira is underlain by a small hematite deposit.

One of the most unusual ore deposits of the district is the area of canga rica about 500 meters southwest of the peak, where enormous blocks of hard ore, weighing dozens of tons, are cemented in a nearly horizontal jumbled mass. The area is separated from the iron formation of the range by phyllite, and no evident source remains from which such a concentration of hematite blocks could have been derived. The writer believes that the hematite fragments are the remnants of a deposit formed in or near the sole of the thrust plate and subsequently lowered to the phyllite of the overridden block as the host plate was eroded away. The mass now slumps a considerable distance downslope. Great quantities of hematite cobbles litter the lower slopes of the hill, lying on light-colored soil derived from phyllite rather than being enclosed in ferruginous laterite as is more common. Much float ore has been collected in piles, and some was undoubtedly shipped, probably via Casa de Pedra.

The lozenge-shaped fault slices lying west of the Serra do Mascate should be a favorable place for the formation of hematite deposits. Some of the material is hematite, but as a reexamination would be necessary to determine the relative proportions of hematite and enriched itabirite, the areas have not been shown as ore deposits. The slices might warrant exploration.

Central part.—The central part of the range is inaccessible and without any roads. The lower contact of the iron formation lies near the narrow summit, and the eastern face is deeply dissected, so that there is almost no enriched itabirite. The only known hematite lies at the north end where the range again becomes fairly broad and is flat topped. A large canga and laterite area on the eastern flank has become the repository for part of the material eroded away, and typically contains a higher proportion of hematite than is apparent in the source area. Strikes and dips are uniformly parallel to the trend of the range.

Northern part.—The northern part of the range is accessible by car from Fábrica. A road under construction to Belo Vale in 1951 would connect with the end of this road at the western contact of the itabirite on the line of section *B–B′*. Much of the summit is broad and covered with enriched itabirite, canga, and laterite, but the northernmost kilometer is deeply dissected on both flanks. The detailed structure is extremely intricate, and bedding more often perpendicular to than parallel with the trend of the range.

Several small hematite deposits crop out near section *B–B′* as shown on plate 1. The adits driven eastward from the western slope, on either side of the section line, cut only phyllite (p. 34), and the ore does not extend far vertically. The canga-capped knoll between the adits, and the slope almost as far as the dry lake, are covered with abundant hard ore boulders that indicate the former presence of larger deposits. An adit was driven 18 meters into the easternmost hematite outcrop. The ore is mostly "medium-soft" containing some harder blocks. A 50-meter adit 350 meters north-northeastward exposes hematite as well as itabirite, which suggests that the area may contain considerably more ore than has been indicated on the map.

The deposit west of the road at the north end of the range probably does not have much depth. It apparently lies in close proximity to the thrust fault, which presumably limits its downward extent. The writer believes that the fault also cuts off the itabirite of this part of the range at a shallow depth, perhaps less than the 200 meters assigned to this block in table 19. Exploration work would be advantageous.

FÁBRICA

The Fazenda da Fábrica, which includes the drainage basin of Riberão da Fábrica and its tributaries, lies across the common boundary of the Casa de Pedra and São Julião quadrangles 10 kilometers airline north of Congonhas. The distance by road is about 12 kilometers. The new highway crosses the entire length of the fazenda near its southern boundary, and the old road extends through the middle of the ferruginous belt. This property, owned by the Cia. de Mineração de Ferro e Carvão, has been more carefully explored than any other iron-ore area of the district, although actual production has been very small and confined only to float ores. From 1937 to 1940 more than 6,000 meters of adits, shafts, and raises were driven, mapped, and sampled under the direction of a German mining geologist, E. Grösse. In all, 41 separate workings, some short and others extensive, were made. The positions of most of these, numbered in accordance with Grösse's system, are shown on plate 9. Areas of canga and rubble were explored by closely spaced test pits. Many of the underground workings have collapsed, but two summaries of the results, one dated May 31, 1939, and the other giving additional information to June 1, 1940, were published soon after the war (Grösse and others, 1946). Much of the underground data shown on plate 9 has been taken from these reports, and Grösse's published reserve figures for hematite ore have been adopted directly. An attempt was made to map those latest adits still accessible which were not included in the published reports.

An explanation of the large scale map, plate 9, is necessary. The base was enlarged from the 1:10,000 scale multiplex compilation. Surface features were mapped in the field, and the positions of adit portals, shafts, trenches, and pits were noted. The illustrations published by Grösse (1946) give details of geology in vertical longitudinal sections with azimuths to the nearest 5°, but the writer found, when he tried to plot them, that the directions are based on magnetic readings. From the surface positions of a few raises shown on the profiles to connect with underground galleries, the actual positions of a few workings could be plotted; others are only approximate. Accessible workings were examined to correlate Grösse's terms with those of the writer, and to check general reliability. The observations seem excellent and extremely detailed, made as they were from day to day as the headings progressed, but the writer does not agree with certain interpretations, particularly the overall relationship of the geologic units and the structural setting. In fairness it must be stated that Grösse revised his interpretation as time went on, and would probably have arrived at a more logical explanation had not the outbreak of war caused a cessation of the work. The chief difference between the findings of Grösse and the writer are that Grösse considered the ferruginous belt to be synclinal, whereas the writer interprets it as anticlinal in the present report. This should not affect the reserves of near-surface ore.

GEOLOGY

The rocks within the area, as shown on plate 9, belong to the middle and upper groups of the Minas series. They include itabirite, weathering products of dolomite, and phyllite of the upper group with minor quartzite and itabirite. The keys to the geologic pattern are clay and wad, which can be shown by exposures in the eastern part of the district to be derived from dolomite (p. 42). No fresh dolomite has been found in the Fábrica area. Typical white to red compact clay and minor wad are exposed at the surface in the upper valley of the Côrrego da Prata and just east of the map area; elsewhere they have been found only in underground workings. They are usually separated from ordinary itabirite by "transition beds" of relatively thick-bedded iron oxide and soft sand which probably represent weathered ferruginous dolomite. A few of these beds give the characteristic "crunch" of the "splash rock" so well exposed at Usina. These "transition beds" are particularly susceptible to hydration and have been extensively replaced by limonite in some places.

As shown on plate 9, the rocks in the northwest corner of the map area belong to the Mascate thrust slice, which is very thin in this area. Adits 10, 11, and 33 cut the "clay and transition beds" before reaching itabirite. This is the only place except at Casa de Pedra where dolomite has been indicated along the east edge of the Mascate block, but as shown on plate 1, little of this upper contact is exposed. Phyllite may underlie the laterite in the area south of these adits.

The evidence listed below indicates that an extensive fault of unknown displacement separates the Mascate area from the rest of the Fábrica zone, even though it is not actually exposed.

1. There is a major divergence in the trends of the zones.
2. The lower contact of the Mascate block is sinuous and strongly affected by topography, whereas the contacts in the Fábrica zone show little topographic effect.
3. Dolomitic clay is present only on the east side of the Mascate block, but on both flanks of the Fábrica zone.
4. The broad dolomitic clay zone exposed in the upper valley of the Côrrego da Prata trends directly toward the Serra do Mascate and ends abruptly. To the south quartzite of the Itacolumí series shows the same relationship to itabirite. Outcrops of quartzite and itabirite having nearly parallel attitudes strike toward one another across a narrow valley.
5. The transition beds are north of the clay in adits 10, 11, and 33, but to the south in adits 9, 32, and 38, and on the northern and southern flanks of the Fábrica zone the succession toward the center is clay, transition beds, and itabirite. A major fault probably separates the zone of overthrusts from a zone in which the folds are predominant structures that control the distribution of the rocks. These folds extend eastward far beyond the Congonhas district.

Phyllite on both sides of the belt of iron formation undoubtedly belongs to the upper group, and the sequence inward is phyllite, dolomite, transition beds, and itabirite. The zone must be anticlinal, but is complex in detail, for minor crumbling and drag folding is prevalent in all exposures. Cross sections (pl. 9) attempt to portray the details, but the data are insufficient to ensure accuracy. The dolomitic zone is apparently faulted out along part of the northern flank of the anticline west of the Côrrego dos Macacos. Another fault probably follows the stream, crosses the low area near the fazenda house; and continues past adit 5. It may limit the tongue of phyllite extending westward from adit 26 and pass eastward north of shaft 8. A fault along the Côrrego da Jacutinga causes a minor offset on the clay zone and seems to coincide in trend with offsets of a thrust fault farther south. Clay occurs along the entire southern flank of the zone except for a short stretch between adits 28 and 16, but minor movement may have taken place.

Adits 6, 27, and 15 showed that itabirite forms the core of the hill southeast of the fazenda house. All have collapsed, but the general succession of beds suggests the presence of a short anticline or elongated dome with transition beds and a dolomitic clay zone on its flanks.

The physiography has been closely controlled by structure and rock distribution. The Côrrego da Prata follows the dolomitic clay zone, which swings northeastward around the nose of the plunging anticline to meet the Côrrego dos Macacos fault where the two streams join to form the Riberão da Prata. The Côrregos dos Macacos and da Jacutinga follow fault zones. The broad low area near the fazenda house is underlain chiefly by the dolomitic clay zone on the nose of the anticline.

A few natural exposures and underground workings occur along the southern part of the zone east of the Côrrego da Jacutinga, but the geologic interpretation is conjectural. The general pattern from this point to Vigia suggests that itabirite comes to the surface in the cores of a series of anticlines that are in part emphasized by faults. Axes presumably plunge gently eastward and westward to accomplish this. The area eastward from adit 29 would represent the west end of the first of these elongated domes.

Distribution of ore.—Most hematite ore in the Fábrica belt occurs in the upper part of the middle group near the contact zone with the overlying phyllite. The most clear-cut example is the ore body east of adit 28; another is the small mass exposed above adit 21, where the contact may be thrust southward on a steep fault. The ore in adits 13 and 5 is in contact with clay; elsewhere hematite apparently is localized near or in the transition zone. By contrast, adits which cut deep into the core of the fold, as adits 18, 4, and 12, found little or no ore.

Despite 4 years of continuous exploratory work, exact delimitation of individual ore bodies is impossible with the present information. Grösse attempts to delimit the ore bodies on his map, but this writer is inclined to doubt some of the connections made between the different adits and Grösse emphasizes the need for more exploration. It is clear that no continuous deposit like the one at Casa de Pedra is present here. Grösse distinguishes 10 principal ore masses exclusive of the minor pockets in the clay beds and calculates reserves for each. He may be too optimistic in some of the estimates, but on the contrary he has made no allowance for ore below the lowest adits, nor does he include the smaller deposits northwest of adit 33. This writer does not believe that any recalculation of reserves is justified and accepts those made by Grösse, pointing out, however, that even his calculated reserves cannot be classified as "measured ore."

Grade and physical character of the ore.—Grösse distinguishes between massive hard ore, which he calls hematite, and mixed ore and "jacutinga," which correspond approximately to the intermediate and soft ores of this report. He estimates that reserves of "hematite," that is, hard ore, are 5,493,000 tons, and of "mixed ore and jacutinga" 58,840,000 tons Screening tests indicated that 57 percent of the total reserves are in sizes greater than 5 millimeters. The tests included detrital ore and canga, however, so the percentage of coarse material from bedrock ore would be smaller.

Itabirite.—Reserves of itabirite are unquestionably very large, but as Grösse was exploring for shipping-grade ore, he did not study this material in detail. In his profiles he distinguishes between "banded itabirite," which is hard; "friable banded itabirite," in which the ferruginous layers are hard and the siliceous ones disaggregated; and "banded jacutinga," in which both the hematite and quartz are pulverulent. His analyses show an iron content ranging from 35.91 to 51.86 percent (table 12, analyses 8–12) for these materials. In his reserve table he estimates 4,744,960 tons of "friable banded itabirite" which can be easily beneficiated by screening. The figure probably refers to concentrates rather than bulk ore, though he does not specify this, nor does he give the average grade. As shown in table 19 the total amount is much greater.

Surficial ores.—As shown in plate 9, a large part of the ore zone is covered with surficial deposits. At least two remnants of an older canga surface lie south of the itabirite zone, one on Morro dos Cachimbos on the quadrangle boundary and the other about 500 meters west-southwest of adit 21 on the edge of the large-scale map. The laterite-covered surface west of adit 23 probably formed at the same time. The resistance of this surface to erosion suggests that the laterite must be cemented to canga below the surface, and small patches of canga are exposed in places. This older canga surface undoubtedly antedates the most recent uplift and furnished much of the rubble of the area. Canga has also formed at lower levels over parts of the present surface.

FÁBRICA TO VIGIA

A few exposures and the distribution of itabirite and hematite float in the 6-kilometer stretch between the east end of the Fábrica property and the Fazenda do Vigia are the only evidence of the continuity of the iron formation in this area. The Riberão da Mata and its tributaries have eroded a broad valley of relatively low relief which contrasts sharply with the prominent ridges of most areas underlain by iron formation. The present surface probably has been formed on phyllite and dolomitic clay, and has only recently intersected the tops of a series of anticlinal crests which are beginning to control the physiography. Although this hypothesis apparently does not provide a source for the laterite and canga of the valley, the writer believes that sufficient material has already been eroded from the exposed crests, and carried in from the Serra do Pires to the southwest, to furnish the volumes present. The low relief has permitted the accumulation of this material to remain in place, rather than be eroded and dissipated as in the higher regions.

Roads in the area are adequate for present mining activity, and new ones can be built easily and cheaply where required.

Small deposits of hematite crop out at several places, and strong concentrations of float ore in the region indicate the presence of other ore bodies, but no reserves have been shown in table 20. Just outside the Fábrica boundary, south of shaft 8 (pl. 9), two 4-meter pits expose an almost solid capping of hematite blocks. Some ore has been produced from a small opencut. Partly leached hematite ore is exposed on the road 75 meters to the south. Abandoned workings 350 meters east of shaft 8 expose thin-bedded, medium-soft ore that contains a few hard beds in an opencut 15–20 meters across and 8 meters deep. The same material occurs in a 20-meter adit immediately to the south. A deposit at least 20 meters thick is indicated but no length or depth can be determined. Massive hard hematite crops out 150 meters east-northeast of these workings. The area warrants exploration.

Abundant hematite float covers a ridge north of the Côrrego do Angú Duro about 1.5 kilometers northwest of Pires. Antônio Pacífico Homem, Jr., picked up several thousand tons of surface ore from the northern flank of this ridge but made no attempt to explore the underlying bedrock, which is exposed only in a small cut about 50 meters north of point 1,103 near the west end of the area. The material in this cut is massive fine-grained hematite ore containing abundant coarse martite crystals as much as a centimeter across (fig. 31).

Sr. Falabella worked an area of hematite float 1.5 kilometers north of Pires in 1947, exposing hematite and itabirite in the bottom of a shallow cut. Trucking costs left little or no margin of profit, however, and the cut was soon abandoned. Hematite float occurs just north of the cut made for manganiferous wad on the east bank of the Riberão da Mata 2 kilometers north-northeast of Pires.

Substantial amounts of hematite can undoubtedly be mined from deposits in this general area even though no figure for reserves can be stated.

The most active mining has been done by ICOMI, which has stripped an extensive laterite area along the road south of hill 1,113 in the western part of the Fazenda do Vigia. Material to a depth of 2–4 meters has a high proportion of chapinha which upon screening averages more than 60 percent iron. Cemented zones, in which the material is too hard to break without blasting, have not been mined. Magnetic itabirite has been exposed in places, and some outcrops have lineation and minor fold axes that plunge gently westward. Screening was unsatisfactory because excessive clay raised the alumina content to several percent, so washing has been used increasingly. Total production by 1951 was about 200,000 tons, and ample reserves of rich residual material were in sight. The ore was trucked to Congonhas, or to Cruzul for shipment by aerial tram (p. 81) to Congonhas, and thence to Volta Redonda.

Small pits in laterite and leached magnetic itabirite have been made in the vicinity of the dolomite quarry at Vigia, but little ore has been produced. This material is ordinarily trucked eastward to Crockatt de Sá.

Throughout the entire belt from Fábrica to Vigia itabirite directly underlies the surficial cover or lies at a shallow depth below phyllite, dolomitic clay, and perhaps unweathered dolomite. The thickness of the formation is probably several hundred meters in this area, and as it must be doubled in the crest of the anticlinal zone, the total reserves may be very large. The presence of the upper part of the formation near the surface on both flanks of the zone should be favorable for the discovery of hematite ore. The influence of the fault system on the structure and distribution of the formation needs further study.

VIGIA TO SÃO JULIÃO

The area eastward from Vigia is tributary to São Julião and Crockatt de Sá. An old ore bin and chute is located on the railroad about 300 meters north of kilometer 495, but is in disrepair and evidently has not been used for many years. The laterite area to the west contains abundant hard hematite float and was the source of the iron ore shipped, though it is probable that the point was also used for loading manganese ore. Hematite float occurs elsewhere, but no deposits are known.

Most of the present production of the area supplies the 18-ton blast furnace at Usina Wigg, São Julião. Canga and leached porous itabirite amenable to charcoal reduction are used for feed. An opencut in sandy magnetic itabirite 1.4 kilometers south of the furnace furnished the necessary material in 1951. Much of the friable quartz was removed by screening, and the product was reported to average 60 percent iron.

Itabirite reserves cannot be accurately determined because of the poor outcrops and complex structure in this area. Much of the section is apparently either dolomite or ferruginous dolomite, which closely resembles what the writer has called "transition beds" at Fábrica. Mine workings and exploration adits are abundant in the area, but none of the deeper workings are accessible and little can be seen in the few shallow ones still open.

EAST OF SÃO JULIÃO

Although most rocks of the middle group east of São Julião have been shown as dolomite on the map (pl. 2), many are ferruginous and are the source of much float ore and magnetic chapinha. A fairly large quantity of this material has been mined in the past and shipped via the railroad siding at Usina. A few siliceous zones have been distinguished as itabirite. The relationship of the northern strip of dolomite and itabirite to the principal zone is not known, but it probably represents a higher zone in the section, enclosed in the upper phyllite.

Masses of hematite ore too small to be shown on the map are exposed in cuts on top of the hill north of kilometer 499, Ouro Preto branch. They are in place, surrounded by leached ferruginous dolomite or itabirite, and probably have resulted from replacement or enrichment of the original formation. No reserves can be measured, though in aggregate there must be considerable hematite ore in this area.

NORTHERN BELT

The belt of itabirite at the north edge of the São Julião quadrangle has been explored only by a few opencuts in low-grade manganiferous material. There are no roads west of the highway, but construction of roads should not be difficult when needed. The area is, however, one of the least favorable in the district, as no hematite deposits are known and accumulation of surficial ore is not extensive.

SERRA DO PIRES

The iron formation of the Serra do Pieres is considered in this report as belonging to the Itacolumí series and hence geologically is not equivalent to the itabirite of the areas discussed heretofore. Smaller masses of itabirite interbedded with quartzite and conglomerate in the "Fábrica syncline" to the west are of relatively little importance and have not been included in the reserve estimate.

Although the specimen shown in figure 34 indicates that some replacement occurred in this iron formation, the known hematite reserves of the Itacolumí series are very small. At present the chief importance and only commercial exploitation of itabirite of this series is for siliceous material which is mined at Cruzul and Poço Fundo and shipped to Volta Redonda. The need for additional silica in the blast-furnace charge and a preferential freight rate accorded iron ores created the single market for this material, which is not suitable for export. Specifications call for a minimum content of 35 percent each for silica and iron. The average grade shipped is about 35 percent iron and 50 percent silica.

ICOMI mines siliceous itabirite from several opencuts at Cruzul, on the southern flank of the Serra do Pires 2 kilometers southwest of Pires. The scarp is very steep at this point, and some production has come from large landslide masses. A 5,400-meter aerial tramway connects Cruzul with an ore bin on the railroad at Congonhas. The tramway carries not only the siliceous itabirite but chapinha from the Vigia operations of the same company (p. 80). A 700-meter spur branch of the tramway extends to a small area of canga northeast of the head of the main cableway, where a modest quantity of surficial ore was mined by a former operator of the property.

Many shallow exploration pits were made along the crest of the range northwest of Cruzul, and a road formerly extended to a small opencut almost at the crest where leached itabirite was mined and screened. Parts of the Itacolumí iron formation weather to reasonably high-grade chapinha ores and enriched itabirite indistinguishable from their Minas series equivalents.

Material on the dump of a deep abandoned shaft some 400 meters south of the ocher mines shows that the extensive laterite area along the west edge of the quadrangle is underlain by itabirite. The westward extension of the Serra do Pires into the Casa de Pedra quadrangle is also composed of medium-grade siliceous itabirite, somewhat enriched in the surface zone and overlain by canga along the southern flank.

Antônio Pacífico Homem, Jr., has shipped large quantities of chapinha from opencuts in laterite and weathered siliceous itabirite along both sides of the Congonhas–Pires road a short distance south of Pires. Production has been intermittent for many years. Screening and washing suffice to make a salable product from the leached material, but the unweathered blocks have been left untouched.

MANGANESE

HISTORY AND PAST PRODUCTION

The mines in the vicinity of São Julião, in what has always been known as the Miguel Burnier district, exploited the most important manganese deposits in the "quadrilátero ferrífero." According to Scott (1900), manganese ore was discovered just east of São Julião in 1888 during construction of the Ouro Preto branch of the railroad and was first mined in 1894. Production increased rapidly, reaching an annual rate of 63,000 tons in 1899, and continued at a substantial rate until the 1920's. The mines produced until the 1940's, but there has been no mining activity for about a decade. The writer does not know what the total production for the Burnier district has been, or what part of the total came from the area within the São Julião quadrangle. Scott estimated reserves for the properties owned by Usina Wigg in 1900 (slightly more than one-half of the total) at 2,000,000 tons, but no reliable account of the later history of the district has been written so that the writer does not know how accurate this estimate is. It seems probable that total production for the part west of the east boundary of the quadrangle was not less than 500,000 tons. Several companies were active in the early days, but at present the entire area is owned by Usina Wigg.

During the 1930's A. Thun e Cia. explored and developed deposits of low-grade manganese ore in the Serra da Bôa Vista, about 4 kilometers west of Casa de Pedra near the line of section *D–D′*. A few tens of thousands of tons was produced. Other small deposits were worked in the Poço Fundo area. The Cia. Siderúrgica Nacional, present owner of the property, has made no effort to mine these ores but has shipped several thousand tons, stockpiled at Casa de Pedra, which was acquired with the other assets.

Indústria e Comércio de Minérios (ICOMI) is the most active company at present. This company has mined manganese ores from many small deposits in the district, but the total production has not been large. Much of the ore has come from deposits on the Fazenda da Bocaina west of Crockatt da Sá, São Julião quadrangle, which were worked for many years by the Cia. de Mineração da Bocaina, S. A., before ICOMI bought an interest.

Other companies and individuals have mined small deposits at different times in the past, and many abandoned pits were noted during the course of mapping, but little or no information concerning them is available.

MINES AND PROSPECTS

BURNIER DISTRICT

The writer will continue to use the name Burnier not only because it conveniently delimits a geographic district, but also because the deposits have a distinct geologic environment that distinguishes them from other manganese ore bodies of the Congonhas district. According to Scott (1900), the manganese zone, which averaged 2–3 meters in thickness, was worked by the opencut method near the surface. Many old pits still mark the trace of the former outcrop, but only decomposed itabirite and earthy wad in the walls can be seen today. Underground development was by shaft from the surface and long adits from lower elevations. Scott states that main haulage ways were driven about 30 meters apart, vertically, and raises were cut every 40 meters into the stopes, which were timbered and then filled. In the upper levels the mines were dry and the ore was hard. At greater depths the ore was much softer, where the water content was higher. Mining presumably ceased because of increased costs and gradually diminishing grade rather than exhaustion of the deposits. Copies of old mine maps, preserved in the office of Usina Wigg, show that most of the workings extend about 30–50 meters below the surface, and that most of the ore to this depth has been extracted. Scott (1900, p. 188) says "that mining had reached a depth of 150 metres," but his next statement that "the stream . . . is some 300 metres lower than the lowest point reached in the mine" casts doubt on his figures for depth, inasmuch as the local relief from outcrop to valley is only about 200 meters. The detailed survey and research necessary to compile and interpret this fragmentary information has not been made.

Local details of the geology have not been entirely solved. The manganese bed extends from a point near the railroad junction at São Julião, through the crest of hill 1,202, and doubles back to a northeastward-trending fault. A zone of magnetite-amphibole schist just north of the old workings, which seems to provide a reliable guide to the local structure, is apparently offset about 200 meters by this fault. The manganese bed extends northeastward from the railroad near the curve north of kilometer 500, bends to an easterly direction near the crest of the hill, and continues for several kilometers beyond the edge of the quadrangle. The overall relationship suggests, however, that the structure may be more complex, for the southern limit of the dolomite zone east of kilometer 500 is probably a fault of considerable displacement, whereas to the west the dolomite rests conformably on itabirite. This area is closely related to that of the Dom Bosco quadrangle to the east in its lithology and structural pattern, and a satisfactory interpretation must await completion of the field work in the adjacent area.

The principal workings west of the railroad extend from a point about 500 meters northwest of kilometer 495 for a distance of about 1.5 kilometers along an ore bed which also lies just south of a zone of magnetite-amphibole schist. The characteristic black wad is exposed in many shallow opencuts. Siliceous itabirite lies south of the manganese-ore zone, so that the general relationship is similar to that east of São Julião. Wad is exposed at places in the upper valley of Riberão Burnier, but the writer was not able to trace the zone throughout. A second, an echelon manganese zone comes in south of the first one about 1.5 kilometers west of the railroad and probably continues under the laterite cover of the workings 700 meters east of section *B–B′* A shaft on the outcrop 425 meters north-northwest of hill 1,141 probably connects with a long adit driven into the hill from a point 250 meters south-southwest and 90 meters lower. Both are now inaccessible. An attempt was made a few years ago to explore the west end of this zone, but without success. An adit, still open in 1951, extends about 75 meters northeastward into the hill from a point below the Vigia-São Julião road east of section *B–B′*. It begins in nearly horizontal phyllite and ends in dark-brown to blackish clay and "splash rock", derived from dolomite, which have caved and buried track and equipment. The adit probably cut a fault zone at the point where it caved. Short adits and shallow surface pits are abundant in this general area. Most of those which have not caved expose black wad or ferruginous "transition beds," and the others commonly have these materials on their dumps.

VIGIA

Several small workings expose a manganese-rich zone in black wad about 0.8 kilometer west of the large dolomite quarry at Fazenda do Vigia. ICOMI produced several hundred tons of ore from a short adit that intersected a 3-meter zone of manganese oxides mixed with wad and limonite. The material was soft and broke readily. It is reported to have averaged 42 percent manganese, whereas hard boulders on the surface contained 54 percent manganese. The relationship of the ore to the enclosing rocks and the grades at the surface and at depth indicate that these ores are of the Burnier type, but, they do not have the continuity and are not as extensive as the Burnier ore. Mapping shows that they occur in dolomite lenses above the main zone of chemical sediments.

An opencut 200 meters west of these manganese prospects has been worked for many years for manganiferous "splash rock." Small but regular shipments of this material are made to Rio de Janeiro, São Paulo, and Santos for use as purifiers in the city gas systems. Other opencuts in similar material to the west and northwest may have been made for the same purpose.

SERRA DO PIRES AREA

Two zones of black wad that contain small amounts of manganese ore occur along the southern flank of the Serra do Pires and have been explored by opencuts and short adits. The more extensive workings are near the west edge of the quadrangle. The best exposures are in an abandoned mine 125 meters east of the quadrangle border at the point where the Itacolumí quartzite overlaps the Minas series rocks. A zone about 20 meters wide and 125 meters long has been worked by opencut and short adits. The northeast wall consists of quartzite which dips moderately northeastward. A breccia zone about 15 meters wide in the center of the cut is composed chiefly of fragments of sericitic quartzite from less than 1 to about 15 centimeters across and siliceous itabirite blocks that reach a maximum of 30 centimeters or more in a matrix of fine-grained rock fragments cemented by veinlets and irregular masses of psilomelane. The west edge of the cut consists of black wad that contains massive limonite and some pyrolusite and psilomelane. The writer attributes the breccia to the thrust fault bounding the Serra do Pires block, and the minerals to the concentration of manganese by ground waters channelized by the fault zone.

Just north of the principal opencut a series of smaller cuts have been made in nonbrecciated kyanite-bearing quartzite of the Itacolumí series which contains scattered veinlets of psilomelane. The manganese probably came from the same source but was carried farther from the fault along irregular fissures. Production has been very small.

POÇO FUNDO

At Poço Fundo, 2 kilometers northeast of Casa de Pedra, many small opencuts are in an area a kilometer long by a few hundred meters wide trending northeastward along the contact between the Minas and Itacolumí series. A manganese-cemented breccia in a cut 500 meters southwest of the switchback and the general relationship of the rocks in this area indicate that this contact is a thrust fault. The immediate local setting of the deposits varies. Some ores, chiefly those nearest the contact of the two series, are psilomelane in wad and soft itabirite. A few cuts expose narrow veinlets of manganese oxides in kyanite-bearing impure quartzite. Oxide films and interstitial fillings are molded on quartz crystals in veins that also contain unoriented blades of kyanite. The largest cut is only about 50 meters long, and most are much smaller. Some were entered by short adits, now largely caved, and worked as glory holes. Total production is not known; it may have been as much as several thousand tons. Reserves are nonexistent, and the size and distribution of the workings indicate that the ore occurred only as pockets in the country rocks.

SERRA DA BÔA VISTA

Concentrations of manganese in ferruginous and dolomitic members of the middle group occur in places along the entire length of the western range. The principal deposits within the Congonhas district lie west of Casa de Pedra near the line of section *D–D′*. Two manganiferous zones are present, a stratigraphically lower one of manganese oxides in itabirite and an upper one containing large amounts of wad, also interbedded in the iron formation. The lower, western zone has been explored by small cuts at several places for a distance of about 500 meters, but the manganese oxides have a spotty distribution and production was not great. The zone is 3–5 meters thick in the wider parts.

On the eastern slope extensive workings were made along a 20-meter zone of black wad and itabirite that contained veinlets of psilomelane and pyrolusite. The zone is exposed for about 500 meters horizontally, and has a relief on the outcrop of nearly 200 meters. Adits were driven on several levels north and south from exposures in a steep ravine near the center of the deposit. Only a few workings are now accessible near the portals, and the writer does not know the extent of the mining activity. The size of the dumps, however, indicates that a large quantity of material was extracted. Most of the ore was shipped as "ferromanganese" containing about equal parts of iron and manganese (see table 17, analyses 9 and 10).

Earthy wad is exposed in several places in the area underlain by dolomite south of section *D–D′*, and a few small pits were made which did not show any minable ore. Many prospects northward along the range show minor concentrations of manganese oxides in itabirite and wad, but no worthwhile deposits have been found and production has been very small.

BOCAINA

The name Bocaina has been used for two groups of deposits, one on the land of Usina Wigg which has been described in this report under the Burnier district (p. 82) and another to the south, 1.5 kilometers west of Crockatt de Sá, where manganese oxides have extensively replaced phyllite of the upper group of the Minas series. Five deposits have been found and worked in an area about 500 meters long, but in contrast to the deposits in the chemical precipitates they apparently do not have stratigraphic control.

The deposit know as no. 1 is on the west side of a small creek at the point where a cross fault cuts off a thick quartzite member. Evidence in the weathered zone shows that the continuation of the dolomite lens exposed to the north may be faulted against the quartzite, but no fresh rock is exposed and most of the zone is covered by soil. A zone of limonite along the fault about 15 meters thick contains veins and concretions of vuggy psilomelane and crystalline pyrolusite, and the quartzite against the fault is cut by narrow veinlets of oxides. The deposit has been explored and mined by opencut and several short adits for about 150 meters along the fault.

About 300 meters west of mine 1 and 80 meters higher, an opencut measuring 25 by 10 meters, which is called mine 2 by the operators, contains many irregular veinlets of manganese oxides in weathered gray phyllite. The richer parts were estimated to be 50 percent oxides by volume and considerably more by weight. Hand cobbing eliminated most of the phyllite. Westward along the zone several smaller prospect cuts reveal isolated narrow veins which probably are part of the same deposit. An adit was driven from a point about 35 meters down the hillside to the south, but did not extend far enough to intersect the downward extension of the zone when the mine was examined in 1951. If the mineralization is related to the present erosion cycle as the writer believes, it is doubtful that ore will be found at depth.

Mine 3 is 200 meters west-northwest of mine 2 and 25 meters higher. A nearly circular cut about 20 meters across is entered by a narrow cut trending east-northeastward into the steep hillside. Manganese oxides have replaced phyllite both along easterly dipping bedding planes and a nearly vertical east-west joint system to produce a rectangular pattern of intersecting veinlets. Some lenticular high-grade masses have dimensions of a few meters. The prospect trenches and old workings suggest that mines 2 and 3 are parts of a single ore zone that extends along the hillside for several hundred meters and has a width of about 20 meters, but the zone cuts at a large angle across the bedding and may also be related to a fault which cannot be detected in the uniform phyllitic strata.

A small deposit 250 meters N. 10° E. of mine 2 consisted of a lenticular mass about 30 meters across and 2 meters thick in the center that dipped moderately northeastward parallel to the hillside in the plane of the bedding. Most of the ore was exhausted by 1951. Another small deposit 120 meters west and 80 meters higher on the ridge was mined in former years.

Three grades of manganese ore were produced, depending primarily on the iron content. Divisions were made in the percent iron at less than 6, 6–10, and more than 10. Manganese content of selected ore reportedly ranges from 36 to 46 percent. The ore of mine 1 contains 40–43 percent managanese but is high in iron because of the limonite. The others commonly yield lower iron but also lower manganese because of the unreplaced phyllite fragments. Production is reported to have been several thousand tons, but exact figures were not available.

OTHER MANGANESE DEPOSITS IN PHYLLITE

Small concentrations of manganese oxides as veins and irregular replacements of phyllite have been mined sporadically for many years. None have proved to have any significant size or continuity, and the total production cannot be more than a few thousand tons. An analysis of this type of ore is given in table 17, analysis 12. Many small prospect cuts are shown on plates 1 and 2 across the north edge of the Casa de Pedra and São Julião quadrangles.

POTENTIAL FUTURE PRODUCTION

Known reserves of manganese ore in the Congonhas district are small, but in all probability considerable quantities will be produced when the demand becomes greater and prices are high enough to encourage exploration and development. Future production depends largely upon reserves in the Burnier district. The deposits may have been largely exhausted by the end of the period of active mining, but most of these mines became inactive when prices were relatively low. Although records are inadequate the miners assert that the ore did not appear to be pinching out with depth and that the only changes in it were increasing softness and higher water content. Ore of present or future value may therefore remain in deposits which formerly were unprofitable. Exploratory work has not been done because the owners do not feel that the ores could be mined under current conditions. Drilling might be an unsatisfactory method of exploration in material too soft to core, especially in a zone of wad in which interpretation of sludge samples would be difficult. In spite of the expense, the most satisfactory method of appraising the situation would be to reopen one of the mines.

A source of manganese that may be exploited at some future date is the wad. Analyses nos. 3–8, table 17 show that wad contains more than 20 percent metallic manganese in some places and averages more than 10 percent. It could be easily produced by large-scale mining. The quantity of this material must be large, for it is exposed in many places. The distribution suggests stratigraphic control, but the deposits probably have the irregularity of thickness and grade characteristic of replacement deposits. The principal zone is 20 meters or more thick in places and may average 10 meters for not less than 10 kilometers. These dimensions indicate 100,000 cubic meters per meter of depth, or, at a specific gravity of 1.5, 150,000 tons containing 15,000 tons of manganese. The depth is unknown, but if the wad continues to the bottom of the workings in the Burnier district it may be at least 100 meters in places. More than 1,000,000 tons of metallic manganese may therefore be present. The foregoing figures are speculative, intended only to show the general order of magnitude and what might be expected if a practical method of extracting the metal could be devised. Analyses 13 and 14, table 17, show that some cobalt and nickel might be obtained also, although these analyses are probably not representative of much of the material. It should be pointed out that the wad continues eastward and may be even more abundant in the area east of the São Julião quadrangle, so that a centrally located processing plant could depend on much larger reserves. Some standard-grade lump ore should be a byproduct of a large-scale operation.

The Bocaina deposits and other smaller ones will undoubtedly yield a moderate amount of ore for some time, but the writer doubts that any noteworthy reserves can be developed in advance of mining.

OCHER

Nearly all the ocher in the Congonhas district is produced from opencuts in the klippe south of Fábrica. Nodules and fragments from the weathered zone are mined selectively and cleaned of adhering soil. Care must be taken to exclude material of inferior quality, partly ferruginized phyllite and yellow limonite. The deposits have been worked steadily for many years, and the opencuts now extend several hundred meters in a north-northwesterly direction through the crest of the knob. The productive zone ranges from a few to as much as 10 meters in width. The material is trucked to plants where it is processed through jaw crushers, fine-grinding mills, settling tanks, and drying ovens. Two plants, one at Congonhas and the other about 0.8 kilometer north-northeast of Pires, produce about 1 ton each per day of the finished product.

Ocher from other small pits in the Fazenda da Fábrica was shipped as crude ore for processing elsewhere.

STEATITE

Steatite has been quarried from the earliest days of the settlement of the Congonhas district for utensils and for building and ornamental stone. Colonial churches dating from the 18th century have elaborately carved façades and sculptures which by their perfect state of preservation are evidence of the chemical inertness of the rock. On the contrary, the extreme wear of steps and lintels fashioned of this soapstone demonstrates the softness which makes it so popular with artisans. At the present time steatite cooking pots are turned out rapidly on primitive lathes powered both by water wheels and by electricity; the latter is used in a small factory at the east edge of the town of Congonhas. A market has recently been found for sawn and polished stone as decoration for modern buildings in Rio de Janeiro, and large blocks are cut by gang saws and polished with carborundum. Slabs have also been shipped for use in telephone switchboards. Some skill has been acquired in making candlesticks, vases, decanters, lamp bases, trays, and other attractive items for which the demand is increasing rapidly. By applying wax to well-polished surfaces a rich green to black color is brought out. Firing the articles at a high temperature gives an extremely hard finish and changes the color to brown.

The most active steatite quarry is east of Riberão Goiabeira 500 meters northeast of its junction with the Rio Maranhão in the Congonhas quadrangle. Other quarries, many abandoned, are scattered throughout the steatite areas of the district. Blocks are cut with hammer and wedge or sharpened drill steel, and pried loose with crow bars. Preliminary trimming to the desired shape is ordinarily done in the quarry to save hauling unnecessary weight.

TALC

Vein talc for grinding purposes was mined for only a short period during the 1940's, when Sr. Falabella installed a mill in Congonhas. At least four veins, all in the São Julião quadrangle, were worked. One is on the new highway 0.7 kilometer north of the edge of the quadrangle. It had been abandoned before the highway was built and only thin veinlets of talc in steatite can be seen. A second cut 500 meters west of the highway and 1.5 kilometers south of Pires exposes about one meter of impure schistose talc in steatite and green schist. A granodiorite dike intrudes the ultrabasic rocks. Two other abandoned cuts are 1 and 1.7 kilometers respectively, east of the highway in the vicinity of point *B* of the section line. In the first cut, two schistose talc veins and a massive talc-actinolite vein are exposed in green schist that is cut by granodiorite dikelets. The veins were mined to a depth of about 25 meters and abandoned partly because the overburden was excessive and partly because the material was low grade. The second cut reveals a complex mixture of talc schist, vein talc, carbonate vein material, tremolite schist, greenstone, and granodiorite in a cut about 50 meters long by 10 meters wide. A prominent feature is a narrow zone of slip-fiber amphibole asbestos containing fibers more than 30 centimeters long.

Reserves of minable talc are apparently very small, and the industry has failed for lack of suitable raw material that could be mined and treated profitably. On the contrary great quantities of talc schist are available which could perhaps be purified and used. Magnetic separators should easily remove the magnetite, one of the chief impurities. Improved technology may perhaps enable the industry to produce commercial grades of talc suitable for some purposes. Even though such products would not command the highest prices, the ease of mining and volume of the operation should ensure success if the domestic market is not oversupplied.

DOLOMITE

Dolomite is quarried for metallurgical stone at several places in São Julião quadrangle, and most of it is shipped to Volta Redonda for use in the blast furnace. Specifications call for minimum magnesia and lime contents of 19 and 29 percent, respectively, and maximum silica of 3.00 percent and ferric oxide plus alumina of 2.50 percent. The analyses in table 6 show that whereas some rock easily meets these requirements, other rock does not, so that mining must be selective. The writer did not study the dolomite from an economic standpoint but believes that ample reserves are present for an indefinite period.

Nearly all mining has been done by opencut. Sr. Falabella operated a quarry on the line of section *B–B′*, trucking the stone to Congonhas via a 9-kilometer road. Transportation costs were excessive, however, and work ceased in 1948. The road has fallen into disrepair and is no longer passable. The other quarries ship via the eastern branch of the railroad. The quarry at Vigia is operated by Sr. Celso of Lafaiete. The Cia. de Mineração de Bocaina, S. A. has quarries in the dolomite lens a few hundred meters northeast of the manganese deposits. Stone from these quarries is loaded at Crockatt de Sá. The Cia. Siderúrgica Nacional has large quarries in the dolomite zone 2.2 kilometers south of Usina near the east edge of the quadrangle. The stone is trucked to São Julião for railroad shipment. A little underground exploration has been done by adit. Other quarries have been worked intermittently along the valley of the Riberão de Burnier.

Dolomite for use as marble is cut by wire saw in a quarry near the CSN operations south of Usina. This dolomite makes a fair grade of white slab for sink tops, trim, and other ornamental uses. The blocks are shipped from the district for cutting and polishing.

QUARTZ

Considerable prospecting was done during the war years for quartz crystals of oscillator quality, and activity continued sporadically thereafter. Many of the more prominent quartz veins have been opened by shallow trenches. So far as is known little if any usable material was produced. Some clear quartz has been found in stream gravel and on old terraces, but not in sufficient quantity to sustain interest in exploration.

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