Physiographic, Stratigraphic and Structural Development of the Quadrilátero Ferrífero Minas Gerais, Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 641-A

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

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By JOHN VAN N. DORR 2d

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PHYSIOGRAPHIC, STRATIGRAPHIC, AND STRUCTURAL DEVELOPMENT OF THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL

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ABSTRACT

The Quadrilátero Ferrífero is an area of some 7,000 square kilometers in central Minas Gerais, Brazil, centered about lat. 20°15′ S., long. 43°30′ W. For 250 years the region has poured forth a variety of mineral riches, now totaling more than $2 billion, and future production will undoubtedly be even greater. The main products are iron ore, manganese ore, and gold. To assist this development, the Brazilian and American Governments in 1946 jointly undertook the first detailed geologic study of the region; this report is a synthesis of the results of work and mapping by 17 Brazilian and American geologists under this program; other reports discussing the economic geology, the metamorphic geology, and the igneous geology of the region as a whole are being prepared.

The region is one of the highest in Brazil and forms the watershed between two major drainage systems. Major streams are deeply incised, and total relief is about 1,400 meters. Intermittent erosion has produced a number of prominent erosion surfaces, the oldest persistent surface possibly dating back to the middle Mesozoic. These erosion levels are of economic importance, for they control the development of certain supergene ore deposits.

All rocks of the region are strongly weathered, most to depths of 50 meters or more. With the exception of an unjointed, unfoliated granite, the more complex the mineral composition, the more intense the weathering, other factors being equal. Products of lateritic weathering and saprolite are widespread.

The region is underlain by granitic gneisses, granites, and similar coarsely crystalline rocks; mafic and ultramafic intrusive rocks of various ages and the alteration products thereof; and three series of metasedimentary rocks of Precambrian age with a minimum aggregate thickness of about 14,000 meters. A few small areas of Tertiary continental sedimentary rocks are known.

The metasedimentary rocks of the region are divided into the Rio das Velhas Series, first metamorphosed some 2,800 million years ago, unconformably overlain by the Minas Series, which in turn is unconformably overlain by the Itacolomi Series. The Minas Series was metamorphosed by intrusive rocks dated by radioisotope methods as being formed some 1,300 million years ago. The age of the Itacolomi Series is indeterminate, but it was metamorphosed to the same degree as the Minas Series and is thus believed to be also older than 1,300 million years.

The Rio das Velhas Series is composed of two groups, the Nova Lima and the Maquiné. The Nova Lima is a flyschoid eugeosynclinal suite now dominantly composed of chlorite, sericite, quartz-chlorite, and quartz-sericite phyllite and schist. Metavolcanic rocks are common. Other rock types include graywacke, subgraywacke, quartzite, carbonate-facies iron-formation, metachert, carbonaceous and graphitic phyllite, and tilloid. The Nova Lima is the host for widespread gold mineralization and, to the south of this area, for important manganese deposits in the Lafaiete district. The base of the Nova Lima Group has never been found, but the minimum stratigraphic thickness must be on the order of 4,000 meters.

Overlying the Nova Lima Group with locally gradational, locally unconformable contact lies the Maquiné Group, a molasse suite subdivided in the type locality in the Rio das Velhas valley into two formations, the Palmital and the Casa Forte. The Palmital Formation, composed dominantly of quartzose chloritic and sericitic phyllite and schist, wedges out to the southeast; and the overlying Casa Forte Formation, composed dominantly of protoquartzite, grit, and conglomerate, there overlies the Nova Lima Group with apparently conformable contact. In much of the eastern part of the region the Maquiné Group cannot be subdivided, but is composed of rocks similar to those in the type locality, with less conglomerate. The maximum thickness of the Maquiné Group is perhaps 1,600 meters.

Overlying the Maquiné Group with angular unconformity is the Tamanduá Group, here included with the Minas Series. The group crops out in a relatively small part of the region and is known only in the east-central part. The lower formation, the Cambotas, is an orthoquartzite perhaps 1,000 meters in maximum thickness, and it is overlain by an unnamed formation composed of sericite and quartzose phyllite and dolomitic iron-formation with a maximum thickness of perhaps 250 meters. The group is believed to represent prismatic paralic sedimentation.

Conformably overlying the Tamanduá Group and, in most of the region, unconformably overlying the Rio das Velhas Series is the Caraça Group of the Minas Series, divided into two formations, the Moeda and the Batatal. The Moeda Formation varies greatly but systematically in thickness and in lithology. In the west-central part of the region the formation consists of as much as 1,000 meters of grit, protoquartzite and orthoquartzite, and conglomerate, with lenticular phyllite bodies. In the east-central and much of the northern, far western, eastern, and southeastern parts of the region it is less than 100 meters thick and consists of quartzite or sericitic quartzite. It is a transgressive blanket formation. The conformably overlying Batatal Formation, commonly less than 100 meters thick, is composed of phyllite; it also is a blanket formation.

The Itabira Group, conformably overlying the Caraça Group, contains the major economic mineral resources of the region, which consist of various types of iron ore, manganese ore, bauxite, building stone, and water; the water is largely unexploited. Two intergradational formations form the Itabira Group: the Cauê Itabirite, composed of metamorphosed oxide-facies iron-formation, and the Gandarela Formation, composed of dolomitic and calcitic marble, carbonate-rich phyllite, and thin units of itabirite. The Cauê is intergradational with the Batatal Formation and averages perhaps 250 meters in thickness; the Gandarela averages perhaps 300 meters in thickness. Both are blanket formations thought to have been deposited in a stable-shelf environment.

The Piracicaba Group of the Minas Series overlies the Itabira Group with erosional but not angular unconformity to the west, and with a gradational contact in the east. The Piracicaba Group has been divided into five formations. The lowermost, the Cercadinho Formation, found throughout the region, consists of ferruginous quartzite, grit, and phyllite, and has a maximum thickness of about 400 meters. The Fêcho do Funil Formation conformably and gradationally overlies the Cercadinho and is composed of siliceous dolomite, dolomitic phyllite, and quartzose phyllite. Its maximum thickness is about 410 meters, and it wedges out to the northeast and east. Overlying the Fêcho do Funil Formation with gradational contact is the Taboões Quartzite, an orthoquartzite with a maximum thickness of about 120 meters. The Taboões is found only in the western and northwest central part of the region and wedges out to the south and east. It is conformably and gradationally overlain by the Barreiro Formation, composed of phyllite and carbonaceous and graphitic phyllite, with a maximum thickness of about 120 meters. The Barreiro Formation either wedges out to the west or has been eroded away in that area; it is in gradational contact with the overlying unit in the north-central part of the region and is found through the central part and much of the eastern part of the region. All formations of the Piracicaba Group through the Barreiro are stable-shelf blanket deposits.

At the close of the Barreiro sedimentation an abrupt change in the sedimentary environment occurred, for the uppermost formation of the Piracicaba Group is a typical eugeosynclinal assemblage composed of graywackes, chloritic and sericitic schists and phyllites, tilloid, and tuffaceous rocks. This assemblage is named the Sabará Formation and has a maximum known thickness of perhaps 3,500 meters. The formation is structurally conformable with the underlying Piracicaba Group formations, and it is locally intergradational with the Barreiro Formation in much of the region; however, in the west and south it seems to be on an erosion surface. The formation probably once extended over the whole region, but it has been removed by erosion in many places.

Overlying the Minas Series with small angular unconformity but deep erosional unconformity lies the Itacolomi Series, composed of grit, protoquartzite, quartzose sericitic phyllites, and conglomerate. It was very probably a nearshore sediment. The total thickness may be about 2,000 meters; its top is always limited by the present erosion surface.

The Precambrian sequence was metamorphosed to the greenschist facies or higher. It is moot whether there was more than one episode of regional metamorphism; the youngest and oldest rocks do not differ appreciably in metamorphic grade. The youngest stratigraphic units are not certainly known either in the contact aureoles of intrusive granitic rocks or in the far eastern part of the region, where the highest metamorphic grade is found.

Unmetamorphosed sedimentary rocks, some dated as late Tertiary by fossils, include fossiliferous lignite and claystone beds found in valleys and ancient sinkholes. A rock called "mudstone," found principally on the higher erosion surfaces, is thought by the writer to have been formed by alteration of volcanic ash, possibly of Mesozoic age.

The first recorded orogeny was that after Rio das Velhas time. The Rio das Velhas strata were folded and tilted, but it is not now possible to evaluate closely the degree of structural disturbance on a regional basis because of intense later deformation. The unconformity between the Rio das Velhas and the Minas Series is locally as sharp as 90°. Granitic rocks were formed in part of the Rio das Velhas uplift. It is believed but not yet proved that granitic rocks to the south and west of the region here discussed were the source area of much of the coarser sedimentary rocks of Minas Series and Itacolomi age.

The Precambrian metasedimentary rocks of the region were folded into a peculiar pattern of bordering synclines around a central uplifted block. The central block is known as the Rio das Velhas uplift, a north-south structure some 100 kilometers long and about 26 kilometers wide at its narrowest point. It veers to the northeast at the north end. This is probably the first structure to have formed in the post-Minas orogeny and probably started to form during the pre-Minas orogeny. Around it were formed the Santa Rita syncline to the east, north-south in elongation; the Dom Bosco syncline to the south, east-west in elongation; and the Moeda syncline to the west, north-south in elongation. The north boundary of the region is the overturned structure trending N. 70° E. called the Serra do Curral; its conjugate limb to the north has been destroyed by younger granite except at its east end. In the central and east-central parts of the region lie the Gandarela syncline and the Conceição-Caraça uplifts. Peripheral to the synclines lie major domal uplifts now occupied by granitic rock of several ages. In the extreme northeastern part of the region are synclinal structures that preserve relatively small areas of metasedimentary rocks surrounded by granitic rocks.

Cross folds are found on all major folds, crosscutting the major structuers at angles from 30° to 45°. All major folds are overturned toward the northwest and west in at least part of their trace. Thus, the deforming stresses came from the southeast and east. Directions of movement were strongly influenced by crystalline buttresses to the west, to the south, and in the southernmost part of the Rio das Velhas uplift.

Continuation of stresses from the southeast thereafter produced major thrust faults in the eastern and southern parts of the region. In the southern part of the Quadrilátero Ferrífero, movement was channelized by the central and southern buttresses, and the Dom Bosco syncline was fragmented into a series of imbricate thrust blocks along its entire length. In the east and east-central parts of the region, the Fundão fault, a master structure which has been mapped for a length of 88 kilometers, formed; and to the east of this fault imbrication is common. Only one major thrust fault is known to the west and north of the Fundão fault, although some minor thrusting is found. The Santa Rita syncline, on the east edge of the region, is severely sliced by many north-trending thrust faults with displacement toward the west.

The root area of the orogen cannot lie far to the east of the Quadrilátero Ferrífero, as also attested by the systematic eastward rise in grade of metamorphism in the mapped area.

Granite formed during the major orogeny—some syntectonic, some posttectonic. The age of the latter was determined by rubidium-strontium methods on feldspar as 1,230 million years.

Cross faulting occurred after the orogeny ended. Most of it was minor, with displacements measured in tens of meters, but some of its was major with displacements measured in hundreds of meters, at a few places displacement was more than a thousand meters. Such faults are at angles of 30°–45° or about 90° with the trend of the major fold structures which they transect, regardless of fold orientation. Neither cross faults nor earlier thrust faults are significantly folded, although both may be refracted in passing between rocks of different physical properties. Minor faults tend to swing into the planes of bedding or foliation of more plastic rocks.

INTRODUCTION

LOCATION AND IMPORTANCE OF AREA

Most of the Quadrilátero Ferrífero is included in the rectangular area between lat 19°45′ S. and 20°30′ S. and long 43°22′30″ W. and 44°7′30″ W. in central Minas Gerais, Brazil; but outliers and continuations of the rocks, structures, and ores continue to the east and west some tens of kilometers beyond those limits, as shown in figure 1 and on plate 1. The region, an area of about 7,000 square kilometers, takes its name from the abundant occurrence of iron-formation and iron ore.

The geology of this region was mapped by a team of geologists during the years 1946–62. The physiographic, stratigraphic, and structural geology and the rock relations of the region as a whole are the subjects of this report, which is in part a compilation of the data reported by these and other geologists, in part a presentation of data collected by the writer, and in part an interpretation by the author of all these data.

The Quadrilátero Ferrífero played an essential role in the development of both the Portuguese Empire of the 18th and early 19th centuries and in the evolution of the Brazilian nation. During the Colonial period, several hundred tons of gold produced from the rich placer deposits of the region formed a large part of the financial foundation for rapid expansion of the Portuguese Empire and the influence of that nation in world affairs. Major engineering works were constructed by large gangs of slaves to bring water 10 km (kilometers) and more to the higher workings; streams and rivers were diverted to expose the rich gravel deposits. John

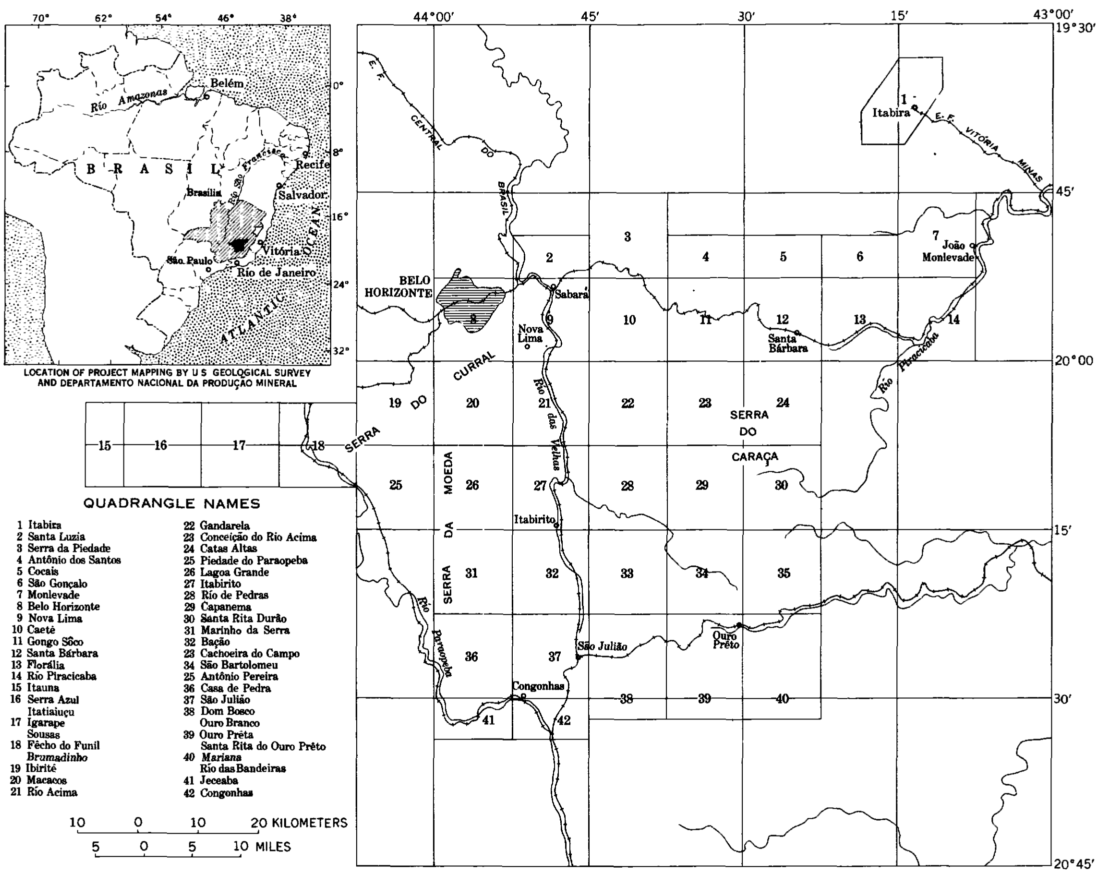

Figure 1.—Index map of the Quadrilátero Ferrífero, showing location and names of the quadrangles mapped.

Mawe (1816) described and illustrated the methods of extraction, which were highly advanced for the time. Early in the 19th century the placer deposits were exhausted and lode mining commenced, largely with European capital. By midcentury, most of the lode mines had reached the limits of economic exploitation, and a period of decay set in which lasted nearly a century. In the middle of the 20th century iron mining began to expand; at the present time both quantity and value of production are rapidly increasing and will soon far surpass the value of the gold mined in earlier years. On this solid base, the industrialization of the region and of the nation is now progressing rapidly, aided by significant production of aluminum from local bauxite deposits and hydroelectric power from the rivers of the region and nearby regions.

During the early 20th century the Catalan forges of the 19th century were displaced by small (15–50 tons per day) charcoal blast furnaces, which were in turn outstripped by larger and more modern integrated steel plants in, or dependent on, the region. A small but significant production of manganese ore has come from the region, for export during the first half of the 20th century and largely for domestic use thereafter.

The long history of mining and the isolation first imposed by law by the Portuguese Empire and in later years by the rugged topography have set their marks on the population of the region; the people are independent, freedom loving, and individualistic, although conscious and proud of the traditions of the past. This area cradled the first stirrings of revolt against the Crown and toward the creation of a free Brazil.

Within the Quadrilátero Ferrífero proper the soils are poor, and farming is generally on a subsistence basis. Deforestation for the charcoal blast furnaces and the railroads, which used wood for fuel until the decade of 1950, has destroyed the fine virgin forests which are so vividly described in the accounts of the early explorers and travelers; reforestation by eucalyptus has been accomplished on a large scale in the last decade, however. Much of the region is sparsely populated, and the standard of living outside the industrialized towns is low by Brazilian standards.

Picturesque towns relict from the days of gold mining, such as Catas Altas, Agua Quente, Santa Rita Durão, and Antônio Pereira, attest former prosperity by their large and beautiful baroque churches, some of which are now being restored and preserved, others of which are in ruins. Some of these old towns are taking on new life with the advent of new mining activity; others are off the path of development, and their economy depends precariously on charcoal gathering and subsistence agriculture. Most have great charm but few facilities for the passerby.

Within the region certain cities stand out for their specialized activities. Mariana (pl. 1), with many beautiful churches, is an ecclesiastical center and has a small textile factory. Ouro Prêto, the first capital of the State and the focus of former gold mining activity, is a tourist center and the site of the National School of Mines. Nearby is Saramenha, the site of a large aluminum reduction plant and ferroalloy plant. Congonhas is a tourist center because of a famous church with exceptional baroque statuary and is also a busy mining center. Itabirito is a textile and shoe factory city, specializing in football shoes; the nearby Esperança plant makes very high quality cast iron. Rio Acima manufactures ceramic products, as does Caeté, which also has a nearby iron plant specializing in centrifically cast iron pipe. Nova Lima is the site of the famous Morro Velho gold mine, which has produced for 150 years and in 1931 was the deepest mine in the world. Barão de Cocais is the site of a small but active steel plant. Monlevade is the site of the largest privately owned steel plant in Brazil and the largest steel plant based on charcoal in the world, with a production of about 500,000 tons per year; it is a model modern city. To the north lies Itabira, which in 15 years was changed from a sleepy 19th-century town to a bustling modern city by the successful large-scale mines of the Cia. Vale do Rio Doce, which produced about 8 million tons of iron ore in 1965.

The metropolitan center of the region is Belo Horizonte, which grew from about 200,000 to nearly 1,000,000 inhabitants in the period from 1945 to 1965. All the amenities of life are there available, and the city is the political, commercial, and industrial center of the State. Industrial products range from steel, pipe, structural forms, refractory brick, cement, textiles, tractors, and radio tubes to prefabricated kitchens and other commodities.

DEVELOPMENT OF PROJECT

In 1944 Brazilian and American officials began discussions directed toward a joint study of the geology and evaluation of the mineral resources of this region. In 1945 an agreement was reached, and in 1946 the first American geologists and topographic engineers arrived in Brazil under the auspices of the U.S. Department of State to begin the project with their Brazilian colleagues of the Departamento Nacional da Produção Mineral. Lack of adequate base maps in the region seriously hampered operations; the areas around Congonhas do Campo and Itabira were chosen to start the work because base maps of parts of these areas were available and because both were sites of active mining enterprises for which a geological background was needed. Thanks to the continuing efforts of officials of the Departamento Nacional da Produção Mineral, aerial photographs of part of the region at a scale of 1:10,000 were made available, and later aerial photographs of the entire region at a scale of 1:25,000 were furnished by the Commissão Vale do São Francisco and the Departamento Nacional de Produção Mineral. These were used by Serviços Aerofotogramétricos Cruzeiro do Sul, SA, a Brazilian mapmaking company, to map the topography of the region at a compilation scale of 1:10,000 for publication at 1:25,000, with a 10-meter contour interval. The cost of these maps was defrayed in part by the Brazilian Government, in part by the American Government. Topographic maps of small but economically important areas were made at a scale of 1:2,000 by Geofoto, SA, from aerial photographs.

With adequate base maps in hand, work could be accelerated, and in 1951 the mapping team was enlarged. The region was divided into areas with some geological homogeneity, composed of two to four quadrangles each. Those areas were mapped by the individual geologists as specified on plate 1. Each geologist was reponsible for mapping the assigned area, for evaluating the mineral resources therein, and for preparing an area report. The areas mapped before 1951 had proved to be among the more complex in the region, and it was only during this second phase that the details of the Precambrian stratigraphy were worked out.

The igneous and metamorphic rocks of the region were of a complexity that demanded special attention, and therefore a petrologist was assigned to the party in 1957 to study those problems. Although not given specific mapping responsibility, he reconnoitered 1½ quadrangles largely composed of granitic rocks for the regional map, in addition to his petrographic responsibilities.

By the end of 1961, essentially all field mapping was finished, and laboratory work and the preparation of reports has occupied the staff since then. More than 100 man-years of geologists' time were spent on this project between 1946 and 1965.

Reports discussing individual areas are being published by the U.S. Geological Survey as professional papers. In addition to these larger publications, about 45 other papers appeared in professional and technical journals.

This report is an attempt to describe the physiographic, stratigraphic, and structural geology of the region. Companion regional reports were prepared by Norman Herz on the metamorphic geology of the region and on the igneous and granitic rocks of the region, and another by the present writer on the economic geology of the region. Regional reports are necessary because the reports on the individual areas within the region were prepared at widely different times by geologists thoroughly familiar only with parts of the area. As the knowledge of the region grew and evolved, interpretations made early in the work, although seemingly well based at the time, became obsolescent, just as many interpretations made in this report will also become obsolescent after more detailed work is done in the future. Furthermore, much three-dimensional exploratory work has been done on ore deposits in the past few years, and many area reports were written without the benefit of information gained thereby. The detailed area reports were written from many points of view, and diversity of interpretation was encouraged within broad limits in order to have as wide a range of ideas considered as possible. In the regional reports prepared by this writer, there is no attempt to give the details of much of the geology and ore deposits; the individual area reports must be consulted for them.

The quadrangle geologic maps accompany area reports, the first of which was U.S. Geological Survey Professional Paper 290, by P. W. Guild (1957). The other area reports have appeared or will appear as chapters in U.S. Geological Survey Professional Paper 341. It had been planned that the chapters covering all the individual areas would be in final form before the general reports were written, but this proved impossible, and this paper was prepared before final, or, for two reports, first-draft manuscripts had been prepared on certain specific areas. Quadrangle maps accompanying manuscripts which may not be published in the foreseeable future are included in the pocket of this report as plates 2–10, in order to have them available to the public in a reasonable time; geologic sections indicated on plates 7–10 are given on plate 11.

References to unpublished manuscripts are cited as "written communications"; the use of different dates of authors' contributions may refer to different drafts of the given manuscripts or to separate unpublished manuscripts. A few final reports omitted data or descriptions that appeared in earlier drafts—material considered by this writer to be important. In such situations the draft is referred to instead of the published report.

In this report, specific localities are referred to a coordinate system based on measurements in meters from the southwest corner of individual quadrangles. Thus "N. 1,000, E. 6,500, Gandarela" refers to a point 1,000 m (meters) north and 6,500 m east of the southwest corner of the Gandarela quadrangle. This point can be found on plate 1, which is at a scale of 1:150,000, by using the index map showing the location of the Gandarela quadrangle and the bar scale below. More accurate locations will be obtained by using the individual quadrangle maps published at a scale of 1:25,000.

ACKNOWLEDGMENTS

Admiration is here expressed for those officials of the Department of State and of the Administration for International Development and its predecessor organizations who, although not scientists, had the understanding and appreciation of the need and potential results of scientific and economic inquiry to finance an undertaking as large as the present one. Vision was required to continue with an infrastructure project that could give tangible results only after some years. Special appreciation is due Mr. William Warne, Dr. Howard Cottam, Mr. Robert Groves, Mr. Leonard Saccio, all the AID predecessors, and to Ambassador Lincoln Gordon. Others too numerous to name were also instrumental in vitalizing this project.

A succession of Directors-General of the DNPM devoted much time and effort to making this program a success, particularly Dr. Mario da Silva Pinto, Dr. Avelino Ignácio de Oliviera, and the late Dr. Antonio José Alves de Souza. The work was administered within the DNPM by the Divisão do Fomento de Produção Mineral; Directors who contributed most to the program were Drs. Alberto Ildefonso Ericksen and Irnack Amaral de Carvalho, later Director-General of the DNPM. Many other officials of the DNPM also contributed greatly to the work.

Among the Brazilian geologists who contributed freely of their knowledge were Glycon de Paiva, Othon Henry Leonardos, Octavio Barbosa, Francisco José Pinto de Souza, Iphygenio Soares Coelho, James Büchi, Luciano Jacques de Moraes, Elisário Tavora, Claudio Dutra, Manoel Teixeira da Costa, and Djalma Guimarães. This list is far from complete.

In charge of the Divisão do Centro of the DFPM during the fieldwork was Dr. José Alves, who was of unfailing assistance in innumerable ways to all the geologists taking part in this project.

The geologists who took part in the project are: B. P. Alves (1947–64), Burton Ashley (1953–54), A. L. M. Barbosa (1947–64), Aristides Noguiera da Cunha (1947–51), J. E. Gair (1954–56), P. W. Guild (1946–51), Norman Herz (1956–61), R. F. Johnson (1954–56), C. H. Maxwell (1956–62), S. L. Moore (1955–57), J. E. O'Rourke (1952–54), J. B. Pomerene (1950–58). R. G. Reeves (1958–59), G. A. Rynearson (1951–57), G. C. Simmons (1957–62), R. M. Wallace (1956–61), and Amos M. White (1956–58). Their contributions are not to be measured alone by their reports and maps. The interchange of ideas and observations within the group and with other geologists working in the area was stimulating and led to better understanding of all facets of the many problems. Wallace, Pomerene, Gair, Herz, Simmons, and Maxwell assisted in giving field experience to geological students of several Brazilian universities. Barbosa and Alves worked only part time on the project, devoting much of their effort to teaching in nearby universities during their work for this project. The writer was in charge of the project throughout (1946–64).

In addition to the above-mentioned geologists, other professionals have contributed greatly to the project. M. F. Denault, Edward Barner, and John Collins, topographic engineers, were indispensable in mapping topography by planetable during the difficult initial years of the project, and Denault laid out flight lines, obtained the aerial photographs, and initially planned the topographic-mapping program.

Most geologic and topographic maps printed with these reports were prepared in Brazil through the stage of color proof. Francis X. Lopez, cartographer of the U.S. Geological Survey, introduced into Brazil new techniques of preparing complex multicolor maps for publication, assisted by Celio Macedo, now head of the Secção de Cartografia of the DNPM. Geologists of this project are deeply grateful to Messrs. Lopez and Macedo for their assistance. The material was prepared by Brazilian companies under contract with the AID, under the quality control of Lopez and Macedo. The late Robert Kojima was also of notable assistance in programing and preparing illustrations for printing.

Without the full cooperation of the many mining companies active in the Quadrilátero Ferrífero, the work would have been much more difficult. In many of the areas studied, no living facilities exist except in the guesthouses of the active companies; hospitality was freely extended. In remote areas, mules were provided for transportation, and sometimes woodsmen who knew the trails and problems of the country were assigned to work with project geologists. The Companhia Vale do Rio Doce had a number of collapsed adits opened and pits dug to expose hidden geology; the St. John del Rey Co. shut down its hydroelectric system for a day so that a critical water tunnel could be mapped. With one exception, all companies freely provided all needed information on reserves, exploration results and analyses, production, and other necessary data. Without this information the work would have taken much longer and would have been much less complete. It is hoped that the results of the investigations will in some measure repay the friendly open-handed cooperation, typical of the country, which was received.

TRANSPORTATION

An asphalt-topped highway, BR-3, extends southward from Belo Horizonte to Rio de Janeiro, passing down the east flank of the Serra da Moeda for most of its length and thence southeast out of the region (pl. 1). Near Lagoa Grande the Estrada das Inconfidentes, a paved highway, branches east to Ouro Prêto, passing through Itabirito and Cachoeira do Campo. A paved highway to São Paulo runs north of most of the area, crossing the Serra do Curral in the Itatiaiuçu quadrangle. Another leads east from Belo Horizonte, for the most part north of the mapped area, to São Gonçalo de Rio Abaixo and Monlevade. This will eventually reach Vitória. A branch leads northeast to Itabira.

Other roads in the area were unpaved in 1962. They are for the most part transitable by jeeps for the entire year and by ordinary vehicles for most of the year. Small back roads should be attempted only in specialized vehicles; local information should be obtained on their transitability, which changes from year to year.

The railroad network is shown on plate 1. All railroads except the main line from Rio de Janeiro to Belo Horizonte, passing through Congonhas, Jeceaba, and Fêcho do Funil, are meter gage. The main line is broad gage (1.62 m). Most passenger transportation within the region is by bus. The transportation network is discussed in greater detail in the forthcoming chapter on the economic geology of the region. Frequent airplane service to most of the major cities of Brazil is available from Belo Horizonte.

CLIMATE

The climate of the Quadrilátero Ferrífero, which has had strong impact on the development of the landforms and economic resources of the region, is semitropical, and extremes of temperature are not known. Frost may occur in isolated valleys, but snow and ice have not been recorded. The maximum temperature is rarely over 30°C, and the mean annual temperature is slightly below 20°C in much of the region. Mean annual rainfall varies with location from somewhat under 1,500 mm (millimeters) to somewhat over 2,000 mm, increasing to the southeast.

The total rainfall varies greatly from one year to another, and the maximum is well over twice the minimum recorded. The rainfall is very seasonal. At Itabira, two-thirds of the annual precipitation occurs in 5 months, and the months of June and July normally pass without significant rains. In December, a week or two of almost continual rain is common; this may also occur in January. Throughout most of the rest of the year rain normally falls in short hard showers, accompanied by spectacular displays of lightning and very occasional destructive windstorms, particularly in September and October.

As can be imagined, the wide variation in precipitation, both in the annual cycle and from year to year, causes great fluctuations in the water table. This causes considerable hardship for those dependent on surface water and for hydroelectric plants.

Details of the local fluctuation in climate and in precipitation and temperature in the area were given in reports by Gair (1962), Dorr and Barbosa (1963), and C. H. Maxwell (written commun., 1964).

TOPOGRAPHY AND PHYSIOGRAPHY

From a physiographic viewpoint the Quadrilátero Ferrífero is one of the more scenic parts of Brazil. It is marked by high and rugged peaks, long chains of hogback mountains, high plateaus, some deep canyons, and pleasant open valleys. It is an area of great vistas, and, on a clear day, from the tops of the ridges and mountains one can see at least 100 km in many directions.

The region is astride the watershed between two major river systems, the São Francisco, which flows about 1,500 km north to within 9° of the equator before turning southeast to reach the sea, and the Rio Doce system, which flows 250 km northeastward and thence 200 km eastward to reach the sea. The maximum elevation in the region is about 2,100 m, in the Serra do Caraça; the minimum is about 600 m, where the Rio Piracicaba leaves the region.

DRAINAGE SYSTEMS

The major river systems were superimposed on the structure and thus are antecedent. These include the Rio Paraopeba in the west and the Rio das Velhas in the central part of the region; both are major tributaries of the São Francisco, the first joining that river about 140 km north of the Quadrilátero Ferrífero, the other, about 300 km north. The Rio Piracicaba drains the northeastern part of the region, and the Rios Gualaxo and Carmo the southeastern part; both join the Rio Doce, the former about 75 km northeast by east of Monlevade, the latter about 60 km east of Antônio Pereira.

The smaller tributaries of these major rivers are generally well adjusted to the structure of the rocks, seeking out the softer and less resistant formations, and, in the thicker and more uniform formations, following faults, joint systems, and bedding.

Many of the medium-sized tributaries of the major streams are well adjusted to rock structure in all but a few places. Stream piracy is still active; King (1956,

p. 197) remarked on the capture of the Rio Mata Porcos, originally a tributary of the Paraopeba, by the Rio das Velhas system. Radical changes in drainage direction have also been noted in the Itabira district (Dorr, 1964, p. 1236) and observed in other localities, such as the northern part of the Moeda syncline.

The Rio Paraopeba and its major tributary the Rio Maranhão drain the Quadrilátero Ferrífero west of the Serra da Moeda and the southwestern part to 4 km east of Ouro Branco and as far north as the middle of the Dom Bosco syncline (pl. 1). The Maranhão cuts the Serra da Moeda near Jeceaba, the only stream to do so in the 60-km length of this range; the water gap is narrow but not particularly steep. The Paraopeba in turn cuts the Serra do Curral at Fêcho do Funil in a narrow water gap, one of the two streams to breach this range in about 100 km.

The Rio das Velhas rises in the Mariana anticline (Antônio Pereira quadrangle) and flows over the southeast corner of the Bação complex in an open valley before entering deep, steep, and narrow gorges in entrenched meanders in the constriction of the Rio das Velhas uplift between Itabirito and Rio Acima. Between Rio Acima and the vicinity of Raposas the valley becomes broader, but the river again flows in deeply entrenched meanders to the north side of the Serra do Curral, near General Carneiro, where the valley again opens. This river drains the Moeda syncline, much of the Dom Bosco syncline, and all of the Rio das Velhas uplift as far east as the Serra das Cambotas. Deep and steep canyons in the Rio das Velhas Series rocks have been excavated by the major tributaries.

East of the Serra das Cambotas and north of Bento Rodrigues, drainage is by the Rio Piracicaba, which heads in the Conta Historia syncline (Capenema quadrangle). The upper reaches of this river and the valley near Monlevade are spectacular canyons, in the upper reaches largely following rock structure, in the lower reaches crosscutting structure in entrenched meanders.

The Gualaxo-Carmo system drains the southeastern part of the region and is characterized by deep narrow valleys, in part controlled by structure, in part crosscutting the structure.

Thus the master streams, most of which are entrenched deeply in the harder rocks and less so in the softer rocks and all of which cross the ridge-forming rocks at some point in their courses, must have been outlined at a time when the relief in the region was much lower. The central and western parts of the region are part of the north-flowing drainage general through much of central Brazil; the eastern part is drained across the geologic grain of the shield zone.

In the Quadrilátero Ferrífero, significant quantities of alluvium have been able to accumulate in only four areas: one near Mariana, one just north of Serra do Caraça, one on the Piracicaba upstream from the town of Rio Piracicaba, and one on the Rio das Velhas upstream from Raposas. Despite the deep weathering, the gradient of major and minor streams is steep enough to remove all the detrital material brought to the streams. A contributing factor is the fine particle size produced by the tropical weathering; relatively little coarse sand is produced. North of the region, however, aggradation is great; Burton (1869) reported that 100 years ago river boats of 40 tons burden came upstream from the São Francisco River as far as Sabará; today a rowboat would have difficulty except in the flood season. Most reservoirs silt up rapidly; silt encroached on the Rio de Pedras reservoir on the headwaters of the Rio das Velhas at least 1 kilometer during this work. Those in the Moeda syncline, however, where the land has been protected from overgrazing and destruction of the surface cover, did not silt up between 1946 and 1964.

INFLUENCE OF THE ROCK TYPES ON TOPOGRAPHY

Ease of weathering and erosion of rocks and stability of their weathering products clearly are important controls in topographic evolution. In general, the more complex the composition of the rocks and the finer grained the mineral constituents, the more easily the rocks are weathered in tropical and semitropical environments. Another general control of weathering is the degree of shearing and fracturing of the rock. A third control is the rock isotropism. From the interplay of these major controls and other minor ones with larger rock structures and with earth movements and climatic changes, the topography and physiography of the region evolved.

GRANITIC ROCKS

The granitic rocks of the Quadrilátero Ferrífero are in general the least resistant rocks of the region to weathering and thus to erosion. They form broad lowlands, low rolling hills, and relatively gentle slopes and are dissected by a dendritic drainage pattern. Weathering in granitic rock generally extends to a depth of 50m or more.

Most granitic rocks of the region break down to a clayey pink soil and saprolite. Locally the soil is highly aluminous and even somewhat bauxitic. The soil and saprolite are subject to rapid and intense gullying where the protective surface of grass or forest is broken by mule trails, overgrazing, improper cultivation, or deforestation. The large area of badland topography in the southeastern part of the Bação complex is but one of many examples of soil destruction.

In many of the granitic areas resistant ribs and knobs of unweathered granitic rock survive; these form bold smooth outcrops and waterfalls with very spectacular pot holes in many localities, as along the Rio Arrudas between Belo Horizonte and Marzagânia (Belo Horizonte quadrangle). In some areas, such as the Caeté complex in the Antônio dos Santos quadrangle, only about 0.001 percent of the granitic terrain is fresh granitic outcrop; in others, as along the west flank of the Serra da Moeda in the Marinho da Serra quadrangle, possibly as much as 25 percent of the granitic area is relatively fresh outcrop.

Certain granitic rocks crop out boldly and are much more resistant to erosion and weathering than the average. Such rocks as the Borrachudos Granite in the Itabira district, the Florália, and Santa Bárbara quadrangles well exemplify the effect of lack of jointing, coarse grain size, and isotropic structure on weathering. In the Itabira district the Borrachudos Granite stands in bold relief above the foliated and jointed granitic gneiss of somewhat similar composition. In the Monlevade area certain of the other coarser grained and more massive granitic rocks are also very resistant to erosion.

The interface between fresh granitic rock and saprolite varies radically; in some quarry faces a complete transition can be seen in a few centimeters, but elsewhere the transition is more gradual and occurs over a number of meters. Exfoliation is the rule on the interface.

ARGILLACEOUS ROCKS

The argillaceous rocks of the region are now largely phyllite and schist. They are readily and deeply weathered. Saprolites are found to great depths; the writer has been in adits more than 100 m below the surface in which weathered schistose rock can be smeared into paste between the fingers.

In the Itabira district not one natural outcrop of fresh schistose rock was found. Few fresh outcrops were found in other areas, and fresh argillaceous rocks are generally unknown except in deep gold mines and railroad tunnels deep in canyons. Because of their general disaggregation, argillaceous rocks are nonresistant to mechanical erosion, and many of the deeper canyons have been excavated in them, particularly in the Rio das Velhas uplift.

Many of the fine-grained phyllites in the Piracicaba Group of the Minas Series and some of the phyllitic rocks of the Itacolomi Series are particularly subject to landslides and soil creep where overgrazing, deforestation, gold mining, highway construction, or other activities of man have disturbed the dynamic equilibrium between slope, climate, vegetation, and soil competence. Many hillsides in such rocks are corrugated by creep and pocked by landslide scars. Because the phyllitic saprolites are easy to excavate, they have been preferred for highway alinements, but the poor mechanical qualities of the fills and the unstable profiles of the cuts have often made original savings illusory. Along the highway from Cachoeira do Campo to Mariana, some stretches have been abandoned entirely; others have not stabilized in 10 years.

The argillaceous rocks in many places are slightly cemented or replaced at the surface by bauxite or limonite, depending on the composition of the rock. This cement serves to hold the surficial layer, from 1 to 10 cm (centimeters) in thickness, against mechanical erosion and permits the formation of steep and oversteepened slopes until this carapace is breached, after which erosion is rapid.

QUARTZOSE ROCKS

The quartzose rocks of the region have several modes of topographic expression, depending primarily on their composition and secondarily on stratigraphic thickness and on the degree of shearing and fracture to which the rocks were subjected. Graywacke intermediate in composition between argillaceous and quartzose rocks weathers most rapidly and deeply, and fresh outcrops of such rocks are rare indeed. Subgraywacke and protoquartzite are more resistant to weathering and erosion but commonly do not crop out well except where they occur as thick massive beds. Outcrops of arkose are unknown. Outcrops of arkosic quartzite and feldspathic quartzite are known in several formations, although the feldspar has been altered at the surface in most places.

Many quartzites contain notable quantities of muscovite and sericite. Such rocks, found particularly in the Maquiné Group and in the Moeda Formation, are very resistant to erosion and in many places form bold ridges and outcrops, particularly where the rocks are massive. Where thin bedded or strongly sheared, they weather and erode readily. With decreasing quantities of white mica, the quartzites are increasingly resistant to mechanical and chemical erosion. The massive orthoquartzites of the Cambotas and Moeda Formations are among the most resistant rocks in the region, forming great ridges and scarps. Weathering in such rock is by intergranular solution of quartz; where the rocks were structurally crushed, very fine white sand, locally pure enough for use as glass or foundry sand, may accumulate between outcrops. Sericite breaks down to clay, but coarse muscovite is resistant to weathering. Soil derived from such rock is, of course, sterile, and the rocks crop out in small craggy patches and larger bare areas with a sparse and specialized flora where the general surface is level.

One quartzite, the Taboões, is exceptionally pure, containing 98 percent silica. For some reason, this quartzite is commonly deeply weathered and disaggregated; perhaps the even and small grain size promotes intergranular leaching.

DOLOMITE

The carbonate rocks of the region vary greatly in composition and therefore in reaction to erosion and weathering. Pure massive dolomite is in many places fairly resistant to erosion and to solution and forms scarps and a peculiar hummocky type of topography, as along the northwest side of the Rio Socorro (pl. 1) near its headwaters (Gandarela quadrangle). Soil formed on dolomite is clayey, and in most places dark brown or black from small amounts of manganese and iron commonly present; such soil is very fertile. One weathering product of dolomite was described at length by Guild (1957, p. 42) as a peculiar spongy material in which the outlines of the original crystals are preserved by limonite and (or) manganese oxide.

Phyllitic dolomite and dolomitic phyllite are among the least resistant rocks of the region to weathering. They form a deep saprolite and generally underlie gentle slopes. Quartzose dolomite is in many place less resistant to chemical weathering than pure dolomite but may crop out prominently.

Many bauxite deposits in the region are closely related to argillaceous dolomite or dolomitic phyllite of the Gandarela and Fêcho do Funil Formations; they occur where removal of the weathering product has been prevented by the physiographic environment of the deposit or by the development of a hard aluminous and ferruginous crust over the deposit.

Sinkholes are known on the Gandarela Formation. All but one of the larger ones are in the Gandarela syncline (pl. 1). One is on the west flank of the Serra do Itabirito about west of the town of Itabirito, the Lagoa das Cobras.

IRON-FORMATION

Four types of iron-formation crop out in the region: itabirite, dolomitic itabirite, amphibolitic itabirite, and carbonate-facies iron-formation. Except in canyons and other small areas of accelerated mechanical erosion, only normal itabirite, composed of hematite, very minor magnetite, and quartz, crops out fresh. Fresh normal itabirite is also not a commonly occurring rock but is known in canyons, in a few areas on ridgelines, in monadnocks projecting above the ridgelines, and in landslide scars on oversteepened slopes. Some of the highest monadnocks, such as the Serras da Piedade and Itatiaiuçu, are composed of such rock, which there produces rugged and spectacular topographic forms.

CANGA

Canga is a weathering product of iron-formation and caps most of the major ridgelines in the region. It is essentially iron hydroxide cementing larger or smaller quantities of detrital iron-formation, also generally hydrated at the surface, and of hematite. This rock, inert to chemical weathering and very resistant to mechanical weathering, forms smooth slopes and plateaus. Most of the higher old erosion surfaces are preserved by canga, and the rock is now forming on lower benches, flat valleys, and pediments.

HEMATITE

Large masses of hard high-grade hematite are the most resistant rocks of the region to weathering and mechanical erosion. Certain ore deposits form spectacular crags and scarped features visible for many kilometers. This rock may break down on weathering into soft noncoherent hematite (Dorr, 1965, p. 42–43) which crops out naturally in very few places.

PHYSIOGRAPHIC DEVELOPMENT

The physiographic development of the Quadrilátero Ferrífero is conditioned not only by the lithology and structure of its rocks but also by a complex history of epeirogenic uplift. Observers since Harder and Chamberlin (1915, p. 370–378) have commented on the several distinct levels of erosion preserved in the region. Recently King (1956) attempted to relate these levels to others preserved in eastern Brazil, giving names to four of them and assigning them ages on the basis of fossiliferous rocks overlying erosion surfaces outside the Quadrilátero Ferrífero.

King's work consisted of a reconnaissance of eastern Brazil from Bahia to the southern part of São Paulo and much of central Brazil west of those limits. The work was done in 2½ months, during which time he traveled 21,000 km by jeep, much of it over very poor roads, averaging 280 km per day, a feat of endurance not likely soon to be equaled. Adequate topographic base maps in much of this part of Brazil were then nonexistent; those then available in the Quadrilátero Ferrífero, at a contour interval of 100 m, were inaccurate, elevations being in error as much as 100 m. Under these circumstances it could not be expected that the details of correlation of erosion levels could everywhere be accurate or complete.

Despite these handicaps, King's work was a distinct contribution to the problem, representing as it did the first attempt to relate the ancient surfaces of the Quadrilátero Ferrífero to those so well developed in other parts of Brazil. Elsewhere some of these are fossil surfaces, being overlain by sedimentary rocks which have been dated by their fuana and flora. Within the Quadrilátero Ferrífero only one surface is overlain by suprajacent fossiliferous rocks; the age of the higher and older surfaces is unknown. The staff of the present project had no opportunity to try to correlate the erosion levels within the area studied with those outside their area of immediate interest, and thus the validity of King's interregional correlations cannot be confirmed. It is the writer's opinion, not shared by all members of the staff, that the ages assigned by King to the highest surfaces may be generally correct, although certainly no proof of this now exists.

Table 1 lists eight major erosion levels observed in the Quadrilátero Ferrífero during this work. King specifically mentioned four of these surfaces and assigned definite ages to them; it was not possible to agree with all his assignments, but the main scheme of King's erosion levels and nomenclature has been followed. Closer and specialized study undoubtedly will reveal new facets of the physiographic problems not here considered and will correct errors made herein. Such a study would be most useful from many viewpoints; it was outside the scope of the present project.

TABLE 1.—*Erosion levels, Quadrilátero Ferrífero*

[Modified from L. C. King (1956)]

Elevation (meters)	Area of best development	King's assigned age	King's name
2,000-2,100	Serra do Caraça		
1,750-1,850	Serra do Caraça-Itacolomi		
1,500-1,650	Conta Historia-Tutamea	Triassic	Gondwana.
1,250-1,400	Serra de Rola Moça-Moeda syncline.	Cretaceous	Post-Gondwana.
1,100-1,200	Flanks of Serra do Curral		
1,000-1,100	Lagôa Seca-Central Gandarela syncline.		
850-950	Rio das Velhas valley-Chapada de Canga.	Mid-Tertiary	Sul-Americano.
700-750	Rio das Velhas valley	Late Tertiary	Velhas.

Five erosion cycles in eastern Brazil were named by King: the Gondwana, post-Gondwana, Sul-Americano, Velhas, and Paragasu. Of these, only the first four are represented in the Quadrilátero Ferrífero. The surfaces destroyed by these erosion cycles, given the same names as the cycles, are naturally older than the time of their destruction and were dated by the sediments deposited on them.

King visualized that the destruction of the surfaces occurred by pediplanation and that the destruction of two or more surfaces may have been going on at the same time; thus, since the oldest, no cycle has gone to completion throughout the area as a whole. There is reason to suppose that still older surfaces existed at the time the oldest named cycle began, a possibility admitted by King.

The best preserved old surfaces are all underlain by canga, the most evenly resistant widespread rock of the region and the only one which, because it is a weathering product, regenerates itself (Dorr, 1964, p. 1234). Because of this self-renewing feature, the rock surfaces underlain by canga are probably the only ones which even approximate the original levels. Other surfaces on quartzite and other rocks have been modified and lowered by later erosion to such a degree that very little if any of the original surface remains, although the topographic feature is preserved in more or less modified form.

The highest erosion remnant is the relatively flat top of the Serra do Caraça, more than 2,000 m above the sea. Maxwell (written commun., 1964) pointed out that this surface is locally overlain by deposits of well-rounded coarse gravel and cobbles. Nowhere else in the region is this level preserved by a relatively flat surface. More than 100 km to the north, the Pico de Itambé, 2,038 m above sea level, may also represent this surface. King and others have suggested that this high surface may represent a Paleozoic erosional plane; 250 km to the west, Permian and Carboniferous sedimentary rocks rest on a planed surface of Precambrian rocks (J. C. Mendes, written commun., 1963).

Other high peaks and surfaces such as those around Pico de Itacolomi, Serra do Batatal, the Serra da Piedade, and in the Serra do Caraça may indicate the presence of another high erosion level between 1,700 and 1,850 m, but its age is unknown. Although King correlated both these high surfaces with his Gondwana surface, the abrupt relief between such areas as the Serra do Batatal and other nearby surfaces at more than 1,800 m, the Serra do Ouro Fino at more than 1,600 m and the southwest end of the Gandarela syncline at more than 1,600 m, all of which he also correlated with the Gondwana surface, makes such a correlation of the higher surfaces questionable.

The highest surface generally present in the region is that named the Gondwana surface by King. King believed that the surface several hundred kilometers to the west that he also called the Gondwana underlies the Botucatú Formation of Triassic age and the Upper Jurassic plateau lavas; thus, it there must predate those rocks. Within the Quadrilátero Ferrífero, no mode of dating this surface is known, and continuity of the surface to the areas of dating is not certain. If, as is conceivable, the mafic dikes of the Serra do Caraça are of the same age as the Upper Jurassic and Lower Cretaceous plateau basalts of the Paraná basin, the ages assigned by King to the older surfaces must be radically revised and the surfaces will be much younger, for no remnant of the flows which should have been on these old surfaces now remains. If, on the other hand, the Caraça mafic dikes are much older than the basalts,

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King's age assignments may well be correct. As yet the necessary age determinations on the mafic dikes have not been made, and no outcrops of this rock fresh enough to permit accurate work are known.

The Gondwana surface is preserved today as high areas of subdued relief or as ridgelines generally accordant with such areas. With the exception of the monadnocks mentioned, these are the highest parts of the region. King cited the ancient surfaces at the west end of the Gandarela syncline at elevations of about 1,500–1,650 m as belonging to this cycle. The Conta Historia area clearly belongs to the same cycle and lies at an elevation of about 1,550 m, as does the top of the Serra do Ouro Fino, at more than 1,600 m. To the west, on the western side of the Rio das Velhas, the highest peaks of the Serra da Moeda and the Serra do Itabirito belong to this cycle. The ridgetop at Tutamea in the Serra da Moeda (Lagoa Grande quadrangle) is a broad area of rolling topography that is perhaps the largest remnant of this surface. It lies between 1,500 and 1,550 m, and most of the sharp ridgeline of the Serra da Moeda is between those elevations, except at the south end. The Serra do Itabirito is generally somewhat lower, but the highest ridges are also above 1,500 m, and a few have flat tops as well. The Serra da Piedade has a prominent surface between 1,530 and 1,550 m.

According to King (1956, p. 200), the Gondwana surface lies at about 1,400 m in the Serra do Curral. This writer doubts that the Gondwana surface is preserved in the Serra do Curral south of Belo Horizonte, except possibly in Pico de Belo Horizonte. At the west end of that range in the Igarapé quadrangle, two isolated flat-topped peaks above the general level of the ridge are above 1,400 m; these might be relicts of the Gondwana surface.

In the southern part of the region, many ridges lie near 1,500 m in elevation in the Ouro Prêto area, but in the Serra do Itacolomi there is no apparent surface at this level, although a well-defined level at about 1,450 m and another at about 1,650 m are present. The Serra do Ouro Branco, to the west, is capped by an ancient broad erosion surface between about 1,450 and 1,500 m which may represent the Gondwana surface.

According to King, the next younger surface, the post-Gondwana, underlies lower and middle Cretaceous sedimentary rocks outside this region; he said that the post-Gondwana cycle was incomplete and few large surfaces were produced. One of the best surfaces is the Serra da Rola Moça (elev 1, 350–1,450 m), part of the Serra do Curral some 15 km southwest of Belo Horizonte (fig. 2). In the writer's interpretation, much of the Serra do Curral west of Belo Horizonte is controlled by this surface, above which protrude some monadnocks, such as Itatiauçu in the Igarapé quadrangle. In the west end of the Serra do Curral a widespread remnant of a surface at about 1,300 m is preserved; this surface is somewhat higher to the east.

FIGURE 2.—Post-Gondwana surface preserved on canga sheet, Serra da Rola Moça. Note typical abrupt topographic unconformity and monadnocks in the background. Lowland in the background is on granitic gneiss; the ridgeline is on Cauê Itabirite. Elevation about 1,350–1,370 m. View is to west-southwest.

Although King correlated the surfaces at about 1,100 m in the Serra do Curral south of Belo Horizonte with his post-Gondwana surface, the writer believes that this well-defined erosional level is better correlated with a younger surface not named by King. There is a very well developed higher surface, clearly younger than the Gondwana surface, between 1,300 and 1,400 m in much of the region south of Belo Horizonte which the writer correlates with King's post-Gondwana level. Many broad, gently rolling surfaces, which the writer refers to the post-Gondwana cycle, are found in the Moeda syncline, dissected by younger deeply incised streams (fig. 3). In the Marinho da Serra quadrangle, very well preserved canga-covered pediments are found on this surface (Wallace, 1965, plate 2); such canga-covered pediments were probably very common before destruction by later erosion. In the eastern part of the Dom Bosco quadrangle, eight rounded hills culminate between 1,400 and 1,460 m.

On both the east and the west sides of the Rio das Velhas valley, broad dissected surfaces are developed around 1,200–1,300 m, particularly on the east side, where the resistant quartzose rocks of the Maquiné Group have preserved the surface. (See pls. 5 and 6, this report, and Gair, 1962, pls. 1 and 2.) To the south, much of the area in the west half of the Dom Bosco syncline may represent dissected remains of this surface, also younger than the post-Gondwana. (See Johnson, 1962, pls 1 and 2.)

FIGURE 3.—Ancient surfaces on the Moeda Plateau, Lagoa Grande quadrangle. Ridge in the far background is on Cauê Itabirite, elevation about 1,500 m, corresponding to the Gondwanda level. The rugged scarps in middle distance are on the Cercadinho Formation, top about 1,350 m, corresponding to the post-Gondwana surface. Other remnants of this surface are visible to the left. Dissected foreground surface is about 1,250 m. View is to the northeast.

To the east, correlation with King's older surfaces is much more tenuous. The structure of the rocks is more complex, the country is more broken, and erosion more complete. It is possible that the broad surface between 1,150 and 1,300 m on top of the Serra das Cambotas might correspond to the post-Gondwana surface. South of the Serra do Caraça the country is most broken and the terrain is dominantly phyllitic. Conceivably the crest of the Alegria hogback in the Capanema and Santa Rita Durão quadrangles, about 1,375 m in elevation, may correspond to the post-Gondwana surface, but this is not certain. Another erosional remnant, Pico do Frazão, is 1,350 m in elevation and has a large, relatively flat area above 1,200 m. In most of the southeastern and eastern Quadrilátero Ferrífero, there are no identifiable remnants of the post-Gondwana surface.

According to King, the post-Gondwana surface began to be destroyed in the Late Cretaceous. The next major erosion surface cited by him was called the Sul-Americano, supposedly formed during the middle Tertiary, as he believed that the surface is overlain by the Barreiras Formation of central and northern Brazil. This surface was stated to be well developed in Minas Gerais and in the Quadrilátero Ferrífero at an elevation of about 930 m near Itabirito and 850 (?) m south of Belo Horizonte.

However, in the Serra do Curral south of Belo Horizonte a well-developed surface exists at about 1,100 m below the post-Gondwana and above the Sul-Americano surface. The writer believes that King either missed an important surface in this area or confused two surfaces because of the lack of adequate maps. Lagoa Seca, about 2 km south of the city on BR-3, is one remnant of this intermediate surface. The flat on the Cercadinho Formation just northwest of Pico do Belo Horizonte, and many other local shoulders and breaks in slope at about this elevation both to the east and west of Belo Horizonte, some of them canga covered, also represent this level. The common and locally large pediments both on the north and on the south sides of the Serra do Curral farther to the west (Pomerene, 1964, pl. 3) head at about this level. Many of the tops of rolling hills in the granitic and argillaceous areas of the Quadrilátero Ferrífero approximate this elevation, particularly in the Bação complex. The south flank of the Gandarela syncline, an old flat surface pocked with sinkholes, approximates this elevation almost to Barão de Cocais. Johnson (1962, p. B30) pointed out that very well developed terraces are to be found at elevations between 1,100 and 1,200 m north of Morro do Caxambu (Dom Bosco quadrangle). Because of these features, the writer believes two major surfaces developed between King's post-Gondwana and Sul-Americano surfaces. No elements for dating them are known.

The Sul-Americano erosion cycle is marked, according to King, by broad surfaces and terraces at elevations between 1,000 and 850 m. Such surfaces are clearly defined along the Rio das Velhas, east of the Serra do Caraça, and in the Paraopeba Valley. The largest remnant is probably the Chapada de Canga (Catas Altas and Santa Rita Durão quadrangles), where an ancient pediment carved on the Minas Series rocks at its west end merges into an area covered by the Fonseca Formation (Maxwell, written commun., 1964), Tertiary fluviatile and lacustrine sediments deposited on a planed granitic surface, at the east end. The Sul-Americano surface is naturally below the sedimentary rocks; it might represent an old wide river valley or might be a much wider surface. About 10 km east of the east limit of the Santa Rita Durão quadrangle lies Fonseca, near which town thin beds of lignitic material with plant fossils said to be late Tertiary in age underlie the canga cap of the Chapada de Canga. This large canga surface very probably covered a much greater area in its original form; it is gradually being destroyed. The Piracicaba River has incised a canyon 100 m deep through the canga and Tertiary sediments into granitic rock. Because upper Tertiary sediments have accumulated on the erosion surface on the granite, this surface is possibly middle Tertiary, as stated by King.

The youngest erosion cycle, the Velhas, is marked by deep canyon cutting, and King referred the entrenched meanders of the Rio das Velhas and other rivers of the region to this cycle, supposed to have started in the late Tertiary. Some of these canyons are as much as 200 m below the wide terraces marking the Sul-Americano cycle. (See fig. 4.)

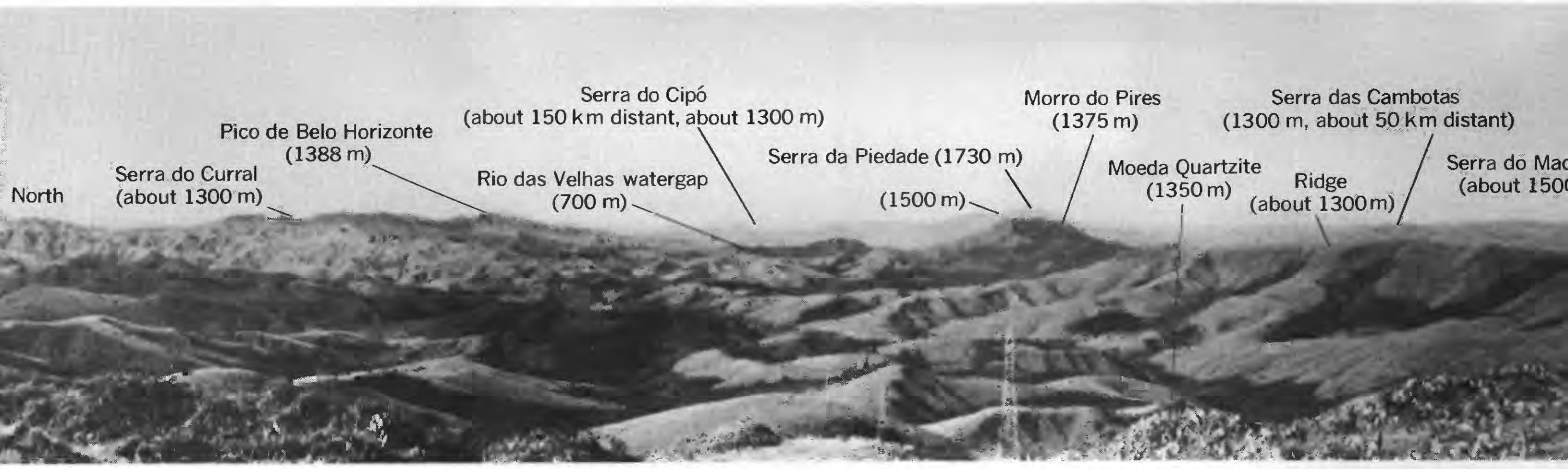

FIGURE 4.—Panoramic view from near N. 3,200 E. 6,550, Macacos quadrangle, looking from north to nearly east. Camera elevation is 1,400 m. Crags in the foreground are Moeda quartzite; dissected rocks of the Nova Lima Group are in the middle distance; ridgelines on the horizon are Minas Series rocks. Serra da Piedade is 40 km, and Pico de Belo Horizonte about 20 km, from camera. Rio das Velhas, the master stream, flows in entrenched meanders behind Morro do Pires northward through the watergap in the Serra do Curral.

Long-continued weathering of the higher surfaces has had important economic consequences in the Quadrilátero Ferrífero. If King's age assignments for these surfaces are correct, the Gondwana and post-Gondwana surfaces have been exposed to weathering for more than 100 million years. As discussed in another paper (Dorr, 1964), these higher surfaces are the ones under which the major deposits of iron ore of supergene origin have formed. Under the younger surfaces, some concentration of iron is known and locally thick beds of canga have accumulated, but the major supergene iron ore deposits are below the older and higher surfaces. The accumulation of bauxite is less dependent on the age of the surface, for such deposits are known on all except the Velhas surface. Manganese deposits, concentrated to economic grade by supergene action, are also less dependent on the age of thé surface. The major manganese deposits all occur at higher elevations, and only one with commercial production can be related to the Velhas cycle. None of the high-grade lode gold ores concentrated by supergene processes are related to low-level surfaces, although of course the lower grade primary sulfide gold ores have no relation to present erosion surfaces.

STRATIGRAPHY

The Precambrian metasedimentary rocks of the Quadrilátero Ferrífero were first formally named by Derby (1906, p. 396–397) as the Minas Series:

The schistose series of the Serra do Espinhaço [this includes the Quadrilátetro Ferrífero] and adjacent regions, which may conveniently be denominated the *Minas Series*, consists of a great complex of predominantly argillaceous schists, with subordinate masses of ordinary quartzites, ferruginous quartzites (itabirites passing to pure iron ores), and limestones. All of these rocks are greatly sheared, and characterized by a greater or less development of a micalike mineral (biotite, sericite, micaceous hematite, chlorite, talc, etc.); and, as in general they are much decomposed, there is great difficulty in distinguishing the different members (except the quartzose and ferruginous ones), and thus far no successful attempt to work out the order of succession in them has been made. It is tolerably certain that the quartzose, ferruginous, and calcareous members are repeated at various horizons, and eventually they will serve as reference lines for establishing the subdivisions of the series; but before this can be done the repetition due to folding and faulting must be determined and taken into account. Apparently the whole series has been bent into closely appressed overturned folds, and doubtless it has been much faulted. Until the region, or at least a typical portion of it, has been accurately mapped, any attempt to determine its detailed structure is hopeless.

Since Derby's work, continuing efforts have been made by geologists to perfect the order of succession and to clarify the structural and stratigraphic complexities of the rocks and the region. The following pages are the latest, but certainly not the last, effort to bring order into the very complex relations seen and described by the great pioneer geologist. The present effort is, however, the first based on the careful regional mapping demanded by Derby more than half a century ago.

As a result of this mapping, related as closely as possible to earlier studies of many geologists, the Precambrian stratified rocks of the Quadrilátero Ferrífero have been divided into three series; one named formation of Tertiary age and several unnamed units of rocks of presumed Tertiary or Recent age have also been recognized. Plate 12 gives the stratigraphic column as used in this report and a summary of the lithologies of the formations, compares this column with several others worked out by earlier writers, and attempts a correlation between the various columns. Description of the rocks as here classified will precede discussion of the development of nomenclature.

In many Precambrian strata, metasedimentary rocks that may be clearly divided into mappable stratigraphic units at one place may elsewhere be so metamorphosed that the original distinguishing characteristics cannot be seen. All rocks may be gneissified in areas of greater metamorphism, as in the Itabira district, or more susceptible units may be so changed, as in the Monlevade area, where certain lithologic units have been gneissified and others remain identifiable. In this project, completely reconstituted gneissic rock in which all characteristic features of original sedimentary units have been destroyed is considered new rock formed at the age of its metamorphism. In the Monlevade area, some stratigraphic units can be correlated with confidence with named units in the rest of the region but are separated by gneissified units whose stratigraphic position corresponds to pelitic or dolomitic rocks in the normal stratigraphic section. Names were assigned these gneisses (Reeves, 1966), and they are tentatively correlated with the less metamorphosed rocks known elsewhere in those intervals. Such gneissic rocks commonly have distinctive features other than their stratigraphic position.

As in all Precambrian terrane, the lack of fossils requires that correlation be based on lithology. The varying grades of metamorphism and degrees of structural disturbance combined with changing primary sedimentary facies introduce uncertainty into the resolution of several stratigraphic problems.

In the Quadrilátero Ferrífero, certain distinctive sequences of rock types are widespread and were used with confidence in correlation. Sequence of rock types proved far more reliable than examination of individual rocks or specimens either in the field or, particularly, with the microscope. A few rocks, such as itabirite and certain varieties of ferruginous quartzite, and specific sedimentary features, such as characteristic pebbles, proved to be helpful guideposts in establishing positions in the stratigraphic section. On the other hand, the use of minerals which could have had either a sedimentary or a metamorphic origin, such as feldspar, proved unreliable as stratigraphic guides.

For the reasons cited, correlation of the rocks within the Quadrilátero Ferrífero with widespread areas of rocks of similar appearance and metamorphic grade outside this region has not been attempted and is perilous except on the basis of detailed mapping. Although itabirite crops out in many parts of the Brazilian Shield, and in the past such rock has been correlated with the Minas Series of this area, it is now known that itabirite occurs in this region in each of two groups in two of the series and in a rock of clastic origin generally similar in lithology that is in the third series. All three series are separated by profound unconformities indicating great time lapses. Clearly, no interregional correlation based solely on the presence of itabirite is well founded.

Similarly, although the orthoquartzite forming the Serra de Tiradentes at São João del Rei, some 100 km to the southwest, is very similar in lithologic and sedimentary features to the main quartzite of the Tamanduá Group and the phyllitic rocks underlying it with angular unconformity to the Nova Lima Group, elements to make a secure correlation are not yet available. The writer believes, on the basis of discontinuous outcrop of the characteristic manganese carbonate-silicate beds associated with graphitic phyllite between the Lafaiete district and São João del Rei (Dorr and others, 1956, p. 286; Ebert, 1963), that the phyllitic rocks there are Nova Lima Group; but until detailed mapping has proved this, it cannot be considered to have been established.

Correlation over wide areas by the aspect or mineral composition of quartzites is equally perilous; detailed tracing of beds in this region shows that facies, thickness, and mineral composition all change rapidly and that metamorphic and tectonic variation give the same stratigraphic unit different aspects at different localities.

The stratigraphic sequence presented in this paper is the synthesis of the work of many geologists. Those who contributed most to the detailed subdivision of the Minas Series were G. A. Rynearson and J. B. Pomerene, who investigated areas in which the stratigraphic sequence of the Minas Series was not severely deformed, faulted, or highly metamorphosed. J. E. Gair and J. E. O'Rourke made the greatest contributions to the understanding of the Rio das Velhas Series, and G. C. Simmons and C. H. Maxwell described and named the Tamanduá Group. A. L. M. Barbosa, P. W. Guild, R. M. Wallace, and C. H. Maxwell contributed most to a fuller understanding of the Itacolomi Series. Naturally, the DNPM–USGS staff drew on the valuable stratigraphic information provided by predecessors in the region, particularly Derby, Guimarães, Harder and Chamberlin, Freyberg, L. J. Moraes, F. Lacourt, and O. Barbosa.

RIO DAS VELHAS SERIES

The Rio das Velhas Series was defined by Dorr, Gair, Pomerene, and Rynearson (1957) as comprising those schistose metasedimentary and metavolcanic rocks in the Quadrilátero Ferrífero older than the Minas Series.

These rocks were then divided by those authors into two groups: the Nova Lima Group, the older, and the Maquiné Group, the younger. In 1961 Simmons and Maxwell defined a still younger group which they included in the Rio das Velhas Series and named the Tamanduá Group, which did not crop out in the area previously studied. The writer considers these rocks to be Minas Series, and they will be discussed under that heading.

The Rio das Velhas Series, as shown on plate 1, is the most widespread stratigraphic unit in the Quadrilátero Ferrífero and occurs in generally anticlinal areas. These rocks have locally been subjected to strong metamorphism and metasomatism. It is possible that much of the area shown on plate 1 as granite was derived through ultrametamorphism or granitization from the Rio das Velhas Series, for locally the granitic gneiss grades into rocks of this series (Dorr and Barbosa, 1963, p. 41–42; also fig. 24, this report).

The rocks of the Rio das Velhas Series can be traced out of the Quadrilátero Ferrífero to the south, to the west for an unknown distance, and to the east, where they soon give place to younger granitic rocks. They cannot be traced to the north, where Minas Series rocks are superposed and granitic rocks intervene.

NOVA LIMA GROUP

Subdivision of the Nova Lima Group into named formations was not attempted during the mapping because deep weathering, thick soil, and saprolite cover made such a separation impractical in the available time. Rocks believed by the writer to be the equivalent of the Nova Lima Group were subdivided into formations in the area to the south and southwest of the Quadrilátero Ferrífero by Ebert (1963).

As shown on plate 1, many of the more easily mappable lithologic units were traced in the Quadrilátero Ferrífero, giving a general idea of the structure of these rocks. A. F. Matheson (oral commun.) studied these rocks for the St. John del Rey Mining Co. and prepared an unpublished map at a scale of 1: 60,000 of the region south of Belo Horizonte and north of Itabirito in which he distinguished two major units in the Nova Lima Group rocks, one dominantly quartzose, the other dominantly phyllitic. The quartzose rocks, which crop out in the axial area of an anticline, are the older.

Simmons (1968a, p. G9), as a result of mapping in the extreme western part of the Quadrilátero Ferrífero, distinguished two stratigraphic facies in the Nova Lima Group by the presence or absence of iron-formation and ferruginous phyllite in those rocks. The ferruginous rocks there were believed to be younger than the nonferruginous phyllites. Tolbert (1964, p. 780–781), following Callaghan (private rept.), distinguished three stratigraphic zones in the Nova Lima group in the Raposas-Morro Velho area, two of which contain iron-formation. He stated that it is impossible to tell which zone is the oldest. Others who have mapped in the general region have expressed no opinion as to the divisibility of the rocks into formations, but most have mapped individual units, including iron-formations, quartzite and conglomerate zones, graywacke, graywacke schist, and other rocks in the dominant chlorite-sericite-quartz phyllite and schist.

The writer believes that, when it proves economically justifiable, the Nova Lima Group will be subdivided by careful mapping into more than two formations and that much structural information can be gained in the process.

CONTACTS AND THICKNESS

The Nova Lima Group is apparently the oldest of the subdivisions of the Rio das Velhas Series. Gair showed that it is unconformably overlain by the Maquiné Group (1962, p. 33) in the type localities of these formations in the Rio das Velhas valley. To the east, the contact between these groups in the valley of the Rio Conceição (Capanema, Conceição do Rio Acima, and Catas Altas quadrangles) is indeterminate as to age relations because the contact is poorly exposed and may be faulted for some of its extent (Maxwell, written commun. 1962); Moore, 1969). In the Antônio pereira and Santa Rita Durão quadrangles the contact is also indeterminate. The simplest structural solutions in these areas would suggest that the Nova Lima Group is the older, as shown by Maxwell in a series of block diagrams of the quadrangles mapped by him (written commun. 1962).

The base of the Nova Lima Group has not been recognized anywhere in the mapped area. The rocks are so strongly deformed and weathered that normal top and bottom criteria are obliterated. Where the Nova Lima rocks are in contact with granitic rocks, the contact is everywhere an intrusive one, as discussed below.

Because the stratigraphic top and bottom of the Nova Lima Group are both unknown, the original thickness of the unit is also unknown. Structural complications make estimates of thickness hazardous, but it is probable that not less than 4,000 m of sedimentary rock is exposed in the Rio das Velhas valley. Exposures elsewhere are less complete, but an equal or greater thickness may be present in the Caeté quadrangle and in the Congonhas-Ouro Branco area.

LITHOLOGY

Because of inadequate outcrops, deep weathering, complex structure, and, particularly, the nature of the rocks themselves, the Nova Lima Group cannot be systematically described from a stratigraphic viewpoint; only the lithology of the rocks studied can be discussed. The rocks of the Nova Lima Group have been described in most detail by Gair (1962, p. 9–29), who was favored by many extensive underground workings and drill holes in fresh rock in the vicinity of gold mines. His work, carried on in the type locality of the group, is the most complete description of these rocks. Gair also studied the petrography of the Nova Lima Group as revealed in drill cores from the Itabira district (in Dorr and Barbosa, 1963, p. 10–16). O. Barbosa (in Guimaraes, 1935) published petrographic descriptions of many of the rock types in the Nova Lima area. (These rocks were then included in the Minas Series because the unconformity that is the present basis of the separation of the Minas Series as now defined from the Rio das Velhas rocks had not then been recognized.) Wallace (1965) was fortunate in having several railroad tunnels and a few other fresh outcrops available for study in the Itabirito quadrangle; Guild (1957, p. 20–22) described rocks in the Congonhas area, now correlated with the Nova Lima, as the "greenschist sequence" of the Minas Series from cores and a few fairly fresh outcrops. Because little fresh rock of this group has been found elsewhere in the region, detailed petrographic descriptions are elsewhere unavailable. Easily weathered rocks, such as graywacke, are undoubtedly much more common than reported.

Most rocks of the Nova Lima Group weather to buff, red, pink, and purple saprolite, in many exposures retaining a strong banding which is clearly related to foliation. Weathered chlorite is commonly the cause of the color; in certain metamorphic zones weathered biotite produces similar red and pink tones. In areas of deeply weathered rock in the medium and higher grades of metamorphism, it may be most difficult to distinguish between biotite schist of the Nova Lima and biotite gneiss of the granite gneisses. A useful but not infallible guide is the presence of small muscovite plates from small pegmatites, which are rare in the Nova Lima rocks except at the contact with granitic rocks but quite common in granitic rocks.

In the type area, Gair distinguished the following varieties of schists and phyllites: Quartz-sericite schists and phyllites, quartz-chlorite and quartz-chlorite-sericite schists and phyllites, carbonate-rich schists, quartz-biotite (or stilpnomelane) schists and phyllites, quartzose and feldspathic schists, graphitic phyllites, ferruginous schists, and metavolcanic schists. He also distinguished other rocks as follows: Carbonate-facies iron-formation, quartzite, graywacke, quartz-dolomite and quartz-ankerite rock, sericitic quartzite, and schistose conglomerate. In the Itabira district, meta-arkose (?) was also found; conglomerate was mapped in the Macacos quadrangle (Pomerene, 1964, p. D9) and reported in the Dom Bosco quadrangle (Johnson, 1962, p. B7). Maxwell (written commun., 1964) and Simmons (1968a, p. G9) reported chlorite schist and phyllite, and Simmons (1968a, p. G9) reported carbonaceous phyllite. Wallace (1965) found a thin lens of garnetiferous limestone in a railroad tunnel. In zones of contact metamorphism, staurolite schist and garnet schist are common. Thus, the Nova Lima Group contains the metamorphic equivalent of almost every major type of sedimentary rock except evaporites and organic fuels.

Much of the widespread talc schist and talc phyllite in the Nova Lima Group is probably metamorphosed and highly sheared ultramafic intrusive rock, closely related to soapstones and thus younger than the Nova Lima Group.

SCHISTS AND PHYLLITES

The picture of extreme diversity given above by the recital of lithologies disappears when dominant lithologies are considered, for many of the rock types are subordinate and known from only a few places.

The dominant lithologies are chlorite phyllite and schist, quartz-chlorite and quartz-chlorite-sericite phyllite and schist, and sericitic quartzite. Intergradational ferruginous phyllite and iron-formation are characteristic although volumetrically minor. All are fine grained except in metamorphic aureoles. These rocks grade into one another and undoubtedly represent a great mass of poorly sorted fine-grained argillaceous sediment, local accumulations of chemical sediments, and much intermixed material of volcanic origin. A. F. Matheson (oral commun.) remarked that part of the Nova Lima Group as exposed in the Gaia Tunnel (Rio Acima quadrangle) had the aspect of the metamorphosed andesitic lavas of the Canadian shield. O. Barbosa (in Guimaraes, 1935) and Guimaraes (1931, 1935, 1958) also emphasized the volcanic contribution to much of this rock.

Gair's description (1962, p. A9) of the dominant schists and phyllites of the Nova Lima area is as follows:

> Schists and phyllites: Interbedded metasedimentary and metavolcanic schists and phyllites form the bulk of the Nova Lima Group. Fresh rocks are mainly green or gray-green, but at the surface the schists and phyllites commonly are pinkish, red, maroon, or buff owing to weathering. Secondary concentrations of hydrated iron oxides at or near the surface have modified the rock to a dense brownish ferruginous schist in places. Natural exposures are generally small. Graphitic phyllite is widespread but not abundant. Except for graphitic phyllite, the weathered rocks generally cannot be related to specific unweathered schists and phyllites, making it difficult or impossible to map varieties of schist or phyllite. Although different types of

schist and phyllite have been identified at individual locations, they have been mapped together as a single stratigraphic unit.

Petrographic studies of more than 100 thin sections of the schistose and phyllitic rocks of the Nova Lima Group by Gair (1962, p. 12–13) showed that quartz is a major constituent in almost all types. Sericite and muscovite are relatively common; biotite occurs in some types; and fuchsite, the chromian mica, is found in some. Chlorite is a major mineral in many rocks and subordinate or minor in others. Sodic plagioclase is not rare but is a subordinate or minor mineral in most rocks. Tourmaline in minor amounts was seen in a number of thin sections. Epidote, graphite, magnetite, and rutile are accessory minerals in many rock types. Carbonate appears in minor quantity in some rock types and as major mineral in the carbonate-rich schists. Sulfides, possibly introduced by hydrothermal fluids, possibly primary, were seen in some thin sections.

In the Itabira district, similar rock types and also meta-arkose are found, all coarser grained because of a higher grade of metamorphism; there, garnets are abundant and andalusite has been found. Alkali metasomatism clearly affected the rocks in that area (Dorr and Barbosa, 1963, p. 11–12). In the Itabirito quadrangle, south of the area studied in detail by Gair, Wallace found (1965) rocks similar to those reported by Gair.

Rocks in the Gandarela quadrangle correlated with the Nova Lima Group are so fine grained that the mineral components cannot be identified in thin section. Herz (1962, p. C75) cited a chemical analysis of an argillaceous rock collected by J. E. O'Rourke and calculated (written commun. 1960) the probable mineral composition as follows: Quartz, 38 percent; sericite, 33 percent, chlorite, 28 percent; iron oxide, 1 percent.

Metavolcanic rocks described by Gair are largely chlorite schists, with some hornblende, epidote, clinozoisite, and subordinate sodic plagioclase and quartz, indicating an originally mafic rock. "Relicts of intergrown and crisscrossing plagioclase laths and possible stretched quartzose amygdules in some of these rocks are the only direct evidence of volcanic origin found" (Gair 1962, p. 16). Dorr and Barbosa (1963, p. 13) described and figured rock from the Nova Lima Group of the Itabira district believed to be a metatuff because of the embayed plagioclase crystals and grain-size differences between feldspars and the chlorite groundmass. Rocks near Congonhas described by Guild as part of his "greenschist sequence" (1957, p. 20–22), now correlated with the Nova Lima Group, also are rich in chlorite, epidote, zoisite, clinozoisite, and hornblende. They seem similar to the rocks described by Gair and very possibly represent metavolcanic rocks. The abundant chlorite and chloritic schists and phyllites elsewhere in the region strongly suggest that the volcanic fraction in the Nova Lima Group is sizable and occurs everywhere, although rock fresh enough to permit petrographic confirmation was scarce.

The widely varying composition of these rocks might well indicate that the original volcanic contribution was much mixed with sedimentary material before and during deposition, locally being a rather pure tuffaceous rock, locally flows, and elsewhere a siltstone mixed with volcanic ash.

Although the dominant rock types described above account for the great bulk of the Nova Lima Group, other rock types to be described below are important from a genetic and economic viewpoint. Furthermore, they occur in relatively narrow bands and thus are most useful in mapping the internal structure of the otherwise nondescript rocks.

IRON-FORMATION

Thin discontinuous lenses of iron-formation characterize the Nova Lima Group in this region. They are found from the Itabira district to the Sousas quadrangle and from the Belo Horizonte to the Congonhas quadrangles and farther to the south in the Lafaiete area. Near Nova Lima, in part of the valley of the Rio Conceição, in the area north of Gandarela, and in the Sousas area, these lenses reach thicknesses of some tens of meters and can be traced continuously for several kilometers; many of these are shown on plate 1, and more were shown on the individual quadrangle maps by Gair (1962, pls. 1 and 2) and Pomerene (1964, pl. 2). Elsewhere, as in the Itabira district, the Congonhas area, southwest and southeast of Caeté, and east of Mariana, they may range from a few centimeters or tens of centimeters to more than 10 m in thickness. Most thin lenses are not shown on plate 1, and most were too thin to show on the individual quadrangle maps. The number of individual lenses in a ferruginous zone is difficult to establish because of structural complexities, but Alves (oral commun., 1954) found as many as seven in the Caeté quadrangle; more may be present in the Nova Lima and Macacos quadrangles, where they seem to be most numerous.

All specimens of iron-formation from the Nova Lima Group obtained from below the surface zone of oxidation proved to be either carbonate facies (James, 1954) or carbonate-magnetite facies. Carbonate-facies iron-formation was first recognized in the region by Gair (oral commun., 1955; 1962, p. A16–A22) and Matheson (1956). This discovery was so belated because on outcrop it is most difficult to distinguish between oxidized carbonate-facies iron-formation, characteristic of the

Nova Lima Group, and the better exposed oxide-facies iron-formation, characteristic of the overlying Minas Series.

Below the zone of oxidation most of the iron in carbonate-facies iron-formation (quartz plus siderite plus magnetite) is in bivalent form. On the outcrop and in shallow openings, most of the iron in such rock has oxidized to the trivalent form, either as limonite or martite. Fresh dolomitic oxide-facies iron-formation (quartz plus dolomite plus hematite plus varying quantities of magnetite) contains most of its iron in trivalent form but on the outcrop appears very similar to oxidized carbonate-facies iron-formation, as the weathering products of siderite and dolomite are similar and both rocks contain magnetite which alters to martite. Mobile limonite on the outcrop hides primary mineral identities and relations in both facies.

Analyses and thin-section study of fresh rock from the Raposas and several other mines in the Nova Lima and Rio Acima quadrangles and from the São Bento mine, Santa Bárbara quadrangle, show clearly that the iron occurs both as magnetite and siderite, the two minerals varying widely in relative abundance (Gair, 1962, p. A19; Simmons, 1968b, p. H9). Quartz content ranges from 38 to 60 percent in the unweathered rock. Although no other completely unweathered material is known, it seems probable that most if not all of these Nova Lima iron-formations were carbonate facies or carbonate-magnetite facies. There is no good evidence to the contrary.

Pomerene (1964, p. D7) listed useful criteria for distinguishing the carbonate from the oxide facies on the outcrops. Another criterion is that graphitic and carbonaceous phyllite is closely associated with carbonate-facies iron-formation in many localities, whereas these rocks are not known to be associated with dolomitic oxide-facies iron-formation, as predictable from the Eh environment of these facies (James, 1954; Castaño and Garrels, 1950).

In places, bands of iron-formation grade, with an increasing content of aluminous material and decreasing quartz and iron, into ferruginous phyllite. Such rock is very common in the Sousas area (Simmons, 1968a) and in the Santa Bárbara (Simmons, 1968b), and Gongo Sôco (Moore, 1969) quadrangles and is known in many other places. Gair described the carbonate-facies iron-formation as being closely related spatially with metavolcanic rocks (1962, p. 21 and 22). This is in strong contrast to the oxide-facies iron-formation found in the Minas Series, which is not so associated.

The carbonate-facies iron-formation of the Nova Lima Group has been the host rock for widespread hypothermal gold mineralization in the region. The most important gold mines with this host rock are the Raposas (Nova Lima quadrangle) (Gair, 1962; Tolbert, 1964) and the São Bento mine near Barra Feliz (Santa Bárbara quadrangle) (Simmons, 1968b).

QUARTZ-DOLOMITE AND QUARTZ-ANKERITE ROCK

In the Nova Lima and Rio Acima quadrangles Gair described a peculiar rock as "a gray, massive quartz-carbonate rock that resembles dolomite" associated with schist of somewhat similar composition into which it grades (1962, p. A23). It consists of a mosaic intergrowth of quartz and carbonate with minor plagioclase, chlorite, and graphite and occurs in discontinuous lenses. The sedimentary origin of this rock type has not always been recognized, but both Gair (1962, p. A26) and Matheson (1956) showed clearly that it is an integral part of the Nova Lima Group. In the Morro Velho mine the rock is called "lapa seca." The premetamorphic nature of this rock is not clearly apparent, nor is it known why the iron carbonate should be ankerite rather than siderite or ferrodolomite.

This rock crops out poorly but has been mapped in the Rio Acima and Nova Lima quadrangles. It is the host rock for the gold ore in the Morro Velho, Bela Fama, and Bicalho mines and, judging from descriptions of mines now collapsed, may have been the host rock in other gold mines in the Caeté area (Moraes and O. Barbosa, 1939) and at Bico de Pedra (Guimarães, 1961, p. 229).

QUARTZITE

Quartzite in the Nova Lima Group crops out widely, but because it is commonly very impure, it weathers easily, breaks down to a saprolite, and is not easily mapped as a lithologic unit. Where badly weathered, such rock has the aspect of quartz-sericite schist. This highly impure quartzose rock crops out near and south of the highway between Sabará and Caeté and is a prolongation of the quartzose zone mapped by Matheson in the vicinity of Sabará. (See p. A16.)

Rather pure, locally resistant, massive quartzite was mapped by Wallace in the Itabirito quadrangle. This green and gray slightly chloritic and sericitic quartzite shows well-preserved crossbedding, locally highly intricate, in roadcuts along the Rio Acima-Itabirito Highway. To the west this feature is obliterated by shearing, and the rock becomes schistose. Gair also mapped quartzite lenses in the Rio Acima and Nova Lima quadrangles.

Many schistose rocks of the Nova Lima Group are quartzose and grade into impure quartzites and back into quartz-mica schists both along and across the strike. Systematic separation of such rocks must await more detailed mapping.

Metachert, now pure fine-grained white quartzite, grades laterally into iron-formation in many localities, notably in the Caeté quadrangle.

CONGLOMERATE

Conglomerate is a very uncommon rock in the Nova Lima Group, but a large exposure of coarse conglomerate occurs in the Macacos quadrangle along the Rio de Janeiro–Belo Horizonte Highway (Pomerene, 1964, pl. 2 and fig. 3). One contact of this rock is exposed in a roadcut, where there is an abrupt transition from weathered red phyllite to boulder conglomerate; here, boulders of quartzite up to 50 cm in diameter are found in a phyllitic matrix. Away from the contact, which is believed to be the stratigraphic base of the zone, the size of the detrital material grades through cobble size to pebble size. The zone can be traced for 3,000 m. with an outcrop width of 200–500 m. (Pomerene, 1964, D10). The coarse detrital material is well rounded and makes up 20–50 percent of the rock.

The coarse boulders are medium-grained quartzite and vein quartz; the smaller cobbles and pebbles higher in the section consist of vein quartz, smoky quartz, quartzite, phyllite, schist, and highly weathered material that may have been granite or other feldspathic rock. Some schist and phyllite fragments are angular and probably fractured.

The smaller pebbles are oriented parallel to foliation and conceivably may have been somewhat squeezed, although their axial ratios of 1:2–1:3 are not unusual in stream or beach pebbles. The larger boulders are well rounded.

The conglomerate is overlain by a sheared gray phyllite, typical of the Nova Lima Group, and a short but thick lens of pure white quartzite containing some fuchsite.

This conglomerate corresponds closely to the material termed "paraconglomerate" or "tilloid" by Pettijohn (1957, pp. 261–265) and attributed by him to subaqueous density currents, and it is believed by the writer to be of this origin.

This rock is unique in the region. The writer knows of no other conglomerate bed with similar lithologic features either in the region or in adjacent areas, although polymictic conglomerates are not rare in younger rocks.

Four small lenses of schistose pebble conglomerate were mapped in the Nova Lima Group in the Nova Lima quadrangle (Gair, 1962, pl. 1).

GRAPHITIC AND CARBONACEOUS PHYLLITE

Graphitic and carbonaceous schists and phyllites are rather common in the Nova Lima Group. They are gray to black except at the surface, where they may be bleached, and are normally very fine grained. In the lower levels of the Morro Velho mine, which extends to more than 2,500 m. below the surface, methane has been reported, perhaps derived from the organic content of such rocks. Simmons (written commun., 1962) reported the extraction of small quantities of organic matter from carbonaceous phyllite in the Nova Lima Group.

ENVIRONMENT OF DEPOSITION AND NATURE OF ORIGINAL SEDIMENTS

The generally sparse outcrops of the Nova Lima Group and the pervading metamorphism and weathering cause great difficulty in interpreting the original nature and environment of deposition of these rocks.

The Nova Lima Group consists of the following rock types: Preponderant fine-grained clastics, lesser volcanics, some chemical precipitates, and rare coarse clastics. The fine-grained clastic rocks were probably clay and silt, with admixtures of varying quantities of volcanic ash. O'Rourke (written commun., 1956) was the first to point out that these fine sediments were the result of mature weathering; he based his opinion on the high alumina content of the rock. Herz (1962, p. C75) recently reemphasized the point.

The volcanic rocks were probably volcanic ash, apparently with some flows, as indicated by probable amygdules seen in the Gaia tunnel. The source of the ash and the flows is as yet unknown, for no feeders or ancient volcanoes have been found.

The coarser grained sedimentary rocks range from boulder conglomerate (tilloid) to quartzite and include meta-arkose and graywacke. At least some quartzite is crossbedded. All purer clastic quartzites are lenticular and few are as thick as 100 m. Recrystallization of quartz in micaceous quartzites and quartz-mica schist destroyed all evidence of original grain size and nature of original sediment. The presence of graywacke and the tilloid strongly indicates the action of turbidity currents in the basin of deposition and thus significant relief in the basin.

The chemical or biochemical sediments are mostly carbonate-facies iron-formation, quartz-carbonate rock, chert, and a single known marble zone. Were not the first two the hosts for gold deposits and the last fortuitously revealed by a railroad tunnel, little would be known of these rocks, as they are thoroughly altered at the surface. James (1954) discussed the genetic environment of carbonate-facies iron-formation and showed that it is deposited in a relatively reducing environment with Eh close to or below zero, probably in silled basins. Restricted circulation caused by volcanic island arcs was believed by him to favor such an environment, and the abundant volcanic contribution to the Nova Lima sediments may well be evidence for nearby volcanism. The depositional environment of quartz-ankerite-dolomite rock may be presumed to have been similar to that of carbonate-facies iron-formation, although the reason for the strong compositional banding of the one rock and not the other is as obscure as the reason for the banding of iron-formation in general.

Thus, it can be said that the Nova Lima Group exhibits many characteristics of the sediments of eugeosynclinal environment, as pointed out by O. Barbosa (1954), because they include heterogenous clastic sediments of many kinds and an important volcanic contribution. A close study of this assemblage must be made before the group can be divided into smaller stratigraphic units. This will undoubtedly prove possible, for certain units have been traced for 100 km and possibly extend for more than 200 km (Dorr and others, 1956, p. 293; Ebert, 1963).

METAMORPHISM

The metamorphic geology of the Quadrilátero Ferrífero has been discussed in detail by Herz (written commun., 1966). However, here and in subsequent sections, distinctive aspects of the metamorphism of each major stratigraphic unit are noted.

The Nova Lima Group consists largely of pelitic rocks of sedimentary and volcanic origin, providing a mineral assemblage and bulk composition particularly sensitive to dynamic and contact metamorphism. Its pervasive metamorphism and recrystallization, which obliterated most primary sedimentary structures, is thus attributed more to bulk composition than to intense deformation or repeated deformation. Contact zones bordering intrusive granitic rock contain wide bands of garnet and staurolite schists, in contrast to overlying less reactive rocks.

In the Itabira district, in the northeastern part of the Quadrilátero Ferrífero, Dorr and Barbosa (1963) described the transition from a biotite schist of the Nova Lima Group into granitic gneiss, also biotitic. The foliation of both rocks is parallel, the contact crosscuts structure, and the granitic rock is at least in part formed from the Nova Lima rocks.

In the Monlevade district, just to the south, Reeves (1966) considered the Monlevade Gneiss to have formed from rocks of the Rio das Velhas Series and, because of the presence of lenticular iron-formation, quartzite, and amphibolite, probably equivalent to the Nova Lima Group. This rock occupies large parts of the Monlevade and Rio Piracicaba quadrangles and extends to the west, where it was not differentiated from the granitic rocks mapped there by Herz. The undoubted metasedimentary units (quartzites and iron-formations) of the Monlevade Gneiss are clearly unconformable with the overlying Minas Series, and thus the tentative correlation of these rocks with the Nova Lima Group by Reeves seems reasonable both on stratigraphic and structural grounds.

In the Gandarela quadrangle, in the central part of the region, the pelitic rocks of the Nova Lima Group, which there also contain lenses of iron-formation, are at a very low rank of metamorphism and are classified as slates or argillites. The area is far from known granitic bodies, and the rocks appear to be at the lowest rank of metamorphism in the region. Quartzose rocks in the area are strongly sheared, however. The degree of metamorphism there seems to be independent of the intensity of mechanical deformation.

MAQUINÉ GROUP

The rocks now included in the Maquiné Group (Dorr and others, 1957) overlie those of the Nova Lima Group in the type locality, the east side of the Rio das Velhas valley. The group was mapped by Gair in the Nova Lima and Rio Acima quadrangles; by Maxwell in the Capanema, Santa Rita Durão, and Catas Altas quadrangles; by Moore in the Conceição do Rio Acima quadrangle; by O'Rourke in the Gandarela and Rio de Pedras quadrangles; by Alves in the Caeté quadrangle; and by Barbosa in the São Bartolomeu, Antônio Pereira, and Mariana quadrangles.

Relations between the Maquiné and Nova Lima Groups in the type area, and particularly in the Rio Acima and Nova Lima quadrangles, were believed by Gair (1962, p. 29–30, 33) to show a slight angular unconformity. He suggested alternatively that relations there could be explained by expectable slippage between rocks of unlike competence during severe folding. Moore (1969) considered that the Maquiné Group lies unconformably on the Nova Lima Group in part of the area mapped by him and to be in thrust faulted contact elsewhere. Maxwell (written commun., 1962) considered that the obscure contact in the central part of the Capanema quadrangle is probably strongly discordant but may be faulted; in the southern part of this quadrangle it is faulted. O'Rourke (written commun., 1956) believed the contact in the areas he mapped to be slightly unconformable. Neither Alves nor Barbosa have described the contacts in the areas mapped by them, but the writer, although more familiar with the contact in the Caeté than in the São Bartolomeu quadrangle, believes that no strong angular unconformity exists in these areas and has observed a gradational contact. In summary, it seems probable that (1) locally an erosional unconformity certainly exists, (2) it is not strongly angular, (3) the contact is in part gradational, and (4) the Maquiné rocks were deposited on a surface of low relief. The amount of erosion that may have taken place between Nova Lima and Maquiné sedimentation is now impossible to evaluate because of the lack of regional stratigraphic horizons in the Nova Lima rocks.

The Maquiné Group is divided into two units: the Palmital Formation (O'Rourke, written commun., 1958) and the overlying Casa Forte Formation (Gair, 1962, p. 31). This division can only be followed for a strike length of some 20 km in the Vargem do Lima syncline in the valley of the Rio das Velhas (pl. 1). It proved impossible to map these units separately in other parts of the Quadrilátero Ferrífero. Around the Serra do Caraça the lower part of the Maquiné Group has certain similarities to the Palmital Formation.

The Maquiné Group is set off from the Nova Lima Group by being characteristically quartzose and conglomeratic, which makes the rocks relatively resistant to erosion. They stand above the Nova Lima in bold scarps or steep slopes where the rocks are juxtaposed.

PALMITAL FORMATION

The Palmital Formation has been mapped in the Caeté, Gandarela, Rio Acima, and Rio de Pedras quadrangles. Its characteristic lithology is also present in the southeastern part of the Capanema quadrangle but was not mapped separately there.

The Palmital Formation was described by O'Rourke (written commun., 1958) as the lower lithologic unit of the Maquiné Group. It consists dominantly of sericitic quartzite and quartzose phyllite and contains some phyllite and slate beds. The formation overlies rocks of the Nova Lima Group with local angular unconformity, but in some places, with apparent angular conformity. It is conformably overlain by the Casa Forte Formation.

CONTACTS AND THICKNESS

The contact between the Palmital Formation and the underlying Nova Lima Group is concealed in most places by the debris derived from the more quartzose Palmital beds. In the Rio Acima quadrangle Gair traced a basal conglomerate along this contact, which he considered to be probably unconformable with a low angle. In the western part of the Gandarela and Rio de Pedras quadrangles, O'Rourke (written commun., 1958) found that quartzose schist and phyllitic quartzite of the Palmital overlie the Nova Lima Group without angular unconformity or a basal conglomerate. The contact as exposed in the vicinity of Gandarela N. 12,500, E. 2,000 was interpreted by Dorr to be gradational over several tens of meters, marked by increasing numbers of thin quartzose beds in the phyllitic transitional zone until the whole rock was quartzose. Near Caeté N. 5,000, E. 3,310, the contact was abrupt, as observed by Alves and Dorr, but no basal conglomerate was seen. Thus the Palmital lies on the Nova Lima Group with locally unconformable, locally conformable, and locally gradational contacts.

The contact of the Palmital Formation with the overlying Casa Forte Formation is gradational and marked by conglomeratic and conglomerate beds.

The Palmital Formation ranges in thickness from a feather edge in the southern part of the Rio de Pedras quadrangle to about 1,400 m in the Rio Acima quadrangle. The apparent thickness of about 2,100 m in the Gandarela quadrangle is possibly due to tectonic repetition of some beds, indicated by complex local folding near Gandarela N. 5,000, E. 3,500.

The formation feathers out on the west limb of the Vargem do Lima syncline near Rio de Pedras N. 3,500, E. 12,000; to the southeast the Casa Forte Formation is in contact with the Nova Lima Group. This is a wedgeout caused by nondeposition of the Palmital sediments, for no sign of significant faulting which could have cut out the formation was seen, and the formation gradually thins on this limb from the Rio Acima quadrangle across part of the Gandarela quadrangle to the place in the Rio de Pedras quadrangle where it disappears entirely. The Palmital on the east limb of the syncline also thins to the southeast across the Rio de Pedras quadrangle but is in fault contact with adjacent rocks in the Capanema quadrangle. Maxwell (written commun., 1962) did not separate the Palmital and Casa Forte Formations in the Capanema quadrangle along the west side of the Serra Geral, nor did Barbosa in the São Bartolomeu quadrangle to the south. Maxwell's descriptions indicate a possible wedgeout in the Capanema quadrangle of rocks corresponding in lithology to the Palmital (written commun., 1962). Extreme deformation of the rocks in those areas make interpretation difficult.

LITHOLOGY

Lenses of quartzite in quartzose phyllite characterize the Palmital. The quartzitic beds range from a few meters to more than 75 m in thickness and in length from a few meters to more than a thousand. In the Gandarela and Rio de Pedras quadrangles these quartzites are somewhat coarser than to the southeast. In many areas the quartzite now is composed of perhaps 15 percent of angular quartz grains averaging, according to O'Rourke, about 0.3 mm in diameter in a matrix of very fine (0.01 mm) quartz; the rock contains about

12 percent sericite. Original more homogenous quartzite was crushed during the tight folding.

Gair (1962, p. A30–A31) described the petrography of the Palmital Formation in some detail. He found by thin-section study that at least one bed was graywacke and suggested that closer study might reveal that this rock is more common than now known. Chloritoid in quartzose rock is more abundant on the east side of the Vargem do Lima syncline than the west and occurs in rosettes and blades comprising as much as 30 percent of the rock. The mineral is easily confused with kyanite in the field. Small amounts of kyanite also have been found. Gair also tentatively identified some fuchsite.

As originally mapped by O'Rourke, the Palmital Formation contained a number of conglomeratic lenses and beds, some traceable for many kilometers. Gair, subdividing the Maquiné Group in the area immediately to the west of the area mapped by O'Rourke, by definition included all conglomeratic beds except the basal conglomerate in the Casa Forte Formation, thus redefining the then unpublished definition of the Palmital Formation. Gair's usage is here followed. The contact as mapped by O'Rourke in the Gandarela and Rio de Pedras quadrangles was readjusted in the field by the writer to fit Gair's usage, the contact being placed at the lowest conglomerate of the Casa Forte.

CASA FORTE FORMATION

The Casa Forte Formation as defined by Gair (1962, p. A31–A33) is separated from the Palmital Formation on the basis of the included conglomerate beds. It is generally more quartzose and less sericitic and phyllitic than the older rock.

CONTACTS AND THICKNESS

The Casa Forte Formation conformably overlies the Palmital Formation in the Nova Lima, Rio Acima, Gandarela, and Rio de Pedras quadrangles. It has not been mapped separately elsewhere.

The original thickness of the Casa Forte Formation is unknown, as it crops out only in the center of an isoclinal syncline. If there is no repetition of beds by internal folding, the apparent remaining stratigraphic thickness is about 600 m at maximum outcrop width.

Where the underlying Palmital Formation lenses out in the Rio de Pedras quadrangle, the Casa Forte Formation overlies the Nova Lima Group without apparent discordance between the two units. The Casa Forte Formation gradually narrows in outcrop width toward the southeast, as the result either of stratigraphic thinning or of structural position in the axial part of an isoclinal syncline. Because lineation plunges southeast, the writer believes the formation thins stratigraphically rather than tectonically.

LITHOLOGY

The Casa Forte Formation consists of schistose and massive sericitic and chloritic quartzite, conglomerate, and lesser amounts of sericitic and chloritic schist and phyllite.

Quartzite of the Casa Forte Formation may be schistose to compact and massive. Locally it is in beds several meters thick, some of which are conspicuously crossbedded. Massive beds crop out boldly and form peculiar haystack hills 20 m or more above surrounding terrain (Gandarela N. 5,300, E. 3,350). (See pl. 5.) Where schistose or more thinly bedded, the quartzite crops out as low ridges scarred by solution pits, and these ridges may look much like outcrops of Moeda quartzite and Itacolomi quartzite. The rock ranges from white through buff and brown, depending on accessory and subordinate minerals. It may contain sparse well-rounded pebbles of vein quartz and smaller angular quartz fragments.

Quartzite of the Casa Forte Formation is characteristically sheared into a microaugen structure, as emphasized by O'Rourke and Gair. Angular grains of quartz up to 1 cm across occur in a groundmass of fine-grained comminuted quartz having a grain size of a few hundredths of a millimeter; folia of sericite cut across the groundmass and wrap around the larger fragments.

Conglomerate zones are lenticular but, particularly in the Gandarela and Rio de Pedras quadrangles, can be traced for several kilometers. They can be used for deciphering structure if care is exercised not to confuse different zones, for all are very similar lithologically. Most conglomerate beds are dark brown to buff on the outcrop and form low scarps or linear ridges clearly apparent in aerial photographs. The conglomerate consists of rounded vein-quartz pebbles and elongate pebbles of phyllite, iron-formation, and fine-grained white quartzite, probably metachert, in a matrix of quartzite or ferruginous quartzite. Pebbles of phyllite and metachert (?) are found throughout, but those of iron-formation are much more abundant in the northern part of the belt than in the southern part.

O'Rourke (written commun., 1956) stated that pebbles are elongated as much as 10:1. It seems certain that some elongation is the result of tectonic stress on originally plastic pebbles and cobbles, but it is also probable that many fragments originally were platy rather than rounded, because most vein-quartz pebbles are undeformed.

Chloritoid is present in both the conglomerate and the quartzite; Gair stated that it occurs in fractures in the conglomerates and both concordant to and crosscutting the foliation of the quartzite. Locally, the more phyllitic quartzite may contain much chloritoid, which imparts a splintery fracture to the rock.

The Casa Forte Formation apparently changes in composition along strike from north to south. Conglomerate lenses are more continuous but thinner, and pebbles and cobbles smaller, toward the south. The lenses are more continuous in the Gandarela and Rio de Pedras quadrangles than in the Rio Acima quadrangle. This lack of continuity may be due to increasing tectonic disturbance in the axial zone of the Vargem do Lima syncline, for the north end of this feature is twisted to the east and cut by many more cross faults than are apparent in the southern quadrangles (pl. 1).

MAQUINÉ GROUP UNDIVIDED

In the Conceição do Rio Acima, Capanema, São Bartolomeu, Catas Altas, Santa Rita Durão, Mariana, and Antônio Pereira quadrangles, the thick quartzite formation overlying the Nova Lima Group was mapped as Maquiné Group undivided by Moore, Maxwell, and A. L. M. Barbosa. There the strata consist largely of quartzite. The quartzite may be chloritic, pyritic, sericitic, or rather pure; locally it contains chloritoid. All these types may be conglomeratic. Quartz-chlorite schist, quartz-sericite schist, and phyllite also occurred toward the bottom of the section.

The easternmost part of the Maquiné Group undivided in the southwestern part of the Capanema quadrangle (the continuation of the Vargem do Lima syncline) is composed of schistose rocks that correspond in lithology to the Palmital Formation and are contiguous with the formation as mapped in the Rio de Pedras quadrangle. Maxwell (written commun., 1962) stated that these schistose rocks pinch out to the southeast. It will be remembered that the Palmital also wedged out to the southeast in the adjacent Rio de Pedras quadrangle on the west side of the syncline. The Maquiné Group in the type locality in the Vargem do Lima syncline is nowhere contiguous with the rocks mapped as Maquiné Group undivided on the north and west flanks of the Serra do Caraça or to the southeast of that range, and thus the correlation is not absolutely certain.

CONTACTS AND THICKNESS

In the area east of the Vargem do Lima syncline, deformation is strong and horizon markers absent; therefore, measurement of thickness of the stratigraphic section is unreliable. Maxwell (written commun., 1962) estimated that the stratigraphic thickness of the rocks may be about 1,400 m in the area mapped by him.

The contact relations with the underlying Nova Lima Group rocks are most obscure because of faulting and poor exposures. The rocks are certainly in fault contact in some places and are apparently structurally and stratigraphically conformable in others. Although Maxwell found in the Capanema quadrangle one locality showing strong angular discordance, he could not be certain whether this was a sedimentary or fault contact because of poor exposures; in view of the general concordance elsewhere, it may be considered a fault contact until proved otherwise. Contacts with the overlying rocks in this area are probably unconformable.

In a small area in the southeastern part of the Santa Rita Durão and the northeastern part of the Antônio Pereira quadrangles, an isolated patch of gray quartzite crops out boldly but with little relief. It was correlated with the Maquiné Group undivided by Maxwell and Barbosa because of its lithologic similarity with the upper part of the Maquiné quartzites exposed along the road that climbs the north face of the Serra do Caraça. There is no way of deciphering the thickness or contact relations in this area.

LITHOLOGY

The quartzose rocks in the southeast extension of the Vargem do Lima syncline were reported by Maxwell as essentially similar to the Casa Forte Formation to the west and northwest. They include the same type of deformed conglomerate beds, contain chloritoid and chlorite, and show microaugen structure and extreme internal crushing and shearing. With the exception of the absence of iron-formation cobbles reported to the north by Gair and Dorr, the conglomerates seem entirely similar to those described above. Maxwell found subgraywacke to be present in this area.

Rocks mapped as Maquiné Group undivided in the area of the Serra do Caraça differ somewhat in lithology, possibly in part because shearing was here less intense. Quartzites are more massively bedded where not schistose, locally contain much more chlorite, and are locally pyritic; true conglomerate is not common. Near the base of the section, Moore and Maxwell found chloritic and sericitic quartzose schists, brown, gray, and green on the outcrop, in some zones with scattered pebbles of vein quartz. Overlying is a sequence of chloritic and sericitic quartzite, some highly pyritized. Maxwell (written commun., 1962) also reported subgraywacke and graywacke. Still higher in the section, the quartzite contains less micaceous minerals and is a gray to white massive sericitic to nearly pure quartzite that crops out in rugged scarps and crags. Scattered small pebbles also occur in these strata.

ENVIRONMENT OF DEPOSITION

Sedimentation in Maquiné time evidently changed abruptly in environment and source of materials from that which produced the much more argillaceous rocks of the underlying Nova Lima Group. This change is attested to by the more quartzose composition of the rocks, by the conglomeratic zones and beds, and by the apparent lack of volcanic contributions or of chemical sediments such as iron-formation or carbonate-rich rocks. The Maquiné Group evidently represents a nearshore environment.

An erosional unconformity, perhaps with some structural disturbance of strata below the Maquiné, is masked by the intense deformation of the whole Rio das Velhas Series; it is indicated by the presence of a basal conglomerate beneath the Palmital Formation on the west side of its outcrop. That erosion of the Nova Lima continued during deposition of the Casa Forte Formation is suggested by pebbles and cobbles of iron-formation and metachert in the conglomerates of that formation. Both chert and iron-formation are characteristic of the Nova Lima Group. That these rocks were lithified but not yet recrystallized when eroded is suggested by the latter extreme deformation of these pebbles in the same outcrops where relatively undeformed vein-quartz pebbles are found, deformation of the same order of complexity as that of the phyllite cobbles occurring with them.

The wedgeout of the Palmital Formation to the southeast, as shown on both the east and the west sides of the Vargem do Lima syncline by O'Rourke and Maxwell, is a strong indication of nearshore conditions. The location of the shoreline during Casa Forte time is not known, but the absence of the Maquiné on the west side of the Rio das Velhas Valley suggests, but does not prove, that it was somewhat to the west of present exposures of those rocks. The change in type of sedimentation and particularly of the distribution, size, and frequency of pebbles in the rocks toward the east is also suggestive of a source from the west. The changes in rock type from east to west are expectable under nearshore conditions, as is the apparent thickening eastward in the Capanema and Conceição do Rio Acima quadrangles. The rocks thin abruptly eastward in the Catas Altas quadrangle and were not found in the eastern part of the Quadrilátero Ferrífero. Whether this eastward thinning was caused by nondeposition or post-Maquiné erosion cannot be stated; the latter seems the more probable because of the major unconformity above the Rio das Velhas Series to be discussed in later pages.

Although the presence of phyllite, iron-formation, and metachert cobbles in the Maquiné clearly indicate that some of this rock was derived by erosion of the Nova Lima Group, a second source of sediments, particularly during deposition of the Casa Forte, seems probable because the Nova Lima Group as now exposed cannot be considered a probable source of coarse-grained highly quartzose sediments because quartzose Nova Lima rocks are characteristically fine grained. Whether or not this other source rock was granitic is unknown. Although careful search was made by the staff, only Maxwell (oral commun., 1964) found any evidence in the conglomeratic rocks for granitic pebbles and this in only one locality.

The presence of chloritoid in very significant amounts suggests a highly aluminous source, conceivably deeply weathered Nova Lima Group rocks, for the sediments metamorphosed into such rock. O'Rourke (written commun., 1957) was the first to call attention to the evidence for mature weathering of some of the source rock.

METAMORPHISM

The Maquiné rocks have generally been metamorphosed to the greenschist facies, and, except for the presence of chloritoid and kyanite in areas of maximum stress discussed above, there is nothing else particularly noteworthy about them. Their bulk composition, dominantly quartzitic, precludes the formation of a wide suite of metamorphic minerals.

In the isoclinal Vargem do Lima syncline, the most striking result of the dynamic metamorphism on the Maquiné Group rocks is the tremendous degree of crushing undergone by these rocks. The quartzose rocks were brittle and therefore shattered; the more sericitic rocks sheared. In many places all original sedimentary structures that might have been present, such as crossbedding, have been obliterated, and metamorphic structures superimposed. Top and bottom criteria are destroyed. Bedding has likewise been destroyed to a considerable extent.

In the less deformed areas, as in the Serra do Caraça and southeast of that range, bedding has survived the metamorphism in many localities, and crossbedding can be seen in some rocks.

INTERPRETATION OF THE RIO DAS VELHAS SERIES

The major gaps in our knowledge of the Rio das Velhas Series are caused in large part by three factors: first, the type of lithology that results, under the climatic and physiographic conditions of the region, in poor exposures; secondly, the obliteration of sedimentary structures by the extreme deformation; and thirdly, the lack of mineral resources, except gold deposits, which would justify expensive geologic exploratory effort. Until the present program of mapping, these rocks had been studied only in the vicinity of gold deposits; they had not been mapped at detailed scales except locally; and there was no appreciation of the relations between these rocks and other metasedimentary units of the region, with which they had been confused.

Because the work of the DNPM–USGS team was focused on the iron and manganese resources of the region, primary effort was not devoted to unraveling the problems of the Rio das Velhas Series; information gained was in the normal course of regional mapping. A fertile field remains for future generations of geologists.

The Rio das Velhas Series was separated from the Minas Series (Rynearson and others, 1954; Oliveira, 1956; Dorr and others, 1957) because a profound unconformity was discovered at the base of a persistent quartzite zone in rocks of the Minas Series as originally defined by Derby in 1906. Strata above that unconformity fitted closely the lithology and succession of the subdivision of the Minas Series made by Harder and Chamberlin in 1915. Below the unconformity the strata form a suite which differs in lithology from the Minas Series as defined by Harder and Chamberlin and others. A remaining problem which we had to consider was whether all the rocks here included in the Rio das Velhas Series are so related in time and environment of deposition that they should be included in one major unit or whether they should be divided into separate units.

The use of radiometric dating can be quite deceptive in this area (Hurley, 1961), but future refinements may solve many age relations in the Rio das Velhas Series. As of this writing, the only available determination on these rocks is a rubidium-strontium age of some 2,800 million years on mica from the Nova Lima Group just west of the Rio de Pedras reservoir, Rio de Pedras quadrangle (Aldrich and others, 1964, p. 329). This specimen was taken in the contact aureole of the Bação complex, indicating an older age for the Nova Lima Group. It is quite possible that age determinations on rocks from other parts of the Rio das Velhas Series may show younger ages in other localities, for the rocks have been affected by a more recent orogeny and metamorphic events. These may have imposed their ages on the minerals in the rocks and probably obscured the effects of the older metamorphism. The absolute age of the metasedimentary rocks cannot be established by available methods; only the age of their metamorphism can be determined.

In considering the relations between the two groups of rocks here included in the Rio das Velhas Series and in trying to decipher whether they represent a single evolutionary sedimentary unit or whether they represent units widely separated in time and genetically unrelated, two major lines of approach seem most likely to provide reliable information. The first is the nature of the sediments themselves and the relations between the lithic units; the other is a structural approach stressing the nature of the contacts between the groups. All clastic sedimentary rocks are ultimately a result of diastrophism; therefore the lithic content of the formation, and particularly of conglomerates, affords much information.

The Nova Lima Group consists dominantly of chlorite schist and phyllite, sericitic phyllite, quartz-sericite schist and phyllite, graphitic phyllite, and graywacke and graywacke schist. It contains small amounts of quartzite and characteristic thin lenses of carbonate-facies iron-formation and lesser amounts of tilloid conglomerate and quartz-ankerite rock. Only one marble bed was found in the whole region. A considerable admixture of tuffaceous material was found in the few areas where fresh rock could be studied.

The total assemblage is similar to that described by Pettijohn as the graywacke (flysch) suite (1957, p. 615–616). Pettijohn stated that this suite is marked by great thickness, by its predominantly argillaceous character, by carbonaceous shales, by the relative absence of carbonate rocks, and by subordinate quartzite. Bedded cherts are said to be present, and waterlaid mafic tuffs are said to grade into and resemble the coarser graywackes. The average ratio of sandstone to shale in the flysch facies is about 1:2 in sections cited by Pettijohn and may be of this order of magnitude in the Nova Lima Group as a whole, if the sericite-quartz phyllites are considered as impure sandstone. Although graywacke is found in few exposures, the rock type is particularly susceptible to deep weathering. Considering the abundance of other lithologies of the suite, it is probable that a much higher percentage of this rock may exist than appears at the surface.

Carbonate-facies iron-formation in the Nova Lima Group indicates local reducing environments expectable in the type of sedimentary environment giving rise to the graywacke suite. The ubiquitous association of graphitic phyllite with what were originally silty manganese carbonate beds (Dorr and others, 1956) about 10 km south of the Quadrilátero Ferrífero also indicates such an environment. Carbonaceous and graphitic phyllite are locally associated with the carbonate-facies iron-formation. For reasons still hotly debated, iron-formation is characteristic of Precambrian rocks; in the Nova Lima Group that material, which grades into metachert, may be equivalent to the bedded cherts cited by Pettijohn as typical of the flysch unit in younger rocks.

Above the Nova Lima Group lies the Maquiné Group, consisting of quartzose rocks, subgraywacke, and conglomerates. Pettijohn said (1957, p. 616):

> the typical graywacke (flysch) assemblage commonly increases in coarseness upward. Conglomerates, if any, appear high in

the section. The upward increase in coarseness is associated with an increase in the proportion and coarseness of the sands. The sands, moreover, become cleaner and are subgraywackes and even protoquartzites rather than graywackes * * *. The typical flysch facies has been displaced by the molasse facies—a product of paralic sedimentation.

This statement well describes the Maquiné Group, which is characterized by, in ascending order, a local basal conglomerate, phyllite, phyllitic and schistose rocks with increasing quartz, subgraywacke, conglomerates, sericitic and chloritic quartzite, and clean quartzites and grits. Despite the masking effects of metamorphism and strong deformation, there is little possible question of the nature of these rocks or of the fact that they form a molasse suite coherent with the underlying flysch facies of the Nova Lima Group.

The contacts between the two groups of rocks forming the Rio das Velhas Series are of significance in this analysis. On the west side of the Vargem do Lima syncline the contact between the Nova Lima and Maquiné rocks is essentially concordant, perhaps with a slight angular and erosional discordance. On the northeast side of the Vargem do Lima syncline the contact is gradational. Further southeast it is a fault contact or a suspected small angular discordance.

Fragments of rock believed to have come from the Nova Lima Group have been reported in the Casa Forte Formation in the Vargem do Lima syncline. The Palmital Formation wedges out in the southern part of that syncline. Thus, it seems certain that locally an erosional unconformity exists between the Maquiné and Nova Lima Group, but elsewhere sedimentation may have been essentially continuous. Given the environment of deposition of these rocks—the upper unit, a nearshore or continental suite, and the lower, a geosynclinal basin suite—local erosional unconformities and small angular unconformities are to be expected. The gradation between the phyllitic rocks and the quartzose rocks, so well exposed at the northeast corner of the Vargem do Lima syncline, and the wedgeout of the Palmital Formation and overlap of the quartzose Casa Forte rocks on the argillaceous rocks of the Nova Lima Group are also congruent with the inferred environment.

The lithology of strata here included in the Rio das Velhas Series, and evidence provided by contacts between its two groups, indicate that the Rio das Velhas Series rocks seem to form a single evolutionary stratigraphic entity reflecting a progression from eugeosynclinal to paralic sedimentation.

MINAS SERIES

The Minas Series was first named by Derby in 1906, was divided into five formations by Harder and Chamberlin in 1915, was restricted at the top by Guimarães in 1931, was restricted at the base by Oliveira in 1956, was divided into three groups by Dorr and colleagues in 1957, and was subdivided into nine formations by Wallace (1958), Maxwell (1958), Dorr (1958a, b), Pomerene (1958a, b, c), Simmons (1958), and Gair (1958). The Tamanduá Group, here included as a fourth group of the Minas Series, was first described by Simmons and Maxwell (1961), who assigned it to the Rio das Velhas Series.

As a whole, the Minas Series is quite different in nature from the underlying Rio das Velhas Series, for it consists largely of blanket and tabular formations (Pettijohn, 1957, p. 618) relatively consistent in lithology for great lateral extent, a type of formation not found in the Rio das Velhas Series. The Minas sedimentary rocks are well differentiated, except the highest formation, also in contrast to most of the Rio das Velhas rocks. The uppermost formation of the Minas Series, the Sabará Formation, is poorly sorted and contains much graywacke and tuffaceous rock.

Thus, as illustrated in the stratigraphic column presented on plate 12, the series is here divided into four groups, composed respectively of two lower groups of two clastic formations each, separated by a probable erosional unconformity; a gradationally overlying group composed of two formations of dominantly chemical or biochemical origin; and an upper group composed of five clastic formations, the uppermost quite different in general environment from the other formations of the series.

CONTACT WITH THE RIO DAS VELHAS SERIES

The contact of the Minas Series with the underlying Rio das Velhas Series is structurally and stratigraphically unconformable, but the extent and degree of the unconformity is difficult to establish with precision in all localities. That unconformity was first demonstrated in the Moeda Plateau and along the south side of the Serra do Curral by Rynearson, Pomerene, and Dorr in 1954. Plate 1 shows that mappable lithologic zones in the Nova Lima Group strike nearly at right angles to the Minas Series in the Itabirito quadrangle. Lenses of iron-formation in the Nova Lima Group strike at high angles into the trend of the Minas Series in the Serra do Curral both to the west in the Sousas quadrangle and in the Macacos quadrangle in the central part of the range. The angle of intersection between iron-formation of the Nova Lima Group and the Minas Series in the Gandarela and Itabira quadrangles is lower. Reeves (1966) discussed evidence pointing toward an angular unconformity between the Minas and Rio das Velhas Series rocks in the Monlevade district.

Along the Serra do Itabirito and in other localities where a strongly angular unconformity can be proved, the two series are also locally conformable. This suggests that the pre-Minas folding there was rather tight. On the other hand, the apparent conformity between the Minas Series and the underlying rocks in that part of the Gandarela syncline where rocks trend northwest by north (Gandarela quadrangle), contrasted with the 30° angular unconformity where the Minas beds turn toward the northeast (pl. 1), indicates that the older beds had been strongly tilted in this area before Minas sedimentation started. The tight folds found in these older rocks 20 km to the west are not here present.

In other areas, as along the south flank and eastern part of the Gandarela syncline, near the axis of the Mariana anticline (Antônio Pereira quadrangle), and south of Serra da Piedade (Serra da Piedade quadrangle), bedding is obscure in the Nova Lima Group, and foliation is essentially parallel to the bedding in the Minas Series. Angular relations are strongly indicated by the more complex folding of the Nova Lima Group rocks in some of those areas, and Simmons (written commun., 1964) stated that there is an angular discordance of about 20° in the Santa Bárbara area.

Profound erosion of the Rio das Velhas Series before Minas sedimentation began is certain. The only place where a minimum absolute value of such erosion could be calculated is in the northwest corner of the Gandarela syncline; there marker beds in the Nova Lima Group show that not less than 1,000 meters of sediments was removed. More than 1,000 meters of quartzose rock of the Maquiné Group must have been eroded between the Vargem do Lima syncline and the Serra da Ouro Fino; very probably all of the Maquiné Group was removed in extensive parts of the region before Minas sedimentation began.

Wherever the contact of the two series can be traced, it is evident that the pre-Minas surface was one of very low relief. The maximum local relief on the old erosion surface of perhaps 50 m was produced on a hard quartzite of the Nova Lima Group (fig. 5). The irregular accumulation of polymictic basal conglomerate in the Minas Series is an indication of old valleys, a few of which were several tens of meters deep but most of which were much shallower. Presumably the surface had been peneplaned, as suggested by Harder and Chamberlin (1915).

Regional evidence shows that a great time interval elapsed between Rio das Velhas and Minas Series sedimentation to permit folding of the older rocks and beveling of them to a nearly plane surface. Part of the Bação granitic complex and probably some of the granitic rocks to the north and west also formed or were emplaced during this interval.

DISTRIBUTION, WEATHERING, AND METAMORPHISM

The Minas Series is preserved only in synclinal structures in the Quadrilátero Ferrífero, in the complex mass of the Serra do Caraça, and in the Serra das Cambotas. The Minas rocks commonly lie in orderly sequence, although in many of their exposures they are inverted, for most of the synclines are overturned to the north and west. Many relatively thin lithologic units of the Minas Series can be traced for tens of kilometers along strike without change in lithology except that resulting from variation in metamorphic grade.

Thickness of some of the units varies radically; in most places this is clearly caused by tectonic deformation of the rocks. Formations characteristically thicken in the axial zones of folds and thin on the flanks within a few hundred meters to a few kilometers; the Cauê Itabirite varies in apparent thickness from a few meters to more than 1,400 m. Such variations are not confined to the plastic iron-formation and argillaceous rocks but are also found in more massive quartzites. Naturally this tectonic deformation obscures the original sedimentary features of the rock in many areas.

Most strata of the Minas Series are deeply weathered; exceptions are the massive quartzites, locally the itabirite, and still more locally the dolomite lenses. The only rocks which could be satisfactorily studied petrographically are the monomineralic rocks, some ferruginous rocks, and a few phyllites and schists incised by recent rapid mechanical erosion. Thus, our petrographic knowledge of the Minas Series rocks is uneven; some we know well, but most we know poorly.

The metamorphic grade of the Minas Series ranges from the greenschist facies to the amphibole-almandine facies (Herz, written commun., 1965) and increases generally toward the southeast and east. Variation depends upon the regional position and proximity to younger granitic bodies. Certain formations have been metamorphosed to granitic gneisses in the Monlevade and Itabira areas. Shearing was strong in places. Both shearing and metamorphism obscure sedimentary features, and the greater the degree of metamorphism and shearing, the deeper the weathering.

TAMANDUÁ GROUP

The Tamanduá Group was defined by Simmons and Maxwell (1961) as comprising the quartzites, quartzose and argillaceous schists, and phylitic and dolomitic itabirite stratigraphically between the Maquiné Group of the Rio das Velhas Series and the Caraça Group of

FIGURE 5.—Vertical aerial photograph showing the unconformity between the Minas Series (left) and the Rio das Velhas Series (right) in the Serra do Itabirito near N. 8,000, E. 3,000, Itabirito quadrangle. The Minas Series is here folded past the vertical and dips steeply east. The relief on the ancient pre-Minas erosion surface, formed on the hard quartzite in the Rio das Velhas Series, is somewhat exaggerated by the angle of view. Approximate scale, 1 : 10,000.

the Minas Series. The group was named from exposures in the Serra do Tamanduá (Santa Bárbara and Cocais quadrangles); it also crops out in the Antônio dos Santos, Gongo Sôco, Capanema, and Santa Rita Durão quadrangles. Rocks tentatively correlated with the Cambotas Quartzite of this group crop out in the Florália, Dom Bosco, Ouro Branco, and Santa Rita do Ouro Prêto quadrangles.

The Tamanduá Group was originally divided into one named and three unnamed formations by Simmons and Maxwell. Simmons (1968b) subsequently grouped the three unnamed units into a single formation, and this restriction is followed in this paper. The Cambotas Quartzite crops out extensively and well; the overlying strata, composed of phyllite and iron-formation, crop out poorly and are mappable in only a few restricted areas.

The rocks of the Tamanduá Group are generally similar in lithologic aspect to many other rocks of the region and cannot be traced continuously far from the type locality. Stratigraphic relations between them and others are obscured by metamorphism, faulting, erosion, and overlap of younger formations. Hence, the group is identified only tentatively in parts of the region.

The descriptions below relate only to the areas definitely identified as Tamanduá Group on plate 1. Other areas will be discussed separately.

CAMBOTAS QUARTZITE

The Cambotas Quartzite was defined by Simmons and Maxwell as including the quartzites and phyllitic and quartzitic schists at the base of the Tamanduá Group. The unit characteristically forms bold scarps (figs. 6 and 7), not only where underlain by the relatively nonresistant granitic gneiss, as in the Serras do Tamanduá and das Cambotas, but also where it lies adjacent to the generally less resistant rocks of the Minas Series, as in the Serra do Caraça. It is one of the most resistant formations in the region to chemical and mechanical weathering.

FIGURE 6.—Typical bare outcrops and cliffs of the Cambotas Quartzite in the Serra do Caraça. The chapel of Colégio do Caraça in the foreground is at an elevation of about 1,300 m; the peaks, over 1,750 m. Photograph by Norman Herz.

DISTRIBUTION AND THICKNESS

Rocks mapped as Cambotas Quartzite crop out in the Serra do Tamanduá, the Serra das Cambotas, the east end of the Serra Geral, and the Serra do Caraça. Simmons and Maxwell (1961) divided the Cambotas into two units at the type locality near the junction of the Serra Geral and the Serra das Cambotas—a lower unit 92 m thick composed of phyllitic schist, quartzitic phyllite schist, conglomeratic phyllite schist, and quartzite,[1] and an upper unit 638 m thick composed almost entirely of quartzite. The lower unit cannot be traced laterally with any consistency because of poor exposures and migmatization by the underlying granitic gneiss.

In the Serra do Caraça, Simmons and Maxwell divided the Cambotas Quartzite into four units, consisting from top to bottom of coarse-grained quartzite, 100 m; crossbedded fine- to coarse-grained sericitic quartzite, 580 m.; fine-grained sericitic quartzite, 70 m.; and

FIGURE 7.—Typical cliffy outcrops of the Cambotas Quartzite in the Serra das Cambotas, Santa Bárbara quadrangle.

[1] Although Simmons includes this lower unit in the Nova Lima Group in his most recent report (Simmons, 1968b, p. H10), this writer agrees with the original assignment of these rocks to the Cambotas Quartzite (Simmons and Maxwell, 1961). This opinion is based on the following criteria: (1) The high quartz content of the rocks, typical of the Cambotas but atypical of the Nova Lima Group, (2) the presence of conglomerate beds, regionally most uncommon in the Nova Lima Group and not reported in that group elsewhere in this vicinity, (3) the absence of chlorite, a characteristic mineral of the Nova Lima Group but not of the Cambotas Quartzite, and (4) the fact that the original description did not mention an important structural or stratigraphic break between the lower and upper units (although a bedding-plane fault was noted). The original description states that near the type locality the Cambotas as there defined rests discordantly on the Nova Lima Group. If the lower unit of the original description were Nova Lima rather than Cambotas, an interval equivalent to the whole Maquiné Group must be present between these concordant units.

conglomerate and very coarse grained quartzite, 40 m. Maxwell, who mapped the Serra do Caraça, elsewhere stated (written commun., 1962) that there

> the thickness of the Cambotas Quartzite is variable and nowhere certain * * *. The only locality in the Alegria district which has younger pre-Minas rocks overlying the Cambotas Quartzite is in a zone of complex faulting, so complex that measurement of thickness is impossible. There are no definitive marker beds in the quartzite * * *. The maximum apparent thickness is about 1,000 m.

In the Serra do Tamanduá the outcrop width ranges from 0 to 1,900 m. The thickness is at least 200 m. in much of the range, but the rocks disappear abruptly to the east.

CONTACTS

The Cambotas Quartzite was said by Simmons (1968b) to overlie granitic gneiss with metasomatic contact wherever the contact between those rocks is exposed in the Cocais and Santa Bárbara quadrangles.

To the west, Moore mapped a normal discordant sedimentary contact between the Cambotas Quartzite and the Nova Lima Group in the Gongo Sôco quadrangle; the quartzose grit and conglomeratic grit are there apparently concordant in strike with underlying rocks, but dips may or may not be concordant. An erosional contact between the two groups is proved by the presence of fragments of a distinctive thin-bedded Nova Lima iron-formation in the basal conglomerate of the Cambotas at Gongo Sôco N. 8,100, E. 6,800. The iron-formation crops out about 50 meters to the north. Maxwell (written commun., 1962) stated that in the Catas Altas quadrangle the Cambotas may overlie the Nova Lima Group with unconformable contact. Simmons and Maxwell (1961, p. 9) stated that the Tamanduá Group near its type locality discordantly overlies the Nova Lima Group.

The Cambotas Quartzite overlies the Maquiné Group with apparently concordant contact in most places in the Catas Altas and Capanema quadrangles, but the regional outcrop pattern was said by Maxwell (written commun., 1962) to show a discordance which could be either erosional or structural. At Capanema N. 5,400, E. 6,600, the contact between these rocks is said to be an angular unconformity of 60°. Elsewhere in these quadrangles there are suggestions of a fault contact. Simmons and Maxwell (1961, p. 10) stated that the Tamanduá Group discordantly overlies the Maquiné Group in the western part of the Serra do Caraça. Moore (1969) stated that in the Conceição do Rio Acima quadrangle there is a discordance in dip of 5°–30° and in strike of 10°–80°.

The Cambotas Quartzite thins abruptly to the west in the Serra Geral and disappears a few hundred meters west of the point where the road to Gongo Sôco from the Caeté-Barão de Cocais highway crosses the serra. Moore, who mapped this area, stated (written commun., 1962) that the formation is cut out by a thrust fault; Bölau (1952, p. 482) considered that the formation wedges out to the west. The writer, after a careful field check in 1966, believes that a sedimentary wedgeout is the more probable, for the formation does not reappear west of this area and the postulated thrust fault was not found.

LITHOLOGY

The Cambotas Quartzite is largely an orthoquartzite. Maxwell stated that in the Serra do Caraça the rock is relatively pure quartz with minor amounts of sericite-muscovite, chlorite, clinozoisite, and kyanite. Kyanite is present only in zones of intense deformation (Maxwell, written commun., 1962). Rock types present are pebble conglomerate, grit, and fine- to coarse-grained quartzite; some layers are crossbedded. A few thin zones consist of quartzose sericite phyllite.

In the Serra das Cambotas the unit is lithologically similar, although Simmons reported no chlorite or clinozoisite. There, the most distinctive feature of the rock is the preservation of original sedimentary structures, including ripple marks, scour and fill, and crossbedding. These are preserved despite the fact that the strata have been so crushed that a microaugen texture has resulted and, on weathering, the rock breaks down to silt-sized particles (Simmons, 1968b). In the Serra do Tamanduá the lithology is apparently similar to that in the Serra das Cambotas.

Simmons found that the Cambotas Quartzite in the Cocais area was strongly metasomatized. The partial alteration of the quartzite to granitic rock can be seen a few hundred meters west of the Barão de Cocais–Cocais road, just north of the Serra do Tamanduá, where quartzite occurs as isolated remnants in the gneiss. Bölau (1952, p. 488) determined that feldspar occurs locally in rocks now called Cambotas Quartzite, which he correlated with the basal Minas Series. Simmons and Maxwell also mentioned the presence of this mineral; in some rocks the feldspar is sedimentary in origin, but in others it is a metasomatic product. Its presence or absence has no diagnostic value from a stratigraphic standpoint.

UNNAMED FORMATION

DISTRIBUTION, LITHOLOGY, AND THICKNESS

The unnamed formations of the Tamanduá Group (Simmons and Maxwell, 1961) overlie the Cambotas Quartzite in the type locality in the Gongo Sôco and Santa Bárbara quadrangles, in the Cocais quadrangle, and at all observed localities in the Santa Rita Durão and Catas Altas quadrangles. Simmons originally separated these formations in the Santa Bárbara and Cocais quadrangles, but they have not been separated elsewhere; they crop out only in roadcuts or other artificial exposures or, rarely, in gullies. For this reason, Simmons later (1968b, p. H11–H13) considered the three formations as members of a single formation, despite their varying lithology.

As described in the type locality, the upper unit is phyllitic schist, 35 m thick; the middle unit is dolomitic and phyllitic iron-formation, 41 m thick; and the lowest unit is phyllitic and quartzitic schist, 211 m thick. Simmons stated (written commun., 1964) that the upper formation may be divided into nine lithologic units 2.5 km west of the type locality, but that none of the units could be correlated with those of the type locality. From this it would appear that the lithology of the formation is highly variable. The thickness of these rocks in the Catas Altas and Santa Rita Durão quadrangles was not mentioned by Maxwell (written commun., 1962), but the maximum outcrop width is perhaps 200 m in a place where dips are steep.

In these rocks white mica is second in abundance to quartz; small quantities of chlorite are also present. The iron content of the iron-formation is not known; some 28 m of the total of 42 m of this formation at the type locality is dolomitic and phyllitic itabirite, and the rest is dolomitic phyllite. The writer believes, but cannot prove, that the iron-formation was oxide facies. A single analysis presented by Simmons (1968b, p. H13) showed 71 percent iron; this was from a small soft high-grade iron ore body in the Serra do Tamanduá. Such high-grade iron deposits are known only from oxide-facies iron-formation elsewhere in the region. The rapidly changing lithology as most recently described by Simmons might indicate nearshore sedimentation.

CONTACTS

The contact between the unnamed formation and the Cambotas Quartzite was seen in only two places. In one, at the type locality, it was interpreted as a bedding fault (Simmons, 1968b, p. H13). At the other, in the Santa Rita Durão quadrangle near Morro da Mina, the relations are obscured by severe shearing and faulting, and the fundamental nature of the contact could not be deciphered (Maxwell, written commun., 1962). Simmons (1968b, p. H13) believed that the contact is probably essentially conformable.

The contact between the unnamed formation and the overlying rock of the Caraça Group of the Minas Series was believed by Simmons (1969b, p. H14) to be structurally conformable where observed. At the type locality the contact is marked by several centimeters of quartz but the two units are conformable (Simmons and Maxwell, 1961). Simmons cited no locality where known upper Tamaduá is in angular sedimentary contact with known Minas Series rocks. The persistence of this thin and relatively soft formation for some 35 km across the Santa Bárbara and Cocais quadrangles indicates that if the contact is an angular unconformity, the angle must be less than 3°, hardly noticeable with such poor exposures, and of minor significance. According to Simmons (oral commun., 1964), not only the upper formation of his then threefold division, but all the formations thin to the east, which suggests to the writer a wedgeout rather than an angular or erosional unconformity. Maxwell (written commun., 1962) implied that the unconformity was an erosional one in the quadrangles mapped by him, but did not advance specific evidence. The persistence of thin soft rocks along the east side of the Serra do Caraça indicates that erosion there must have been minor if it occurred.

ROCKS TENTATIVELY CORRELATED WITH THE TAMANDUÁ GROUP

The Serra do Ouro Branco in the southwestern part of the region is an isolated large mass of quartzite which Simmons and Maxwell (1961) and this writer tentatively correlate with the Cambotas Quartzite of the Tamanduá Group. This most impressive mountain is composed of white and gray sericitic quartzite with an apparent maximum thickness of about 1,400 m (Johnson, 1962, p. 10 and fig. 2), bounded on the north by a major fault. To the south, the quartzite is in contact with gneiss at least in part formed by metasomatism of the Nova Lima Group and, with angular unconformity, the Nova Lima Group. This great quartzite mass wedges out gradually to the east, as in the Serra do Tamanduá, and abruptly to the west, as in the Serra Geral.

The quartzite of the Serra do Ouro Branco is composed, according to Johnson, of gray to white sericitic coarse-grained quartzite and grit. The coarse quartz grains, some well rounded, others angular because of crushing, are in a matrix of fine-grained crushed quartz and sericite. Hematite and magnetite, zircon, and locally feldspar are accessory minerals. Well-rounded quartz and quartzite pebbles as much as 10 cm long are reported but sparsely scattered pebbles of vein quartz and quartzite about 1 centimeter in maximum dimension are more common. Ferruginous quartzite and phyllite pebbles also are present. One conglomerate bed 5 m thick composed of 50–70 percent rounded pebbles was found by Johnson, who suggested that the quartzite pebbles may be recrystallized chert. Pebbles in this bed are squeezed and alined parallel to schistosity rather than to bedding.

Bedding in the quartzite is nearly obliterated by schistosity, which may cross the bedding at a large angle. Compositional banding, reflecting original bedding, is locally several meters or more across. Because of the strong foliation in this area, crossbedding is difficult to identify with confidence; many structures in the rock which appear to be crossbedding are due to tectonic causes. Johnson did not definitely identify crossbedding and the writer believes that, although the nature of the rock indicates that the beds were probably crossbedded originally, this feature cannot now be identified.

The isolated quartzite mass of Ouro Branco was correlated with the basal Minas Series by Harder and Chamberlin (1915) and by Guild (1957). Barbosa (pl. 9) mapped it as Maquiné Group, queried. Guimarães (1931) correlated it with the Itacolomi Series. As pointed out by Johnson (1962, p. 10–12), who tentatively correlated it with the basal Minas Series, the stratigraphic position of this rock is indeterminate. It is here correlated with the Cambotas Quartzite on lithologic grounds; it can hardly be Itacolomi because of stratigraphic relationships. The wedgeouts to the east and west are more characteristic of the Cambotas than of the Moeda Formation quartzites. The lack of chlorite and the relative purity of the quartzite strongly suggest that the rock is not Maquiné Group, for it is a paralic orthoquartzite rather than a molasse protoquartzite.

Two arcuate masses of quartzite isolated in granitic gneiss in the Florália quadrangle were mapped by Herz, who correlated them with the Cambotas Quartzite. These are said to lie with angular discordance on the Nova Lima Group of the Rio das Velhas Series (Herz, oral commun., 1965).

ENVIRONMENT OF DEPOSITION

The rocks of the Tamanduá Group differ from those of the underlying Maquiné and Nova Lima Groups in that they are shelf deposits dominantly composed of orthoquartzite, quartzose phyllite, and phyllite. The Cambotas Quartzite is a prismatic paralic deposit; the overlying phyllitic and dolomitic rocks might indicate deeper water, although the rapidly varying lithology indicates nearshore deposition also. The group overlies the older eugeosynclinal and molasse rocks, certainly with deep erosional unconformity and probably with an angular unconformity. Wherever observed, it underlies the Minas Series with angular conformity; no significant erosional unconformity has been certainly demonstrated although it may well exist.

Minor chlorite present gives no hint of the volcanic activity which characterizes the underlying sediments, and the coarse quartzites must have been derived from the erosion of a granitic terrane, for the Nova Lima and probably the Maquiné rocks are too fine grained to supply coarse sediments of this nature. The source of the sediments is not clear, but distribution of the coarser sediments might suggest a source to the west.

CARAÇA GROUP

The Caraça Group was established by Dorr, Gair, Pomerene, and Rynearson (1957) to include the clastic rocks above the major regional unconformity exposed in the western Quadrilátero Ferrífero and below the chemical sediments of the overlying Itabira Group. As originally defined, it included the Caraça Quartzite and the Batatal Schist of Harder and Chamberlin. The Batatal Schist was renamed the Batatal Formation by Maxwell in 1958 because it is largely phyllite and contains other lithologies. The basal quartzite formation as then known, called the Caraça Quartzite by Harder and Chamberlin, was renamed the Moeda Formation from the Serra da Moeda (Wallace, 1958), where the structure is simple and where there can be no question as to its stratigraphic position and its relation to other rocks of the Minas Series and the Nova Lima Group. In 1957 the quartzite making up the main mass of the Serra do Caraça was still unmapped and its age was moot, as Guimarães (1931) considered it to be Itacolomi.

In the course of mapping the Serra do Caraça, Maxwell perceived that the quartzites making up the main mass of the mountain were somewhat different from the quartzite immediately below the Batatal Formation in that area. At the same time, Simmons, mapping in the Santa Bárbara and Cocais quadrangles to the north, found that the principal quartzite in the Serra do Caraça was lithologically similar to that in the Serra das Cambotas and the Serra do Tamanduá and that in the latter ranges two phyllite and one iron-formation zones separated that quartzite from thin quartzite and phyllite zones which he correlated with the Moeda and Batatal Formations. The major quartzite underlying the Serra do Tamanduá, the Serra das Cambotas, and the Serra do Caraça and the phyllitic and iron-formation zones were grouped by Simmons and Maxwell (1961) as the Tamanduá Group, and the major quartzite called the Cambotas Quartzite.

The Caraça Group must be redefined because the original definition was made before the presence of older rocks above the regional unconformity and below the type Caraça Group had been established. The Caraça Group is here redefined as comprising the metasedimentary quartzitic and phyllitic formations conformably underlying the chemical sediments of the Itabira Group of the Minas Series and overlying with essential concordance either the quartzose and phyllitic rocks of the Tamanduá Group or, commonly with angular and erosional discordance, the rocks of the Rio das Velhas Series.

The type locality of the group was originally restricted (Dorr and others, 1957) to the south flank of the Serra do Caraça in the Capanema quadrangle, following the definition by Harder and Chamberlin (1915) as closely as possible, because of the uncertainty of the age assignment of the main mass of quartzite in that mountain. Subsequent mapping proved the wisdom of this restriction, for the main mass of the Serra do Caraça is now assigned to the Tamanduá Group. The Caraça Group is present in the area cited in 1957, and the type locality may be maintained there. The best, most typical, and most accessible exposures of this group are in the Serra da Moeda and in the thinner, platform facies to be described, in the Ouro Prêto region.

At least two geologists on this project believe that the rocks of the Tamanduá Group should be included in the Caraça Group. As will be demonstrated, the rocks of the Caraça Group as here defined are blanket sediments, whereas the rocks included in the Tamanduá Group are lenticular prismatic sediments in the Quadrilátero Ferrífero. The different environment of the two divisions and the fact that an erosional interval possibly separates them seems to the writer to justify the preservation of the divisions as two groups.

MOEDA FORMATION

In the Quadrilátero Ferrífero the Moeda Formation occurs in two intergrading facies. The more prominent is a thick coarse-grained quartzite that crops out boldly; a thin fine-grained facies that crops out obscurely is at least as extensive. In part of the region it was impossible to separate the thin facies from the overlying Batatal Formation because of poor exposures; in such areas the two formations were mapped together as Caraça Group undivided. To the west, north, and east the transition from the thick coarse-grained to the thin fine-grained facies is relatively abrupt, occurring over 3–10 km. This is perhaps best illustrated in the Ibirité quadrangle, where the transition from a thickness of perhaps 500 m to about 100 m or less takes place in about 3 km. In the Bação quadrangle the diminution is slightly less abrupt but better exposed. At the south end of the Serra da Moeda the thinning is much more gradual, however.

DISTRIBUTION AND THICKNESS

The coarse-grained facies of the Moeda Formation crops out in a roughly triangular area with the base in the Serra da Moeda and adjacent parts of the Serra do Curral and the apex to the east in the east end of the Gandarela syncline and the Serra do Ouro Fino. Within this area the formation averages more than 300 m in thickness, with the maximum apparent thickness greater than 1,000 m (See fig. 8.) The coarse-grained facies also occurs in the Monlevade area; there, the maximum thickness of some 500 m is attributable to both tectonic and original stratigraphic thickening.

The thinner, fine-grained facies is peripheral to the coarser facies and has been mapped in the eastern, western, northern, and southern extremities of the region, as illustrated in figure 8. The fine-grained facies is less than 100 m thick but, because of the obscure outcrops, could not be located with certainty in many places and may average less than 50 m in thickness. In the western part of the Serra do Curral, it is between 30 and 70 m thick according to Simmons. In the eastern part of the Serra do Curral, it cannot be more than a few tens of meters thick and locally may be absent. In the east end of the Gandarela syncline it was mapped with the Batatal Formation and may be a few tens of meters thick or less. In the Ouro Prêto area, it averages perhaps 50 m thick and may be missing in part of the Dom Bosco quadrangle. However, it thickens to the north in the São Bartolomeu quadrangle. Around the Serra do Caraça the fine-grained facies crops out only sporadically and is only 10 m to a few tens of meters thick.

LITHOLOGY

The two facies of the Moeda Formation have in common a dominantly quartzose composition. The lithology varies with the thickness, and the two facies will be described separately. They are intergradational along strike.

The coarse-grained facies is composed of quartzite, grit, conglomerate, and phyllite. The rock types are commonly well differentiated, and some of the quartzite approaches orthoquartzite, although nearly all contains varying and locally large quantities of sericite or muscovite. Both quartzite and grit have been sheared and crushed to a microaugen texture in many localities, and the larger grains are there very angular. Where original constituents of the rock can be distinguished, grain size can be seen to change rapidly and widely both along and across the strike of the beds.

The grit and quartzite both contain widely varying quantities of iron oxides, in many places concentrated on shear planes and bedding planes; it is impossible to be certain how much of the iron has been moved and recrystallized during the metamorphism and local metasomatism to which the rocks have been subjected. For the same reason, it is most difficult to be certain how much of the feldspar found in the rock is original detrital feldspar; this mineral is most abundant in proximity to granitic rocks, as is the locally abundant tourmalinite

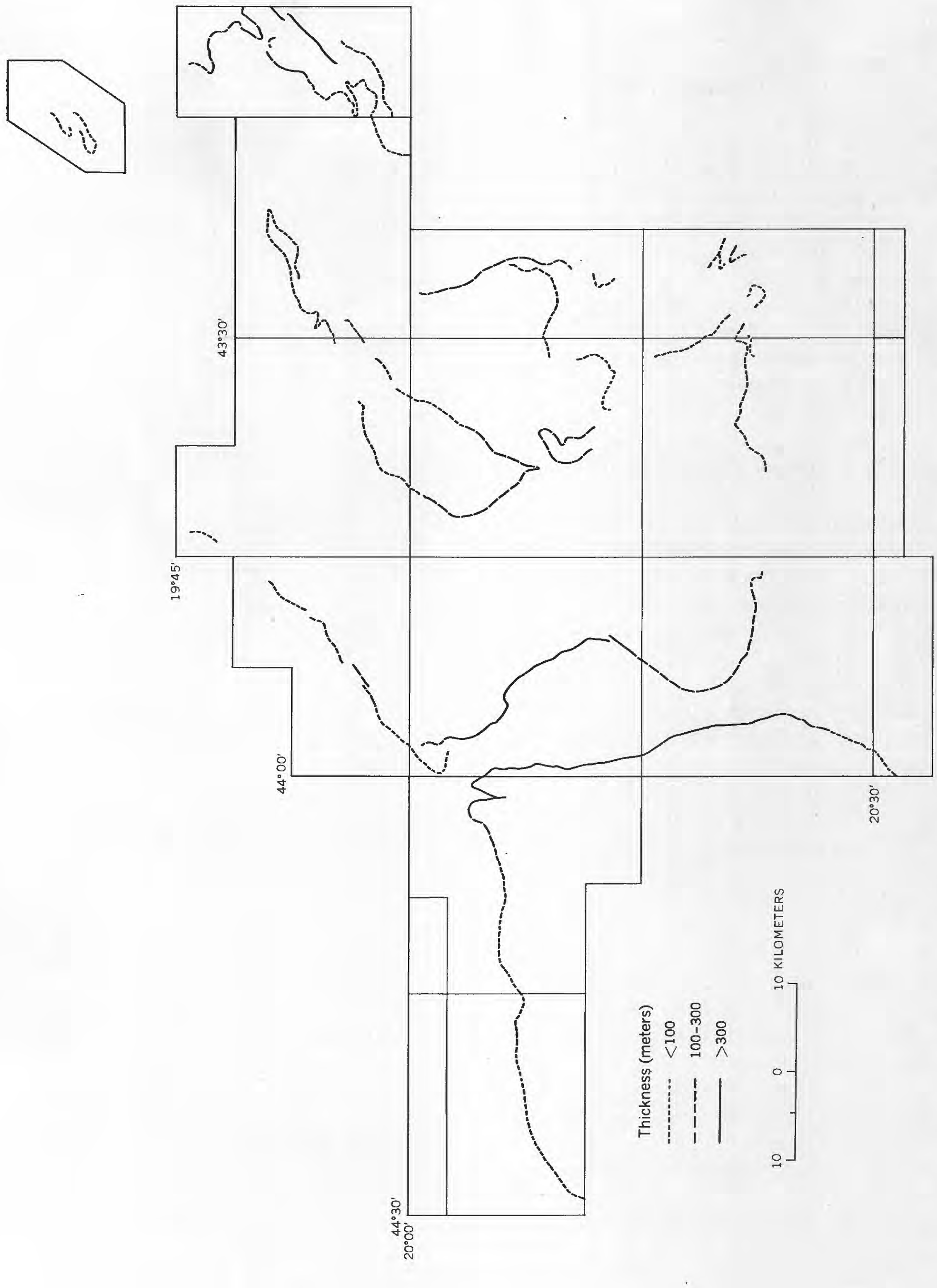

FIGURE 8.—Variations in thickness of the Moeda Formation in the Quadrilátero Ferrífero. Thickness shown is only approximate; local tectonic deformation obscures the true stratigraphic thickness in many places.

and tourmaline (Guild, 1957). Quartzite and grit are by far the most common rock types in the coarse-grained facies of the Moeda Formation.

Conglomerate is a characteristic rock of the coarse-grained facies. Basal conglomerate containing angular and squeezed fragments of the underlying Nova Lima Group phyllites together with well-rounded pebbles, cobbles, and boulders of vein quartz and quartzite of unidentifiable source, and, rarely, amphibolite, is excellent evidence for the unconformable nature of the contact of the Minas Series with the Rio das Velhas Series. The phyllite fragments occur not only at the contact but as much as 10 m above it. They are not found in the many conglomerate lenses higher in the section, and it is significant that no granite, amphibolite, gabbro, or other similar rocks have been found as cobbles in these higher conglomerates. The basal conglomerate occurs in irregular lenses ranging from a few centimeters to perhaps 30 m thick and from 10 m to a few hundred meters in outcrop length; most exposures show a thickness of only a few meters.

In all the conglomerate beds, the quartz and quartzite cobbles vary widely in dimension (figs. 9 and 10); generally they are larger where the conglomerate lenses are thicker. The largest boulder seen was 40 cm in maximum dimension; this was in the basal conglomerate in the Serra da Moeda near Macacos N. 1,000, E. 500. Most cobbles are 5–10 cm in length or smaller. The size of the cobbles gradually and irregularly diminishes from west to east across the approximately 40-km-wide area of occurrence of the coarse-grained facies.

With one exception, the conglomerate lenses are random in distribution throughout the Moeda Formation. In the Serra da Moeda a persistent zone of conglomerate lenses occurs over a strike length of at least 10 km at the base of a quartzite zone overlying a very persistent phyllite member in about the middle of the formation.

Phyllite occurs in the coarse-grained facies of the Moeda Formation in lenses of varying dimension. Where the formation is thickest, in the Serra da Moeda and Serra do Itabirito, these lenses are mappable members as much as 166 m thick (Wallace, 1965), one of which is known to be continuous over four quadrangles. Where the facies is thinner, as in the east end of the Gandarela syncline, the lenses are a few meters to hundreds of meters long. This sericitic phyllite is only slightly quartzose.

The lithology of the fine-grained facies of the Moeda Formation is quite different from that of the coarse-grained facies although the bulk chemical composition of the rocks may be very similar. Except for the presence of basal conglomerate lenses indistinguishable from those in the coarse-grained facies, cobble and boulder conglomerates are not found; pebble conglomerate is relatively rare, although in some places isolated pebbles occur in quartzite. Grit is also an uncommon rock. Quartzite is more evenly grained and finer grained, and in many localities is very phyllitic. Phyllite in separate beds and members was not found, although exposures of this facies are so bad that it may be present but unseen. In general, the rock types are less differentiated, but in some areas, as near Ouro Prêto, the quartzite is evenly grained and relatively pure.

FIGURE 9.—Cobbles in basal conglomerate of the Moeda Formation near N. 1,000, E. 500, Macacos quadrangle. Colonial fort in the background was built to protect gold mine in the basal conglomerate.

PHYSIOGRAPHIC EXPRESSION

The physiographic expression of the Moeda Formation depends upon its thickness. Where 200 m or more thick, it forms scarps with very spectacular and craggy outcrops (fig. 11). West of Itabirito the formation is more than 400 m thick and makes an impressive scarp above the adjacent Nova Lima Group. Farther south along the Serra do Itabirito, the Moeda Formation thins to less than 100 m; the scarp disappears, and the highest rocks along the range are the Nova Lima

FIGURE 10.—Puddingstone conglomerate in the Moeda Formation, Serra da Moeda. The conglomerate is typical of discontinuous lenses in the body of the formation.

Group, there indurated by contact metamorphism. Spectacular scarps 100–300 m high and some 40 km long in the Serra da Moeda bordering the valley of the Paraopeba result from the relatively greater resistance to erosion of the Moeda Formation compared with that of the subjacent granitic rocks.

Where the Moeda Formation is thin and phyllitic, as along the north side of the Gandarela syncline, it crops out very poorly, if at all. Where thin but consisting of well-indurated and relatively pure quartzite, as along the Serra do Ouro Prêto, it forms ridges and extensive dip slopes from which overlying units have been stripped (pls. 7 and 9).

The quartzite weathers into bold slabby outcrops pitted and scarred by solution cavities, as is typical of all the more massive quartzites of the region. Jointing, bedding, and foliation all control the detailed erosional features of the outcrops.

FIGURE 11.—Typical topographic expression of the coarse-grained facies of the Moeda Formation in the Serra das Gaivotas, Ibirité quadrangle. The even ridge in background is the Serra da Moeda, showing the Gondwana surface. Lowland in the foreground is carved on Nova Lima Group rocks.

BATATAL FORMATION

The Batatal Formation (Maxwell, 1958) is the sedimentary unit described and named the Batatal Schist by Harder and Chamberlin (1915, p. 356–357). The formation consists largely of phyllite and includes minor metachert, iron-formation, and graphitic phyllite. It occurs widely but rarely crops out.

CONTACTS

In most places the Batatal overlies the Moeda Formation with a generally sharp contact, but in the Moeda Plateau the rocks may interfinger locally on a small scale (Wallace, 1965) where both formations are well developed. Where both formations are thin and the Moeda Formation is argillaceous, the two are intergradational and may not be separable. The contact is conformable wherever seen. The Batatal Formation is in conformable and sharply gradational contact with rocks of the overlying Itabira Group.

DISTRIBUTION AND THICKNESS

The Batatal Formation is easily weathered and nonresistant and lies between two resistant ridge-forming formations; therefore, it is not well exposed. Its presence is revealed by subsurface workings, by gullies, and by smooth, normally convex, slopes which support a depauperate vegetation of stunted trees and sparse grass. It weathers to a gray to buff or brown soft saprolite which tends to be somewhat limonitized at the surface.

The Batatal was identified throughout the central part of the Quadrilátero Ferrífero and is present, but was not mapped separately from phyllites in the Moeda Formation in the Congonhas area. Along the south border of the region it does not seem to be present in some localities east of Dom Bosco. Good exposures in canyons and gullies have not revealed a mappable thickness in the Ouro Prêto area. In the western Serra do Curral, Simmons (1968a, p. G13) reported that its thickness is consistently about 30 m. The formation is traceable eastward to the Nova Lima quadrangle; thence intermittently eastward to the Serra da Piedade quadrangle. Outcrops are poor in the east end of the Serra do Curral, and the formation may well be essentially continuous although thin. In the central part of the Serra do Curral, it thickens to more than 100 m in some areas, notably to the southeast and east of Pico Belo Horizonte.

Moore, O'Rourke, and Simmons traced the formation in the Gandarela syncline and found it to thin eastward.

Simmons (1968b, p. H15) stated that the formation is present but thin except along the south limb of the Gandarela syncline at its east end; on the north limb it is 9 m thick near the west border of the Santa Bárbara quadrangle. In much of the Monlevade area it is 20–50 m thick, but in the southern part it could not be separated from the Moeda (Reeves, 1966). Maxwell mapped the formation along the east side of the Serra do Caraça and intermittently along the south side, but it was not found farther south in the Santa Rita Durão quadrangle.

Thus, the Batatal Formation ranges in thickness from a few meters to more than 200 m. It is thickest in the Serra da Moeda. It is persistent across the central part of the region but disappears or thins markedly to the northeast and to the southeast.

LITHOLOGY

The Batatal Formation is sericitic phyllite. Particularly in the central part of the region, a field test for the rock is the absence of grittiness between the teeth. Where both the Batatal and the underlying Moeda Formation are thin and poorly differentiated, the Batatal may also contain significant amounts of quartz. Locally the formation contains significant amounts of chlorite, graphite, and carbonaceous material.

Lenses of pure white fine-grained equigranular quartzite are known in an adit in the Serra do Curral near Jangada (Ibirité quadrangle); at about N. 500, E. 4,500, in the Belo Horizonte quadrangle; at N. 8,950, E. 1,900, in the Lagoa Grande quadrangle; in tunnel F in the Rio do Peixe canyon, Lagoa Grande quadrangle; at N. 12,550, E. 11,700, Lagoa Grande quadrangle; and in an exploratory adit in Conceição Peak, Itabira district. The occurrence in the west side of the Lagoa Grande quadrangle, which is on the road to Piedade de Paraopeba, is the most accessible. Such lenses, interpreted as lenses of metachert, are fortuitously revealed by cuts, gullies, and exploratory workings; they may be more common than now known, as they crop out only in unusual topographic situations.

In tunnel F, Lagoa Grande quadrangle, such metachert grades upward into iron-formation (Wallace, 1965). Along the road from Gongo Sôco to the Caeté–Barão de Cocais highway, a thick zone consists of interbedded metachert and phyllite; bands are a centimeter or so thick, are fairly well separated, and alternate from one rock type to the other. Phyllitic bands contain some hematite, and the sequence grades upward into the Cauê Itabirite.

The Batatal Formation also contains dark-gray to nearly black graphitic and carbonaceous phyllite. I. A. Breger (Simmons, 1968a, p. G13) extracted soluble organic material from this rock. Limonite pseudomorphs after pyrite are seen in graphitic phyllite in places. Thin discontinuous lenses of iron-formation also are known, and the phyllite may be very hematitic in the upper few meters of the formation. Magnetite crystals are common in these uppermost beds.

ENVIRONMENT OF DEPOSITION

The Caraça Group consists of the Moeda Formation: an extensive quartzose formation, and the Batatal Formation, an argillaceous formation. The Moeda Formation occurs in two facies: a thick coarse-grained orthoquartzite and protoquartzite, and a thinner, fine-grained facies. The transition between the two facies is in most places fairly abrupt.

The thicker facies, averaging perhaps 300 m in thickness but much thicker in some parts of its outcrop, is characterized by coarse grain size, abundant conglomerate lenses, and well-differentiated phyllite lenses and members. This facies is typically developed in the east and west sides of the Moeda Plateau, where it has a north-south extension of some 40 km. Eastward the coarse-grained facies narrows in outcrop width and thins stratigraphically. East of the westernmost parts of the Gandarela syncline and of the Serra do Ouro Fino, it is found only in a small part of the Monlevade quadrangle.

The thinner facies, which averages less than 100 m in thickness, is characterized by finer and more even grain size, by mixing of the argillaceous fraction with the quartzose fraction of the formation, and by the lack of conglomerate lenses. This facies has been mapped in most of the region peripheral to the area underlain by the coarse-grained facies.

Both facies are characterized in many localities by a basal conglomerate made up of fragments of phyllite derived from the underlying Nova Lima Group phyllites and well-rounded vein-quartz and quartzite pebbles and cobbles. The lenticular basal conglomerate probably represents filling of ancient shallow valleys carved in the older rocks. The distribution of the coarse facies, and particularly the size distribution of the cobbles and boulders in the conglomerate lenses in that facies, strongly indicates that the source of the material was to the west and that the coarse facies was a deltaic deposit; the finer facies represent poorly sorted silts deposited in quieter water around the delta.

The Batatal Formation is nearly coextensive with the Moeda. In the Quadrilátero Ferrífero it ranges from a quartz-free argillaceous rock where it overlies the thicker facies of the Moeda Formation, to an argillaceous rock with small amounts of free quartz where that formation is thin and itself somewhat argillaceous. The Batatal varies directly in thickness with the Moeda, being thinnest to the south and east.

Harder and Chamberlin (1915) were the first to point out that the quartzose sediments are transgressive over an old peneplaned surface; it seems probable that the transgression was from west to east. The Moeda Formation preserves the transition from paralic to stable shelf environments in its transition from coarse to fine quartzose sediments. The argillaceous Batatal may be at least in part contemporaneous with part of the Moeda, an offshore sediment deposited on a slowly sinking wide shelf or platform. The presence of lenticular masses of metachert and the gradational contact with the overlying chemical sediments of the Itabira Group also point toward this environment. Both formations are blanket formations, having great lateral extent in comparison with their average thickness.

METAMORPHISM

The Moeda Formation, having a bulk composition not sensitive to metamorphic effects, contains few and simple minerals and does not vary widely with changing metamorphic environment. Argillaceous minerals were changed to sericite and muscovite, their grain size varying directly with the intensity of metamorphism, which increases to the east. Locally, biotite is formed at the appropriate metamorphic grade.

The pelitic Batatal Formation, however, is more complex in its metamorphic reactions. In the Monlevade district, much of the rock was converted to a laminated quartz-muscovite schist containing as much as 10 percent almandine garnet (Reeves, 1966). In the Itabira district garnets also are found in this unit, although the rock is a phyllite rather than a schist. Further to the west this mineral has not been observed in the Batatal. Graphite and carbonaceous matter in certain zones of the rock inhibited recrystallization. Such zones look like argillite where adjacent formations show the grade of regional metamorphism to be well up in the greenschist facies.

Guild (1957) and O'Rourke (written commun., 1954) noted the presence of kyanite in this formation as well as in the Moeda Formation in some localities. Both Guild (1957) and Dorr and Barbosa (1963) cited the locally abundant tourmaline in the Batatal Formation and, in the Congonhas area, in the Moeda Formation. Guild (1957, p. 12) attributed the tourmaline to metasomatic addition of boron from emanations or solutions from post-Minas granitic rocks; Dorr and Barbosa envisaged the same source and related the mineral to the fluids that produced hematite ore bodies in the overlying Itabira Group.

ITABIRA GROUP

The Itabira Group was so named by Dorr, Gair, Pomerene, and Rynearson (1957) and comprises the itabirite included in the Itabira Formation of Harder and Chamberlin (1915), as well as closely related dolomitic rocks in part included by Harder and Chamberlin in their Itabira Formation and in part probably included in their Piracicaba Formation. The older descriptions are rather vague as to exactly what rocks were included in specific formations. The Itabira Group is separated from the Caraça Group because it is dominantly composed of chemical sediments whereas the Caraça Group is dominantly composed of clastic sediments. In 1958 the Itabira Group was divided by the writer into two intergradational units: the Cauê Itabirite, a metamorphosed oxide-facies iron-formation, and the Gandarela Formation, in large part composed of carbonate rocks of various types.

Because the two formations are intergradational, and particularly because the weathering products hide the contact zone in most places, it is difficult or impossible in certain areas to separate the two formations. In 18 quadrangles they were separated; in 10 they were mapped together as Itabira Group undivided. This difficulty led Simmons (1968b, p. H15) to suggest that the rocks should be considered a single formation; other geologists do not concur because the units can be separated in most places, because the economic products from each of the units are different and it is therefore important to make the separation where possible, and because the difficulty in separation is caused more by weathering products than by lack of distinguishing features in the fresh rocks.

The Itabira Group is the most important in the region from an economic point of view. It contains great reserves of high-grade iron ore of metasomatic origin and weathering of the Cauê Itabirite has produced enormous reserves of lower grade but potentially very useful iron ore. Much manganese ore has been produced from both formations of this group, different in nature and use in each formation. Tens of tons of gold were extracted from ores in the Cauê Itabirite during the 19th century. The element palladium was first isolated by W. H. Wollaston from palladic gold from the Gongo Sôco deposit (Henwood, 1871). Bauxite is derived from the Gandarela Formation in many localities. Building stone, road metal, paving stone, and fine ornamental stone, as well as dolomite for metallurgical and refractory purposes, are extracted from the Gandarela Formation. In many localities the Cauê Itabirite can be an ample source of underground water, an economic asset as yet practically untouched. The economic geology of the Itabira Group will be discussed in another paper; in this report the rocks are considered only from a stratigraphic, structural, and physiographic standpoint.

CAUÊ ITABIRITE

The type locality of the Cauê Itabirite is in Cauê Peak in the Itabira district, where the formation is thick and is well exposed by surface and underground workings. Elsewhere the formation is poorly exposed except in roadcuts, tunnels, adits, and a few canyons, because canga, the weathering product of itabirite, conceals its lithology and contacts.

DISTRIBUTION AND THICKNESS

The Cauê Itabirite crops out almost everywhere in the Quadrilátero Ferrífero where structurally expectable and was mapped along some 540 linear kilometers of outcrop. Iron-formation believed by most geologists, including the writer, to correlate with the Cauê Itabirite also has been traced for tens of kilometers to the north on the east flank of the Serra do Espinhaço, where the typical quartzite-phyllite-itabirite sequence is found. Isolated occurrences of gneissic iron-formation, similar to the Cauê where that formation has been highly metamorphosed, are found in the granitic gneisses for tens of kilometers to the east and northeast of the Quadrilátero Ferrífero. (See map in Harder and Chamberlin, 1915, p. 347.) Similar rocks are known in the granitic gneisses some tens of kilometers west of the region mapped, near Oliveira. Iron-formation has also been reported some tens of kilometers to the southeast. It is not known whether these isolated occurrences of highly metamorphosed iron-formation are correlative with the Cauê Itabirite.

The Cauê Itabirite is quite variable in thickness (fig. 12). Where the formation is essentially undisturbed by local deformation, as on the limbs of the Moeda syncline and on the upright limb of the Gandarela syncline, it ranges from 300 to 500 m in stratigraphic thickness. In axial areas of folds—such as the west end of the Gandarela syncline, in the Alegria syncline, in the Conta Historia area, in the vicinity of Morro do Chapeu, and at the north end of the Serra da Moeda—it may have an apparent thickness of more than 1,000 m. In contrast, the formation may thin radically on the flanks of tight folds. Near the main church in Itabira, the formation on the overturned limb of the major syncline is only about 15 m thick, whereas on the upright limb of the syncline near the axial zone in Cauê Peak it is apparently almost 500 m thick. Clearly the formation was highly plastic during deformation.

The formation does not crop out in its expectable position for several kilometers along the south edge of the Bação complex. This area may well have been a positive area during early Minas sedimentation, and the formation may never have been deposited there; both the Moeda and Batatal Formations are also thin and locally missing in that area.

Comparison of figure 12 with figure 8 shows that the areas of maximum thickness of the Moeda Formation and of the Cauê Itabirite to a large extent coincide. Despite the very different nature of the two formations, this may well indicate the zones of maximum subsidence during early and middle Minas time.

There is no way of knowing what the original stratigraphic thickness of the Cauê Itabirite may have been. Because the rock was originally a blanketing oxide-facies iron-formation, a chemical sediment (Tyler, 1948) underlain by claystone and overlain by dolomitic rocks also of great lateral extent, wide primary variation in thickness is not to be expected, and therefore the general thickness of between 200–400 m in relatively undisturbed areas may be considered to approximate original stratigraphic thickness. The only observable systematic thinning is at the west end of the Serra do Curral, the south end of the Serra da Moeda, along the south margin of the Bação Complex, and possibly at the east end of the Gandarela syncline.

CONTACTS

The contact between the Cauê Itabirite and the Batatal Formation is gradational over a few centimeters or, in very few places, 1 or 2 m. Commonly the gradation is marked by the appearance of hematite in the Batatal, gradually increasing in quantity toward the Cauê. The rock becomes banded by the appearance of quartz layers; and phyllite disappears, generally abruptly. In some places there may be one or more bands of iron-formation up to tens of centimeters thick, overlain by thinner bands of phyllite. Locally the iron mineral near the contact is coarse euhedral magnetite, particularly where the Batatal is graphitic. Where the Cauê Itabirite overlies quartzose rocks the contact is abrupt.

The Cauê Itabirite grades upward into the Gandarela Formation. This contact is described in more detail in later pages. The contact is in many places indefinite, as the transitional zone may be tens of meters wide.

LITHOLOGY AND COMPOSITION

The Cauê Itabirite is composed of itabirite, dolomitic itabirite, and amphibolitic itabirite, with very small lenses of phyllite and marble. The rock itabirite has been defined (Dorr and Barbosa, 1963, p. 18) as follows:

> The term itabirite denotes a laminated, metamorphosed, oxide-facies formation, in which the original chert or jasper bands have been recrystallized into granular quartz and in which the iron is present as hematite, magnetite, or martite. The quartz

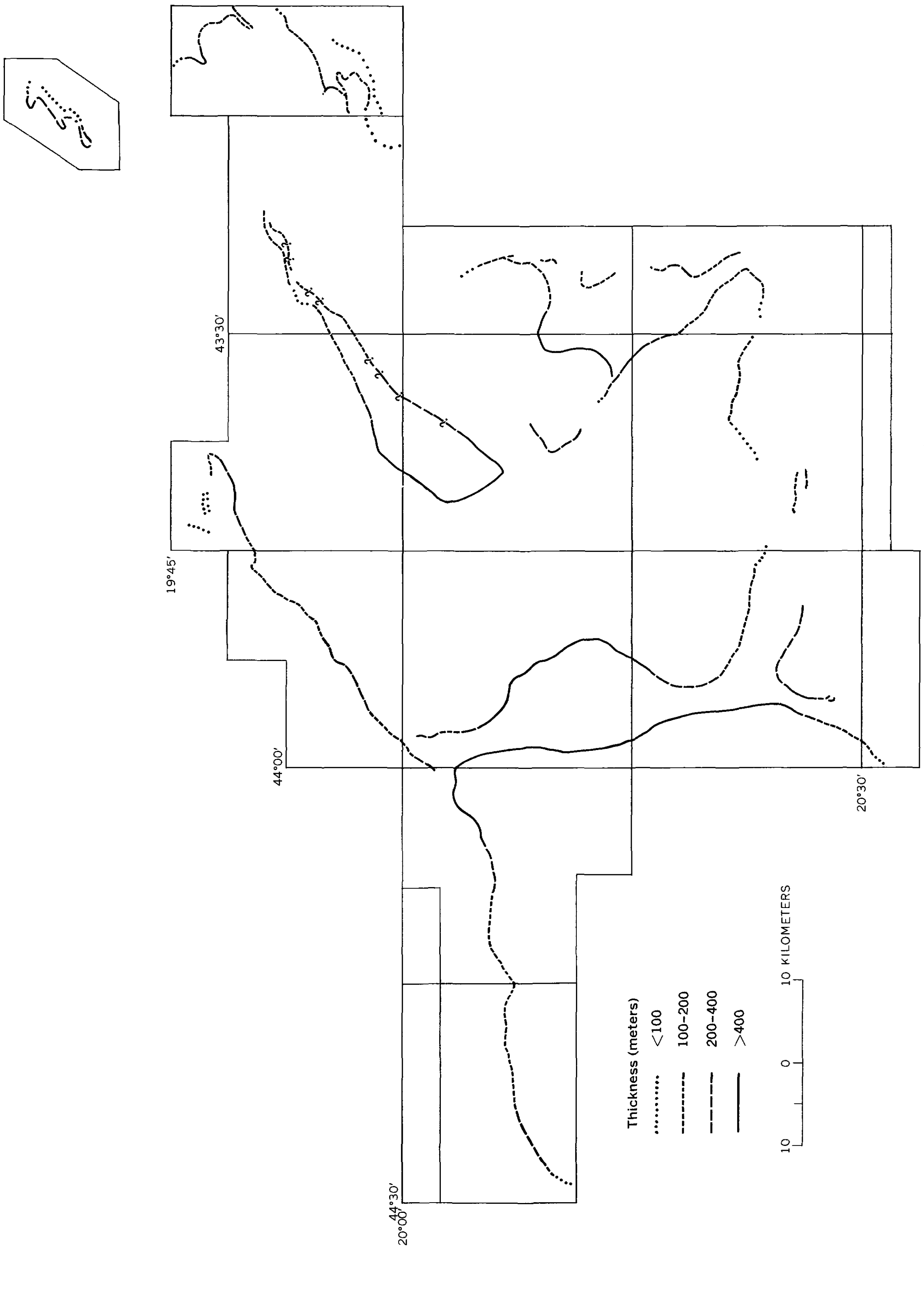

FIGURE 12.—Regional variations in thickness of the Cauê Itabirite.

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

Thus, the normal fresh itabirite of the Cauê Itabirite is a very simple rock from a petrographic viewpoint, being composed almost entirely of quartz and hematite, and locally, magnetite. Such rock makes up by far the major part of the Cauê Itabirite in the Quadrilátero Ferrífero. The chemical composition of unweathered normal itabirite averaged (Dorr, 1964, p. 1212): iron, 37.9 percent; SiO_2, 44.7 percent; Al_2O_3, 0.5 percent; phosphorus, 0.05 percent; H_2O+, 0.3 percent. Assuming all the iron to be present as Fe_2O_3 and all the phosphorus as P_2O_5, the total is 99.7 percent, leaving 0.3 percent for other elements, probably largely calcium and magnesium. An average of 11 random samples in which FeO was determined, taken in widely separated parts of the region by the writer, showed 0.54 percent FeO and 55.0 percent Fe_2O_3, indicating the great preponderance of hematite. The range of the individual analyses was not great.

Dolomitic itabirite is widely present in the Cauê Itabirite, particularly in the upper third of the formation. Fresh rock is exposed in few places for it weathers to great depth. The variations in chemcial composition are still unknown; most of the analyses available were of samples taken in areas of metasomatic enrichment and therefore cannot be assumed to be of unaltered rock. Moore (1969) cited the following analysis of a sample taken in a deep canyon away from areas of known metasomatism in the Conceição de Rio Acima quadrangle: Iron, 29.4 percent; SiO_2, 47.8 percent; Al_2O_3, 0.5 percent; CaO, 3.2 percent; and MgO, 1.6 percent. This is the only analysis of fresh dolomitic itabirite sampled away from areas of metasomatic enrichment known to the writer, despite the many references to this rock in recent literature (Pomerene, 1964; Guild, 1957; Simmons, 1968a, b).

As first pointed out by Guild (1957, p. 15), dolomitic itabirite in many places contains magnetite or mixtures of that mineral and hematite. This is thought to be a primary rather than a metamorphic feature of the rock. Guild also noted that talc may accompany dolomitic itabirite; it is believed to be a metamorphic product. As shown by thin-section study, dolomite substitutes in part for quartz in the quartz bands of the rock and less generally for the iron minerals, and in some places occurs as separate thin bands, forming a triply layered rock.

A third general type of itabirite is amphibolitic. Field evidence indicates that this type forms by contact metamorphism of dolomitic itabirite by nearby granitic rocks and thus it does not correspond to the silicate-facies iron-formation of James (1954). Typical localities may be observed where the Itatiaiuçu-Itauna road crosses the west end of the Serra do Curral (Itatiaiuçu, N. 500, E. 1,600), in roadcuts on the east bank of the Rio Paraopeba (Fêcho do Funil quadrangle), and along Br–31 north of Serra de Piedade (Serra da Piedade, N. 9,500, E. 5,750). At other localities, such as south of São Julião in the quadrangle of that name, such a relation cannot be demonstrated, but at what depth the nearby intrusive granitic rock may lie is, of course, unknown.

The amphiboles which have been identified are cummingtonite, tremolite, and actinolite. Most are so weathered that identification is not possible, but cummingtonite apparently is the most common. The iron mineral of amphibolitic itabirite is generally magnetite. Five samples were taken which were fresh enough to make chemical analyses worthwhile. The average composition, in percent, was: iron, 31.9; SiO_2, 50.8; Al_2O_3, 0.7; CaO, 2.2; MgO, 2.0; phosphorus, 0.08; FeO was determined as 13.2 percent.

It should be emphasized that none of these samples were of completely unweathered rock and that original magnetite probably was in part oxidized to martite.

It is believed that only dolomitic itabirite gives rise to amphibolitic itabirite upon metamorphism. Where normal itabirite was intruded by granitic rocks, it did not form significant amounts of amphibole. Grunerite, a common amphibole in the Lake Superior area—there thought by some to be a metamorphic product, by others to be primary—has not been found despite search. Other iron silicate minerals, such as riebeckite, chamosite, and greenalite, known in iron-formations elsewhere in the world, are unknown in this region. Stilpnomelane was tentatively identified in two areas but is not abundant.

Few other minerals are known in fresh itabirite. Sulfides have been reported only in the vicinity of gold mineralization and were introduced (Dorr, 1965, p. 25). Small amounts of chlorite have been reported in a number of localities; the variety penninite (Herz, oral commun., 1958) is particularly well developed in itabirite where the Rio Acima–Gandarela road climbs the scarp at the west end of the Gandarela syncline. It occurs in dark-green plates several millimeters long oriented across the bedding of the coarsely laminated itabirite. Chlorite is more common in dolomitic itabirite.

Asbestiform amphibole, too weathered for precise identification, occurs in several localities. Such material was attributed to the metamorphism of volcanic bombs by Guimarães (1953), but we found no evidence of any volcanic material in the Cauê Itabirite.

Although analyses of fresh itabirite reveal less than a tenth of a percent manganese in most samples, manganese oxide is not rare in weathered itabirite and many commercially important deposits of manganese ore are known closely associated with itabirite, the largest totaling more than 5 million tons. The larger deposits are in dolomitic itabirite, but many are in normal itabirite; no significant deposits have yet been found in amphibolitic itabirite. The mode of occurrence of manganese in fresh itabirite is not certainly known; presumably it occurs as the oxide but in dolomitic itabirite may well occur as manganoan calcite or manganoan dolomite. Nowhere was the rock explored deeply enough to reach unweathered material. The manganiferous itabirite occurs in lenses up to several meters thick; individual lenses may be more than 1,000 m long; and, in the Serra da Moeda, zones containing manganiferous lenses are found for a strike length of more than 10 km. Manganiferous itabirite most commonly occurs in or close to the transition zone into the Gandarela Formation but is not confined to this part of the stratigraphic section.

Thin concordant schistose, phyllitic, and clayey layers in itabirite are not unusual in some parts of the Quadrilátero Ferrífero. In many exploratory adits and roadcuts, these layers can be observed to connect with crosscutting altered dikes and thus are sills emplaced before the close of the metamorphic period (fig. 13). In other places such concordant layers are very probably sedimentary layers; near the surface they are so thoroughly altered and weathered that the original nature of the rocks cannot be deciphered.

Despite a statement to the contrary by Dorr and Barbosa (1963, p. C22), coarse clastic material is not certainly known in the Cauê Itabirite. Further study in the Itabira district made clear that the material is probably

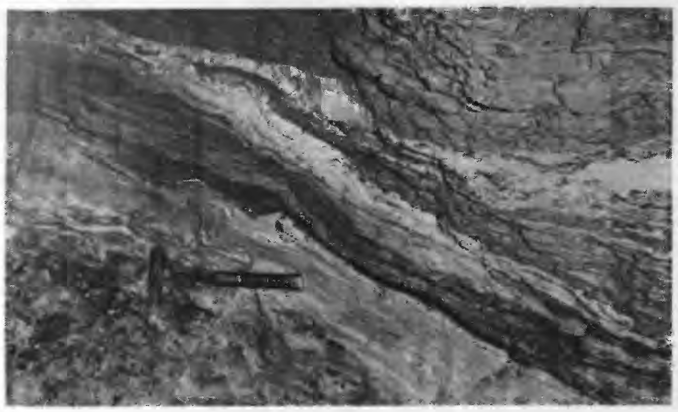

FIGURE 13.—Sill in itabirite exposed in exploratory adit (mine 1) in Itabira district.

crushed vein quartz concordant with the bedding, rather than a primary sediment. Localities cited elsewhere in the Quadrilátero Ferrífero are now interpreted as belonging to the clastic rocks of the Itacolomi Series rather than to the Cauê Itabirite (Guild, 1957; Wallace, written commun., 1961).

Weathered beds thought to have been marble are known in the Cauê Itabirite in many areas. Fresh marble occurs in one lens near the Jangada iron-ore deposit (Coelho, oral commun., 1962); the thickness exposed in an adit was about 20 m. In most other known localities, such as in the Lagoa Grande manganese mine (Lagoa Grande quadrangle), in the Itabira district, and in the Congonhas district, lenses are much thinner, measured in tens of centimeters, and all are weathered. Most are in the upper part of the Cauê Itabirite.

Thus, the Cauê Itabirite consists largely of interbedded laminae of quartz and hematite, in places containing some dolomite, magnetite, and amphibole and occasional lenses of marble and phyllite. The rock is entirely similar in lithology to most major oxide-facies iron-formations known throughout the world.

PHYSIOGRAPHIC EXPRESSION

The Cauê Itabirite is the major ridge-forming formation in the Quadrilátero Ferrífero. This is primarily because the weathering product, canga, (page A73) is inert to chemical weathering and very resistant to mechanical weathering. Canga overlies weathered itabirite, a disaggregated rock not resistant to mechanical erosion. (See fig. 2.) Fresh hard itabirite forms a few monadnocks projecting above ridgelines, such as Serra da Piedade and Itatiaiuçu, and in such places makes blocky and craggy mountains. Normally the canga-covered ridgelines are smooth and rounded, forming ranges continuous for many kilometers and standing a hundred to several hundred meters above the surrounding terrain. Where the parent itabirite dips between 20° and 40°, hogbacks with sharp inface scraps are formed, as in the Serra do Curral; where dips are steeper, more symmetrical ridges are formed except where the canga cap is broken by erosion. In these places blowouts caused by rapid removal of the softened itabirite leave craggy needles of hard itabirite projecting above the steep surface, as in the Grota de Esmeril in the Itabira District. Figure 14 illustrates typical landforms developed where the formation is exceptionally thick.

Where the formation is thick or the dip is very low, broad ridges result. Where the formation is thin, canga may not form and the formation may be hidden for considerable distances by soil and slope wash. In such places the soil gives no hint of the rock below; the formation can be located by using a magnetometer or dip needle.

GANDARELA FORMATION

The Gandarela Formation was first clearly distinguished by O'Rourke (written commun., 1954) and by Pomerene (1964, p. D15) and was named by Dorr (1958b) from the type locality in the vicinity of Fazenda Gandarela in the quadrangle of that name. In that area the formation is thick, and deep erosion has produced excellent outcrops. Elsewhere the formation is very poorly exposed and was mapped on the basis of its weathering products and landforms. These are fairly distinctive to geologists with some mapping experience in the region, but it may be difficult for others to delimit the formation with confidence. The formation is quite variable in detailed lithology throughout the region and is gradational with the Cauê Itabirite over a wide zone; in some quadrangles it could not be separated from that formation or was not present.

FIGURE 14.—Cauê Itabirite between Alegria and Conta Historia, Capanema quadrangle. Gentle slopes below are protected by a thin canga cover, breached by the small stream. The formation here has an apparent thickness of more than 1,000 m. Photograph by Norman Herz.

DISTRIBUTION AND THICKNESS

The Gandarela Formation was mapped in most of the Serra da Moeda, in the central part of the Serra do Curral, and in the Gandarela syncline. An amphibolite believed to be the metamorphic equivalent of the formation occurs in the Monlevade area and was named by Reeves (1966) as the Sítio Largo Amphibolite. The Congonhas district was mapped before the formation had been recognized, but it is separable in much of that area. It is not separable in most of the area immediately east and south of the Serra do Caraça (Maxwell, written commun., 1962) or in the Itabira district (Dorr and Barbosa, 1963). In some of these places the rocks are known to contain lithologies typical of the Gandarela Formation in the expected stratigraphic position, but they are so thin or so poorly exposed that they cannot be mapped.

The thickness of the Gandarela Formation is variable. In the type locality, the formation seems to be about 750 m thick. In the Serra da Moeda, it is about 500 m thick at the north end and about 200 m at the south edge of the Marinho da Serra quadrangle. In the Serra do Itabirito, the formation thins from about 400 m near the Codornos Dam in the Lagoa Grande quadrangle to a knife edge in the Bação quadrangle at N. 1,800, E. 300 (Wallace, 1965). Pomerene (1964, p. D16) measured a thickness of 400 m in the Serra do Curral at Acaba Mundo and believed the formation is of about the same thickness in the Macacos quadrangle. The formation thins rapidly to the east and was not found in the Nova Lima quadrangle and only sporadically in small discontinuous outcrops to the east in the Serra do Curral; the abruptness of this thinning is in part tectonic. To the west along the Serra do Curral, the Gandarela thins to about 150 m in the Rio Paraopeba water gap (Fêcho do Funil quadrangle). The formation wedges out completely 1.4 km west of the east boundary of the Igarapé quadrangle.

Perhaps the formation is thickest in the west end and north limb of the Gandarela syncline in the Gandarela, Caeté, and Gongo Sôco quadrangles. In the western part of the Gongo Sôco quadrangle an apparent thickness of 900 m was calculated from mapping by Moore. In the central part of the same quadrangle near the present village of Gongo Sôco, the formation was calculated to be about 600 m thick. One kilometer north of Barão do Cocais, Simmons (1968b, p. H18) measured a section about 70 m thick.

The south limb of the Gandarela syncline is strongly faulted in many places, and the true thickness of the formation is there unknown. In the Gongo Sôco quadrangle a broad plateau marked by three large sinkhole lakes has developed on the outcrop belt. Farther east in the Santa Bárbara and Cocais quadrangles the formation was estimated by Simmons to range between 40–70 m in thickness.

In the Ouro Prêto-Mariana area, as calculated from mapping by A. L. M. Barbosa, the Gandarela Formation is on the order of 75 m in thickness; to the north in the region of Antônio Pereira it may be on the order of 200–500 m. Westward along the south edge of the Quadrilátero Ferrífero the structure is so complex that no firm estimate of thickness is possible; Johnson (1962) estimated a thickness of perhaps 200 m in the northern exposures in the Dom Bosco quadrangle and more than 400 m in the southern.

CONTACTS

The Gandarela Formation lies with gradational contact on the Cauê Itabirite and is overlain with local disconformable contact by the Piracicaba Group of the Minas Series. The disconformity is an erosion surface; no angular discordance is known.

The contact with the Cauê Itabirite is an arbitrary one. The original definition stated (Dorr, 1958b, p. 63): "The contact of the Gandarela Formation with the underlying Cauê Itabirite is commonly gradational over a few meters to tens of meters. The boundary should be drawn where dolomitic itabirite or dolomite becomes predominant over normal itabirite." It is now known that dolomitic phyllite of the Gandarela Formation may lie directly on Cauê Itabirite, although this is not common.

As stated in the description of the Cauê Itabirite, that formation may be dolomitic in part, and, where it is dolomitic, the dolomitic itabirite is more common in the upper part of the formation. Similarly, the Gandarela Formation in many localities contains lenses and lentils of dolomitic itabirite and normal itabirite. Such lenses may occur anywhere in the formation but are more common in the lower part. Were the rocks everywhere visible in fresh outcrops there probably would be little difficulty in seperating them, but unfortunately they are commonly covered by canga and are thoroughly leached and hydrated; thus, much uncertainty is introduced. Where marble or dolomitic phyllite overlies itabirite, contacts are drawn with little question, for marble weathers to a characteristic soil, and dolomitic phyllite is covered by soil quite different from that on most normal itabirite.

Where the contact between normal itabirite and dolomitic itabirite is gradational, much difficulty follows. The weathering product of dolomitic itabirite, where not hidden by canga, is more hydrated than that of normal itabirite. It is ocherous, tends to be yellow instead of dark brown, may be porcellaneous with an aluminous aspect—although chemical analyses (Pomerene, 1964, p. D20) showed little more Al_2O_3 than the normal weathered itabirite in such material—and may be magnetic from the higher original magnetite content of dolomitic itabirite. Magnetite octahedra may be visible. The presence of amphibole replaced by limonite is a sure sign of dolomitic itabirite. The canga overlying dolomitic itabirite may be denser and may contain less quartz and commonly contains more alumina than that over normal itabirite. Where slopes are gentle, the variety "chemical canga" (Pomerene, 1964, p. D30; Dorr, 1964, p. 1224) is common over dolomitic itabirite. So many exceptions to all these guides are known that no single one can be blindly followed; field experience is the best guide in separating the Cauê Itabirite from the Gandarela Formation.

LITHOLOGY AND COMPOSITION

The Gandarela Formation consists largely of dolomitic and calcitic strata. The most conspicuous rock in the type locality is marble, for the most part dolomitic. Elsewhere in the region, dolomitic phyllite, dolomitic iron-formation, and phyllite may be dominant rock types.

In the type locality the marble is red, white, and gray; O'Rourke (written commun., 1954, and pl. 5) divided the formation in the Gandarela quadrangle into three members on the basis of color. These members were separated one from another by thin but extensive lenses of itabirite, in part dolomitic. In other quadrangles the marble cannot be so separated, and elsewhere color has no discernible stratigraphic significance; the itabirite lenses are absent or too random in distribution to correlate with those in the type locality.

The red marble is generally somewhat higher in iron content than the other colors, but all types may contain several percent of iron or manganese. The iron is present both as ferroan dolomite and calcite and as finely divided hematite and magnetite. Manganese minerals are not megascopically or microscopically visible in the marble, and the element undoubtedly occurs as manganoan dolomite or calcite (O'Rourke, written commun., 1954; Dorr and others, 1956, p. 303).

The marble is fine grained and dense, in many localities showing strong flow structures and healed breccias. Bedding is obscure in many outcrops. Hundreds of chemical analyses of these marbles have been published; these indicate that for the most part the rock is dolomite or dolomitic marble but that locally it is pure calcite marble. Whether the original sediments were dolomite or calcite is not known; the irregular distribution of calcite marble would suggest that dolomitization occurred. If so, this must have taken place before or during metamorphism, as the rock is now dense and equigranular. The widespread presence of talc also suggests that magnesium-bearing solutions once permeated the rock. No vestige of organic life now remains, although the abruptly lenticular nature of some marble lenses suggests either giant boudinage or original bioherms.

An unusual lithologic zone in the Gandarela Formation marble is a sharpstone intraformational conglomerate composed of tabular fragments of metachert and dolomite in a dolomite matrix. This zone ranges from a few centimeters to more than 1 meter in thickness and has been located in the São Julião, Dom Bosco, Lagoa Grande, Belo Horizonte, Gandarela, and Gongo Sôco quadrangles. The rock was well described and illustrated by Guild (1957, p. 16). Outcrops are too scattered to indicate whether the sharpstone conglomerate occurs at one horizon or at several horizons in the marble beds; if further work proves it to be confined to a single zone, it would be a most useful marker in regional correlation. Wherever observed, it was in the upper part of the Gandarela Formation.

Pyrite is a widespread but sparse constituent of the marble and is associated with sparse chlorite in some exposures. Talc is also a common associated mineral; it occurs on shear and bedding planes and, to a lesser extent, disseminated in the marble. Phlogopite was reported by Moore (1969) in the Gongo Sôco quadrangle, and amphibole was noted by Guild in the Congonhas area. The marble is host for various introduced sulfied minerals, notably the copper sulfieds, but these have not been found in commercial quantities. A small deposit of stibnite and its oxidation products was found near Belo Horizonte, presumably derived from an epigenetic deposit in marble (I. S. Coelho and Luis de Castro, oral commun., 1965). Fluorite lenses were reported by Pomerene (1964, p. D18) near Acaba Mundo in the Belo Horizonte quadrangle and by Johnson (1962, p. B15) near Dom Bosco.

In much of the region, particularly in the southern part, phyllite and dolomitic phyllite [2] are important rock types in the Gandarela Formation. Dolomitic phyllite weathers rapidly and deeply to a saprolite similar in appearance to, but somewhat more spongy than, that formed from other phyllites. Such rock can be correlated only on the basis of the general stratigraphic succession.

Johnson (1962, p. B15) described fresh grayish-green dolomitic phyllite in the Dom Bosco quadrangle as being composed of sericite or chlorite with some dolomite, enclosing lenses and streaks of granular quartz, with much magnetite and some epidote. Bedding is distinguished by color banding and may be either essentially parallel to or may crosscut foliation at a high angle. He also described greenschist of possible volcanic origin in two outcrops in the same area. These are the only known occurrences of such rock in the Gandarela Formation in the region and were also mentioned by Guild (1957, p. 48–49). This material occurs in bands a few tens of centimeters thick and consists dominantly of chlorite, which constitutes as much as 80 percent of the rock, with quartz, biotite, and euhedral magnetite.

The basal beds of the Gandarela Formation are dolomitic itabirite in much of the region. In some parts of the region, notably in the Serra do Curral in the Nova Lima, Ibirité, and the eastern part of the Fêcho do Funil quadrangles and in the quadrangles immediately south of the Serra do Caraça, substantial parts of the whole formation may be composed of dolomitic itabirite, and the marble facies of the formation may be very subordinate or absent. Elsewhere the Gandarela Formation characteristically contains lenses and bands of dolomitic itabirite and, more rarely, normal itabirite. Most such lenses are small, ranging in thickness from a few centimeters to a few meters and in length from a few meters to a few hundred meters; but at the west end of the Gandarela syncline, O'Rourke (written commun., 1954) mapped two outcrop bands which he traced for more than 10 km with few interruptions (pl. 5).

Simmons (1968b) pointed out that in the Barão de Cocais area, dolomitic itabirite is much more coarsely banded in the Gandarela Formation than in the Cauê Itabirite. Guild (1957, p. 49) earlier reported a similar relation in the Congonhas district.

Pomerene (1964, p. D20) described a "dolomite ironstone" in the lower part of the Gandarela Formation that consists of grossly banded siliceous limonite and some hematite and magnetite. He believed it represents limonitized and silicified weathered dolomite.

PHYSIOGRAPHIC EXPRESSION

The Gandarela Formation stratigraphically overlies the most resistant formation in the region and underlies a ridge-forming formation. Thus, its physiographic expression is to some extent controlled not only by its own lithology but also by the structure, thickness, and attitude of adjacent units. Almost everywhere it lies at

[2] In this weathered terrain, identification of carbonate minerals in the outcrop of complex rocks is usually impossible. Because dolomite is the most common carbonate in those few places where determination is possible, geologists of the DNPM–USGS team arbitrarily considered all phyllite containing carbonate to be dolomitic phyllite.

lower elevations than the stratigraphically underlying Cauê Itabirite, and, in such localities as the west end of the Gandarela syncline, drainage follows the contact as a preferred zone. Where the marble is thick and overlying units thin or soft, drainage follows the upper contact, as the Rio Socorro in the central part of the Gandarela syncline. Where marble predominates and the sequence is upright, the land surface is hummocky and marked by isolated craggy outcrops. Where the rock sequence was rotated well beyond the vertical, as in part of the Serra do Curral, the topographically overlying Cauê Itabirite forms great scarps which, except in a few localities of rapid mechanical erosion, supply debris that conceals the topographically lower rocks. Where the formation is nearly vertical, scattered outcrops may be found in stream valleys and at the base of cliffs in the Cauê Itabirite. Along the inface slope of the Moeda Plateau, the Gandarela Formation is covered by soil and canga and is marked by a gentle slope and small local relief. Where the formation is dominantly phyllitic, as in the Dom Bosco quadrangle, it is indistinguishable topographically from the other phyllitic formations of the region.

Sinkholes develop on the marble, and locally lakes of some size are found in them. The largest are the Lagoa das Antas, on the south limb of the Gandarela syncline, which is some 500 m in diameter, and the nearby Lagoa das Coutas, which is more than 600 m long Gongo Sôco quadrangle). Other smaller lakes occur near Pico de Itabirito and near Fazenda Gandarela. Shallow undrained depressions without permanent water are known elsewhere, as at Lagoa Sêca south of Belo Horizonte.

Thus, the topographic expression of the Gandarela Formation is distinctive and may be used with confidence for mapping, although the characeristically poor exposures prevent accurate location of its contacts and soil and canga conceal the greater part of the unit.

ENVIRONMENT OF DEPOSITION

The Cauê Itabirite once covered almost completely the 7,000 square kilometers of the Quadrilátero Ferrífero, 155 km from east to west and 100 km from north to south. If itabirite near Serro and Morro do Pilar (towns north of Itabira) was once continuous with that of the Quadrilátero Ferrífero, as believed by the writer and other geologists (Harder and Chamberlin, 1915; O. Barbosa, 1954), the maximum known north-south extent was another 100 km. There is good reason to think the formation may have continued at least 200 km more to the north. The formation seems to thin to the southwest near Jeceaba, but John Forman (oral commun., 1965) reported highly metamorphosed itabirite on trend with the south end of the Serra da Moeda some 40 km southwest of the Quadrilátero Ferrífero. The formation thins radically to the northwest at the west end of the Serra do Curral. On the east and north sides of the Quadrilátero Ferrífero, however, no signs of a wedgeout are known. The structure of the south side is too complex to permit judgment as to probable continuity southward; in the Ouro Prêto–Mariana area the formation is prominent and persistent. Thus, the Cauê Itabirite can be classified as a sheet or blanket deposit (Pettijohn, 1957, p. 618).

The Gandarela Formation is not known to be as extensive as the Cauê Itabirite; however, it is known for a distance of 130 km from east to west (assuming the equivalence of the Sítio Largo Amphibolite with the Gandarela Formation) and 65 km from north to south; it, too, fulfills Pettijohn's definition of a blanket deposit. The formation has not yet been recognized outside the Quadrilátero Ferrífero, but, because the outcrops are obscure and the formation has been recognized as a unit within the Quadrilátero Ferrífero only in recent years, it may be present. Simmons (1968a) considered the erosional disconformity at the top of the Gandarela to be responsible for its absence at the west end of the Serra do Curral; this might be the situation elsewhere.

All formations of the Caraça and Itabira Groups are intergradational blanket deposits, and the two forming the Caraça Group are normal transgressive stable-shelf deposits. The Gandarela Formation is also a typical offshore stable-shelf deposit, and thus it seems probable that the Cauê Itabirite, too, was deposited on a stable shelf.

The worldwide occurrence of banded iron-formation in the Precambrian and the almost complete absence of this rock type in post-Algonkian sediments has long been known. No completely satisfactory hypothesis of the genesis of this rock has yet been advanced, and the problem of source of the enormous quantities of iron involved (for the Cauê Itabirite, some 5×10^{12} tons of elemental iron) remains enigmatic. As shown above, there is no internal evidence that the Cauê Itabirite and the Gandarela Formation were deposited in other than a stable-shelf environment or that they were related to island arcs or volcanism, were estuarine or freshwater deposits, or, in fact, were other than normal epicontinental marine deposits. Thus, it is here assumed that they were deposited as chemical or perhaps biochemical deposits in a normal marine environment. The origin of iron-formation is discussed in more detail elsewhere, where the various types present in this region are examined as a group.

The Gandarela Formation, with its intercalations of original claystone, now phyllite, and intraformational sharpstone conglomerate in the dominantly carbonate sediments, appears to have been deposited in epicontinental seas which in the central part of the region were free from fine detrital sediments. In the southern part of the area considerable quantities of fine detrital material were deposited. The single, very local occurrence of rock of possible volcanic origin emphasises that strong contemporaneous volcanism was not prevalent in the region.

Contemporaneous sedimentation in an environment of overall marine transgression of the Caraça and Itabira strata in different parts of the area is possible. The Moeda Formation would represent nearshore deposition, the Batatal Formation offshore deposition, and the Cauê Itabirite and Gandarela Formation deposition well offshore. The transgressive sea would produce an on-lap sequence. Oscillations and regressions would be indicated by phyllitic zones in the dominantly quartzose Moeda Formation, by metachert and minor hematite in the dominantly phyllitic Batatal Formation, by rare shale beds and dolomite lenses in the Cauê Itabirite, and by itabirite lenses and zones in the dolomitic Gandarela Formation. Elements to prove or disprove this possible contemporaneity are missing because of the absence of throughgoing marker beds or fossils; in any one locality, the formations are systematically superposed, and the lower formations are there older than the overlying formations.

All formations of the Caraça and Itabira Groups in the Quadrilátero Ferrífero are thickest in a zone extending across the middle of the region in a roughly east-west direction and curving northward on the east side. This may indicate that the area was the site of major introduction of sedimentary materials and of subsidence, particularly in Caraça time.

METAMORPHISM

Metamorphism of the Cauê Itabirite produced a radical increase in grain size with increasing metamorphic grade. Specific data on this variation throughout the region was summarized by Dorr (1964, table 2) and Herz (written commun., 1964) and show that such variation, although qualitatively similar to that described by James (1955) in the Lake Superior region of the United States, is anomalously greater. The increase in grain size has important economic effects; supergene enrichment of the iron-formation is rather closely controlled by this phenomenon.

Amphibolitic itabirite is believed to be a product of the contact metamorphism of dolomitic itabirite. Metamorphism completely recrystallized the carbonate rocks of the Gandarela Formation.

PIRACICABA GROUP

The Piracicaba Group was named by Dorr, Gair, Pomerene, and Rynearson (1957) and is roughly equivalent to the Piracicaba Formation as defined by Harder and Chamberlin (1915, p. 362–363). The latter, however, may have included part of what is now called the Gandarela Formation in their Piracicaba Formation, for at that time the erosional disconformity at the top of the Gandarela Formation had not been discovered; moreover, it was not known that units with similar lithologies occur in both the Itabira and the Piracicaba Groups. The type locality of the Piracicaba Formation chosen by Harder and Chamberlin is in the headwaters of the Rio Piracicaba southwest of the Serra do Caraça, where it is now known that much of the group has been removed by erosion. The varied and persistent lithologic units comprising the Piracicaba Group, so well exposed in the Serra da Moeda and on the north side of the Serra do Curral, were not studied in detail by Harder and Chamberlin.

It seems very probable that Harder and Chamberlin considered the ferruginous quartzites here included in the Cercadinho Formation of the Piracicaba Group to be part of their Itabira iron-formation, for they refer to rounded quartz grains in itabirite. Careful search during this mapping program revealed no single instance of rounded quartz grains in the rock here called the Cauê Itabirite, whereas such material is very common in, if not characteristic of, the ferruginous quartzite of the Cercadinho Formation. Because Harder and Chamberlin considered the iron-formation to be a clastic deltaic formation rather than a chemical precipitate, the presence of rounded quartz grains in iron-formation seemed a congruent rather than exotic occurrence, and they had no reason to reexamine their stratigraphic conclusions because of the presence of clastic quartz.

The Piracicaba Group overlies the Itabira Group with structural conformity but erosional disconformity in the west side of the Quadrilátero Ferrífero. This erosional disconformity has not been found east of the Moeda Plateau and the vicinity of Sabará in the Serra do Curral. It is quite possible that in the east side of the region the group may be in conformable and gradational contact with the older rocks, for in the one good exposure in the Itabira district the contact was gradational, and the few other exposures of the actual contact known in the eastern part of the region do not give critical evidence.

The formations of the Piracicaba Group consist largely of clastic sedimentary rocks, ranging from fine conglomerate through quartzite to phyllite and graphitic phyllite; chemical (or biochemical) precipitates included in the sequence are sporadic beds of dolomite and small lenses of iron-formation. Most formations contain relatively simple and well-differentiated mature sediments. All are now metamorphosed, most to the greenschist facies and in the east side of the region to the almandine-amphibole facies.

The formation at the top of the group consists of graywacke, chloritic schist and phyllite, tilloid, and sandy schists, with small lenses of iron-formation and possibly some chert. The lithology of this sequence differs substantially from that of the underlying formations, and its thickness is greater than that of all the others combined.

In the Monlevade area, all rocks are more highly metamorphosed than elsewhere in the Quadrilátero Ferrífero, and stratigraphic units believed correlative with the Piracicaba Group are altered to gneiss named by Reeves (1966) the Elefante Formation. It contains a Pantame Member believed to correlate with the Cercadinho Formation, and a Bicas Gneiss Member possibly the equivalent of the Barreiro or Fêcho do Funil Formation or both.

The original thickness of the Piracicaba Group is unknown because the group is always limited upward by intrusive granitic rocks, the present erosion surface, or an unconformity with the overlying Itacolomi Series. The maximum known thickness of the Piracicaba Group is in the order of 4,800 m.

CERCADINHO FORMATION

The Cercadinho Formation, the lowest unit of the Piracicaba Group, consists of interbedded ferruginous quartzite, grit, quartzite, ferruginous phyllite, and phyllite. A few small lenses of dolomite are known. The formation was described by Pomerene (1958a) from the sequence exposed in the Corrego de Cercadinho in the Belo Horizonte quadrangle. The formation is distinctive in its lithology and outcrop pattern, the quartzose beds are ridge formers, and the formation is a most useful horizon marker in geologic mapping.

DISTRIBUTION AND THICKNESS

The Cercadinho Formation was mapped from the westernmost quadrangles along the full length of the Serra do Curral for 100 km in a northeasterly direction. It was mapped the full length of the Gandarela syncline except at the east end, where it is faulted and squeezed out. Rocks of the same lithology are present in the east end of the Quadrilátero Ferrífero in the Itabira district but were not mapped separately owing to poor exposures. The formation is known from the north side of the Serra do Curral to south of Ouro Prêto; it was not mapped separately in the Dom Bosco quadrangle because exposures were too discontinuous, or in the São Julião or Casa da Pedra quadrangles because the formation had not yet been identified at the time mapping was done there. The distinctive lithologies are present in all three of these quadrangles, however. Thus, the formation extends for a minimum of about 100 km from north to south and 150 km from east to west. The formation has not yet been surely identified outside the Quadrilátero Ferrífero although rock of similar lithology crops out above itabirite about 10 km east of Morro do Pilar, about 75 km north of the Quadrilátero Ferrífero.

The Cercadinho Formation varies widely in thickness. At the west end of the region, it is invaded by granite and is only about 30 m thick. It thickens eastward to about 80–120 m in the Fêcho do Funil quadrangle and, at the type locality in the Belo Horizonte quadrangle, Pomerene (1964, p. D20) measured a section 317 m thick; 3 km to the southwest the formation is only 80 m thick (Pomerene, 1964, p. D20). Gair (1962, p. 38) found the thickness in the western part of the Nova Lima quadrangle to be about 100 m, but the formation thickens to about 300 m in the rest of that quadrangle. Farther to the east on the north flanks of the Serra da Piedade, specific data are not available, but the formation is very thick.

To the south, in the Moeda Plateau, the formation varies between 400 and 900 m according to Wallace (1965), who attributed the maximum thickness to tectonic thickening. In the Gandarela syncline O'Rourke (written commun., 1954) estimated a stratigraphic thickness of about 300 m at the west end. Farther east Moore estimated (1969) a thickness of 400 m at the west side of the Gongo Sôco quadrangle; this thins eastward to about 200 m. Still farther to the east the formation is squeezed in the syncline, and the upper contact is not known (fig. 15); Simmons found a maximum of 225 m near the east end of this structure. To the south of the Serra do Caraça, Maxwell (written commun., 1964) estimated the maximum thickness of the formation as about 225 m. In the northern part of the Antônio Pereira quadrangle the outcrop of the Cercadinho Formation is several kilometers wide; cross folding and relatively low dips make exact measurements difficult, but the stratigraphic thickness cannot be less than 300 m.

CONTACTS

Pomerene and Ashley, working in the Belo Horizonte and Nova Lima quadrangles, were the first to find the erosional unconformity between the Cercadinho and Gandarela Formation. There it is marked by a basal conglomerate and grit containing fragments of the Gandarela Formation, small hematite chips, and iron-rich concretions (Pomerene, 1964, p. D22). The disconformity was found still farther west in the Serra do

FIGURE 15.—Cercadinho Formation in the Gandarela syncline, Gongo Sôco quadrangle. Rocks in the bottom of the valley and at the top of the ridge are Gandarela Formation. Cliffy outcrops on the far side of the valley are Cercadinho Formation, repeated by isoclinal folding. The Serra do Caraça, formed of Cambotas Quartzite, is in the distance. Photograph by Norman Herz.

Curral by Simmons (1968a), who determined that the Cercadinho Formation gradually transects the Gandarela Formation and the Cauê Itabirite. This could be caused either by an angular discordance on the order of less than 3°, or the Gandarela and Cauê might wedge out to the west and the Cercadinho Formation overlap.

The extent of the erosional unconformity so well exposed in the Serra do Curral is uncertain because the actual contact is visible in few places in the rest of the region. In the Itabira district, a gradational contact was observed between the underlying Itabira Group and conglomeratic quartzite interpreted by Dorr and Barbosa (1963, p. 22–23) as basal Cercadinho Formation. Between that area and the Serra do Curral, no stratigraphic contacts between these rocks have been observed. The units are everywhere structurally concordant, but in the Gandarela quadrangle and south of the Serra do Caraça float similar to the basal conglomerate of the Cercadinho in the Serra do Curral has been found, indicating a probable erosional unconformity in those areas. On the other hand, no such basal conglomerate was found in the Gongo Sôco or Santa Bárbara quadrangles in exposures of the basal beds of the Cercadinho Formation. The writer believes that epeirogenic uplift took place without deformation of the earlier sediments but with a radical change in the sedimentary environment. The upper part of the Itabira Group was reworked to a varying but generally minor degree, and the detritus was incorporated in part in the Cercadinho Formation.

The contact between the Cercadinho Formation and the overlying Fêcho do Funil Formation is everywhere concordant and gradational.

LITHOLOGY

Ferruginous and nonferruginous quartzite, pebble conglomerate, grit, ferruginous phyllite, "silver phyllite," dolomitic phyllite, dolomite, and purple phyllite compose the Cercadinho Formation. These lithologies are interbedded and strongly lenticular; quartzose rocks in some places are crossbedded. Diversity of sequence and the presence of ferruginous quartzite and "silver phyllite" are the distinguishing features of the formation.

Basal beds

The basal beds are quartzite in most places, but grit, pebble conglomerate, or phyllite are found elsewhere. Basal conglomerate and conglomeratic beds contain pebbles of itabirite and pink metachert derived from the Gandarela Formation or possibly the Cauê Itabirite, as well as pebbles of vein quartz and quartzite of indeterminate origin. Small elongated chips of hematite, with maximum dimensions of 8 by 3 by 2 mm, were reported by Pomerene (1964, p. D22). No dolomite pebbles have yet been reported. This material derived from the Itabira Group is coarser and more abundant in the west side of the area and was not found on the east side.

Pomerene (1964, fig. 9) illustrated concretions of specular hematite that occur at the base of the formation in the Belo Horizonte quadrangle. They are almond-shaped ovoids as much as 4 cm long, with concentric structure, and commonly contain as a nucleus an angular quartz fragment. All are oriented with their long axes parallel to regional lineation and are thought to represent deformed and metamorphosed limonite concretions formed on a pre-Cercadinho erosion surface, similar to those now forming on some ferruginous phyllites and quartzites in the region (p. A73).

Quartzite

The quartzite beds of the Cercadinho are both ferruginous and nonferruginous. They range in grain size from grit to fine-grained quartzite, but medium- to coarse-grained quartzite is the most common rock. The coarser sizes are most abundant on the west side of the region. Quartz grains within a single bed are generally well sorted, and the relatively high degree of rounding of the grains is one of the diagnostic characteristics of this formation.

Ferruginous quartzite crops out more widely in the west side of the region but is known everywhere. The iron occurs as hematite or, less commonly, as magnetite or martite, forming the matrix for the quartz grains. The iron content varies abruptly in individual beds across the bedding and to a lesser degree along strike. This variation imparts a grossly banded aspect to the rock in many places. The more ferruginous bands may contain as much as 60 percent iron, but the average is much less, perhaps in the order of 15–20 percent by weight. The crystalline matrix imparts a dark-gray to black color to the rock. For some reason unknown to the writer, the iron minerals of the Cercadinho ferruginous quartzite do not hydrate as readily as the same minerals in the other iron-bearing formations.

The hematite in the ferruginous quartzite was apparently deposited as very fine grained detrital material derived from erosion of the Itabira Group to the west and, locally, as black sand deposits, because some of the ferruginous quartzite beds are crossbedded and conglomeratic. The rapid variation in iron content of the ferruginous quartzite both normal to and parallel to bedding and the gradual diminution in iron content to the east suggest that the chemical or biochemical precipitation of iron minerals which was the rule in the underlying Itabira Group rocks had ceased during the deposition of the sediments under discussion.

Normal quartzite is also a widespread rock in the Cercadinho Formation. It is interbedded with the ferruginous quartzite and is more common than ferruginous quartzite in the eastern part of the region. To the east the percentage of sericite in the normal quartzite increases, the grain size decreases, and the relative quantity of quartzite in the formation as a whole decreases markedly.

Many quartzite beds in the Cercadinho Formation are crossbedded, generally at low angles with the true bedding but in some places at high angles. Well-preserved ripple marks have been found in two places, one in the Belo Horizonte, the other in the Lagoa Grande quadrangle (Wallace, 1965, fig. 9). Ripple marks are closely spaced and indicate fairly shallow water. Graded bedding on a small scale has been seen in several quadrangles.

A peculiar variety of quartzite of wide distribution in the Cercadinho Formation was given the field name of "rice grit" by Pomerene (1964, p. D23). The material occurs in lenses as much as 1 meter thick but rarely traceable for as much as 50 m along strike in any one zone. It is not known whether these lenses occur at one or several stratigraphic horizons; all are toward the top of the Cercadinho Formation. The "rice grit" consists of spindle-shaped grains of quartz with axial ratios of 1:2:3–4; maximum length of grains is about 6 mm. The grains are similar in size and shape to rice grains and make up as much as 50 percent of the rock. Their matrix is fine-grained quartzite, locally ferruginous, locally only slightly ferruginous. All long axes of the grains are alined parallel to the regional metamorphic lineation; the intermediate axis is generally parallel to foliation.

The origin of these spindle-shaped quartz grains, found only in the Cercadinho Formation, has provoked much speculation. Pomerene attributed them to stretching of original subspherical quartz grains, Simmons (1968a, p. G17) to shearing of quartz granules. Because the phenomenon is confined to few and thin lenticular beds in a single formation that is but a small part of a stratigraphic section with many beds of coarse quartz grains and granules, all of which have been subjected to similar deformation, a primary lithologic control may be indicated instead. It is here suggested that the "rice grains" were originally small pellets or concretions of silica gel or cryptocrystalline quartz which deformed into uniform shapes and orientation and recrystallized during orogeny and metamorphism. Conceivably the uniform size is due to winnowing action of the currents when the original pellets were deposited.

Phyllite

The most abundant rock in the Cercadinho Formation, particularly in the eastern part of the region, is phyllite. Some of the phyllite, like some of the quartzite, is very distinctive and cannot be confused with phyllite from other formations. Like all phyllites in the region, however, outcrops are sparse, and the unit is seen only in artificial openings and in localities where mechanical erosion has been unusually rapid.

The most distinctive phyllite was given the field name "silver phyllite" because of its silvery silky sheen. The rock consists of sericite and of hematite in the form of very fine grained plates of specularite. Both platy minerals are oriented parallel to foliation and the specularite adds its high reflectivity to the sericite, producing the distinctive sheen. Hematite is present in varying percentages in the phyllite, ranging up to perhaps 50 percent; in the higher ranges the rock makes a red streak. Quartz is very subordinate, and the rock was originally a hematitic claystone. The "silver phyllite" is interbedded with both ferruginous and nonferruginous quartzite, forms partings between beds of ferruginous quartzite, and occurs without quartzite in zones as much as several meters thick.

Normal phyllite is also found in the Cercadinho Formation but in most places is indistinguishable from the phyllites of other formations. Much of it is quartzose and some is dolomitic. In the foothills north of the Serra do Curral a considerable thickness of poorly foliated weathered purple phyllite is exposed in roadcuts. This material, probably originally dolomitic, weathers to a very weak saprolite that produces pestilential quantities of impalpable dust on unpaved roads.

As well as the minerals cited above, the phyllite of the Cercadinho Formation may contain chlorite, biotite, and chloritoid. This formation seems to be the only one in the Piracicaba Group that contains chloritoid, according to Herz (written commun., 1965).

Dolomite

Small dolomite lenses have been reported in the Cercadinho Formation in the Ibirité, Belo Horizonte, and Nova Lima quadrangles, the largest some 20 m thick and perhaps 200 m long. Elsewhere this rock has not been seen; the writer believes that it was not deposited outside the areas mentioned.

Strata-bound epigenetic minerals

Related to the stratigraphy of the Cercadinho Formation is the occurrence of several epigenetic minerals, the presence of which seems closely related to the composition of the rocks composing the formation. These include manganese oxide and notable euhedral hematite, kyanite, and imperial topaz crystals.

In the Ibirité and Belo Horizonte quadrangles and in Poço Fundo in the Casa da Pedra quadrangle, many small prospect pits and a few larger ones have explored supergene concentrations of manganese oxide to shallow depth in the phyllitic rocks of the Cercadinho Formation. At the time of the mapping, these openings had collapsed and slumped to such an extent that little could be seen of the environment of the mineralization and less of the host rocks. The linear distribution of the workings and the presence of what appeared to be weathered manganiferous dolomitic phyllite suggest that the manganese oxide represents surficial concentration of unidentified manganese minerals deposited syngenetically in the rock. Elsewhere the formation is not manganiferous.

Characteristic of the Cercadinho Formation ferruginous quartzite is the development of large euhedral hematite crystals in localities where hydrothermal alteration has been strong. Such crystals, in many localities near and in quartz veins, are known from many parts of the region, notably just east of the Pico de Frazão, Antônio Pereira quadrangle and near N. 7,800, E. 12,400, Lagoa Grande quadrangle (Wallace, 1965). At the latter locality Rynearson found a group of crystals as much as 50 cm across and weighing as much as 150 kg (kilograms) each; one was sent to the National Museum in Washington, others are in the DNPM museum in Belo Horizonte. Smaller tabular crystals which can be cut and polished for jewelry are found in a number of localities.

Kyanite occurs in many of the aluminous formations in the region, but, with a few exceptions, large-bladed crystals are characteristic only of the Cercadinho Formation. These are best developed in kyanite-quartz veins in the phyllite and occur as blue to gray radiating crystals as much as 10–15 cm long normal to the walls. Pyrophyllite is a common accessory mineral. Wallace (1965) believed that the alumina in the kyanite was derived from the phyllite of the wallrock, as the mineral also occurs as scattered discrete crystals in the country rock. Throughout most of this region, coarse blue kyanite crystals characterize the formation and are not always associated with quartz veins.

Fine gem-quality imperial topaz in euhedral crystals as much as several centimeters long is found in saprolite over Cercadinho phyllite in a linear zone several kilometers long in the Ouro Prêto and Dom Bosco quadrangles, associated in some places with large terminated quartz crystals. The mineral may well have formed by the reaction of fluorine-bearing hydrothermal solutions with the highly aluminous phyllite.

The occurrence of unusually fine crystals of these aluminous minerals in the Cercadinho phyllite would seem to indicate some special property of these rocks. Because of the difficulty in finding fresh rock to study, no contribution to this problem was made in the present study other than the recognition of the virtual restriction of the topaz and the best development of the kyanite in the cited host; it is hoped that others will carry forward the study.

Weathering properties

The quartzite of the Cercadinho Formation is resistant to weathering where thick and massive. It forms the ridgeline of the Serra do Curral for several kilometers east of Pico do Belo Horizonte and a prominent ridge north of that Serra in part of the Belo Horizonte, Ibirité, and Fêcho do Funil quadrangles.

Weathered phyllitic rocks of the formation are soft and nonresistant and most unstable in artificial exposures. Roadcuts, particularly on dip slopes, are nearly impossible to hold, and inordinate maintenance expense is incurred in road alinements which ignore this fact. Near Ouro Prêto large retaining walls have been swept away by the inexorable slow creep of these deeply weathered rocks.

FÊCHO DO FUNIL FORMATION

The Fêcho do Funil Formation was named and described by Simmons (1958, p. 65–66) from a sequence in the quadrangle of the same name. In the type locality, the formation consists of brown and dark-gray dolomitic phyllite; argillaceous and siliceous dolomite; and pink, gray, and tan phyllite, locally silty. It is in gradational contact with the underlying Cercadinho Formation and the overlying Taboões Quartzite.

DISTRIBUTION AND THICKNESS

The Fêcho do Funil Formation has been mapped in the Serra do Curral eastward from the Igarapé quadrangle to the Belo Horizonte quadrangle. It was not recognized in the Nova Lima quadrangle or to the east. It has also been mapped in the Moeda Plateau in the Lagoa Grande, Itabirito, and Marinho de Serra quadrangles. Although it is present in the São Julião and Casa da Pedra quadrangles, the formation was not mapped because it had not yet been distinguished at the time of the mapping; in the Dom Bosco quadrangle it was not mapped because of poor exposures. It is present and thick in the Ouro Prêto district and was also mapped in the Santa Rita Durão quadrangle to the north, but it was not identified in the Capanema or Catas Altas quadrangles. It does not occur in the Gandarela syncline and may be presumed not to have been deposited there. In the Itabira district, thin lenticular zones of manganiferous saprolite derived from dolomitic rocks above typical Cercadinho beds may represent the formation. In the Monlevade area the zone is now gneiss and no rock corresponding to the Fêcho do Funil lithology can be identified. Thus, the formation is everywhere present except in the eastern Serra do Curral, in the Gandarela syncline, and east of the Serra do Caraça.

The formation varies gradually in thickness. In the type locality Simmons (1968a) measures a thickness of 410 m. It thins to 100 m to the westward before being cut out by intrusive granite and thins to the eastward in the Belo Horizonte quadrangle to perhaps 100 m. Good exposures in the Rio das Velhas canyon north of Sabará do not reveal rocks of the lithology of the Fêcho do Funil Formation, and it may be presumed that this formation wedges out in the western part of the Nova Lima quadrangle, as it is not present in the Gandarela syncline either.

To the south of Belo Horizonte in the Moeda Plateau, the formation was estimated by Wallace (1965) to average 300 m in thickness. In the Ouro Prêto area the outcrop width suggests a thickness of 200 m or more. In the Santa Rita Durão quadrangle, Maxwell (written commun., 1963) estimated a thickness of about 175 m.

The Fêcho do Funil Formation is one of the least resistant to weathering in the region and forms low relatively flat or smoothly rolling slopes. In the Moeda Plateau the Rio Mata Porcos has carved a deep and steep canyon in this formation, providing intermittently good outcrops of this generally nonresistant sequence. Commonly only saprolite is seen, even in deeply incised canyons, but included lenses of dolomite crop out boldly. The formation is subject to landslide and creep where it underlies steep slopes.

LITHOLOGY

The Fêcho do Funil Formation is composed of dolomitic phyllite, phyllite, siltstone, and impure dolomite. The dolomitic phyllite has nowhere been observed fresh, but the spongy texture of the rock in weathered exposure is typical of such rock. As pointed out by Simmons (1968a), in the type locality the formation consists of rocks containing differing quantities of three constituents—dolomite, quartz, and sericite. Dolomite may be substituted by calcite and quartz and is almost entirely absent from some phyllite. Some phyllite is slightly ferruginous but nowhere contains as much hematite as phyllite of the Cercadinho Formation. Siltstone is very fine grained and in most places sericitic.

Lenses of impure marble are common in the formation. This rock at the type locality contains 36 percent SiO_2, 4 percent Al_2O_3, 16 percent CaO, and 11 percent MgO, with 23 percent loss on ignition (Simmons, 1968a). Wallace (1965) reported seven analyses of marble from the Moeda Plateau which are much purer; SiO_2 ranges from 1 to 7 percent, Al_2O_3 from 0.1 to nearly 2 percent, CaO from 28 to 51 percent, and MgO from 1.4 to 19 percent, with the loss on ignition ranging from 41 to 48 percent. Four of the seven samples approach the end members of the limestone-dolomite series. The iron content ranged from 0.6 to 4.2 percent, and one sample contained 1.8 percent manganese. Some of the iron is present as hematite and magnetite, but some is probably ferroan calcite and dolomite. All the manganese probably occurs as manganoan calcite or dolomite, as no primary manganese oxide minerals are visible. Johnson (1962, B14) reported nearly pure dolomite from the Cumbé quarry, Dom Bosco quadrangle. The dolomite lenses may be as much as 30 m or more thick and as much as several hundred meters long. Although in the Moeda Plateau these lenses tend to be near the base of the formation, they may occur anywhere in the formation.

These lenses are bluntly lenticular. A well-exposed example can be seen in the valley to the south of Ouro Prêto–Belo Horizonte Highway in the Ouro Prêto quadrangle near Botafogo, where the phyllite wraps around the end of a dolomite lens that has been quarried. It is possible that the lenticularity may be due to a giant boudinage structure, or the lenses may be bioherms. Naturally, in completely recrystallized Precambrian marble the lack of fossils is not critical.

This marble has locally been quarried for metallurgical purposes and for building and paving stone. Near the Corrego do Eixo in the Marinho da Serra quadrangle, noneconomic occurrences of tetrahedrite and other copper minerals occur in several separate lenses (Rynearson, written commun. 1951). Small concentrations of manganese oxide occur in the saprolite derived from the rock throughout the area.

TABOÕES QUARTZITE

The Taboões Quartzite was named by Pomerene (1958b) from the type locality in Côrrego Taboões in the Ibirité quadrangle. It is composed of fine-grained quartzite.

DISTRIBUTION AND THICKNESS

The Taboões Quartzite is found only in the Igarapé, Fêcho do Funil, Ibirité, Belo Horizonte, and Lagoa Grande quadrangles—an east-west distance of 45 km and a north-south distance of about 22 km. At the type locality the Taboões Quartzite is 121 m thick; elsewhere in the Ibirité quadrangle it may be thicker. In the Belo Horizonte quadrangle it thins to the east and is only locally present in the east half of that quadrangle. West of the type locality the formation continues across the Fêcho do Funil quadrangle, where Simmons (1968a) measured two sections, 75 and 60 m thick, respectively. It extends some distance into the Igarapé quadrangle, where it is about 30 m thick and is there cut out by intrusive granite. In the Moeda Plateau the Taboões Quartzite is much thinner and crops out only at the north end, where it ranges from 40 m in the north to 2 m near the south boundary of the Lagoa Grande quadrangle (Wallace, 1965).

Where not deeply weathered and disaggregated, the Taboões Quartzite forms a low ridge. Where strongly weathered and completely disaggregated, it forms depressions instead of ridges and is in many places marked by deep gullies. Where the formation is thin, it is difficult to locate, as the normal topographic expressions cannot develop.

CONTACTS

The Taboões Quartzite grades downward within a few centimeters to a meter into the underlying Fêcho do Funil Formation, which is normally phyllitic at the top. It grades upward into the Barreiro Formation, also phyllitic, within a few centimeters. In the western part of the Serra do Curral it is overlain by the Sabará Formation with a rather abrupt contact.

LITHOLOGY

The Taboões Quartzite is an equigranular fine-grained massive orthoquartzite; chemical analyses show that the rock contains 98.5 percent SiO_2 (Pomerene, 1964, p. D26; Simmons, 1968a). Its grain size is in the order of 0.05 mm, and the grains are subrounded to subangular. The rock is completely massive and bedding planes are not seen in outcrop. Both on weathered and on unweathered outcrops the quartzite is distinguished from all other quartzites in the region by the presence of small voids about 1 mm in diameter stained with brown limonite, which give the rock a curiously speckled appearance. Their origin is unknown.

Although the fresh quartzite is gray, vitreous, and hard, weathering dissolves the quartz cement and the rock becomes noncoherent, although it stands well in cuts because of the interlocking grains. It is stained brown in some localities and is white in others. The weathered rock is a favorite source of sand for cleaning and scouring for the local rural inhabitants and roadcuts in many places are marked by small excavations where sand has been removed for that purpose. It has also been used as a source of high-quality silica sand for refractories and as a dressing on blacktop pavement. In one locality in the Lagoa Grande quadrangle, the weathered quartzite was infiltrated and locally replaced by manganese oxide derived from the topographically higher Fêcho do Funil Formation; a few tons of commercial ore were removed.

BARREIRO FORMATION

The Barreiro Formation [3] was named by Pomerene (1958c, p. 68–69) for the well-exposed sequence of schist, phyllite, and graphitic phyllite along Corrego do Barreiro in the northeast corner of the Ibirité quadrangle.

DISTRIBUTION AND THICKNESS

The Barreiro Formation crops out on the north flanks of the Serra do Curral from the Igarapé quadrangle in the west to the Belo Horizonte quadrangle in the east; the formation wedges out in both directions. It is present in the Moeda Plateau and along the south border of the region in the Ouro Prêto and Mariana quadrangles and, to the east, in the Santa Rita Durão quadrangle. For structural reasons, it does not crop out in the Catas Altas quadrangle and, like the underlying Taboões Quartzite, was not deposited in the Gandarela syncline or the east end of the Serra do Curral. It is not known in the Monlevade area, but rocks of this lithology are present in the Itabira District. Thus, it is known for a maximum distance of 110 km in an east-west direction and for 90 km in a north-south direction but was not deposited everywhere in the region. Rock of similar lithology has been seen east of Morro do Pilar, some 75 km north of Itabira.

The formation never crops out well, and estimates of thickness are uncertain at best. It is about 124 m thick in the type locality and about the same thickness in the Moeda Plateau. It is perhaps 15 m thick in the Itabira District.

[3] English speaking readers should be careful not to confuse this name or formation with the widespread Barreiras Formation of mid-Tertiary age found in Amazonia. No confusion will be possible in Portuguese as the two words have quite different meanings.

CONTACTS

The Barreiro Formation overlies the Taboões Quartzite with conformable and gradational contact. The contact is gradational over a few centimeters and is marked by an abrupt change from pure quartzite to phyllite. It is structurally conformable with the Sabará Formation, and in some areas the contact is gradational (Pomerene, 1964, p. D27), in others, marked by an erosional unconformity (Simmons, 1968a).

LITHOLOGY

The Barreiro Formation is dominatly composed of phyllite and graphitic phyllite. The nongraphitic phyllite is pink and light gray; the graphitic phyllite is black to dark gray.

In the type locality and many other places, the lowermost beds of the Barreiro Formation are nongraphitic phyllite. These lower beds, some 10–20 m thick, are overlain by graphitic phyllite, in the type locality in two zones totaling about 100 m in thickness separated by a 4-meter break of nongraphitic phyllite. In much of the region, the graphitic phyllite is the key lithology of this formation, for it is not easily confused with strata of other formations.

A sample of the graphitic phyllite collected by Pomerene contained 4.4 percent carbon, Simmons (1968a, p. G20) reported that Breger extracted small quantities of soluble organic material from this graphitic phyllite and that analysis of the sample collected by Simmons showed that the rock contained 1.5 percent soluble and insoluble carbon.

The graphitic phyllite locally contains cubic casts which were probably pyrite. In a relatively small area near Ouro Prêto, the rock contains as much as 20 percent pyrite and has been mined on a small scale for the pyrite content, used for making sulfuric acid. This pyrite is very probably syngenetic pyrite, as first suggested by O. Barbosa (1954).

The rock weathers easily, crops out only in artificial openings and gullies, and has poor mechanical characteristics for highway and other engineering works.

SABARÁ FORMATION

The Sabará Formation, a eugeosynclinal assemblage, was named by Gair (1958) for the excellent exposures in the valley of the Rio das Velhas just north of the city of Sabará, where that river cuts the Serra do Curral in a long canyon. The highway on the east bank and the railroad on the west bank provide the most continuous exposures yet discovered across the strike of this formation.

Throughout the region, the Sabará Formation is deeply weathered to saprolite, and only in a few localities can rock fresh enough for thin-section study be found. Outcrops of the saprolite are scattered and inconspicuous. The complex bulk composition of the formation makes it more sensitive to contact and regional metamorphism than other formations of the Minas Series. Because of these facts and the great thickness of the formation, there is much uncertainty as to the detailed lithology and as to the correlation of particular horizons or zones from one part of the region to another.

DISTRIBUTION AND THICKNESS

The Sabará Formation has been mapped continuously from the west side of the Itatiaiuçu quadrangle near the west end of the Serra do Curral to the east side of the Santa Luzia quadrangle near the east end of the Serra do Curral, a distance of about 65 km. It crops out in part of the Gandarela syncline but is squeezed out east of the Gongo Sôco quadrangle. Rocks of similar lithology were seen in the Itabira district but not mapped individually owing to the poor exposures. Rocks at this stratigraphic position in the Monlevade area are all transformed to gneiss. In the Ouro Prêto area the Sabará Formation is widespread, and it has been mapped in the southern part of the Santa Rita Durão quadrangle; it is not found in most of the Serra do Caraça area, as only older rocks crop out there. In the Dom Bosco area and probably in the Congonhas area, rocks of similar lithology are known but are not mapped separately. The formation is not found in the Moeda syncline, probably having been eroded off in pre-Itacolomi time. Thus, the Sabará Formation is widespread in the Quadrilátero Ferrífero.

The maximum apparent thickness is at the type locality and in the Belo Horizonte quadrangle, where the formation is about 3,000–3,500 m thick. Maxwell (written commun., 1963) stated that it is about 1,000 m thick in the Santa Rita Durão quadrangle. Moore (1969) stated that it is more than 1,000 m thick in the Gongo Sôco quadrangle.

The formation is always limited upward either by an ancient or modern erosion surface or by intrusive granitic rocks. Along the north side of the Serra do Curral it is everywhere in contact with younger granitic rocks that have strongly metamorphosed the formation. In the Ouro Prêto area and in the Santa Rita Durão area it is unconformably overlain by the Itacolomi Series. In the Gandarela syncline and the Itabira district it is squeezed into the cores of synclines. Its original thickness is therefore unknown.

CONTACTS

The upper limit of the formation is an erosion surface or a contact with intrusive granite. The lower contact varies in nature within the region, and the Sabará Formation directly overlies the Barreiro Formation, the Taboões Quartzite, the Fêcho do Funil Formation, and the Cercadinho Formation at one place or another. The Barreiro and the Taboões are formations of limited regional extent; it is not known whether this is the result of nondeposition or pre-Sabará erosion. Structually, the Sabará Formation is everywhere concordant with those underlying formations. In the Belo Horizonte quadrangle the contact is gradational (Pomerene, 1964, p. D27); farther west it is abrupt (Simmons, 1968a). In the Serro do Curral the base is marked by a conglomeratic zone a few centimeters thick, consisting of fragments of phyllite in a phyllite matrix. In the Antônio Pereira quadrangle A. L. M. Barbosa discovered a boulder conglomerate composed largely of dolomite boulders and cobbles overlying with structural conformity the Fêcho do Funil Formation (fig. 16).

FIGURE 16.—Basal conglomerate of the Sabará Formation near N. 11,800, E. 7,100, Antônio Pereira quadrangle. The cobbles and boulders are almost all dolomite, presumably from the Fêcho do Funil Formation.

A. L. M. Barbosa and J. H. Grossi Sad (oral commun., 1966) found in a new roadcut near Saramenha (Ouro Prêto quadrangle) that there the Sabará rests on an erosional surface cut on rocks of the Fêcho do Funil Formation. Thin quartz veins in the lower rocks are said to be truncated by this surface. The rocks above and below this surface are concordant, and no basal conglomerate is present.

Thus, the contact appears to be transitional with no significant pre-Sabará erosion in some parts of the region but abrupt and with significant pre-Sabará erosion in other parts. The structural concordance of the Sabará with all directly underlying formations in all parts of the region shows that no orogeny occurred in the time interval represented.

LITHOLOGY

The dominant rocks of the Sabará Formation at the type locality are mica and chlorite schists with interbedded graywacke, subgraywacke, and quartzite. The chlorite schists grade upward into biotite-muscovite schists with porphyroblasts of garnet and staurolite as the contact with the granitic rocks is approached. Graywacke and subgraywacke occur in lenticular beds and zones as much as 70 m thick; these make up about 10 percent of the lower half of the formation, whereas the upper two-fifths of the formation is almost entirely schist (Gair, 1962, p. A40–A41).

In the type locality, and everywhere else along the north flank of the Serra do Curral, the upper part of the formation has been thoroughly metamorphosed by the intrusive granitic rocks to the staurolite isograd and it is difficult to decipher the exact original nature of the rocks.

Abundant chlorite and biotite schist in the type locality of the Sabará Formation may well represent metamorphosed tuffaceous rock. Although criteria to definitely prove such an origin have been largely destroyed there by contact metamorphism and strong shearing, in other parts of the region much of the rock has a definitely tuffaceous aspect; in places the material appears to be a volcanic agglomerate. Such material has been reported from many parts of the region. Although deeply weathered, much of such rock would probably best be termed greenstone where it is not highly metamorphosed.

Fresh graywacke and subgraywacke crop out well only in the type locality, where active canyon cutting by the Rio das Velhas has removed most saprolite. Elsewhere these rock types have not been widely observed but are believed to be present under the soil and saprolite cover.

In the valley of the Rio Socorro, outcrops of quartzite and feldspathic quartzite were reported by Moore (1969). The grain size of the quartz and feldspar ranges up to 1.0 mm, and the feldspar makes up as much as 15 percent of the rock. Epidote and sericite or chlorite are other constituents of this rock.

In the upper part of the formation in the type section a thin poorly laminated lenticular "iron-formation" occurs, interpreted by Gair as a ferruginous metachert. The rocks here are highly metamorphosed, and it is not possible to distinguish with certainty ferruginous metachert and iron-formation in such an environment. Thin lenticular beds of iron-formation are known in the Congonhas area and in the Dom Bosco quadrangle in rocks of lower metamorphic grade that are believed to correlate with the Sabará. Barbosa mapped (pls. 9 and 10) extensive ferruginous quartzite and itabirite beds in the Sabará Formation in the Ouro Prêto and Mariana quadrangles.

Two persistent thin beds of white pure very fine-grained quartzite also occur in the upper part of the Sabará Formation, interpreted by Gair as metachert. They are clearly part of the Sabará Formation in the vicinity of Marzagão. (See Gair, 1962, pl. 1.) Pomerene (1964, p. D28) found similar rock in the Ibirité quadrangle entirely surrounded by granitic rocks; he noted that it had the appearance of Arkansas novaculite. Pomerene suggested that this material might correlate with rock other than the Sabará Formation. The present writer believes it more reasonable to correlate the Ibirité material with that near Marzagão, as such a minerologically simple rock would not easily be altered by granitizing processes or invading granitic magmas and could be expected to remain relatively unchanged.

Three kinds of conglomeratic rock occur in the Sabará Formation—a sharpstone phyllitic conglomerate, true boulder and cobble roundstone conglomerate, and tilloid. The sharpstone conglomerate is at the base of the formation in contact with the Barreiro Formation north of the Serra do Curral (Pomerene, 1964; Simmons 1968a). The angular detrital material is phyllite in a matrix of phyllite; the fragments are small, and the bed a few centimeters thick. Roundstone basal conglomerate several meters thick in the Antônio Pereira quadrangle is composed of dolomite cobbles and boulders (fig. 16).

Higher in the section a few zones of scattered well-rounded quartz pebbles in a phyllite or quartzose phyllite matrix are found in the western Serra do Curral. Maxwell (written commun. 1964) referred to scattered small pebbles in a phyllite matrix in the Santa Rita Durão quadrangle and to scattered pebbles and cobbles of granite, quartz, and quartzite in graywacke in the same area. Roundstone conglomerate is found in two exposures north of the Serra do Curral in the Igarapé quadrangle (Simmons, 1968a) in which pebbles and cobbles of granite, quartzite, quartz, and phyllite occur in a phyllite matrix. The writer observed granite cobbles as much as 20 cm in maximum dimension in the outcrop along the Belo Horizonte–São Paulo highway.)

Tilloid (fig. 17) composed of widely scattered large granite boulders as much as 1 m in maximum dimension in a matrix of chlorite schist or phyllite is revealed by a deep roadcut just south of Mariana; smaller scattered cobbles and boulders in chloritic phyllite are also found near the base of the Sabará Formation near Fazenda Mirandinho at the south edge of the Santa Rita Durão quadrangle. Such rock is revealed only fortuitously by roadcuts and is possibly much more common than now known.

Thus, in contrast to the underlying Minas Series stable-shelf sediments, the Sabará Formation indicates a repetition of the eugeosynclinal environment of the Nova Lima Group: volcanism again contributed sediments to the region, many of the rocks are turbidites, and the presence of granitic boulders indicates nearby crustal instability and the unroofing of batholithic masses. The concordant and gradational contacts with the shelf sediments indicate that this particular area was not itself strongly deformed at this time, but clearly the long period of crustal quiescence indicated by the mature and well-differentiated underlying sediments came to an end at the beginning of Sabará time.

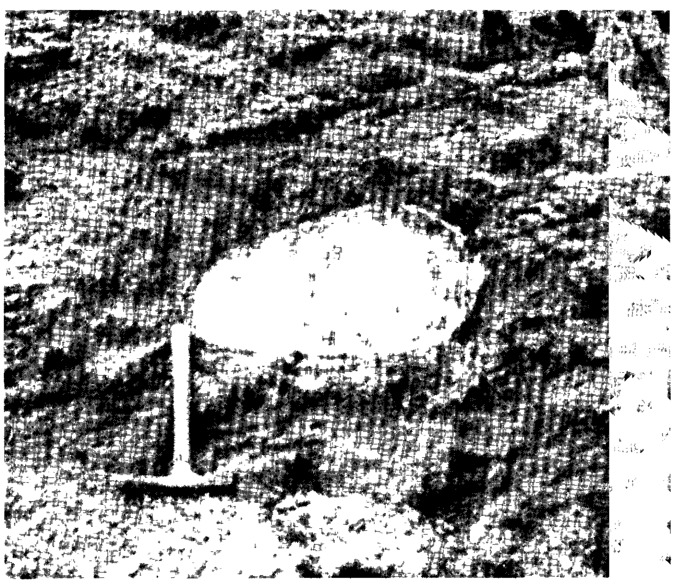

FIGURE 17.—Boulder of granite in phyllite matrix in tilloid of the Sabará Formation, near N. 16,600, E. 9,100, Mariana quadrangle.

ENVIRONMENT OF DEPOSITION

The rocks here included in the Piracicaba Group are, with the exception of the Sabará Formation, all blanket shelf deposits. The Sabará Formation represents a flysch suite deposited in a eugeosynclinal environment.

The erosion interval at the end of Itabira time marked a withdrawal of the sea or an epeirogenic uplift of the land surface. In this region, major folding is not evident; at most, a very minor warping occurred. The amount of erosion that took place in this region was not great. Whether the Gandarela Formation was completely removed in those parts of the region where it is missing or whether it never had been deposited could not be determined. In the eastern part of the region nondeposition is indicated, but relations in the western Serra do Curral suggest that the formation may have been removed by erosion there. The presence of coarse pebbles, cobbles, and finer fragmental material from the Itabira Group in the basal conglomerate of the Cercadinho Formation in the Serra da Moeda and the western Serra do Curral, and the generally coarser sediments in the Cercadinho in the west-central part of the region, indicates extensive erosion of the Itabira Group in an area west of the Quadrilátero Ferrífero. The less abundant hematite in the Cercadinho Formation to the east also suggests an origin to the west.

The alternating beds of fine, medium, and coarse lenticular crossbedded and ripple-marked quartzite and of phyllite which compose the Cercadinho Formation are typical of nearshore or deltaic sediments deposited on a rather flat surface. The impure dolomite and dolomitic phyllite of the overlying Fêcho do Funil Formation indicate gradual encroachment and deepening of the sea. On these sediments, regional in extent, were deposited the more restricted quartzite and phyllite of the Taboões and Barreiro Formations, which are local accumulations of very well differentiated and mature sediments. The high graphite and locally high pyrite contents of the Barreiro Formation indicate an euxinic environment, the result of local downwarping.

The graywacke-subgraywacke-metatuff-tilloid-protoquartzite-metachert-phyllite suite of the Sabará Formation clearly marks a sudden and complete change both in depositional environment and source of sediments from those which produced the well differentiated sediments of the rest of the Minas Series.

Pettijohn (1957, p. 640) stated the following on the normal course of development of geosynclinal sediments:

> There is what may be called the normal geosynclinal cycle. The geosyncline is initiated, filled, and commonly, though not always, deformed. The sediments which accumulate during the different stages are more or less petrographically distinct. The early stages of the geosynclinal cycle are commonly marked by a starved section—the euxinic facies, mainly black shales with, perhaps, very thin and evenbedded siltstones, siliceous limestone or chert. This facies is succeeded by the normal flysch facies, the rhythmically bedded dark shales and graywackes.

This description of normal geosynclinal sediments suggests that the Piracicaba Group of the Minas Series may represent this normal development. The Cercadinho Formation was the first blanket sediment in this group, a shelf sediment, deposited on a flat surface. The Fêcho do Funil may represent the first downwarping of the miogeosyncline, with siltstones and siliceous dolomite common. The Taboões and Barreiro Formations correspond to the thin, starved, and, in the Barreiro, the euxinic section, overlain by the thick eugeosynclinal flysch suite of the Sabará Formation. The sequence represents a single geosynclinal sedimentary cycle. The rocks were slightly deformed after Sabará sedimentation and before Itacolomi time.

The sudden and drastic change of sedimentation that began with the Sabará Formation is thought by some to justify setting that formation apart in a separate group in the Minas Series (A. L. M. Barbosa, written commun., 1966) or as a lower part of the overlying Itacolomi Series (Teixeira da Costa, 1961, p. 60). However, there is no compelling evidence anywhere in the Quadrilátero Ferrífero of a significant angular discordance in the sedimentary sequence now included in the Piracicaba Group. In certain parts of the region, as in the Ibirité quadrangle, sedimentation seems to have been uninterupted, and the Sabará is gradational with the underlying Barreiro Formation (Pomerene, 1964, p. D27). In other areas the Sabará Formation overlies the Cercadinho and the Fêcho do Funil Formations. The absence of the Taboões and Barreiro Formations can as well be attributed to nondeposition as to erosion; the former formation certainly lenses out southward in the Lagoa Grande quadrangle (Wallace, 1965). Except for the cited localities near Fazenda Gualaxo and Saramenha, there is no sign of significant subaerial erosion in these areas. The thin basal conglomerate found in some localities at the base of the Sabará Formation contains no exotic rocks, merely those from the underlying formation, plus some quartz grains and pebbles. The angular phyllite fragments in this conglomerate could not have been transported any significant distance; even if the material now phyllite had already been lithified, for the shale would be very soft.

Further evidence on the erosional discordance at the base of the Sabará should be sought to supplement present inadequate information caused by lack of outcrops. New roadcuts and other excavations in scattered parts of the region will in the course of time provide critical evidence now lacking as to the lateral extent of the erosional interval now definitely known only in the southern part. If this erosion surface proves widespread, and if the conformity of the beds below and above this surface proves to be a general rule throughout the region, very possibly the surface should be used to separate the Sabará from the rest of the Piracicaba Group. If subdivided into formations by more detailed mapping, the Sabará could then be raised to group status. The conformity of these rocks with the underlying Minas Series rocks, in contrast with the angular unconformity of the Sabará with the overlying Itacolomi Series rocks, indicates that the Sabará should remain in the Minas Series.

METAMORPHISM

Most formations of the Piracicaba Group are found in the axes of synclines, where they were subjected to strong deformation but were protected from the contact metamorphism produced by invading granitic rocks, which occur largely in anticlinal areas. Thus, they tend to show a relatively low grade of regional metamorphism but may be strongly folded and sheared.

The major exception to the above generalization is found on the north side of the Serra do Curral, where granitic rocks transgress all the formations of the Piracicaba Group except the Taboões Quartzite, which wedges out before contact with the granite. Here, the effect of the bulk composition of the formations on their metamorphism is clearly apparent. The heterogeneous complex sediments of the Sabará Formation were strongly affected, for staurolite and garnet zones are strikingly developed parallel to the contact in bands more than 1 kilometer across. The better differentiated sediments of the lower formations were not so strongly affected. Quartzites were metasomatized for only a few tens of centimeters at the granite contact, and phyllites were recrystallized into somewhat coarser grained micaceous rocks for distances measured in meters or tens of meters.

ITACOLOMI SERIES

Strata now included in the Itacolomi Series were discriminated by Harder and Chamberlin (1915, p. 364–368) as the Itacolomi Quartzite,[4] considered by them to be part of the Minas Series. In 1931, Guimarães raised the unit to the rank of a series on the basis of the angular unconformity between the quartzite and the underlying rocks of the Minas Series. The Itacolomi Series is now considered to consist of two facies, one of quartzite and one containing much phyllite. The phyllitic facies was named the Santo Antônio Formation by O. Barbosa (1949, p. 7), who assigned the unit to the Minas Series. Guild (1957, p. 22) established this sequence as equivalent to the Itacolomi Series and renamed it the Santo Antônio facies (p. 25). Quartzite of the type locality will herein be referred to informally as type Itacolomi, and the phyllitic sequence of O. Barbosa and Guild will be referred to as the Santo Antônio facies.

[4] Readers should not confuse the stratigraphic unit with the rock known as itacolomite, a flexible micaceous quartzite named originally from the Quadrilátero Ferrífero but occurring in many parts of the world. This rock has no stratigraphic significance whatsoever, being found in the Rio das Velhas, Minas, and Itacolomi Series. Many geologists have confused the two terms; for this reason most geologists in Brazil since Derby and Harder and Chamberlin have avoided using the term "itacolomite."

TYPE ITACOLOMI

The quartzites grouped informally as type Itacolomi are those described by Harder and Chamberlin (1915), Freyberg (1932), Lacourt (1935), A. L. M. Barbosa (in Dorr and others, 1961, p. 20–22), and others. They crop out boldly and well in the type locality, the Pico de Itacolomi and vicinity, south of Ouro Prêto. The type locality is isolated by deep canyons and, the farther from the type locality, the less certain the correlation (A. L. M. Barbosa, in Dorr and others, 1961, p. 20). Harder and Chamberlin (1915, p. 364) pointed out that the relatively clean quartzite of the type locality grades laterally into phyllitic and schistose rock of quite different aspect.

Until the mapping by A. L. M. Barbosa (pl. 10), geologists considered the thick section of phyllite in the Pico de Itacolomi to be an integral part of the Itacolomi Series (Lacourt, 1935). Barbosa, however, determined that the phyllite is equivalent to the Sabará Formation of the Minas Series, thrust over Itacolomi quartzite and in turn overlain by Itacolomi quartzite (A. L. M. Barbosa, in Dorr and others, 1961, p. 20–21).

DISTRIBUTION AND THICKNESS

Quartzite of the type Itacolomi Series occurs in the Ouro Prêto and adjacent Mariana quadrangles. Quartzite of similar appearance unconformably overlying the Minas Series also occurs in the Pico de Frazão in the Antônio Pereira quadrangle.

In the type area, intense shearing and particularly thrust faulting make any estimate of thickness perilous; A. L. M. Barbosa (written commun., 1965) suggested that the series may be as much as 2,000 m thick. The formation is limited upward by the present erosion surface, and we have no evidence as to the original thickness, which may have been much greater. South of Passagem de Mariana and elsewhere, the type Itacolomi locally contains abundant garnet; the presence of this relatively high temperature metamorphic mineral suggests that a great thickness of younger but premetamorphic rock has been eroded since metamorphism.

LITHOLOGY

The type Itacolomi is dominantly quartzite and grit and contains varying quantities of sericite. The quartzite is conglomeratic and also contains many lenses of conglomerate. Thin and very lenticular interbeds of phyllite are present in some areas.

Most strata consist of coarse quartz grains in a matrix of fine-grained quartz, sericite, and muscovite. Feldspar may be either detrital or a metasomatic product; A. L. M. Barbosa (written commun., 1965) emphasized that the presence or absence of this mineral is of no stratigraphic significance. It forms a very small percentage of the rock. Hematite and martite are common interstitial constituents. On the main mule trail south from Mariana, a zone containing much iron is found near the base of the sequence, and similar zones occur elsewhere. In many places, hematite and martite are disposed on shear planes cutting the bedding at low angles. The quartzite is crossbedded at many localities.

The conglomerates consist of rounded pebbles, cobbles, and, in one locality, boulders as much as 0.5 m in maximum dimension of vein quartz, quartzite, itabirite, and, sparsely, phyllite; A. L. M. Barbosa confirmed the presence of one cobble well enough preserved to be certainly identified as a granitic rock. Many pebbles and cobbles are somewhat squeezed and discoid; their long dimensions are in the plane of foliation and may be at right angles to bedding. Phyllite fragments in such localities are sheared out into long wisps.

L. J. de Moraes pointed out to the writer that itabirite cobbles show that the iron-formation had been slightly folded before erosion, a fact first noted by Lacourt (1935). Despite careful search, nowhere were cobbles or boulders found with the characteristic sharp and intricate crenulation and folding now found in that rock, although in modern gravel deposits cobbles and boulders with such folding can be found. This indicates that the most intense folding occurred after Itacolomi sedimentation but that some folding had occurred before.

All conglomerate beds in the type Itacolomi are lenticular. Some are more than a few meters thick, and a few are more than 10 m thick. The lenticularity of the conglomerate beds suggests scour and fill. No persistent basal conglomerate has been reported in the type Itacolomi, but exposures of the bazal zone are rare indeed.

Phyllite in the type Itacolomi consists largely of sericitic lenses not more than a few tens of centimeters thick (A. L. M. Barbosa, written commun., 1965). Kyanite is found both in phyllite and quartzite.

The Itacolomi quartzites are crossbedded, and Lacourt (1935) mentioned the occurrence of ripple marks in the quartzite. Bedding is coarse to massive in the coarser grits and quartzites. The finer sediments are more thinly bedded.

A. L. M. Barbosa (written commun., 1965) stated that, ignoring the thin phyllitic lenses, about 50 percent of the Itacolomi strata in the type locality consists of medium-grained quartzite and grit, about 30 percent of conglomeratic quartzite, and about 20 percent of conglomerate.

CONTACTS

The Itacolomi Series in the type locality rests with angular unconformity on the Sabará, Barreiro, and Fêcho do Funil Formations of the Minas Series. The maximum angular unconformity found was about 12°, just to the south of Ouro Prêto.

The polymictic conglomerates found in the Itacolomi Series (Freyberg, 1932, p. 105) prove major erosion of the Minas Series before and during Itacolomi sedimentation, and the unconformable relation is beyond question. There is no way of evaluating the time interval involved, but it was great enough to permit removal of at least 1,000 m of Minas sediments before local accumulation of Itacolomi sediments began.

SANTO ANTÔNIO FACIES

The rocks originally named the Santo Antônio Formation were described by O. Barbosa (1949) from the Morro Santo Antônio in the Casa da Pedra and São Julião quadrangles. The rocks that crop out there are phyllitic quartzite, roundstone and sharpstone conglomerate, phyllite, and ferruginous and nonferruginous quartzite. Probably, both O. Barbosa and Guild included in their Santo Antônio some rocks which are now assigned to the Cercadinho Formation; at the time of their work this formation had not yet been distinguished as a separate unit and exposures in the area are obscure. The Santo Antônio sequence in most localities is easily weathered and only locally forms ridges or hills; where quite phyllitic, it underlies low valleys and gentle slopes.

DISTRIBUTION AND THICKNESS

The Santo Antônio facies of the Itacolomi Series is the youngest Precambrian metasedimentary rock wherever it crops out and is always limited upward by an erosion surface. It rests upon an erosion surface carved into the Piracicaba Group of the Minas Series in all known exposures. In the type locality it rests on rocks which the writer would correlate with the Cercadinho Formation, elsewhere on all the other formations of the Piracicaba Group expect the Taboões Quartzite.

The facies is known to crop out in the Lagoa Grande, Casa da Pedra, São Julião, Antônio Pereira, Capanema, and Santa Rita Durão quadrangles (pl. 1). Individual areas of outcrop are not large and are isolated one from the other in three general areas, the largest of which is 9 km long. It survives only in downfaulted and downfolded areas.

The original thickness is, of course, unknown, as the top is nowhere exposed. The apparent thickness in the

Lagoa Grande area is about 150 m, in the Congonhas area in the order of 1,00 m, and in the Santa Rita Durão area in the order of 1,000 m, if not repeated by folding or faulting.

LITHOLOGY

The principal difference between the Santo Antônio facies and the type Itacolomi Series is the much greater clay content of the original sediments of the Santo Antônio facies, resulting in rocks in general more easily weathered than the relatively pure coarse-grained quartzite and grit of the mountain-forming type Itacolomi. O. Barbosa (1949, p. 7) described the unit as consisting of sericitic quartzite, with thick layers and lenses of conglomerate and phyllite. Guild (1957, p. 23–25) added detail and showed that the sericitic quartzite varies greatly in mica content, which is locally dominant. Grains of quartz range in size from hundredths of a millimeter to a few millimeters. With increasing grain size the rock grades into conglomerate, in which the pebbles, cobbles, and boulders range up to 50 cm in maximum dimension. The matrix is commonly very sericitic, locally phyllitic. (See Guild, 1957, fig. 11.) Coarse detrital material is locally well rounded and locally quite angular and consists of fragments derived from all the identifiable rocks in the Minas Series as well as a peculiar red cherty-appearing rock which has not been seen in place in this region. Cobbles derived from the Cercadinho and Gandarela Formations and the Cauê Itabirite have been identified; the phyllitic and quartzitic pebbles and cobbles cannot be surely assigned to individual formations. Conglomerate beds as thick as 20 m were reported by O. Barbosa.

Phyllite is subordinate in the type locality, according to Guild, being present in lenticular beds interbedded with the coarser clastic rocks. The phyllite consists of sericite and small amounts of muscovite and kyanite. Chloritoid-garnet schist has been reported.

Hematite, and to a much lesser extent magnetite, occurs to greater or lesser degree in all clastic beds of this facies. Undoubtedly these minerals were derived from erosion of the Minas Series itabirite during Santo Antônio sedimentation. These minerals are not segregated into bands except in two general areas.

Near Casa da Pedra N. 8,900, E. 12,500, well-banded ferruginous quartzite is exposed that in its present metamorphosed state appears identical with itabirite. That this material is at least in part clastic in origin is proved by tracing it laterally, where it may be seen to contain pebbles and cobbles, particularly near its base. One lens of such quartzite is 6 km long and 400 m thick (Guild, 1957, p. 23); others are much shorter and thinner. Such lenses contain thinner lenses of clean quartzite and of sericitic phyllite, as well as the conglomerate mentioned above, in contrast with the Cauê Itabirite, which never contains coarse, and rarely contains fine, clastic sediments. Jurgen Eichler, however, believed (oral commun., 1962) this lens is to be correlated with the Cauê Itabirite and not with the Santo Antônio facies. The lenticularity of the body, its stratigraphic position, and its lithologic nature force the writer to disagree with Eichler. In its present metamorphosed state, it is not possible to prove that this lens was not in part of chemical origin; it is equally difficult to prove that it was not an originally finely banded clastic sediment similar to the recent unconsolidated sediments to be described on page A76.

Pseudoitabirite also is found just south of Fazenda Alegria in the Santa Rita Durão quadrangle. There, hematite was further concentrated and forms crossbedded deposits of high-grade hematite containing as much as 69 percent iron at the Germano deposit (Maxwell, written commun., 1962). Primary sedimentary structures in the rock and the abnormally low phosphorous content led Maxwell to believe it to be detrital in origin.

In the Lagoa Grande quadrangle the rocks are essentially similar to those in the type area but are more phyllitic and less hematitic and include some graphitic phyllite (Wallace, 1965). Most conglomerates contain round pebbles and cobbles, although some very angular material is found near Lagoa Grande N. 8,800, E. 10,300. In this area, cobbles from the Cercadinho ferruginous quartzites are common, and itabirite cobbles are less common. Although a basal conglomerate was not found in the Congonhas area (Guild, 1957, p. 23), Wallace mapped a basal conglomerate throughout the whole extent of the Lagoa Grande outcrop of the Santo Antônio facies. In the Lagoa Grande area, the quartzites are complexly crossbedded (fig. 18).

FIGURE 18.—Festoon crossbedding in the Santo Antônio facies of the Itacolomi Series, Lagoa Grande quadrangle.

The largest area of outcrop of the Santo Antônio facies is that in the Santa Rita Durão and Capanema quadrangles. In the southern part of this exposure, the sequence rests on the chloritic Sabará Formation, which, except for the virtual absence of conglomerate, is rather similar in general lithology. To the north, the Santo Antônio facies lies on the Cercadinho and Fêcho do Funil Formations. In this area also the formation has a basal conglomerate composed of fragments derived from underlying Piracicaba Group rocks and contains fragments from the Itabira Group, notably from the Cauê Itabirite. These pebbles, cobbles, and boulders occur in a phyllitic matrix unlike that in the type locality. Lenses of polymictic roundstone conglomerate 20 m thick may occur higher in the section and contain a very high percentage of itabirite cobbles and boulders as large as 20 cm in maximum dimension. All coarser clastic rocks of the Santo Antônio Facies are crossbedded, a characteristic feature where not destroyed by later shearing and metamorphism.

RELATION BETWEEN THE TYPE ITACOLOMI AND THE SANTO ANTÔNIO FACIES

There is no way of knowing whether the type Itacolomi is older, younger, or contemporaneous with the rocks mapped as the Santo Antônio facies; nowhere are the two facies contiguous. The type of sedimentation and the marked lateral gradation from the more quartzose rocks of the type locality in the Pico de Itacolomi into more phyllitic rocks to the east leads the writer to believe that the two are at least in part essentially contemporaneous. They probably represent different locations with respect to the shoreline, source of sediments, and type of material deposited during sedimentation.

ENVIRONMENT OF DEPOSITION

The original sediments of the type Itacolomi were coarse sands and gravels deposited in a deltaic or littoral environment in an area of considerable topographic relief. Fine sands, silt, and mud also characterized the sediments away from the type locality, suggesting that the rocks at type locality may represent the shoreline facies where the finer material was winnowed out to be deposited in quieter waters nearby, with the lenticular conglomeratic zones representing turbidites or possibly sudden incursions of coarser material carried by floods or during fluctuations of the sea level. The folded itabirite, the deep pre-Itacolomi erosion of the underlying rocks, and the angular unconformity at the base of the Itacolomi all indicate that orogenic forces were beginning at this time. This erosional unconformity is entirely different from that at the base of the Cercadinho Formation and the possible one at the base of the Sabará Formation, which give no evidence that local folding occurred.

As both O. Barbosa and A. L. M. Barbosa pointed out, the Minas Series rocks were eroded rapidly, and no peneplain developed between the uplift that caused the erosion and the depositon of the Itacolomi sediments, which are tectonic sediments. They suggested that the sediments may have been deposited in intermontane basins or at least separate basins. This is entirely possible and is suggested by the local variation in lithology of the rocks and particularly the included conglomerates, but it is not certain, for conceivably the differences could result from local drainage systems dropping their load into a large body of water. Similarities are greater than differences in these rocks.

The coarse detrital material in the Itacolomi clearly proves that the Minas Series was somewhere eroded as deeply as to the Itabira Group. However, nowhere in the Quadrilátero Ferrífero is that group missing except in the major uplifts. The Itacolomi sediments everywhere now lie on Piracicaba Group rocks. Although conglomerate is present in all areas of exposure of these rocks, it is perhaps most common in the westernmost area, near Congonhas, and least common in the northeastern area, in the Santa Rita Durão quadrangle and environs. It is also coarsest in the Congonhas area. This might suggest that the sediments were derived from a nearby area outside the Quadrilátero Ferrífero, possibly to the southwest, and were carried into the area of deposition by torrential streams. It is of course possible that the major uplifts such as the Rio das Velhas uplift began to develop at this time, and the conglomeratic material from the Minas Series came from these sources. This seems unlikely, as no Itacolomi is known in the northern part of the Quadrilátero Ferrífero.

Derivation of part of the Itacolomi sediments from a second source other than the Minas Series is strongly suggested by the coarse grain size of the quartzite and grit which make up most of the Itacolomi Series in the type area and in the Congonhas area. This material is much coarser grained than the dominantly fine-grained rocks of the Piracicaba and Itabira Groups of the Minas Series and could not have been derived from those rocks.

It is thus more probable that the Itacolomi sediments were derived from a mountainous granitic terrain outside the Quadrilátero Ferrífero from which the Minas Series rocks were also being stripped and were not deposited in restricted intermontane basins. Because of the great thickness of argillaceous rocks which would have had to be removed before the Itabira Group rocks were exposed, thick deposits of pelitic sediments contemporaneous with the Itacolomi of this region must have been deposited farther away from the shoreline. These have not yet been identified but might be represented in the younger granitic gneisses cropping out for 200 km and more east of the Quadrilátero Ferrífero.

The Itacolomi sediments as now exposed, characterized by ripple marks, crossbedding, and rapidly shifts in sedimentary facies, appear to be paralic sediments.

HISTORY AND PROBLEMS OF REGIONAL STRATIGRAPHIC CORRELATION

In 1932 Freyberg wrote (p. 106), "Only when there becomes available an accurate topographic map suitable for geologic surveying, with a scale not less than 1:25,000, can the tectonics be more exactly explained." As Freyberg knew, understanding of the tectonics depends on understanding of the stratigraphy, which in turn depends on careful regional geologic mapping on an adequate base map. Before this project, the only base maps available were at a scale of 1:100,000 and had a contour interval of 100 m. Lacourt mapped on this scale in the Ouro Prêto area but published on a scale of 1:200,000. Ericksen and colleagues mapped the Itabirito area at the same scale (DNPM, unpub. data). These two geologic maps, made on inadequate bases, were the only ones attempted in the region, except for mineral-deposit studies. Sketch maps, such as the excellent one at a scale of about 1:3,000,000 by Harder and Chamberlin (1915), showed only the grossest relationships.

Although von Eschwege, Gorceix, and many others in the 19th century contributed invaluable information on the general geology and, more particularly, on the mineralogy of the region, the first to apply modern stratigraphic concepts and modern systems of nomenclature in the region were Derby and, particularly, Harder and Chamberlin. Worthy heirs were Moraes Rego (1932), who published important stratigraphic information in an ephemeral publication most difficult to locate today; L. J. de Moraes, a keen observer; F. Lacourt, whose more general work remained unavailable for 15 years after completion; and particularly O. Barbosa, who applied Harder and Chamberlin's concepts on a wide scale. D. Guimarães continued the classic mineralogic and petrographic approach of earlier workers.

Freyberg, an indefatigable field geologist badly hampered by lack of base maps, summarized very well the knowledge accumulated up to 1932. By 1945 several systems of nomenclature of the stratified rocks in this region had been proposed, none based on mapping of more than limited areas. Definitions of units were vague, type localities only rarely mentioned if at all, and limits of stratigraphic units never precisely stated or tied to specific localities and lithologic units. Important data were published in ephemeral journals. Because no professional society or governmental organ was charged with unifying stratigraphic nomenclature, no set procedures existed for officially recognizing or changing nomenclature.

Under these circumstances it seemed best to follow the system of nomenclature proposed by Harder and Chamberlin—the most complete, clearest, and in widest use at the time this project began. This choice was approved by officials of the Departamento Nacional da Produção Mineral. With a few exceptions, that system proved, with modernization and limited redefinition, to be entirely suitable for use in describing the Minas Series. The proposal of Guimarães to raise the Itacolomi Quartzite of Harder and Chamberlin from formation to series rank on the basis of an angular unconformity at its base is entirely justified and was followed.

Because a correct stratigraphic sequence is basic to an understanding of structure, the tectonic framework also could not be worked out until regional mapping had been accomplished. Thus, Guild (oral commun., 1948) seems to have been the first to realize that the sequence in the Serra do Curral was overturned; still later was it realized that the granitic rock immediately to the north of that range, shown on then-existing maps as "Archean," was in fact younger than the Minas Series.

In subdividing Precambrian metasedimentary rocks, the only reliable criteria for establishing major stratigraphic units are regional structural and erosional unconformities, witnesses of major orogenic and epeirogenic events. The actual time span represented by such unconformities is unknowable without reliable age determinations. Clearly a regional erosional unconformity without structural discordance may represent a time span equal to a regional angular unconformity. However, structural discontinuities are easier to find and trace, and they mark unequivocally major events; erosional unconformities are much more difficult to evaluate because sure evidence of interformational erosion is difficult to find and nondeposition, overlap, offlap, and later metamorphism of the sediments render interpretation precarious. Of great assistance in interpretation is the presence of suites of related lithologies, such as a flysch suite or a suite of related platform sediments. The lithology of polymictic basal conglomerates is also most helpful.

It was on these bases that the present subdivision of the Precambrian metasedimentary rocks of the Quadrilátero Ferrífero was made.

To illustrate some of the problems encountered in deciphering the stratigraphy and the stratigraphic nomenclature of the region, we found that Harder and Chamberlin included some rocks herein assigned to the Rio das Velhas Series in the Caraça Quartzite, their basal unit of the Minas Series. Guimarães (1931) confused lithologic and stratigraphic units, lumping together basal Minas and Itacolomi quartzites. Others (Guimarães, 1931; Lacourt, 1935; O. Barbosa, 1949) included some parts of the Rio das Velhas Series of this project in the equivalent of Harder and Chamberlin's Piracicaba Formation or "upper Minas." Still others split the same rocks between the upper and lower Minas Series. A common cause of confusion was the attempt to correlate stratigraphic units on the basis of their metamorphic rank, which our mapping has shown to vary both systematically from east to west across the region and also with proximity to intrusive granitic masses. "Epizonal" rocks were considered by some to be Minas Series or Itacolomi Series, regardless of lithology or stratigraphic position.

The lower limit of the Minas Series, a stratigraphic term in common use since 1906 (Derby), had never been clearly defined at the time our work started. Rynearson and Pomerene, with some assistance from Ashley and the writer, discovered in 1951 in the region of Belo Horizonte and the Moeda Plateau the major tectonic and stratigraphic unconformity between the quartzites corresponding to Harder and Chamberlin's Caraça Quartzite and underlying phyllitic and schistose rocks. This information was published in 1954. In the same year O. Barbosa suggested the possibility of comparable relations in a larger region. Barbosa showed a thrust fault rather than an unconformity between these rocks in the Quadrilátero Ferrífero on his map published in 1954. That map included in his older unit, which he called the Barbacena Series, much rock of post-Minas age and included in the Minas Series stratigraphic units of pre-Minas age.[5] In 1956, Oliveira restricted the Minas Series to the strata above the major angular unconformity demonstrated by Rynearson and colleagues and below an angular unconformity with the Itacolomi Series.

An erosional disconformity between the Itabira and Piracicaba Formations of Harder and Chamberlin, discovered by Pomerene and Ashley in 1952, was taken as the line of separation between those two units, a separation indefinitely defined by Harder and Chamberlin. In 1957 Dorr, Gair, Pomerene, and Rynearson formally proposed the name Rio das Velhas Series for the stratified rocks below the angular unconformity at the base of the Minas Series as restricted by Oliveira. They also divided these two major series into groups so that further subdivision would be possible, for mapping had by that time proved that many more stratigraphic units existed than had before been identified. New group names, the Nova Lima and the Maquiné Groups, were proposed by O'Rourke and Gair for the hitherto unrecognized division of the Rio das Velhas Series. Harder and Chamberlin's formation names were raised to group rank in the Minas Series because the new groups nearly coincided with the formations as defined by those geologists with the exception of the Caraça Group, which was made to include both the original Caraça and Batatal Formations, as the sediments are closely related and locally inseparable.

As stated, Guimarães had earlier separated the overlying Itacolomi Series from Harder and Chamberlin's Minas Series on the basis of an angular unconformity found between these units.

Detailed tracing of lithologic units permitted further breakdown of the series and groups discussed above into formations and, for some formations, members. The Minas Series, as mapped in 1958, was divided into nine formations by the USGS–DNPM team.[6] The Maquiné Group of the Rio das Velhas Series was divided into two formations by O'Rourke (written commun. 1958) and Gair (1962). The Itacolomi Series had been subdivided into two facies by O. Barbosa (1949, 1954) and Guild (1957). Reeves (1966) recognized and named two gneissic formations and a quartzite member in the Monlevade area, corresponding to specific units in the Minas Series in less metamorphosed parts of the region. Simmons and Maxwell (1961) recognized a group of rocks in the Serras das Cambotas and do Caraça between the basal Minas Series as it occurs in the Moeda Plateau and the Rio das Velhas Series, subdividing this group into four formations. They assigned this new group, the Tamanduá Group, to the Rio das Velhas Series. Simmons (1968b) later combined the top three formations into one formation.

There is some question as to the proper series assignment of the Tamanduá Group. To evaluate the assignment, a recapitulation of the development of nomenclature of the rocks assigned to the Caraça Quartzite by Harder and Chamberlin is necessary. Those geologists included in their Caraça Quartzite all the quartzite in the Serras do Caraça, Tamanduá, and das Cambotas, assigning the unit to the bottom of the Minas Series. Later Guimarães assigned the quartzites of the Serras do Caraça and das Cambotas to the Itacolomí Series; Bölau (1952), agreeing with Harder and

[5] For these reasons, as well as the lack of an adequate definition, the term Barbacena Series is not used in reports resulting from this project. Some of the rocks included by O. Barbosa in his Barbacena Series are undoubtedly the stratigraphic equivalents of some rocks in the Rio das Velhas Series of these reports.

[6] The subdivision was then made because in that year the Brazilian Geological Society held its annual meeting in the Quadrilátero Ferrífero. It was deemed desirable to present the results of 11 years work because the Minas Series was the focus of scientific and economic interest at that meeting.

Chamberlin, believed that they belonged to the basal Minas Series.

At the time members of this team named the various formations of the Minas Series (1958), the Serra do Caraça had not been mapped and, because the stratigraphic position of all quartzites in that range had not yet been established and because structure was there most complex, the basal quartzites of the Minas Series as restricted by Oliveira (1956) were named from the Moeda Plateau region, where the structure was relatively simple and the stratigraphic succession unequivocal. It was then known at least part of the Serra do Caraça was made up of quartzite correlative with the Moeda quartzite, and therefore Harder and Chamberlin's name for the basal Minas Series rocks was retained with group status to include both the Moeda Formation and the Batatal Formation, which also occurs there, to be consistent with the upgrading of the other original formation names to group status. This proved wise, for further mapping proved that the Serra do Caraça is made up of quartzites of three different ages and lithologies, the Maquiné, the Cambotas, and the Moeda, and that the Cambotas forms the bulk of the mountain range.

Moore was the first to suspect that quartzite in the Serra das Cambotas and its lithologic equivalent in the Serra do Caraça might be older than that mapped as the Moeda Formation. Later detailed mapping by Simmons and Maxwell showed that this was indeed true and that the quartzite of the Serras das Cambotas and do Caraça was lithologically somewhat different from the Moeda Formation and underlay that formation. These geologists assigned these older quartzites and overlying phyllitic beds to the Rio das Velhas Series on the supposition that a major unconformity existed between them and the Moeda quartzite.

Exposures of the critical zone of contact in the areas of outcrop of the Tamanduá Group are uniformly poor and, although the zone of contact between the Moeda Formation and the Tamanduá Group and between the Tamanduá Group and underlying units total many tens of kilometers in length, only a few significant data on the contacts have been found. These incomplete data lead the writer to believe that the Tamanduá Group is better assigned to the Minas Series than the Itacolomi Series (Guimarães) or to the Rio das Velhas Series (Simmons, Maxwell, and Moore) for the following reasons.

1. In the Serras do Tamanduá and das Cambotas, the Cambotas Quartzite is shown by ripple marks, cross-bedding, scour-and-fill structures, and other sedimentary features to be upright, not overturned (Simmons, 1968b). The unquestioned units of the Minas Series concordantly overlie the Tamanduá Group with normal stratigraphic succession and are not overturned. There are no apparent signs of major faulting between the units. The structure in the Serra do Caraça is more complex and the rocks more deformed, but the Cambotas Quartzite there also underlies the unquestioned Minas Series in normal stratigraphic sequence. Thus, the Tamanduá Group and therefore the Cambotas Quartzite must be older than the overlying units of the Minas Series and cannot be correlated with the Itacolomi Series.

2. No locality was found by Simmons, Moore, or Maxwell in areas mapped by them where the Tamanduá Group underlies the unquestioned Minas Series with demonstrable angular relation. A number of localities are cited in reports by these geologists where the rocks are in structural concordance. An erosional unconformity may or may not exist between the Moeda Formation and the Tamanduá Group; the writer believes, but cannot prove, that an erosional unconformity exists. That it is not great is shown by the lateral persistence for some 25 km of the soft relatively thin phyllitic beds of the upper Tamanduá Group.

3. The Cambotas Quartzite rests with certain erosional unconformity and probable angular unconformity on the Nova Lima Group in the Gongo Sôco quadrangle. Rocks now tentatively correlated with the Cambotas Quartzite rest with angular unconformity on the Nova Lima Group in the Florália quadrangle (Herz, oral commun., 1965), in the Serra do Ouro Branco (Barbosa, 1949; Guild, 1957; Johnson, 1962), and in the Serra do Espinhaço (Pflug, 1965). No unequivocal evidence for or against an angular unconformity between these units is known elsewhere.

4. In the part of the region in question, as in other places where the Tamanduá and Maquiné Groups are missing, the Caraça Group of the Minas Series rests unconformably on the Nova Lima Group. Simmons (1968b, p. H8) stated that in the south limb of the Gandarela syncline in the Cocais and Santa Bárbara quadrangles the average angular discordance between these rocks is 20°. In the northeastern part of the Conceição do Rio Acima and the southeastern part of the Gongo Sôco quadrangles, Moore (1969) described the discordance between Minas Series and Nova Lima Group rocks as "slight to moderate"; at Conceição do Rio Acima N. 5,300, E. 1,400, there is a difference in both strike and dip of 40°. At the west side of the Conceição do Rio Acima quadrangle, the basal conglomerate of the Moeda Formation contains angular fragments of Nova Lima Group phyllite.

5. The contact between the Cambotas Quartzite and the underlying Maquiné Group of the Rio das Velhas

Series was said by Maxwell (written commun., 1962) to be sedimentary but discordant. Maxwell cited a low angle structural unconformity at Capanema N. 13,600, E. 8,300, and a 60° angular unconformity at Capanema N. 5,400, E. 6,600. In the Conceição do Rio Acima quadrangle, Moore considered this contact to be a fault contact. As shown on plate 1, this writer interprets it to be a sedimentary contact. The angular discordance as mapped by Moore is as much as 30° between the two units.

Thus scattered field evidence shows that a definite angular and erosional unconformity exists between the Tamanduá Group and both groups of the Rio das Velhas Series and, where the Tamanduá Group is missing in this area, between the rest of the Minas Series and the Rio das Velhas Series. No angular unconformity has anywhere been demonstrated in the Quadrilátero Ferrífero between the Tamanduá Group and the rest of the Minas Series. Because the angular unconformity between the Tamanduá Group and the Rio das Velhas Series is very probably the same unconformity found between the Minas Series and the Rio das Velhas Series from the westernmost to the easternmost quadrangles, it seems quite probable that the Tamanduá Group should be assigned to the Minas Series, for this regional unconformity was cited by Oliveira as the basis for the separation of the Minas and the Rio das Velhas Series.

Because the upper Tamanduá Group is not known west of a line between Henrique Fleuiss and the southeast corner of the Serra do Caraça, there is no reason to suppose that it was ever deposited west of this line. The Cambotas Quartzite thins abruptly toward the west and disappears in the middle of the Gongo Sôco quadrangle and is also relatively thin northeast of the Conta Historia syncline (Capanema quadrangle). It seems reasonable to suppose that there it wedged out abruptly westward. The quartzite of the Serra do Ouro Branco, tentatively correlated with the Cambotas, wedges out abruptly to the west

Simmons (personal commun., 1964) emphasized the sporadic distribution of the Tamanduá Group within the Quadrilátero Ferrífero as evidence of a strong unconformity between these rocks and those of the Caraça Group and cited the fact that the Tamanduá is found only on the north and west limbs of synclines as difficult to explain. It is quite conceivable that the Cambotas was deposited as beaches in bays between headlands, in a manner similar to the present beaches being deposited along the São Paulo–Rio de Janeiro littoral; a discontinuous highly lenticular formation would ensue. The writer believes, but cannot prove, that some erosion took place between Tamanduá and Caraça deposition; this does not imply either a long time break or a major deformation. He believes that the presence of large relatively isotropic and rigid lenticular masses of orthoquartzite in dominantly argillaceous terrain localized the synclines during the epoch of deformation and that localization of the quartzites on one side of synclines is expectable rather than anonalous.

Disagreement on correlation of a band of phyllitic rocks resulted from poor exposures along the Serra Geral in the Caeté, Gongo Sôco, and Santa Bárbara quadrangles.

Chloritic phyllites with iron-formation lenses unconformably underlying the Moeda Formation in the Caeté and Gandarela quadrangles have been traced westward without structural or stratigraphic break into the type locality of the Nova Lima Group and eastward into the western part of the Gongo Sôco quadrangle. Moore mapped the band in the Gongo Sôco quadrangle as Nova Lima Group, lying with fault contact on the Cambotas quartzite in the eastern half. Simmons (1968b), however, interpreted this phyllitic zone above the Cambotas Quartzite in the Santa Bárbara quadrangle as the upper formation of the Tamanduá Group and projected it into the Gongo Sôco quadrangle.

The writer, in reinterpreting the stratigraphy and structure for plate 1, assigned the rock in the eastern part of the Gongo Sôco quadrangle to the upper formation of the Tamanduá Group, in agreement with Simmons' assignment, and the western part to the Nova Lima Group, in agreement with Moore's assignment. The two units are thought to be separated by an east-trending fault. The reasons for this tentative assignment are that the phyllitic rocks in this band contain several thin iron-formation zones and are chloritic in the west side of the Gongo Sôco quadrangle, typical of the Nova Lima Group, and are sericitic on the east side and contain one relatively thick iron-formation zone, typical of the Tamanduá Group. The writer considers that both units of the Tamanduá Group wedge out abruptly to the west, because neither is found to the west of the middle of the Gongo Sôco quadrangle. When better exposures of the rocks in the area are made by roadbuilding or mining activity, the area should be restudied, as present exposures do not permit certain resolution of the problems.

After this paper had been prepared in essentially final form, a report resulting from a reconnaissance of the part of the Serra do Espinhaço between 19°30′ S. and 17° S. appeared in Germany and Brazil (Pflug, 1965). The Brazilian version of this report will be cited here. The region discussed comprises some 30,000 square kilometers immediately north of the eastern part of the Quadrilátero Ferrífero; a planimetric sketch map of the area and part of the Quadrilátero Ferrífero at a scale of about 1:1,000,000 was included, showing distribution of stratigraphic units and of lithology.

Pflug advocated that the Minas Series should be divided into three interfingering lithologic facies, deposited synchronously. These facies were called by him the "Diamantina facies" (quartzite), the "Itabira facies" (itabirite), and the "Guanhães facies" (eugeosynclinal sediments). North of the Quadrilátero Ferrífero, the facies crop out in three north-trending belts distributed from west to east, respectively: the first, 40–100 km wide, said to represent miogeosynclinal sedimentation; the second, 10–15 km wide, said to represent sedimentation at the transition between the miogeosyncline and the eugeosyncline; the third, over 100 km wide, said to represent sedimentation in the eugeosyncline (Pflug, 1965, p. 31–33 and fig. 14). This interpretation contrasts with the subdivision of the Minas Series into four superposed groups, subdivided into 11 formations and several members, made by the DNPM–USGS geologists in the Quadrilátero Ferrífero.

The basal formation of the Minas Series in the Quadrilátero Ferrífero, the Cambotas Quartzite, can be traced from its type locality northward, with a few breaks of a kilometer or so where it has been eroded off, into the "Diamantina facies" of Pflug. The correlation is secure and is followed in Pflug's map, which unfortunately omitted several large areas of the quartzite between the Serra das Cambotas and the area to the north. Pflug found that an angular unconformity exists between his "Diamantina facies" and rocks similar lithologically to the Rio das Velhas Series, that the Minas Series sediments had come from the west, and that the grade of metamorphism systematically rose from the west to east, all facts consistent with those reported from the Quadrilátero Ferrífero and tending to make more certain the interregional correlation. Pflug did not find a break between the Tamanduá and Caraça Groups and did not subdivide the basal Minas Series quartzites, although he did refer to local unconformities in the quartzite.

This writer has not systematically mapped in the area discussed by Pflug but has crisscrossed it numerous times in geological reconnaissance while trying to decipher the geological frame around the Quadrilátero Ferrífero. In that area he has recognized ferruginous quartzites lumped with true itabirite by Pflug in his "Itabira facies." Two true itabirate zones occur in the northern area with outcrops measured in tens of kilometers in length, but the rock type is there in thinner zones and is not everywhere continuous. Rocks of the eugeosynclinal suite, called the "Guanhães facies" by Pflug, were apparently similar in lithology and stratigraphic position to the Sabará Formation of the Quadrilátero Ferrífero.

The writer therefore believes, with Pflug (1965), Harder and Chamberlin (1915), and O. Barbosa (1954), that the Minas Series as exposed in the region to the north of the Quadrilátero Ferrífero is basically similar in stratigraphy to rocks included in the Minas Series in the Quadrilátero Ferrífero. Detailed mapping will probably show that some formations distinguished to the south will not be present to the north, and some new formations may well be distinguished, as all the formations are not continuous everywhere even in the Quadrilátero Ferrífero.

The distribution in the Quadrilátero Ferrífero of the eugeosynclinal Sabará Formation, similar to the "Guanhães facies" and shown as "Guanhães facies" in Pflug's figure 13, proves definitely that it is much younger than, rather than being a synchronous and interfingering facies of, the basal quartzites of the Minas Series. Not only is the Sabará coextensive with those rocks where it has not been removed by later erosion, but is separated from them by one and possibly two erosional unconformities as well as by about 1,000 meters of well-differentiated sediments, some of which have been recognized to the north. Instead of being confined to the area east of the quartzite outcrops, the Sabará continues to the west with full thickness about 100 km beyond the westernmost outcrops shown on Pflug's map, where it is cut out by younger granite. Thus, neither to the east nor to the west can it be considered to be synchronous or interfingering with the quartzite rocks traceable from the area mapped by Pflug into the Quadrilátero Ferrífero.

Superposition of the Cauê Itabirite above the quartzite which Pflug considered to be a time equivalent of the itabirite is equally clear in the Quadrilátero Ferrífero from the easternmost to the westernmost exposures, or about 140 km in an east-west direction and for some 100 km in a north-south direction.

Thus, the Quadrilátero Ferrífero offers no support for the relatively stable shoreline during Minas Series sedimentation demanded by the interfingering facies concept but offers much evidence of systematically transgressing shorelines resulting in distinctive superposed blanket formations.

The fact that the sediments of the Piracicaba and Itabira Groups are at least as well developed in the Serra do Curral, their present northernmost limit in the Quadrilátero Ferrífero, as anywhere else in the region suggests strongly that these rocks once extended far to the north of their present limit. Available evidence indicates that their present distribution is controlled more by postsedimentation tectonics, granite formation, and erosional events than by the original limits of the sedimentary basin in which they were deposited. It is most difficult to imagine that a series of marine sediments more than 4000 m thick, which can be traced south from the Serra do Curral for 100 km—there being limited by tectonic features—and for 140 km in an east-west direction, should pinch out abruptly to the north. If, as supposed, the Minas Series once extended far to the north of the Serra do Curral, Pflug's facies concept evidently could not be defended, for that concept demands a land area to the north of the Serra do Curral during deposition of the whole Minas Series. He named this hypothetical land area the Sãn Francisco Massif (Pflug, 1965, fig. 14).

The interfingering of phyllite and locally ferruginous quartzite with the purer quartzite of the central Serra do Espinhaço that gave rise to the interfingering facies concept is also clearly evident in the Moeda Formation in the Quadrilátero Ferrífero. In the Serras da Moeda and do Itabirito, where this formation is thick, well exposed, and clearly underlying rather than interfingering with the Itabira and Piracicaba Groups, the quartzite contains many lenses of phyllite, some of which were mapped separately as members of the Moeda Formation (Guild, 1957; Pomerene, 1964; Wallace, 1965). This lithologic succession is a natural one in transgressive nearshore formations and can be matched today in many localities, particularly those with aggrading barrier beaches and lagoons.

The writer believes that careful mapping at adequate scales of the central Serra do Espinhaço may reveal some of the same formations found in the Quadrilátero Ferrífero, arched into a great anticline that was much disturbed structurally, sliced by north-trending, west-moving thrust faults, probably with imbrication, bent by cross folds, and cut by younger granitic and gabbroic rocks. Before erosion, rocks included in the "Itabira" and "Guanhães facies" probably extended over the top of the "Diamantina facies" that now forms the central part of the Serra do Espinhaço, as postulated by Harder and Chamberlin (1915) and O. Barbosa (1954), who called them the Itabira and Piracicaba formations. Itabirite cobbles in ancient (Cretaceous?) high-level gravels west of the Rio das Velhas, more than 200 km north of the Serra do Curral, and well west of the Serra do Espinhaço suggest that iron-formation once covered that range to its west side and possibly beyond.

UNMETAMORPHOSED SEDIMENTARY ROCKS

FONSECA FORMATION

Underlying the "Chapada de Canga" in and east of the Santa Rita Durão and Catas Altas quadrangles is an area of flat-lying poorly lithified sedimentary rocks named the Fonseca Formation by Maxwell (written commun., 1965). The unit is about 85 m thick at the type locality near Fonseca, a town east of Água Quente and outside the Quadrilátero Ferrífero.

At the base of the unit is a conglomerate about 7 m thick consisting of pebbles and cobbles of granitic gneiss, phyllite, and quartzite. Siltstone, claystone, and sandstone overlie this basal conglomerate. About 27 m above the base of the unit, lignite lenses ranging in thickness from 2 to about 80 cm appear in the other rocks; an old analysis indicates the following composition in percent: ash, 17.95; volatiles and hygroscopic water, 44.91; fixed carbon, 37.14 (Gorceix, 1884, p. 88). The formation lies on granitic gneiss and is overlain by canga and ferruginous laterite.

The Fonseca Formation underlies the Fonseca basin, about 35 square kilometers in extent. The top is a relatively plane surface and the bottom a Tertiary erosion surface described earlier in this paper (p. A13). Gorceix was the first to describe these strata; the abundant plant fossils were assigned to the Pliocene or upper Miocene (Gorceix, 1884, p. 88–89). More recently Sommers (written commun., 1962) judged that the fossils could not be dated more closely than late Tertiary.

OTHER TERTIARY ROCKS

Several small accumulations of sedimentary rock of Tertiary age are known in the Gandarela, Macacos, and Nova Lima quadrangles, and undoubtedly others will be found elsewhere beneath canga, bauxite, or soil. One of these deposits, in the Gandarela basin, yielded commercial lignite during the Second World War.

The Gandarela basin, so named and described by Gorceix (1884), is about 750 m long and 250 m wide. In this basin claystone, sandstone, and lignite overlie the Gandarela Formation in a roughly elliptical pattern (pl. 5). A drill hole near the south margin of the basin showed some 60 m of semiconsolidated sediments, which could not be successfully cored, overlying ferruginous rocks interpreted as canga. The drill did not reach unweathered bedrock. Dense vegetation and poor outcrops prevented close study of the Tertiary rocks. Two adits driven on lignite beds were found, but the timber at the portals was crushed and a respectable flow of water emerged; it was not considered wise to enter them and their extent and the thickness of the lignite beds are unknown. At least two lignite beds were reportedly found, one more than 1 meter thick. The lignite seen at the portal and in an old bin contained many fragmentary leaf impressions and much pyrite, largely smeared on fractures and bedding planes. The mine water was very acid, and limonite was being deposited near the portals.

In the eastern part of the area occupied by the Tertiary sedimentary rocks, the beds are nearly flat lying, but near the western margin they steepen to an attitude of about 50° E. This steep dip led Brajnikov (1947) to postulate a fault and an important Tertiary tectonism; careful search for evidence of faulting in the adjacent rocks and the Tertiary rocks by several geologists of our staff was, however, fruitless. It is rather believed that the steep dips are caused by slumping and consolidation of sediments deposited in a sinkhole in the carbonate rocks of the underlying Gandarela Formation. A small sinkhole lake choked with vegetation, the Lagoa de Metro, still exists a few hundred meters northeast of the Gandarela basin but will soon be destroyed, as it is perched on a steep hillside caused by deepening of the principal valley to a level about 50 m below the lake. A canga lip preserves the topographically anomalous feature.

Pomerene found thin Tertiary deposits in the valley of the Rio do Peixe near the Miguelão dam, Macacos quadrangle. Little is known of their extent or thickness, for they are exposed only when the reservoir is empty and are indistinguishable from recent sediments except for the fact that they contain a thin bed of fossilized leaves, identified by Roland Brown as Tertiary (Pomerene, 1964, p. D29). Similar deposits of clay containing fossilized leaves were reported by Gair (1962, p. A41–A42) in the Nova Lima quadrangle; undoubtedly other occurrences of such material are still to be found.

MUDSTONE

Isolated masses of unstratified nonplastic laterized clay, as much as 50 m thick and 300 m wide and as long as 2 km, are found in much of the Quadrilátero Ferrífero. They occur within relatively limited ranges of elevation and seem to be related to the post-Gondwana erosion surface (p. A12). Although unfossiliferous, the material is judged to be Tertiary or perhaps older. Geologists of the staff applied the field name "mudstone" to this material, the origin of which is puzzling.

Although mottled clay is a common result of the laterization of granitic and other rocks in Brazil and other tropical countries, the material here described is different from such weathering products in that it is nonplastic and much more indurated. It never grades into saprolite and thus is not the result of weathering of rock in place but of some transported material, differentiating it from the type laterite of India which it superficially resembles.

The rock is composed of semi-indurated nonplastic clay containing in many localities randomly distributed sparse frosted grains of quartz 1–3 mm in diameter. The quartz grains probably make up less than one-half percent of the rock. Except in the basal part of the bodies, in few places are rock fragments found in the material, and, where found, they are small angular fragments of rocks cropping out near the occurrence. The basal parts of the masses are exposed in only a few places, but there the clay may contain a basal conglomerate composed of angular or rounded fragments of the underlying rocks and vein quartz ranging up to 40 cm in maximum dimension. (See fig. 19.) In one body overlying iron ore, the basal conglomerate is composed of hematite blocks. The bodies are not cut by quartz veins or by dikes.

On the outcrop the "mudstone" presents a rugose surface barren of vegetation, even of moss or lichen, except where soil has washed or blown over the rock (fig. 20). Many outcrops are mottled white and brick red, perhaps more are brick red, and a few are white or chocolate brown mottled with white or light tan. No vestige of bedding survives, but some bodies are cut by joints or shrinkage cracks. In exposures where the third dimension can be seen, it is apparent that the mottling is caused by bleaching of the colored clay in vertical or nearly vertical cylindrical or elongate forms (Guild, 1957, fig. 22). The white clay is formed by complete bleaching of red or brown clay (Guild, 1957) caused by leaching of iron. (See table 2, analyses 1 and 2.) In a few exposures the white clay has been bauxitized along joints.

A number of chemical analyses have been made of the material from various bodies, and typical analyses of the white clay are presented in table 2. Although most analyses available did not determine TiO_2, those that did show an abnormally high content of titania, locally more than 5 percent. Such a high percentage is characteristic of laterites formed from mafic (Goldschmidt, 1954, p. 419) or alkalic rocks.

FIGURE 19.—Basal conglomerate in "mudstone" near N. 6,700 E. 12,900, Lagoa Grande quadrangle

FIGURE 20.—Outcrop of "mudstone" near N. 5,250, E. 4,200; Ibirité quadrangle. The rugose and pitted surface and absence of vegetation and soil are typical.

TABLE 2.—*Analyses of "mudstone"*

	1	2	3	4	5	6	7
SiO_2	36. 2	44. 1	46. 4	42. 0	45. 6	43. 1	42. 2
TiO_2	(1)	(1)	4. 3	5. 2	4. 2	4. 7	4. 5
Al_2O_3	32. 9	38. 9	32. 8	36. 4	33. 2	35. 3	36. 9
Fe_2O_3	[2] 17. 6	[2] 2. 6	1. 8	1. 5	1. 5	1. 5	1. 6
P	0. 05	0. 04	(3)	(3)	(3)	(3)	(3)
Loss on ignition	12. 4	13. 5	11. 7	14. 1	12. 8	14. 0	14. 5
Total	99. 6	99. 5	97. 0	99. 2	97. 3	98. 6	99. 7

[1] TiO_2 not determined; probably reported with Al_2O_3.
[2] Calculated from determination of Fe.
[3] Not determined.

1. Dark-red clay. Analyst, Dr. Cassio Pinto, DNPM (Guild, 1957, p. 43).
2. White clay, same locality. Analyst, Dr. Cassio Pinto (Guild, 1957, p. 43).
3–7. Clays. Analyses by Cia. Magnesita, S. A., Belo Horizonte (Wallace, 1965, p. F30).

"Mudstone" is most abundant in the west-central part of the Quadrilátero Ferrífero and particularly on the Moeda Plateau. Several large bodies are known in the southern part, particularly near Dom Bosco, and on the north slope of the Serra do Curral east of Jangada, but in the easternmost part of the region it occurs only in the Itabira district.

Perhaps the most significant feature of the occurrence of the mudstone is its virtual restriction to elevations between 1,200 and 1,350 m in the Moeda Plateau, the Serra do Curral, and the southern part of the region, where it is most abundant. A small body near Santa Rita Durão and the larger body overlying the Chacrinha hematite ore body above the city of Itabira are somewhat lower, but perhaps 85 percent of the known occurrences, and all the larger ones, are between the cited elevations.

On the Moeda Plateau and in many other occurrences the "mudstone" appears to be plastered on one or both sides of ancient high-level valleys, the floors of which have since been lowered below the bottom of the clay deposits. In other places the base level of local drainage is still above the base of the "mudstone" deposits, which are very resistant to erosion because of their homogeneity and lack of bedding planes or other points of attack by running water. In areas where the general stream level is below 1,200 m, the clay may form topographic noses and isolated rounded hills at about that elevation. Thus, it seems very probable that the material from which the "mudstone" formed is related to the erosion surface between 1,200 and 1,350 m, called the post-Gondwana surface by King (p. A11).

The spatial relations of the "mudstone" with the underlying Precambrian rocks and with the old erosion surfaces have led to several interpretations of the origin of this rock. Guild (1957, p. 43), who was the first to describe the "mudstone", believed it to be a weathering product of dolomite. It is quite true that much of the material overlies dolomitic rocks, particularly the Gandarela Formation, but since the time of Guild's fieldwork a number of occurrences have been found which overlie phyllite, quartzite, and other rocks. Furthermore, the presence of basal conglomerates between the "mudstone" and the underlying rocks, described by Johnson (1962), Pomerene (1964), Dorr and Barbosa (1963), and Wallace (1965), unknown at the time of Guild's work, proves that the mudstone is not a simple decomposition product, but rather that the original material from which the rock formed had been transported. The rounded frosted quartz grains in the "mudstones" have not been observed in the Gandarela Formation, a chemical and fine clastic formation, although they could have come from the quartzites of the Cercadinho Formation.

Pomerene (1964, p. D31) believed the material formed by laterization of siliceous ferruginous dolomite, modified by soil creep and slump. Gair (1962, p. A30) believed it may have formed from reworked ocherous itabirite and emphasized the resemblances to mudflows. Johnson (1962, p. C25) believed that the material was not derived from dolomite but that it had been transported, filling old channels. Wallace (1965, p. F29), who mapped the area in which such deposits are most widespread, showed that their distribution is not closely related to bedrock lithology. He attributed the material to further weathering of preexisting bauxite or lateritic soils. Wallace was the first to note the close relation of the "mudstone" to a restricted elevation range in the area mapped by him; the writer found that this was true on a regional basis, with a few exceptions.

The writer believes that the close spatial association with the Gandarela Formation in many parts of the region is due to the normal topographic expression of that formation, which provided an ideal setting for the accumulation of the material, the laterization of which gave rise to the "mudstone."

The abnormally high titanium content of the rock may provide a clue to the original material from which it was derived, for none of the other rocks of the region contain abnormal quantities of this element. Chemical analyses of the iron-formation and dolomites show very low titanium. Herz (1962, p. C75) has shown that the phyllitic rocks of the Minas Series are low in titanium. The bauxites in the region, commonly the site of concentration of titanium, are not abnormally high in titanium. It therefore is probable that the material from which the "mudstone" formed may have been introduced from sources outside the region.

Such a source might be found in windblown volcanic ash derived from the volcanoes thought to have accompanied the emplacement of the titanium-rich alkaline intrusive rocks a few hundred kilometers to the west and south of the Quadrilátero Ferrífero. Large complexes of such volcanic rocks are found in the vicinity of Araxá and Poços de Caldas in Minas Gerais, in São Paulo, and Rio de Janeiro. Those in Araxá and Poços de Caldas are thought, on the basis of age determinations, to have been active between 60 and 100 million years ago, or in the early Tertiary to middle or Late Cretaceous (Herz, written commun., 1965). This age assignment is not radically different from that made, on completely different grounds, by King (1956) for the post-Gondwana surface on which most of the "mudstone" deposits are found.

Possibly windblown ash from explosive eruptions blanketed the ancient surface and was concentrated in the valleys in that surface by slope wash and local mudflows. The deeper valleys would have been choked and filled with such ash, which would have been very fine to have traveled so far. Basal conglomerates are to be expected in such an environment, as preexisting cobbles and boulders would be surrounded by the fine introduced material and would be easily transported by mudflows. The complete lack of bedding perhaps can be explained by rapidity of accumulation of fine homogenous material and the effects of later laterization.

Neither the hypothesis of origin put forth above nor any other yet advanced satisfactorily accounts for the presence and even distribution of the rounded frosted quartz grains found so ubiquitously in this material in the region.

An hypothesis of origin which would explain the presence and distribution of quartz grains in the rock and the lack of stratification would be that the "mudstone" is thoroughly laterized windblown dust, a type of loess, dating from an ancient arid cycle. By this hypothesis it would be difficult to explain the abnormally high titania in the rock and the close relationship of the "mudstone" to a certain range in elevation, unless it were also postulated that the material forming the loess was in fact derived from volcanic ash during early Tertiary or late Cretaceous time. The origin of this distinctive rock must be considered to be still open to question.

WEATHERING PRODUCTS

Several materials formed by weathering processes from the underlying bedrock are sufficiently widespread to be mappable or of geologic interest. Those of economic value, such as bauxite and canga, will be discussed here as geologic rather than economic features.

SAPROLITE

The most common weathering product in the region is saprolite, a term applied by Becker (1895) to thoroughly decomposed, earthy, but untransported rock. In this report, the term is restricted to weathered rock whose original structure and texture is preserved but in which most original mineral constituents other than resistates have been so altered by weathering processes that they have been destroyed. Most polymineralic rocks, such as gneiss, phyllite, graywacke, and other rocks, were altered to saprolites almost everywhere and completely decomposed; their feldspars and much of the mica were altered to clay minerals. Pure quartzites were disaggregated through solution of cementing material. After some experience, one can with confidence broadly classify rock on the basis of textures and relict minerals in the saprolite. Whether particular granitic rocks were granites, quartz monzonite, or quartz diorite cannot be established with certainty except in fresh rock. Structural features in weathered rock tend to be preserved.

Decomposition of feldspars and micas results in impoverishment of the more mobile elements, particularly the alkalis, calcium and magnesium, with a coordinate increase in the more stable elements such as aluminum, and, under some circumstances, iron. The stability of quartz is believed by the writer to depend primarily on the grain size of the mineral (Dorr, 1964, p. 1230–1231); where finely divided as in the Taboões quartzite, some itabirite, some phyllites, and some schists, it is fairly fugitive. Where quartz is coarse grained, as in many sedimentary grits and granitic gneisses, it is quite stable. In itabirite, leaching of quartz is much reduced where its grain size is greater than 0.1 mm. Mafic dikes and the gabbros do not form deep saprolites because the complex silicates alter readily and contain no primary resistates to preserve original textures.

SPLASH ROCK

Carbonate rocks are exceedingly soluble in this region and weather deeply. Where protected from mechanical erosion, the weathering product is an unusual material consisting of a fine cellular boxwork of limonite and, locally, manganese oxide. These insoluble minerals, derived either from the carbonate rock itself or nearby rocks, are deposited around the individual crystals of carbonate. The latter are subsequently dissolved, leaving a microscopic boxwork of limonite or manganese oxide around voids now filled with water. The material has several identifying characteristics: when struck with a hammer, the hammer sinks into the material with a splash; when rolled between the fingers, small fragment have some initial strength but collapse suddenly, leaving a moist or wet fine paste which roughens the skin; and when dried, a chunk of the material will usually float in water before disintegrating as capillarity sucks the water into the cells with such violence that the walls break.

Guild (1957, p. 42–43) and Pomerene (1964, p. D18–D19) were the first to demonstrate that such material is the weathering product of dolomite. The material had been discussed by earlier geologists as earthy iron oxide or earthy manganiferous rock (Henwood, 1871; Scott, 1900). Soft clayey manganiferous and limonitic rock properly described as earthy is also abundant but should be differentiated from the material here described as "splash rock," as it is not necessarily derived from carbonate rocks.

"Splash rock" is an excellent guide to underlying dolomite or limestone in deeply weathered terrain. Much of the rock mapped as dolomite in the Quadrilátero Ferrífero was on the basis of the presence of "splash rock" at the outcrop or in the adits and cuts in the zone of weathering. No other rock yields this weathering product.

LATERITE

The term "laterite" has been used in many senses in the geologic literature and must now be considered a very general term indeed. Gordon, Tracey, and Ellis (1958, p. 71–73) reviewed the evolving usage of the term since its introduction by Buchanan in 1807 to describe certain alumino-ferruginous material in India derived from the weathering of basalt. Because of its lack of specificity, the term as here used is defined, not with the thought that this is the only correct usage or that the definition includes all conceivable laterites, but rather to help the reader relate the material called laterite in the Quadrilátero Ferrífero to that of other areas in which the term may be used somewhat differently.

Laterite is used herein for the structureless material, commonly highly aluminous and in many places ferruginous, formed by residual weathering of any rock except orthoquartzite or quartz veins. Weathering, in this climate, results in the breakdown of silicates, in decrease of the silica content, and in concentration of hydroxides of iron and, particularly, aluminum. Laterite is distinguished from saprolite on the basis of the lack of residual structure, from most soil on the basis of its residual nature and lack of organic material. Certain residual soils are also laterite, and such soil is called lateritic soil. This writer does not include canga as a laterite, although it could be argued that it is a special product of laterization.

Laterization of most rocks in this region results in a high percentage of bauxite minerals, other hydrolyzates, and resistates in the laterite or lateritic soil and a gradual impoverishment in iron oxide and hydroxide. As shown by Guild (1957, p. 43), clay containing more than 12 percent iron became virtually iron free on continued weathering, and the alumina content rose accordingly. Some buff, pink, or white lateritic soils derived from granitic rocks in this area contain significant, though noneconomic, quantities of bauxite minerals as established by differential thermal analysis (S. S. Goldich, oral commun., 1953).

Although much of the material considered as laterite or lateritic is red, much of it is light pink, light yellow, buff, or white, owing to lack of iron. Some of the commercial bauxite in the region is red because of the high iron content; other bauxite in commercial deposits is light buff to nearly white (fig. 21). Thus, the definition of laterite as "red residual soil" given in the glossary of the American Geological Institute (1960, supplement, p. 37) is incomplete, for the bauxite is an end product of laterization.

Laterization depends upon good subsurface drainage to carry away the soluble constituents of the material being leached. The best developed laterites are on high plateaus, terraces, or shoulders or flanks of ridges where the strong subsurface drainage is stimulated by favorable topography.

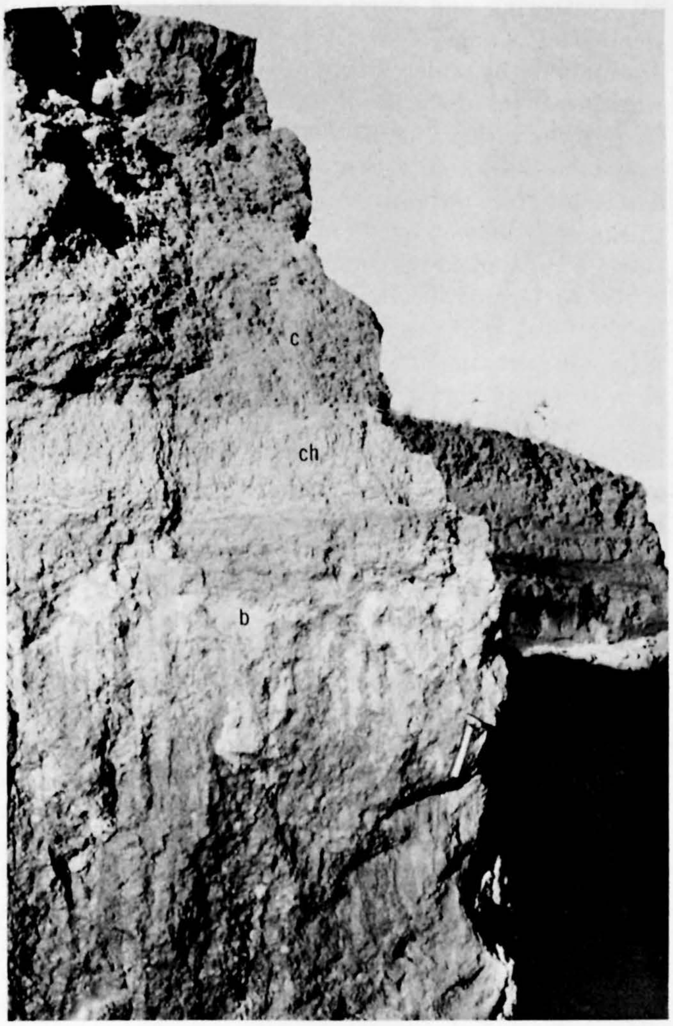

FIGURE 21.—Laterization profile, Mutuca bauxite mine, N. 8,000, E. 2,500, Macacos quadrangle. The uppermost zone is chemical canga (c). The next zone is light-brown to tan highly aluminous and ferruginous hard canga (ch), with strongly marked vertical flutings. Beneath the canga is a zone of pink to buff commercial bauxite (b) 1–3 m thick. The hammer is in bauxite. Below the bauxite is a varying but usually thick high-alumina clay, at least 10 m thick in this area. Here the chemical canga at the top may well be somewhat younger than the underlying zones and unrelated to them in genesis.

The only geologist in this project who mapped large areas as laterite was Guild. He defined laterite as "uncemented iron-formation debris, talus, and deep-red ferruginous soil" (1957, p. 41). To the writer's knowledge, the first two classifications would be excluded from laterite under any commonly accepted definition; the last is here considered laterite. The first two rock types were mapped by other geologists of the team as colluvial ore and as talus or rubble ore; they are very widespread.

Gabbro, diabase, and amphibolite weather to a laterite high in iron and alumina that is probably similar to the material in India for which the term was coined. Its characteristic texture and red or brown color is an excellent guide to the underlying rock. Lateritic soil over granitic rocks is thick and locally high in alumina. Over phyllite, most lateritic soil is thin and sterile, the insoluble hydrolyzates forming a slightly resistant crust a few millimeters or centimeters thick. Tan limonitic nodules, red or black inside, and commonly with a quartz grain as a nucleus and locally magnetic, form in places over certain phyllite zones. Protoquartzite may form a lateritic soil by removal of silica and breakdown of mica and other aluminous minerals. Ferruginous pisolitic concretions are not rare on protoquartzite that contains appreciable hematite or magnetite. Fossil soil and canga may become laterized, exemplified in the Itabira district (Dorr and Barbosa, 1963, p. 32–33), as may other unconsolidated or semiconsolidated sediments protected from or resistant to erosion, such as the "mudstone" deposits described above.

Carbonate-rich rock, when subject to intense laterization, produces certain characteristic features. Aluminous carbonate rock is the best source rock for the commercial bauxite deposits. The purer dolomites and limestones may form a deep porous chocolate-brown to red lateritic soil which, if the original rock was manganoan or ferroan, contains abundant pisolites or nodules of manganese oxide or limonite (Dorr and others, 1956, p. 302–305). Locally, as on the common border of the Gandarela and Gongo Sôco quadrangles, the concentration of manganese oxide pisolites may be commercially interesting.

Laterite and lateritic soil characteristically are porous and soak up water like a sponge. Deep cuts in some localities reveal that interconnecting channelways develop in the material, for, during hard rains, water spurts from small tubular openings as if from an open pipe.

CANGA

Canga is a rock type, originally described four Brazil but occurring in many of the tropical and semitropical parts of the world, that is a weathering product of iron-rich rocks such as itabirite or high-grade hematite ore. The rock is important from a physiographic viewpoint and also from an economic viewpoint, as it has been used as an ore of iron.

Canga has been defined (Dorr, 1964, p. 1219) as a lithified surficial or near-surface rock formed of widely varying quantities of detrital fragments, commonly high-grade hematite or iron-formation, cemented by limonite into a blanketing body. This is essentially the same meaning given to the term by Derby (1910, p. 818, 820–821) and by Harder and Chamberlin (1915,

p. 392). Gorceix (1884, p. 80–83) defined the rock as a ferruginous conglomerate cemented with an argillaceous and ferruginous cement. Gorceix defined the rock as it appeared in a deposit now known to be a ferruginous bauxite (I. S. Coelho, oral commun., 1964); clay or aluminous material is not ordinarily a major constituent of most canga in the Quadrilátero Ferrífero. The term "ferruginous conglomerate" is, strictly speaking, correct, as the rock is composed of cemented coarse detrital material; it is, however, misleading in that conglomerate is commonly a cemented waterlaid gravel, whereas canga is quite different in appearance, mode of origin, and composition from waterlaid gravels. In the region much ferruginous conglomerate that is cemented with a ferruginous or argillaceous cement is not canga.

The detrital fragments in canga are derived from immediately adjacent or underlying rocks and were transported by slope wash or creep rather than by stream action. The itabirite, quartz, and phyllite fragments are angular to subrounded; those composed of high-grade hematite may be angular or may be rounded by weathering (Dorr and Barbosa, 1963, p. C76). They vary in size from 1 mm to more than a meter but in most places range between 1 and 10 cm.

Fragments of hematite in the rock are hard and unhydrated, but itabirite fragments are more commonly thoroughly hydrated with the quartz leached completely or in part, being partially replaced by limonite. Phyllite fragments are not common except over or near phyllitic rocks and are replaced to greater or lesser degree by limonite. Vein-quartz fragments are angular, but most of them break down into smaller pieces with a light blow; leaching along crystal interfaces has weakened them.

The cement in canga is generically called limonite. It is composed of several varieties of hydrous iron oxide, very locally with significant admixture of hematite or of AlO(OH), which may be in the crystal lattice of goethite (Correns, 1952). The cementing limonite ranges from yellow through tan, reddish tan, and brown to nearly black, depending on the minerals, the amount of clay or alumina, the degree of crystallization of goethite, and the porosity. The porosity ranges from very low in certain types of canga to perhaps as much as 50 percent in other types. Permeability is low except in one type. The amount of cementing limonite in the rock may range from perhaps 5 percent in certain types to more than 95 percent in others.

Canga forms large blanketing sheets on high and intermediate surfaces; some sheets are measured in tens of square kilometers. As discussed on page A11, these surfaces defy erosion because the canga is inert to chemical weathering and tough and resistant to mechanical weathering. Canga is effectively attacked by mechanical erosion only by undercutting of the edges of the sheets, where removal of the deeply weathered and soft underlying rocks is easy (fig. 2). Data on the thickness of the canga sheets are scanty. Scarps on the edges of the sheets, and subsurface exploration show that the maximum thickness is more than 30 m; in many places it is between 1 and 5 m and is commonly more than 50 cm.

The surface of the canga-capped plateaus underlain by the Cauê Itabirite and of the canga-covered slopes is bare in part; in part it is covered with a layer of iron-rich, generally highly porous soil containing coarse ferruginous detritus a few centimeters to a few tens of centimeters thick. In few places has canga been found under any great thickness of soil, although it has been found under laterite, mudstone, and lake beds(?) at depths up to 100 m. The vegetation on canga is xerophytic and orchids, cacti, and widely spaced low stunted bushes and gnarled trees are typical.

Canga is most common above the Cauê Itabirite and the Gandarela Formation and laps out over adjacent formations. No large bodies of canga and only a few small ones are known over the iron-formations of the Nova Lima Group, although boulder trains of canga-like material are not uncommon over those rocks. Probably the pre-Minas iron-formations are too thin to give the proper physiographic setting for the development of canga; these rocks crop out as rather narrow ridges rather than flat-topped plateaus. It is also quite possible that the fact that the pre-Minas iron-formations are carbonate facies rather than oxide facies has inhibited the development of canga, for ferrous iron is much more soluble than ferric iron under near-surface conditions, and the iron may have been to a considerable extent dispersed from the site during weathering.

Canga has been subdivided into many types, but a gross division into three types is adequate for most purposes. These subdivisions are normal canga, chemical canga, and canga rica.

Normal canga contains between perhaps 20 and 80 percent detrital fragments of hematite or itabirite, locally with a little phyllite and quartz. It forms primarily on the old erosion surfaces and on slopes up to 20° on Cauê Itabirite but may be found on other rocks, even granite, where topographic conditions favor supply of the proper detritus and dissolved iron to cement the detritus. Normal canga contains between 64 and about 50 percent iron depending on the degree of hydration and the amount of quartz. Al_2O_3 is rarely as much as 6 percent; commonly it is less than half that amount. Figure 22 illustrates rather rich normal canga.

FIGURE 22.—Broken fragments of rich normal canga, about 62 percent iron, lying on a typical canga surface. Note botryoidal forms and concentric growths. Lagoa Seca, near N. 3,800, E. 6,100, Belo Horizonte quadrangle.

FIGURE 23.—Canga rica, at the Aguas Claras deposit, near N. 5,500, E. 10,200, Belo Horizonte quadrangle. The material here will average over 67 percent iron. The blocks and fragments of hard hematite are firmly cemented by limonite.

"Chemical canga" is the name applied to canga very low in detrital material and high in limonite. It is most abundant on the gentle slopes in the valleys and swales on the Gandarela Formation several hundred meters or more away from the Cauê Itabirite, although it too may form on any rock if the topographic position cuts off coarse iron-rich detritus and supplies solutions rich in iron to an environment where it may be precipitated at or near the surface. This variety is generally light brown to tan, contains 6 to more than 10 percent alumina, rarely more than 55 percent and in many examples less than 50 percent iron, and is dense and brittle with very low porosity and permeability. The detrital fraction is commonly about 5–10 percent of the rock, and it is angular and relatively fine, with fragments commonly smaller than 1 cm. Beds are usually thin and covered with soil; the rock type forms extensive surface crusts in few places. This type of canga is similar in aspect to ironstone concretions, although no iron carbonate is known from such bodies.

Canga rica (rich canga) is hematite rubble ore cemented by limonite. The cement may fill all the interstices between the hematite pebbles and cobbles or only enough may be present to hold the pebbles and cobbles together, with most of the interspaces empty. The iron content is commonly about 64 percent, in many cases more than 66 percent. Quartz and alumina are very low, commonly less than 2 percent. The hematite fragments may be angular or rounded and range from small pebble to boulder size. Figure 23 illustrates a typical outcrop of canga rica.

Various hypotheses of the genesis of canga have been advanced and were discussed at some length in a recent publication (Dorr, 1964, p. 1219–1223, 1232–1236). Clearly the detrital part of the rock is derived in large part from the Cauê Itabirite and the hematite lenses therein included. It is believed that iron in the cementing limonite was dissolved from the formation during the weathering process, transported in the ferrous state, and redeposited at or near the surface, where the transporting waters became oxygenated and changed the soluble ferrous iron to insoluble ferric iron. Some iron is probably carried as a colloid and some as ferric iron; both would be deposited by evaporation of ground water near the surface during the dry season.

ALLUVIUM

The fact that the region is now being actively eroded and that most of the streams are well above base level, combined with the fact that weathering in this region breaks most of the rocks down to clay and silt-sized particles, which are easily removed during the heavy freshets of the rainy season, make major accumulations of alluvium rather uncommon in the Quadrilátero Ferrífero. The few places where such alluvium does occur are just above canyons where major streams cut through resistant rocks, as near Honoré Bicalho and Sabará on the Rio das Velhas; where stream gradients abruptly flatten, as on the Rio Conceição southwest of Barra Feliz; and where mining activity or rapid erosion of soft itabirite has dumped large amounts of sand and gravel into a stream too small or with too low a gradient to carry it all away, as between Catas Altas and Agua Quente and below Itabira.

In the smaller streams narrow zones of discontinuous alluvium are found. East of the Moeda Plateau and

Congonhas do Campo, many of these were worked for gold during the 18th century, and both these deposits and some larger ones are marked by irregular heaps of coarse gravel and unnatural drainage patterns, attesting to the thoroughness of the old placering operations.

In few places is there enough sand and gravel to supply more than local needs for these commodities; crushed rock is commonly used for concrete aggregate in place of gravel, and sand is dredged out of the rivers themselves and trucked for considerable distances to supply the building industry of Belo Horizonte and other cities.

Where soft itabirite has been rapidly eroded or extracted on a large scale during mining operations, as just south of Catas Altas and below the Grota de Esmeril in the Itabira district, the alluvium contains high percentages of hematite in sand sizes and as gravel. Locally, this material has been so sorted by the streams that a banded unconsolidated rock composed of hematite and quartz is formed; it is very similar in appearance to some of the ferruginous quartzite of the Cercadinho Formation or the conglomeratic "iron-formation" in the Itacolomi Series near Fabrica in the Congonhas district, which are believed to have formed in an essentially similar manner. Large quantities of hematite are contained in such alluvium and some day may well prove to be of economic importance. Dredging operations for gold below Mariana on the Rio Carmo, during the decade of the 1950's, recovered significant quantities of very high grade magnetite which could not be sold because of the cost of transportation from that locality.

TALUS AND COLLUVIUM

Erosion of the high itabirite ridges and hematite deposits has given rise to major accumulations of talus and colluvium. Because during the weathering of itabirite most of the quartz is removed, these accumulations are of economic interest and have provided millions of tons of high-grade and medium-high-grade iron ore for export and for domestic use. Such deposits are found on the flanks of ridges; mining has shown some of the colluvial accumulations to be as much as 30 m thick. They tend to accumulate most extensively in old valleys and indentations in the ridge side, and most are not continuous for more than a few hundred meters, although some are much longer.

Of the other rocks in the region, only quartzite supplies much talus, and this tends to consist of large isolated blocks which break down to sand size on weathering. Accumulations of sand derived from serrate quartzite outcrops in the Serra do Itabirito, a type of colluvium, are locally very pure and have been used for foundry sand. Tle purity is such that much qualifies as glass sand (Walace, 1965, p. 46).

LANDSLIDES

The breakdown through deep weathering of much of the micaceous and feldspathic rock to clay, coupled with the deforestation of the region since the Europeans moved ino the area—much of it in the 19th and 20th centuries—and the practice of construction of long canals to bring water to the site of gold washings during the 18th and 19th centuries, plus severe overgrazing by domestic animals all have combined to cause many landslides in the region. Most are small, a few hectares or less in extent, but some are larger. The soft phyllites of the Minas Series, and particularly the phyllitic phase of the Cercadinho Formation, are preferred sites for such slides. The construction and maintenance of highways has been seriously hindered by landslides caused by location of the roadbed without regard to the inherently unstable condition of the subsoil in certain formations and under certain topographic situations.

IGNEOUS AND GRANITIC ROCKS

The igneous and granitic rocks of the Quadrilátero Ferrífero consist of large masses of granitic rocks and smaller bodies of gabbro and metagabbro, diabase dikes, hypabyssal porphyritic dikes, and many small bodies of chlorite schist, talc schist, soapstone, and serpentinite that are alteration products of igneous rocks. Metatuffs in the Rio das Velhas and Minas Series were considered as sedimentary rocks because it is believed that they were waterlaid and mixed with varying quantities of normal clastic sediments in a eugeosynclinal environment.

Because Norman Herz has prepared a separate chapter of this professional paper on the geology, petrography, and petrology of the igneous and granitic rocks of the region, these rocks are not discussed in any detail in this chapter. This report presents only those generalizations needed to understand the stratigraphic and structural development of the region; detailed evidence and information will be found in the chapter by Herz.

GRANITIC ROCKS

The generalized geologic map of the region, plate 1, illustrates the distribution of the granitic rocks within the area under discussion, but to fully understand the granitic rocks within the region and their relation to the overall geologic setting, a short description of a wider setting is essential. To the east and southeast of the mapped area, granitic rocks and gneisses are continuous to the Atlantic Ocean, with a few small islands of recognizable metasedimentary rocks, generally at a very high grade of metamorphism. Although these rocks have not been studied in any detail, it is certain that they comprise both ultrametamorphosed sedimentary and intrusive rocks. A long belt of charnockites is known from São Paulo through southern Minas Gerais to Espirito Santo, and it probably continues to the north into Bahia. It is believed that the area between the Quadrilátero Ferrífero and the sea was the focus of at least one post-Minas orogeny.

To the north, the granitic rocks shown on plate 1 continue for some tens of kilometers in most places, before being overlain disconformably by the São Francisco Series. The São Francisco Series is shown on most maps as Silurian, but many Brazilian geologists now believe that the rocks are at least in part late Precambrian. Although the granitic rocks adjacent to the Minas Series north of the Serra do Curral are everywhere younger than the Minas Series, a few kilometers farther to the north older granites are present in the central and western parts of the region. North of the eastern part of the Quadrilátero Ferrífero, the rocks and structure are most complex; younger gabbroic rocks are widespread, and the Serra do Cipo, made up of quartzites at least in large part correlative to the Cambotas Quartzite, forms a broad north-trending arch for several hundred kilometers, the east flank of which is apparently overlain by higher rocks in the Minas Series intruded by post-Minas granite.

To the west, granitic rocks and rocks believed to be equivalent to the Rio das Velhas Series are known for tens of kilometers. The granitic rocks are believed to be in large part pre-Minas, although post-Minas granites almost certainly occur, as attested by some metasedimentary units included in them which, on stratigraphic grounds, seem best related to the Minas Series.

To the south, a complex mixture of Rio das Velhas Series metasedimentary rocks and post-Rio das Velhas granitic rocks extends for at least tens of kilometers. Although part of this area has been studied in reconnaissance, more detailed studies and much age work will be needed before it is fully understood. Minas Series rocks end a short distance southwest of the mapped area but probably reappear farther to the southwest. The Serra do Tiradentes in São João del Rei, 100 km to the southwest, is composed of quartzite lithologically similar to the Cambotas Quartzite, and the unconformably underlying metasedimentary rocks are lithologically very similar to the Nova Lima Group. Granitic rocks there are younger than the eugeosynclinal sediments, and it is most probable that granitic rocks of several ages exist.

The granitic rocks within the Quadrilátero Ferrífero form a complex suite ranging in composition from granite through mafic granodiorite. Most are foliated to greater or lesser degree, being properly called granitic gneisses. The largest bodies of nonfoliated granite, the Borrachudos and Petí granites, are characterized by strong linear structure caused by alinement of biotite blebs. Some of the granitic gneisses are clearly orthogneiss, others are clearly paragneiss (fig. 24), and many are of uncertain origin. Unquestionably there has been much remobilization and anatexis (Guimarães, 1961). The task of unraveling the relations between all these rocks is much complicated by the prevailing deep weathering of granitic rocks, for it is difficult to solve petrologic problems from saprolite.

Radiogenic age determinations on rocks in and near the Quadrilátero Ferrífero have shown that there were two major epochs of granite formation or emplacement: one about 2,700 million years ago, the other about 1,350 million years ago (Herz, written commun., 1965). An event resulting in widespread ages of biotite of about 500 million years, in rocks the feldspar of which is much older, also occurred; with the exception of a pegmatite in the extreme northeastern part of the region, no granitic rock of that age is yet known within the Quadrilátero Ferrífero. Radiogenic ages of minerals in granitic rocks which fall between the cited ages are known but are presently interpreted as recording modification of the minerals by later events rather than as representing true rock ages. Much more detailed mapping of the granitic rocks and many more radiogenic age determinations will be needed before the absolute ages of all these rocks can be determined with confidence.

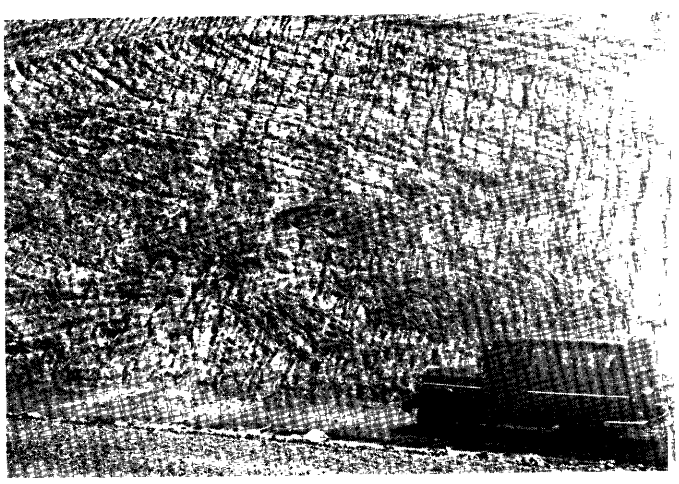

FIGURE 24.—Paragneiss forming from schist. About 20 km southwest of Itabira on the new road from Belo Horizonte to Itabira. The light material is faintly foliated granitic gneiss; the dark is biotite (?) schist. Concordance of foliation from one block of schist to another is apparent. This material is saprolite; vertical lines are the result of rill erosion in the bank and show the greater resistance of schist and phyllite to mechanical erosion.

From the stratigraphic and structural viewpoint of this paper, the most important results of the age work are that field evidence for two or more orogenic events is strongly fortified and that there is definite evidence that granitic masses of considerable size existed before the orogeny which deformed the Minas Series. Such masses inevitably affected tectonic style and oriented strain during that orogeny. Such confirmation of the field evidence is most welcome because the older granitic masses have in places been remobilized at their contacts with younger rocks and elsewhere younger granitic rocks have been emplaced along their borders, as at the south edge of the Bação complex and just north of the Serra do Curral. (See fig. 25.) It is most difficult, if not impossible, to prove on direct field evidence that any granitic rock in the region is older than the Minas Series, although there is much indirect evidence for the existence of the older granite.

Herz showed that the known distribution of the older granitic rocks is not uniform in the region; such masses occur in the Bação complex, in the Bonfim dome to the west of the Serra do Moeda, and to the north of the Serra do Curral, north of a younger granite which has metamorphosed the Minas Series. It is believed, but not certain, that the granitic rocks intruded into and formed from the Nova Lima Group along the south edge of the Quadrilátero Ferrífero also belong at least in large part to the older group, although thin stringers of granitic material are found in the quartzite of the Serra do Ouro Branco at one place.

FIGURE 25.—Granite intrusive into Piracicaba Group schist north of Serra do Curral near N. 7,000, E. 4,300, Serra da Piedade quadrangle. Note alteration of schist at contact. The saprolite surface shown is nearly horizontal. Scale is given by a low bush in the granite and the hammer handle in rill in granite, center.

Pre-Minas granite is not known in the eastern part of the region. It may have once existed there and been remobilized completely, as that area is one of high metamorphic grade relative to the rest of the region, and the focus of the post-Itacolomi orogeny was to the east and southeast of the region. The writer believes, on the basis of the tectonic style of the post-Itacolomi orogeny in that area, that any preexisting granitic rocks there were deeply buried beneath the Rio das Velhas sedimentary rocks, which were in large part altered in that orogeny to the post-Itacolomi granitic rocks now exposed.

There is no reason to believe that the older granitic rocks exposed in and immediately adjacent to the region contributed sediments to the formation of the Minas Series rocks. With the exception of some granite boulders in tilloid of the Sabará Formation near Mariana and in the western Serra do Curral, no granitic pebbles or cobbles are known in the Minas Series, not even in the basal rocks immediately overlying granite in the Serra do Moeda. Except for the Sabará Formation, most Minas Series sediments are well differentiated. It therefore seems probable that the abundant quartzite in the Minas Series was derived from the granitic rocks now exposed well to the west and southwest of the region and was transported some distance to the site of sedimentation. Only one granitic pebble has been reported from the Itacolomi Series conglomerates, and it is thought by this writer that the quartzose material in that unit was also transported some distance to the site of sedimentation.

ULTRAMAFIC ROCKS

Throughout the Quadrilátero Ferrífero, many bodies of ultramafic rock are now altered to serpentinite, soapstone, and talc-chlorite schist. The most common rock is soapstone, locally steatite; serpentinite is much less common. At contacts, the material is sheared to talc schist and smaller bodies are entirely sheared to talc schist (Guild, 1957; Gair, 1962; Dorr and Barbosa, 1963; and Pomerene, 1964). All workers since O. Barbosa (1949) agree that the soapstone was derived from the alteration of dunite and periodotite. Serpentinite is commonly farther from contacts with granitic rock, and steatite is closer to such rock; thus, the steatization may well be related to the granitic intrusion (Dorr and Barbosa, 1963, p. 48). Petrographic features of these rocks were described by Herz (written commun., 1966). In this report, certain problems concerning age and stratigraphic relations are discussed.

DISTRIBUTION

The altered ultramafic rocks are found in greatest abundance and in largest masses in the Congonhas area, in the Itabira district, and astride the boundary between the Rio Acima and Macacos quadrangles. Similar but more tabular bodies were mapped near Caeté. East of the Serra do Caraça in the Catas Altas quadrangle, serpentinite and steatitic rock occur; they are mapped together on plate 1 with greenstone schist because during mapping the poor exposures prevented separation of these rock types. In this zone, serpentinite and steatitic rocks are more common between Agua Quente and Catas Altas. South of Ouro Prêto in the Santa Rita de Ouro Prêto and the Ouro Prêto quadrangles, small bodies of such rock are also found but were not mapped. Unmapped talc schist occurs in the granitic rock south of the village of Suzana in the Marinho da Serra quadrangle, west of the Serra da Moeda. North of the Serra da Piedade, small bodies of altered ultramafic rocks containing asbestos are entirely surrounded by post-Minas granite.

AGE

Two ages of ultramafic rock seem to be indicated by the occurrences in the Quadrilátero Ferrífero. With three known exceptions, all the bodies are in the Nova Lima Group of the Rio das Velhas Series or in granitic rocks derived from those rocks. In only one locality, that astride the Rio Acima–Nova Lima quadrangle boundary, is the Minas Series in apparent sedimentary contact with such rock; elsewhere direct evidence is not available. Since 1954 (O. Barbosa, 1954, p. 21), most geologists have agreed that these ultramafic bodies are pre-Minas in age, for ultramafic intrusive rocks are expectable in the eugeosynclinal sediments of the Nova Lima Group and there is no indication that most of the bodies are post-Minas.

Altered ultramafic rocks which the writer believes to be of a different age are known in three places. Two of these—one in the Itabira District, the other in the Tamanduá iron-ore deposit in the Macacos quadrangle—consist of talc and talc-chlorite schist. These are postore dikes and sills containing fragments of iron ore and are foliated parallel to the foliation in the wallrocks (Dorr, 1965, p. 31; Dorr and Barbosa, 1963, p. C45, C70, and fig. 34; fig. 13, this report). Given the present composition of these dikes, it seems reasonable to suppose that they were originally ultramafic in composition. The rocks are post-Minas in age and were emplaced before the end of the latest metamorphism and after the high-grade hematite ore was formed.

The third and most complex occurrence is the long septum of rock mapped as greenschist shown on plate 1 in the Florália, Santa Bárbara, and Catas Altas quadrangles. This body is about 30 km in mapped length and for most of its outcrop it is less than 700 m wide, although the maximum outcrop width is about 2,500 m. The rock consists for most of its outcrop of chlorite-antigorite-talc schist, but at the south end, particularly between Agua Quente and Catas Altas, it contains intergrading large bodies of serpentinite and steatitic rock apparently identical in aspect with that in many of the bodies believed to be pre-Minas in age. Near Quebra Ossos, the schistose phase contains abundant discrete euhedral crystals of magnetite as much as 2.5 cm on a side and euhedral limonite pseudomorphs after pyrite as much as 6 cm on a side (Maxwell, written commun., 1964).

This complex body lies on the contact between post-Minas granitic gneiss and the Rio das Velhas Series for much of its length, but at the south end it cuts the Minas Series and is in contact with the Tamanduá, Caraça, and Itabira Groups. Locally it may contain mappable slivers of itabirite believed to be derived from the Cauê Itabirite. Thus, this rock too is post-Minas. It has been cut by post-Minas faults, unlike the dikes referred to above which occupy post-Minas faults. This is the rock referred to by Harder and Chamberlin (1915, p. 356–357), who, not having mapped it in detail, considered it to be a metamorphosed lava flow that occurred during sedimentation of the principal Minas Series iron-formation and therefore attributed some of the iron in that iron-formation to a volcanic origin.

GABBROIC ROCKS AND DIABASE

Gabbro, amphibolite gneiss considered to be metagabbro, and diabase probably were intruded at two or more epochs. The oldest is amphibolite or amphibolite gneiss, some so closely associated spatially with soapstone in the Itabira district that Dorr and Barbosa (1963) considered that the original rock might be comagmatic with the dunite there that was thought to be the parent rock for the soapstone and serpentinite. Other considerable masses of such rock, not associated with the soapstones, occur in the granitic gneiss in that district and are locally in lit-par-lit relation to Nova Lima Group schists. In the Monlevade quadrangle, Reeves mapped a long thin body of similar rock in the Monlevade Gneiss that he considered to be a metamorphosed mafic flow or dike (1966, p. E13). Comparable rock is not uncommon elsewhere in the Quadrilátero Ferrífero in granitic gneiss or the Nova Lima Group.

The material is similar in appearance and mineralogic makeup to amphibolite in the higher metamorphic facies of the Minas Series in the Monlevade district, where it may represent metamorphosed impure dolomitic (Reeves, 1966). This problem was considered by Herz (written commun., 1966) and will be discussed in his forthcoming chapter of this professional-paper series.

Unfoliated gabbro, rock intermediate in texture between gabbro and diabase, and diabase are found throughout the region as bodies ranging from a few meters to one mass nearly 2 km wide and 6 km long. Even larger bodies of gabbro are known to exist north of the area mapped. Their shape tends to be tabular, and they are controlled in many places by faults, joints, and bedding. Most are dikes or sills, many are irregular in outline, and several are small plugs. Most thick bodies exhibit chilled walls, some flow structure along walls, and cores of unoriented more coarsely crystalline rock. These features may be seen a few kilometers west of São Gonçalo on the Monlevade–Belo Horizonte highway and in the Itabira district at the east end of the Borrachudos water tunnel. Thin dikes have diabasic texture.

In the Serra do Caraça an intricate system of dikes occupies thrust and normal faults. Fresh dike rock has never been seen, and its petrographic nature is unknown. Moore (1969) stated that the rock is mafic, shows thin chilled zones, and is generally unsheared, except in some fault zones. Maxwell (written commun., 1962) stated that the rock has ophitic texture. Such dikes are probably related to the less weathered diabasic and gabbroic rocks to the north in the Serra das Cambotas, the Itabira district, and elsewhere in the region.

The dike swarm in the Serra do Caraça is largely confined to the Cambotas Quartzite but also cuts the Maquiné Quartzite and the Nova Lima Group. Probably this distribution is related to the brittleness of the host rocks, for orthoquartzite of the Cambotas contains the most dikes, protoquartzite and subgraywacke of the Maquiné fewer, and the argillaceous rock of the Nova Lima Group least. Similar dikes cut the Minas Series elsewhere in the region and probably the Itacolomí Series south of Ouro Prêto. Such mafic rock thus is one of the youngest of the region, a fact also indicated by the unfoliated nature of dikes and their characteristic chilled walls, indicating that at the time of intrusion the wallrocks were cool.

PORPHYRY DIKES

Herz (written commun., 1964) described under the name porphyry dikes, intrusive rocks which have been variously described by other geologists on the DNPM–USGS team. These rocks are commonly weathered, and their relations and extent are obscure. They are known in the Catas Altas, Ibirité, Belo Horizonte, and Fêcho do Funil quadrangles. Johnson (1962, p. B24) and Herz mentioned their presence south of the Ouro Branco quadrangle.

Simmons (1968a) described the occurrence in the Fêcho do Funil quadrangle (N. 2,200, E. 2,550) as a weathered mafic dike, which he related to the diabasic intrusions discussed above. This rock is characterized by large (20 mm) oriented feldspar phenocrysts, now all altered to clay, in a fine-grained brown weathered groundmass. The rock cuts the Piracicaba Group of the Minas Series. Fresh rock of very similar aspect was found by Pomerene (1964) near the Fazenda Rosario, Ibirité quadrangle; Pomerene also related this rock to the diabase dikes. It is here in the staurolite zone of the Sabará Formation. In the same quadrangle, where the road to Fazenda Jangada crosses the Serra do Curral, weathered rock with relations and aspect similar to those of the weathered rock in the Fêcho do Funil quadrangle is found in the Gandarela Formation. In the Catas Altas quadrangle, Maxwell mapped a small body of similar rock intrusive into the Cambotas Quartzite at N. 7,650, E. 2,550.

PEGMATITE DIKES

Although Minas Gerais is famous for the wide variety of minerals occurring in commercial quantity in pegmatite dikes, the area under discussion is notably poor in such minerals, and only in the Monlevade area has production of valuable pegmatite minerals been possible. These deposits are in gneiss thought to have been derived from the Piracicaba Group of the Minas Series; Aldrich, and others (1964, p. 329) dated feldspar from one of them as 545 million years old by the rubidium-strontium method. The main area of commercially valuable pegmatites begins a few kilometers to the east and southeast. Probably these and the pegmatite in the Monlevade area are of different magmatic affiliation and age than those to be described below.

Elsewhere in the region most pegmatite dikes are thin—a few centimeters to a meter or, very rarely, more than a meter in width—discontinuous, and are confined to granitic gneiss and stratified rock adjacent to or fairly close to the contact with granitic rock. A few exceptions are known: Guild (1957, p. 57) found a small pegmatite body in the Cauê Itabirite in the Casa da Pedra area some 3 km from the nearest outcropping granite. Dorr and Barbosa (1963, p. 46) mapped pegmatite bodies perhaps 800 m from the nearest known granite in the Itabira district.

Within granitic rock, pegmatite dikes and pegmatoid bodies are much more common, although also generally small. In the Rio de Pedras quadrangle, much black tourmaline and tourmalinite is found in the Bação complex near the Rio de Pedras reservoir. Poor exposures conceal the exact mode of occurrence of the mineral, which is found as float on the surface of the saprolite and soil. Nearby, on the road to Fazenda Ajuda, a pegmatite dike perhaps 10 m thick contains coarse mica.

In granitic gneiss, several generations of pegmatite dikes are seen in quarry faces. Some occupy ptygmatic folds, others have indefinite walls and grade into the surrounding granitic rock, and still others are straight, cut the other pegmatites, and have sharp walls. All are unfoliated and many have quartz cores.

The Borrachudos Granite has no pegmatite dikes associated with it, although this very coarse grained granite itself approaches a pegmatite in its texture and contains abundant fluorite.

QUARTZ VEINS

Throughout the Quadrilátero Ferrífero quartz veins abound. They include quartz associated with steatitic bodies, "cleavage" quartz, quartz veins that may to varying degree be regarded as metamorphic segregations, and gold-bearing hydrothermal quartz veins.

QUARTZ ASSOCIATED WITH STEATITIC BODIES

Steatite or soapstone is in many places associated with large masses of "bull quartz." Such masses can be seen in the Itabira district (Dorr and Barbosa, 1963, p. 47) and in the Congonhas district (Guild, 1957, p. 29). The same relation occurs in a talc schist and soapstone body near Suzana, Marinho da Serra quadrangle, and elsewhere. Such large quartz masses have not been observed near serpentinite, nor are they found with all steatite bodies. The largest masses are found in the Itabira district, where they are as long as 100 m and 20 or more meters wide on the outcrop. Quartz there seems very pure and contains no silicates, carbonates, or sulfides; the material may be of economic interest.

In the Itabira district these quartz bodies are believed to have been emplaced during the formation of talc from serpentine derived from the original ultramafic rock (Dorr and Barbosa, 1963, p. 47–48). The regional absence of quartz around the serpentine bodies lends credence to the idea. The steatitization is thought to have been effected by hydrothermal solutions rich in CO_2, also accounting for the local presence of much carbonate—magnesite (Itabira) or ankerite (Congonhas)—in the steatitic rocks. Because the steatitic bodies are close to or in the granitic rocks and the serpentine bodies are further removed, it seems reasonable to suppose that the source of the fluids involved was the granitic rock.

CLEAVAGE AND FIBROUS QUARTZ

An unusual type of quartz is very common in the Quadrilátero Ferrífero and was given the field name of "cleavage" quartz. It is closely related to and intergradational with fibrous quartz.

"Cleavage" quartz was described by Guild (1957, p. 30), as follows:

> 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.

In many localities the "cleavage" surfaces, which are rhombohedral, are curved and look like large curved dolomite crystals. "Cleavage" surfaces may be several centimeters across. The material commonly has a silky sheen or luster and is semitransparent.

This type of quartz occurs in segregations and crosscutting short veinlike bodies most commonly associated with the Cauê Itabirite. In many places it is found in dolomitic itabirite, particularly where that rock is manganiferous, but it has not been seen in place in dolomite.

Fibrous quartz is most common in the same environment and is intergradational with "cleavage" quartz. This type of quartz grows from the walls of the enclosing rock toward the center of veins. It occurs as thin (1 mm or less) to thick (5 mm or more) fibers or columns, some separated by hydrous iron or manganese oxides, some only slightly stained by such material. The fibers or columns may be as long as 15 cm, although most are less. Maxwell (written commun., 1962) showed that the fibers were single crystals. In those examined by him, fine hairlike inclusions tentatively identified as rutile were found oriented obliquely to the quartz fibers. If the inclusions are rutile, the quartz is probably not supergene in origin as has been suggested.

QUARTZ AS METAMORPHIC SEGREGATIONS

Material in a vein or irregular mass is considered to be a metamorphic segregation if it was derived from the wallrock under metamorphic conditions with minor transportation. Much quartz in the metamorphic rock of the region must have been formed as segregations during the metamorphic epochs, as the bodies are formless pods or pockets, and their abundance is closely related to the abundance of quartz in the enclosing rock. Thus, in such formations as the Moeda Formation, the Cambotas Quartzite, or the Maquiné quartzose formations, quartz veins are very common indeed, whereas in such rocks as the Barreiro Formation and the more argillaceous parts of the Nova Lima Group, they are relatively rare. With exceptions, such bodies are not persistent along strike for many meters; more commonly they are podlike and seem to have no connection with throughgoing structures or veins, although in many places they are parallel to bedding or in shear zones or in minor fold axes.

A number of these quartz veins in the quartzite are vuggy and may contain water-clear euhedral quartz crystals of a size usable for their piezoelectric properties.

Also to be regarded as a type of metamorphic segregation are the quartz-kyanite veins so common in the Cercadinho Formation. Such veins are found in quartzose rocks also containing high percentages of aluminous material. Guild (1957, p. 29) was the first to suggest that the alumina of the kyanite had been derived from the wallrocks, a suggestion concurred with by all later workers in the area.

The quartz-kyanite veins are continuous for meters to hundreds of meters and ordinarily are concordant with the bedding of the host rock. They are normally composed of a quartz core, with kyanite growing in blue-gray or greenish-gray radiating crystals between the core and the walls, oriented in many cases normal to the walls. Such crystals may be as long as 15 cm; in some localities they are in part replaced by pyrophyllite. Locally kyanite may be in the quartz core, but this is not common. The largest and best exposures of such quartz-kyanite veins are to be seen in the Itabirito quadrangle near N. 5,000, E. 500, in excavations made in the Botica kyanite mine, from which 1,450 tons of kyanite was produced (Wallace, 1965). Herz and Dutra (1964) described the geochemistry of some kyanite occurrences and came to essentially the same conclusions as Guild with respect to the type here discussed.

Other vein deposits which might be considered essentially metamorphic segregations are the quartz-hematite veins in the Cauê Itabirite and the Cercadinho Formation. Such veins have been described by Maxwell (written commun., 1964) and Guild (1957, p. 29–30) and are also known to occur elsewhere. In some veins, many of which follow faults or fractures in itabirite, quartz forms a core, and hematite is hard, pure, fine grained, and unfoliated, identical with unfoliated high-grade hematite ore. Such hematite grades more or less abruptly into itabirite. In many localities both hematite and quartz contain, or are covered by, coarse specularite plates up to 2 cm across and by coarse talc. From visual inspection, the bulk composition of the veins approximates the bulk composition of the itabirite; that is, about half the material by weight is hematite and half is quartz. Such veins may be from 5 to 50 cm thick.

GOLD-BEARING HYDROTHERMAL QUARTZ VEINS

The Quadrilátero Ferrífero has produced in the order of 2,000 tons of gold since mining activity began in the early 18th century. Much of this was won from placers, more of it from hypothermal replacement deposits in the Nova Lima Group rocks, and much from supergene enriched deposits in the Cauê Itabirite and the hematite ores associated therewith (Dorr, 1965).

Gold-bearing quartz veins have been mined in many localities but generally speaking, do not seem to have been either rich, persistent, or very productive. No lode quartz mines are now in operation, and the surface manifestations are obscure and hard to find, owing to the generally deep weathering. Few throughgoing quartz veins occur in the region and still fewer contain the limonite-stained holes and casts of sulfide crystals that might be expected to be the surface manifestation of sulfide-bearing mineralized veins. Perhaps the most accessible occurrence of such material is in the Rio Acima quadrangle on the road from Rio Acima to Gandarela, near N. 3,400, E. 12,800, where a breccia zone in quartzite is mineralized with quartz, pyrite and arsenopyrite, and gold in low values.

The primary gold mineralization in the region is hypothermal where the environment can be deciphered (Gair, 1962; Dorr, 1965). In the Santána mine near Mariana (pl. 10), a system of short gash veins is found in the Batatal Formation and both the schistose rock and the quartz veins are mineralized with arsenopyrite and some gold. Probably most of the gold occurrences in quartz veins in the region were generally similar to this occurrence—short, nonpersistent, low grade, and hypothermal in environment. Reconcentration by weathering and in stream gravels probably accounts for the originally rich placer and elluvial deposits.

The major lode-gold deposits of the area are replacement deposits rather than gold-bearing quartz veins.

REGIONAL STRUCTURE

The Quadrilátero Ferrífero is an island of metamorphosed strata in a sea of granitic rocks. It is a region in which only the roots of great structures remain. A large but unknown thickness of younger strata once overlying the region has been removed, for the youngest remaining sedimentary rocks do not significantly differ in metamorphic grade from the oldest. During major deformation, the rocks flowed plastically, as shown by their internal structures and by the abrupt thinning and thickening of formations which must originally have been relatively constant in thickness.

Three major periods of deformation occurred in the region. The first two, one between the Rio das Velhas and Minas Series and the other between the Minas and the Itacolomi Series, are obscure, and it is not possible to affirm either their degree or their extent. The last and the strongest involved all Precambrian sedimentary rocks; it is post-Itacolomi in age.

Epeirogeny and warping occurred within the named sedimentary cycles but cannot be proved to represent major deformation or erosion within this area, although undoubtedly significant orogeny and erosion occurred in these intervals in the borderlands outside this region, as attested by the sedimentary rocks themselves. Epeirogeny also affected the region in post-Cambrian time and major Tertiary uplift resulted in the present mountainous topography.

At the beginning of the major post-Itacolomi orogeny, pelitic and chemical sedimentary rocks were fine grained and relatively weak, for they failed by folding and plastic flow. During the progress of this main orogenic period, all those rocks recrystallized and grew in grain size, micaceous minerals formed from clays, cherty iron-formation became itabirite, sandstones recrystallized into quartzites, siltstones became resistant quartzose phyllites and schists, and the relative competency of the individual formations changed with time throughout the whole orogenic process. Because of the changing nature of the rocks and secular variation in confining and shearing stress, zones of easy failure became rigid, buttresses formed, and, in the latter stages of the orogeny, rocks fractured instead of folding and yielding by plastic flow. Granitic rocks were emplaced and were formed from preexisting sedimentary rocks, substituting large masses having isotropic structural characteristics for somewhat anisotropic bodies.

This region is but a small fraction of the whole orogenic belt and is on the northwest margin of that belt. Intensity of deformation and metamorphism diminishes from southeast to northwest; therefore different parts of the region have different structural patterns and different tectonic styles. Reports prepared by members of the DNPM–USGS team detail the structural development of specific quadrangles; in this report major structures are described and their interrelations discussed on a regional basis.

PRE-MINAS STRUCTURE

The only reference plane by which the nature and extent of the pre-Minas deformation can be definitely measured is the base of the Minas Series, which was very probably a nearly plane erosion surface with a slight inclination to the east and without major relief at the time Minas sedimentation began. That reference plane has been deformed at least twice since the beginning of Minas sedimentation. These deformations, one of which was very severe, obscured and complicated earlier deformation and rendered interpretation of pre-Minas events most hazardous. The nature of the pre-Minas sediments, eugeosynclinal and molasse suites without throughgoing marker horizons which can be correlated throughout the region, further complicates the evaluation of early structural events.

The Rio das Velhas rocks were folded before Minas sediments were deposited, for the younger rocks rest with locally profound angular unconformity upon the older. Regional evidence also shows that the pre-Minas deformation was stronger in the west than in the east.

Near the west end of the Serra do Curral, Simmons (1968a) mapped local iron-formations in the Nova Lima Group in strong angular unconformity with the Minas Series. Although these iron-formations are now nearly flat lying and arched, the overlying Minas Series has been rotated through about 120° in later deformations; therefore, at the time of Minas sedimentation the pre-Minas iron-formations must have been steeply dipping and strongly folded. South of the Serra do Curral in the Belo Horizonte quadrangle, the angular discordance between local iron-formations in the Nova Lima Group and the overturned Minas Series proves strong pre-Minas deformation in that area. To the south, in the Serra do Moeda, the Minas Series is strongly discordant with quartzite lenses in granitic gneiss thought to have been derived from the Nova Lima Group (Marinho da Serra quadrangle). Along the Serra do Itabirito, folds hundreds of meters in amplitude with east-trending axes in the Nova Lima Group are truncated by the regular, generally north-northwest, trace of the basal Minas outcrops. A major quartzite lens in the Nova Lima Group in the Itabirito quadrangle is at right angles to the strike of the Minas Series (fig. 5). Thus, in the west-central and western parts of the region, strong pre-Minas folding must have occurred.

To the east, this pre-Minas folding became less intense. In the northwest end of the Gandarela quadrangle a 30° discordance in strike and dip between marker beds in the Nova Lima Group and the overlying Minas Series is apparent. Farther to the east, in the Santa Bárbara quadrangle, Simmons (1968b) found that the angular discrepancy between the Nova Lima Group and the Minas Series was about 20°. An angular discordance also exists in the Monlevade and Itabira districts in the extreme eastern and northeastern parts of the region. Gentle fold structures in the Nova Lima Group are suggested by outcrop patterns in the Caeté quadrangle and probably in the western part of the Gongo Sôco quadrangle (Moore, 1969), but farther to the east these disappear and a moderate tilting of the rocks below the reference plane is the only clearly pre-Minas structure. In the southeastern part of the region, post-Minas deformation was so complex that the degree and nature of the pre-Minas deformation cannot be deciphered.

Thus, the structural evidence suggests that the focus of the pre-Minas deformation was to the west or southwest. Also, pre-Minas granitic rock is known in the western and northwestern parts of the region and is suspected to the southwest. Stratigraphic evidence within the Minas Series indicates that the sediments making up those rocks came from the west or southwest. Therefore, it seems reasonable to conclude that the focus of the pre-Minas orogeny was to the west and southwest and that this orogeny resulted in the formation of a major orogen which influenced later geologic events and processes. The area making up the Quadrilátero Ferrífero must have been on the east side of this orogenic belt; the extent and trend of this belt are still undefined.

PRE-ITACOLOMI FAULTING

Faulting which occurred either in pre-Minas or pre-Itacolomi time has not been documented in the region, although several of the geologists of the DNPM–USGS team have stated their belief that such faults must exist and that some faults that were active in post-Itacolmi time may have been originally formed in pre-Minas time. This seems reasonable, but is not proved. Similarly, no post-Minas–pre-Itacolomi faulting has yet been proved, although it may have occurred. Elements for such proof are lacking because the Itacolomi Series is absent in most of the region.

POST-MINAS–PRE-ITACOLOMI DEFORMATION

The Minas Series was warped and uplifted in the interval between its sedimentation and Itacolomi sedimentation; within this region the Itacolomi Series rests on almost every formation of the Piracicaba Group, indicating not less than 1,000 m of pre-Itacolomi erosion, possibly much more in some localities. The angular unconformity is nowhere great; the maximum observed was 12°. In the Quadrilátero Ferrífero the interval thus represents mild diastrophism and warping rather than orogeny and may perhaps be best regarded as the first stirrings of the great paroxysm that followed Itacolomi time.

Warped cobbles of itabirite probably derived from Cauê Itabirite are found in Itacolomi conglomerates. Unless removed from the anticlinal areas within the region, these cobbles must have come from some area outside the Quadrilátero Ferrífero because the Cauê Itabirite is everywhere present within this region where expectable except in a small area south of the Bação complex. There, the presence of higher Minas formations indicates that the Cauê Itabirite is absent because of nondeposition not erosion. The source of the coarse detrital material was probably to the west and southwest, suggesting stronger tectonic activity in that direction during the interval between Minas and Itacolomi sedimentation.

POST-ITACOLOMI OROGENY

The major orogeny of the region occurred after deposition of the Itacolomi Series. However, the relatively systematic sequence of alined anticlines and synclines found in many younger orogens cannot be found in the Quadrilátero Ferrífero. Although many major structural features strike northeast, several strike northwest and two of the largest strike north and east, respectively. Most of the synclinal folds are overturned toward the west and northwest at least in part but they are separated by broad domal areas which acted as disruptive buttresses in the course of orogenesis. The structural pattern inherited from earlier deformation and the post-folding formation of granitic rock that literally engulfed preexisting strutures and stratigraphic sequences complicate the picture still more.

Complex fault patterns further obscure the analysis, particularly in the eastern and southeastern parts of the Quadrilátero Ferrífero, where thrusting occurred on a major scale. They, too, reflect rock transfer toward the west and northwest.

The description of the individual major structures rests upon this complex history and upon remaining and identifiable stratigraphic units. For practical purposes, these include of certain units in the Rio das Velhas Series and the Minas and Itacolomi Series. On plate 1, the major structures involving the two upper series are best outlined by the distribution of the Itabira Group.

Orogenic forces thus came from the east and southeast. In the southeastern and eastern parts of the region, both folding and fracturing deformed the rocks; in the central and western parts of the region, deformation was dominantly by folding except along the south boundary. Thrust faulting followed folding, and normal faulting followed thrust faulting. Granite was mapped as being thrust faulted only in the Mariana quadrangle; here, the thrust fault might be pregranite in age, as the rocks involved are thought to be granitized Nova Lima Group. The granitic rocks are cut by many normal faults.

Before the folding and faulting of this orogeny, the rocks now compressed into the Quadrilátero Ferrífero must have occupied hundreds of square kilometers to the east of their present location, for the total crustal shortening amounts to tens of kilometers in an east-west direction.

MAJOR FOLDS

The Quadrilátero Ferrífero is bounded on the east by the Santa Rita syncline, on the west by the Moeda syncline, and on the south by the Dom Bosco syncline. The first is grossly overturned and sliced by thrust faults; the second is overturned in part; and the third is generally upright but telescoped by many thrust faults. To the north, the region is limited for 100 km by the generally overturned north sides of the Rio das Velhas uplift and the Bonfim dome, forming the Serra do Curral. Farther to the east, it is limited to the north by the Serra do Tamanduá, the eastern extremity of the Gandarela syncline, which forms the east and southeast flank of the Rio das Velhas uplift. The Gandarela syncline is isoclinal and overturned at the east end but at the west end, near the center of the Quadrilátero Ferrífero, it is open and upright. The eastern outliers in the Itabira district and the Monlevade district are respectively composed of a complex syncline and a system of synclines and anticlines, both trending N. 45°–50° E.

The Rio das Velhas uplift is the master structure within the region, for most of the other major structures are peripheral to it at least in part. It occupies the south-central part of the Quadrilátero Ferrífero, trends north by west and then to the northeast and disappears in the sea of granitic rock to the northeast. The Caeté uplift of Bölau (1952) is the northeast extension of this feature. Another major anticlinal feature largely within the Quadrilátero Ferrífero is the Conceição-Caraça uplift, lying between the Gandarela syncline and the Santa Rita syncline.

Superimposed on all these major folds are many smaller folds and on those still smaller ones ranging down to crenulations. Some are parallel to major structures; others are cross folds.

SANTA RITA SYNCLINE

This syncline was described in detail by Maxwell (written commun., 1962), who discovered and mapped the northern two-thirds of the structure. Deciphering this structure was a notable feat of geologic mapping; a reasonable interpretation of the rock relations on the east flank of the Serra do Caraça had never before been advanced despite the fact that it has been the site of mining activity for 150 years.

The Santa Rita syncline is perhaps the most complex major fold in the region. The major north-south structure, the earliest to form, was itself later folded by northwest-trending open cross folds expressed on plate 1 by salients and reentrants in the contact between the Cambotas Quartzite and the younger rocks along the south side of the Serra do Caraça. The north end was greatly compressed against the Caraça quartzite mass and dismembered by thrust faulting. The cross folds are cut by a system of northwest-trending faults and by high-angle thrust or reverse faults, trending north-south.

The cross folding is best developed in the Santa Rita Durão and Capanema quadrangles but is also present in the Antônio Pereira and Mariana quadrangles to the south—there best shown, perhaps, in the convolutions of quartzites included in the Rio das Velhas Series and strata of the Minas Series on the east flank of the syncline. North-trending high-angle reverse faults slice the syncline into many parts, involving the youngest known beds of the Itacolomi Series as well as the Rio das Velhas sequence. Granites intruded the faults in many places and have formed from the pelitic rocks of the Rio das Velhas Series on the east flank; quartzites correlated by A. L. M. Barbosa and Maxwell with the Maquiné Group are relatively unaltered.

The major syncline is strongly overturned to the west in the Antônio Pereira and in the Santa Rita Durão quadrangles. The overturned east flank dips east from 25° to 45°, the west flank also dips east at similar angles. The structure is so disturbed by cross folds and thrust faults that it is impossible to locate its axial trace. To the north, on the east flank of the Serra do Caraça, the syncline is abruptly and radically compressed and is nearly vertical. There, its west limb is in part cut out by a steep reverse fault in the southern portion of the Catas Altas quadrangle. In the central and northern parts of this quadrangle, the west limb is missing. The east limb continues north in an ever narrowing sliver of quartzite and itabirite bounded on the west by post-Minas greenstone and on the east by post-Minas granitic rock in metasomatic contact with the Minas Series (Maxwell, written commun., 1962).

The cross folds deforming the Santa Rita syncline are larger than those found in other major synclines and one of them, the Conta Historia syncline, develops to the northwest into an important fold that underlies the Serra do Batatal and the Serra do Ouro Fino (Maxwell, written commun., 1962). The writer concurs with the suggestion by Maxwell that this fold once was continuous with part of the complex west end of the Gandarela syncline. Because both limbs of the Santa Rita syncline are cross folded, those structures probably formed after the major syncline had developed, possibly as a result of a change in direction of regional stresses, possibly as a result of new couples set up by the earlier deformation. The cross folds plunge to the southeast. It is clear from the outcrop pattern that cross folding preceded thrust faulting of the Minas and Itacolomi

Series. The northwest-trending faults may have developed during the cross folding and perhaps precede thrust faulting. The cross folds are the sites of important bodies of supergene iron and manganese ore in the Itabira Group, as described by Buchi (1961), Maxwell (written commun., 1962), and Dorr (1964).

The tight and dismembered north end of the Santa Rita syncline contrasts with the wider and nearly recumbent main body of the fold south of the Serra do Caraça. Evidently major westward and northwestward displacement of the rocks occurred in the central part of the syncline, and the massive monolithic body forming the Serra do Caraça formed a buttress against which the eastward-trending forces wrapped the Minas Series into a tight fold.

The structural evolution of the central part of the syncline may have been defined either by the original sedimentary limits of the Maquiné and Cambotas Quartzites or by erosion which may have removed much of these rocks south of the Serra do Caraça before the deposition of the Minas Series. The Cambotas does not occur south of the central part of the Capanema quadrangle except, questionably, in the Serra do Ouro Branco.

The southern part of the Santa Rita syncline was held to the east by the Mariana anticline. The writer believes that pre-Minas granitic rocks that form an unexposed part of the Bação complex underlie the fold at no great depth and formed a keystone around which the younger Minas Series rocks were forced and compressed during post-Itacolomi deformation. The contact between the Minas Series and the Rio das Velhas Series on the west limb of the Santa Rita syncline is a thrust fault in much of the axial zone of the Mariana anticline, with the Minas overriding to the northwest. In the east limb, however, Minas Series and Itacolomi Series rocks were overridden by the Rio das Velhas Series. The deformation was similar to, but less intense than, that on the east side of the Serra do Caraça, probably because the buttress is deeper in relation to the present surface.

DOM BOSCO SYNCLINE

The Dom Bosco syncline is the second most complicated major structure in the region. Its south side is enigmatic for most of its extent because it is sliced and torn by thrust and tear faults of unknown but probably considerable displacement. The axial plane cannot be accurately located, and its trace as shown on plate 1 may well be much in error.

The syncline lies south of the Rio das Velhas uplift, and extends eastward from its junction with the Moeda syncline in the Marinho da Serra quadrangle to the Mariana quadrangle, where it is obliterated by a major thrust fault that brings the Nova Lima Group over strata of the Itacolomi Series. The north limb is folded sharply around the Mariana anticline to continue northwest as the west limb of the Santa Rita syncline.

The syncline may be divided into two main parts: an eastern part characterized by a series of arcuate thrust and tear faults, and a western part in which tear faulting is more important. In the eastern segment successive thrust faults have pushed Rio das Velhas rocks over Itacolomi and Minas Series rocks, Minas Series rocks over Itacolomi Series rocks, Minas Series over Minas Series rocks, and Itacolomi Series over Rio das Velhas Series rocks in a great succession of imbricate thrust plates. Movement was from east to west.

Individual thrust plates preserve the synclinal structure, with the apparent fold axes in each individual plate somewhat offset, indicating that the thrust faults are younger than the folds. The north limb of the syncline is not involved in the thrust faulting except at the extreme east end. A high order of field mapping was demonstrated by A. L. M. Barbosa in unraveling this complex structure.

In the central and western parts, the structure of the Dom Bosco syncline changes from dominant thrust faults in west-moving slices to gradually increasing complexity of internal folds; the axes of the minor folds trend parallel to the axis of the major fold. Thrust faults are prominent in the southern part of the syncline. At its west end, the north limb of the syncline is a simple fold, although its south limb is complexly faulted (Johnson, 1962; Guild, 1957).

In the eastern, central, and western parts of the Dom Bosco structure the strata are generally upright. However, the western part of the fold is locally overturned toward the south.

The southern part of the Dom Bosco syncline in the Dom Bosco, São Julião, and Casa da Pedra quadrangles is most complex. It is a westward continuation of the zone of thrust faulting that sliced the east end of the structure. The relatively regular and even thrust faulting found to the east breaks up into a large number of individual thrust plates, seemingly bounded to the north and south by tear faults and by east-west high-angle faults with considerable vertical displacement. The area is one of greatly confused structure, which only becomes somewhat more simple west of São Julião. The large block of quartzite which forms the Serra do Ouro Branco may have caused finer fracturing of the thrust plates to the north of it as they slid westward past this monolith, which itself is strongly sheared in a general N. 70° W. direction.

In the Casa da Pedra–Fabrica area a series of imbricate thrust plates is piled up against the Serra da

Moeda, overriding the east side of the Moeda syncline and thus possibly originating in an expectable anticlinal fold at the junction of the Dom Bosco and Moeda synclines, a fold possibly destroyed by the faulting. Guild, who studied the area before adjacent areas had been mapped, was the first to demonstrate major thrusting in the Quadrilátero Ferrífero and made a fundamental contribution to the structural geology of the region. Three and possibly five thrust plates are here exposed (Guild, 1957, p. 35). Some are folded into wrinkles and subsidiary folds with orientations mainly in the eastern quadrants and plunging to the east and southeast. A remnant of Itacolomi rocks is preserved in one of these folds, and it is locally isoclinally folded and overturned.

The Dom Bosco syncline plunges gently east at the west end; the subsidiary folds are canoe shaped, as pointed out by Johnson (1962, p. B28).

Most of the south side of the east-west belt of metasedimentary rocks folded into the Dom Bosco syncline is bounded by the Engenho fault (Guild, 1957, p. 36), which is upthrown to the south. Johnson considered that a branch of the fault was the locus of the large mafic dike in the Serra do Ouro Branco. Farther to the east the fault separates granitic rocks to the south from the Itacolomi Series.

The structural evolution of the Dom Bosco syncline was possibly initiated by uplift of the Rio das Velhas block to the north and an unnamed large block to the south. Many subsidiary small east-west folds formed during that period of folding, as wrinkles on the major structure, but a major north-south shortening of the magnitude of the east-west compression shown in the Santa Rita syncline did not occur. Later, major west-directed stresses produced the imbricate thrust plates along the south limb of the fold and also its major tear faults.

The distribution of the thrust faulting along the south limb of the syncline suggests that the south block was the active one and itself had a westward component, as is also suggested by the westward bend at the south end of the Serra da Moeda (pl. 1). Very probably the presence of the large granitic mass of the Bação complex channeled the stresses and movement into a westerly direction instead of to the northwest as is common elsewhere in the region. Similarly, the imbrication of thrust plates against the south end of the Serra da Moeda indicates that a buttress existed there, as suggested by Guild, indicating the presence of a pre-Minas western granitic mass. The last event was the movement on the Engenho tear fault. This had an upward component in the south block and possibly a western component as well.

MOEDA SYNCLINE

The Moeda syncline borders the west edge of the Quadrilátero Ferrífero and is one of the larger structures in the region (pl. 1). The gross structure is simple, but many cross folds exist within the central area; this is best seen on the more detailed maps accompanying the report by Wallace (1965). Those maps illustrate well the greater power of structural portrayal and analysis made possible by detailed stratigraphic subdivision, for 10 units were mapped in the Minas Series instead of the three shown on plate 1.

The Moeda syncline can be traced for about 40 km south from the Serra do Curral to its junction with the Dom Bosco syncline. The west limb can be traced for nearly 20 km more to the southwest corner of the Quadrilátero Ferrífero and then continues a few kilometers southwesterly from there before losing its identity in post-Minas granitic and gneissic rocks. The east limb merges into the north limb of the Dom Bosco syncline in a gentle curve which contrasts with the junction between the Dom Bosco and Santa Rita synclines to the east.

Taking the base of the Minas Series as the datum, the Moeda syncline is about 16 km across at its widest point but narrows to about 5 km at its north and south ends. The west flank, known as the Serra da Moeda, dips regularly to the east at 30°–45° and only locally dips more steeply. The trend is even and regular, running about north-south to the Casa da Pedra quadrangle, where it flexes to the southwest. The limb is cut by few cross folds or cross faults. The east limb, known as the Serra do Itabirito, is much more complex, bowing out from its junction with the Dom Bosco syncline and trending northeast to the Itabirito quadrangle, thence warping again to the northwest across the Itabirito and Macacos quadrangles, and gradually turning more to the north at the north end. That limb is cut by many cross faults and warped by several cross folds. For much of its extent, the east limb is either nearly vertical or overturned toward the west, dipping as low as 45° E. in a few areas.

The axial trace of the syncline, in part located by infolded Itacolomi Series strata, is generally north-south but flexes far to the east in the Lagoa Grande quadrangle. The north end is complicated by a thrust and tear fault and by a saddle and cross fold; the nature of the junction with the Serra do Curral is not clearly understood.

As demonstrated by Wallace and indicated by aeromagnetic surveys (W. B. Agocs, oral commun.), the syncline is not a deep one. It seems to flatten abruptly and has a W-shaped cross section. Maximum depth to the base of the Minas Series may be in the order of

2,000 m. Pomerene (1964, fig. 25, p. 39) illustrated well the supposed cross section by a photograph of an actual small fold found just to the north.

Mapping by Wallace showed that two systems of cross folds traverse the structure, one trending northwest, the other northeast. The sharpest of these folds is reflected in the nose of Itabira Group trending southeast from the Serra do Moeda in the Lagoa Grande quadrangle (pl. 1). Most of these folds are not clearly reflected in the Caraça and Itabira Groups but were found by careful mapping of the individual formations of the Piracicaba Group. In the center of the syncline, the two systems intersect to form a domal structure (Wallace, 1965).

Extremely tight internal folding in the Cauê Formation produces radical thickening of that formation in places. The more massive Moeda Formation is also thickened by internal folding and by plastic flow, for its bedding is almost completely obliterated in some areas such as near Morro do Chapéu, Macacos quadrangle, where strong schistosity and flow cleavage is normal to bedding. Just northwest of that locality, Pieter van Leuwen (oral commun., 1962), mapping an iron-ore deposit, believed he found a five-fold repetition of one horizon in the iron-formation. Such structural complexities would never be suspected on most maps and undoubtedly are much more common than now known, for internal folding in evenly trending formations is hard to prove without distinctive horizon markers and good outcrops.

The junction of the Moeda syncline with the Serra do Curral is enigmatic; the critical areas for deciphering it are covered by soil and canga. We have here a major syncline oriented north-south butting against a major homoclinal structure striking about N. 60° E. for about 100 km. The junction is in about the middle of the N. 60° E. structure. The puzzling aspect is the uninterrupted and undeviated sequence of the Piracicaba and Itabira Groups on the north side of the Serra do Curral and also the apparently uninterrupted trend of the Itabira Group across the junction and into the Moeda syncline. If the synclinal fold merely opened out on its flanks and merged into the transecting structure, a hiatus and deflection would be expected in the trend of the Itabira and Piracicaba Groups in the Serra do Curral. Obviously a more complicated structure exists.

About 5 km south of the junction, the Moeda syncline is very narrow. This construction is interpreted as a saddle fold, a type of fold found elsewhere in the region. The syncline opens again to the north but is cross folded on the east side, revealing an unconformable contact between the Caraça and Nova Lima Groups. The Caraça Group is much sheared in this area and thins radically along the south flank of the Serra do Curral. The northernmost tip of the Serra do Itabirito is cut by a thrust and tear fault that is well revealed in surface and subsurface exposures in the Mutuca II mine and environs. To the west, in the Serra das Gaivotas, a south-trending septum of Caraça Group strata that is essentially anticlinal in structure is in thrust contact on its east side with the Nova Lima Group.

Pomerene (1964, p. D39) believed that this western thrust fault connects with that exposed in the northeast corner of the Moeda syncline, assuming that it is the major plane of movement. The writer suggests that the thrust fault on the east side of the Serra das Gaivotas may swing to the northeast rather than to the southeast (fig. 26) and that the well-exposed fault on the east side of the syncline is a separate structure. The writer would interpret this postulated fault as cutting across the soil- and canga-covered area at the junction of the structures, swinging gradually to the northeast, and finally running nearly parallel to the Caraça–Nova Lima contact and dying out several kilometers to the northeast in the older rocks. A zone of intense brecciation is revealed by the large roadcuts on the north and south sides of the Viaduto de Mutuca, about Macacos N. 13,000, E. 3,200), where the Moeda Formation is thin and mylonitized. If this interpretation is correct, the northern part of the Moeda syncline was thrust northwestward for some unknown, but not necessarily great, distance against, and to some extent over, the overturned limb of the preexisting homoclinal structure now forming the Serra do Curral.

SERRA DO CURRAL

The Serra do Curral is a throughgoing linear mountain some 100 km long extending from the Serra da Piedade quadrangle on the east to a short distance west of the Itatiaiuçu quadrangle. The range has been given many local names along its extent, and the name Serra do Curral is commonly applied only in the area just south of Belo Horizonte. Its geologic structure is homogeneous, however, so this one name was applied to the whole range by the USGS–DNPM staff in the interest of simplicity.

The homogeneous nature of the structure is clear on plate 1. The same stratigraphic units dip steeply or are overturned throughout the whole Serra do Curral. The most complex part of the range from the structural viewpoint is in the Belo Horizonte and Ibirité quadrangles (Pomerene, 1964, p. 37), where it is cut by a number of small thrust faults which swing into the plane of the bedding and disappear, by cross faults, and particularly by subsidiary folds, the axes of which parallel the axis of the range in a manner similar to that in the Dom Bosco syncline to the south.

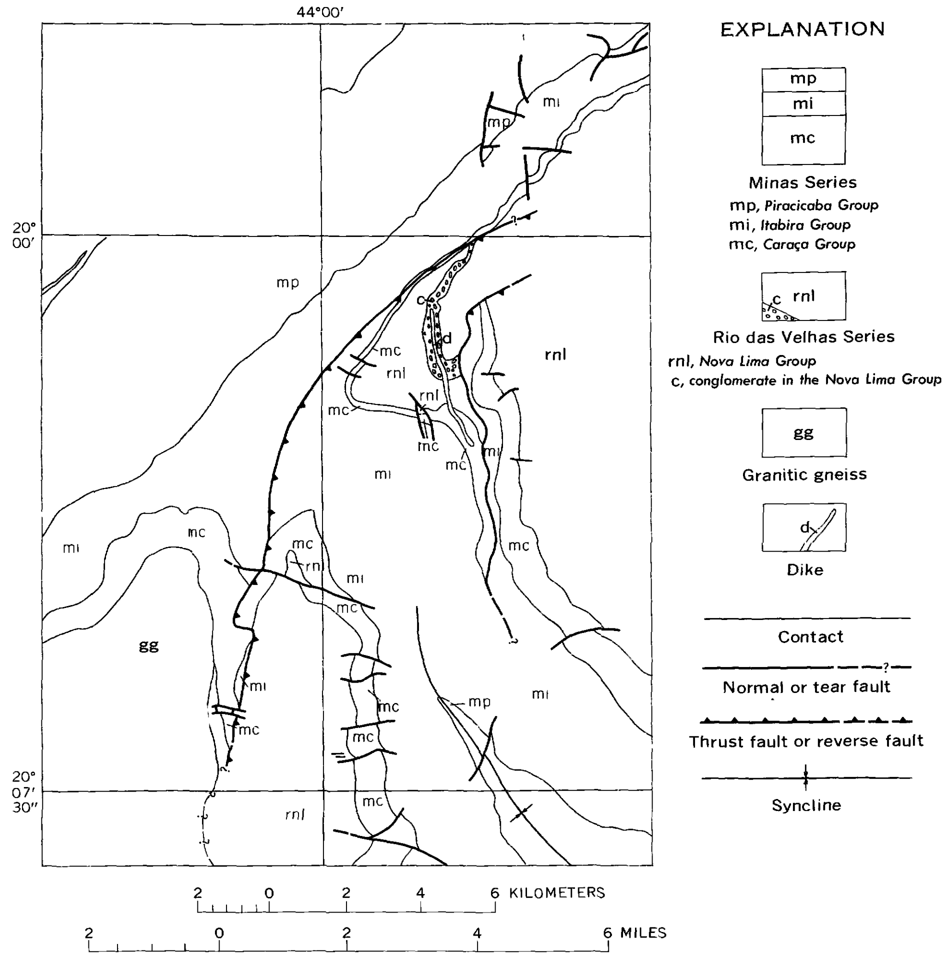

FIGURE 26.—Alternative explanation of structure at junction of the Moeda syncline with the Serra do Curral, to be compared with plate 1. See plate 1 for structural details, topography, and drainage.

Such subsidiary folds are also present farther west in the Fêcho do Funil quadrangle, as mapped by Simmons (1968a). Mine exploration carried on after Pomerene completed mapping showed that in the Ibirité quadrangle a subsidiary fold, not visible on the outcrop, occurs in the Samambaia iron-ore deposit. Other folds probably occur in the Belo Horizonte quadrangle, and the writer believes, but cannot prove, that the sudden thickening of the Cauê Itabirite in the great Aguas Claras iron-ore deposit is caused by such a fold. Sharp flexures or cross folds occur in a few places, such as that in the southeastern part of the Santa Luzia quadrangle and on the west boundary of the Fêcho do Funil quadrangle; such cross folding is not common.

The east end of the Serra do Curral, locally called the Serra da Piedade, swings abruptly to the north and continues a kilometer or more back in a westerly direction, reflecting the structure of the rock, here folded into a sharp syncline named by Alves, who discovered it, the Piedade syncline (Alves, 1961). (See pl. 1.) The north limb of the syncline is cut out by a cross fault which puts granite against Cercadinho Formation rocks. If this contact is followed to the west about 1 km, another cross fault can be found, west of which Alves mapped a sharp and small eastward-plunging tight anticline exposing Itabira Group and Caraça Group rocks at its core and Piracicaba Group rocks on both the north and the south flanks. These rocks are in contact to the north and probably to the west with intrusive granite; a small thrust fault may be present to the west. Isolated in the granite to the north is a block of metasedimentary rock some 3 km long and more than 1 km wide consisting of a thin remnant of the Nova Lima Group, overlain by the Caraça, Itabira, and part of the Piracicaba Groups of the Minas Series. This block and the rocks in it strike about N. 15° E., and the beds dip 40°–60° NW. and make a sharp angle with the general trend of the Serra do Curral and the adjacent metasedimentary rocks to the south. The nearest rocks of the north limb of the Piedade syncline strike about east and dip south.

Interpretation of this enigmatic structure at the east end of the Serra da Piedade, dismembered by faulting and largely engulfed in younger granite, is tenuous. W-shaped synclines (larger synclines with smaller longitudinal anticlines in the middle) are not uncommon features in the region; numerous examples are found in the Itabira district, in the Moeda syncline, and elsewhere. The small anticline just north of the Serra da Piedade might be the beginning of such a subsidiary longitudinal anticline within the Piedade syncline. Were this so, the anomalous northeast-trending block now surrounded by granite could be explained as being the remains of the south limb of the subsidiary anticline, folded back by a cross fold. A suggestion of such a cross fold is to be seen roughly on strike to the southwest in the Serra do Curral (pl. 1). The north limbs of that anticline and of the Piedade syncline would then be somewhere to the northeast, completely destroyed by the invading granite. From this area to the westernmost extension of the Serra do Curral, no sign of the north limb of the Piedade syncline can be found, although such a limb must have once existed. To the west, post-Minas granite is in intrusive contact with the Minas Series along the entire north flank of the Serra do Curral. causing a notable contact aureole.

Conceivably, the north limb of the Piedade syncline veered sharply to the north, paralleling the structure in the Serra das Cambotas, for the prevailing structural trend north of the mapped area is north for hundreds of kilometers.

Bearing on this problem is the great thickness of the Sabará Formation at its type locality along the Rio das Velhas, some 10 km to the southwest. Gair (1962) mapped this 3,500-meter-thick section of the formation as deformed but not repeated by folding back upon itself. Teixeira da Costa (1961) suggested that some of the area mapped as Sabará Formation along the Rio das Velhas belong to the north limb of the Piedade syncline, because of the presence of quartzite and "iron-formation." Simmons (1968a, p. G29) agreed with this view and cited the presence of lenticular quartzite bodies in the granite as evidence. He, too, suggested (oral commun., 1964) that a highly metamorphosed lenticular "iron-formation" in the rocks mapped as Sabará might be better correlated with the Cercadinho ferruginous quartzite or the Cauê Itabirite. The writer, agreeing with Gair, thinks Teixeira da Costa's and Simmons' evidence is not critical, because the quartzite zones (metachert?) are not stratigraphically identifiable and lenticular iron-formations and ferruginous quartzite in the Sabará Formation have been mapped in many parts of the region (Guild, 1957; Johnson, 1962; Reeves, 1966; Barbosa, pls. 9 and 10 of this report). Cercadinho and Cauê iron-rich rocks are typically continuous along strike. Regardless, if the subsidiary longitudinal anticline within the Piedade syncline were as persistent as some in the region, the north limb of the Piedade syncline would have been far to the north before granitic emplacement, and any repetition would be caused by the subsidiary anticline. The problem is an excellent example of Dor's second law of scientific investigation: "The less the evidence, the greater the number of opinions and the more firmly held they are."

GANDARELA SYNCLINE

The major structure lying to the southeast and east of the northern part of the Rio das Velhas uplift is known as the Gandarela syncline. It is in part open and upright and in part isoclinal and overturned toward the northwest. He who walks the 5-kilometer ridge at the west end of the syncline,[7] observing the parallelism of the structure beneath his feet to that in the valley of the Rio das Velhas below to the west, is immediately aware that the blunt end of the Gandarela syncline belongs to the Rio das Velhas uplift rather than to the tight isoclinal syncline stretching to the northeast. To the west lies one structural style, to the east, another.

The Gandarela syncline splits at its west end, as shown by O'Rourke's careful mapping (pl. 5), one axis veering to the west and north of west from the generally southwest trend of the main fold, the other axis veering almost south, with the blunt end between them belonging to the Rio das Velhas structure. The two limbs are roughly parallel for about 10 km to the northeast of the west end, but beyond the main axis swings to the east-northeast, and the limbs converge as the fold becomes tighter, isoclinal, and overturned. The south limb is largely cut out by the great Fundão fault in the vicinity of and east of Barão de Cocais, and the Piracicaba Group is largely squeezed out of the center of the fold. In the Gongo Sôco and Conceição do Rio Acima quadrangles, both limbs dip 40°–60° S., and at the east end of the fold both limbs dip 45°–60° S. The fold disappears on the east bank of the Santa Bárbara river in the São Gonçalo quadrangle, cut off by the Fundão fault.

[7] Surely the view from this ridge is one of the most impressive in the whole region. To the east, sliced by deep rugged canyons, soars the high massif of the Serra do Caraça, with a gothic skyline and waterfalls several hundred meters in height making white ribbons down sheer quartzite scarps; to the west lies the great stepped chasm of the Rio das Velhas valley, bounded to the west by the scarps and ridges of the Serra do Itabirito. Forty-five kilometers beyond that Serra protrude the castellated crags of the Serra do Itatiaiuçu, and 100 km to the north lies the broad high arch of the Serra do Cipo. The area has no permanent inhabitants except rabbits, foxes, anteaters, armadillos, and an occasional wolf and jaguar. Silence is tangible.

In the Gandarela syncline, axes of subsidiary folds are parallel to the main synclinal axis, particularly at the east end. The syncline is cross folded at two places north of Barão de Cocais, attributed by Simmons (1968b) to doming by gabbroic rocks exposed in a stocklike body to the north. Because the cross folds are related in direction to the other cross folds and because elsewhere the gabbro is controlled by postfolding faults, it may well be that the folds controlled the emplacement of the posttectonic gabbro rather than the converse.

The Gandarela syncline plunges northeast at its west end and southwest at its east end at low angles, locally reversing. The width of the outcrop of the Piracicaba Group is a very rough measure of the tightness of folding and the depth of the synclinal keel. The width of outcrop of the Itabira Group may also be a rough measure of the degree of compression; at the west end the Cauê Itabirite is grossly thickened by internal crenulations and folds, indicating flowage of material into the axial zone. To the northeast (except at the extreme east end) such crenulation and internal folding are less pronounced or absent in large areas; probably, material has been squeezed out of the limbs. In the southern part of the west, blunt end, many small folds transect the trend of the formation, indicating compression from the south and southeast. O'Rourke found a shear fold in the Gandarela Formation just west of the Fundão fault (pl. 5), and this fold indicates the same type of deformation in the axial area.

OURO FINO SYNCLINE

The Ouro Fino syncline is the small refolded syncline lying immediately to the south of the west end of the Gandarela syncline and separated from it by the Fundão fault and the west end of the Conceição anticline. At its south end, this structure is parallel to the Rio das Velhas uplift and trends northwest, but the north end is parallel to the Conceição anticline and the Gandarela syncline and trends northeast. The flexure is abrupt and more than 90°. The fold is closely related to the Gandarela syncline to the north and to the Conta Historia syncline, a cross fold on the Santa Rita syncline, to the south. The refolding of the structure was controlled by the Fundão fault, which limits it to the west and northwest (pl. 6).

The Caraça Group and the Cauê Itabirite are the only units of the Minas Series still preserved in the Ouro Fino syncline. The Moeda Formation, which rims the syncline except where faulted out, overlies the Nova Lima Group with sedimentary contact north and east of the fold but is in fault relation to those strata on the northwest and south sides. The Moeda is faulted against Maquiné Group rocks to the west. In the northwest corner of the structure the Moeda is piled in imbricate thrust slices branching from the Fundão fault, with spectacular scarps as much as 150 m high, but these slices merge and die out to the south, where the formation is locally faulted out.

As illustrated on plate 1, the Fundão fault changes direction about 90° just north of the syncline, changing from a northeast-trending thrust fault to a southeast-trending tear fault parallel to and limiting the Rio das Velhas uplift and cutting off the Conceição anticline. As also shown on plate 1 and in more detail on plates 5 and 6, a long projection of the Moeda Formation extends southward from the Gandarela syncline, and is truncated by the Fundão fault; the dip of these rocks reverses from 20° to 30° N. near the contact with the Itabira Group to 10°–25° SE. near the fault. Thus, the fault cut off a saddle fold or transverse anticline, overriding the Moeda Quartzite with Nova Lima Group rocks, an extension of the Conceição anticline, from the southeast.

In the central part of the Ouro Fino syncline in the zone where the strike of the axial plane abruptly swings about 90° from northeast to southeast, Maxwell (written commun., 1962) noted east-trending minor folds and lineation. These structures, in conjunction with the outcrop pattern and the relationship to the major Fundão fault, indicate that the whole syncline originally was oriented northwest parallel to the Rio das Velhas uplift but that the north end was refolded to its present northeast trend by movement of the overriding sheet of the Fundão fault, as first pointed out by O'Rourke (written commun., 1956). The syncline was originally separated from the Gandarela syncline by a broad saddle fold, now truncated by the fault. The Ouro Fino syncline is a rootless structure at its northeast and north ends, as inferred by O'Rourke.

The excellent mapping of the Gandarela and Rio de Pedras quadrangles by O'Rourke and the Capanema quadrangle by Maxwell and the structural analyses by these men are basic to the understanding of this complicated structural development.

STRUCTURES IN THE ITABIRA AND MONLEVADE DISTRICTS

The Itabira and Monlevade districts have certain structural features in common and some different from each other and from those in the rest of the Quadrilátero Ferrífero. Both are separated from the main body of the region by some 15 km of paragneiss and orthogneiss and contain downfolded remnants of Minas Series rocks that have been eroded off or destroyed in the intervening space. As indicated by the prevailing higher grade of metamorphism, the rocks were subjected to higher temperatures, probably because more deeply folded into the substratum. Both areas show moderate-sized fold structures in contrast to the large ones preserved to the west. Thrust faults are minor and rare. However, the largest normal faults known in the region are to be found in the Monlevade district.

The Itabira district consists of one northeast-trending syncline of Rio das Velhas and Minas Series strata surrounded by metasomatic and igneous granite. As defined by the base of the Minas Series, the syncline is about 10 km long, is isoclinal for much of its length, and is locally overturned toward the northwest, locally nearly vertical. The syncline ends to the northeast against a fault which may be pregranitization, for vestiges of iron-formation are found in the granitic gneiss east of the fault.

The southeast limb of the syncline, which is poorly exposed, is sinuous but not complexly folded; and the Cauê Itabirite, which is very strongly lineated, is much thinner on the southeast limb than on the northeast limb. The northeast limb has been folded into two very marked subsidiary synclines and their conjugate anticlines, those in the central part of the district tight and overturned and the most easterly syncline open and upright. In these subsidiary folds and in the axial zone of the main fold, the Cauê Itabirite is much thickened. The larger synclines are marked by subsidiary longitudinal anticlines within them (Dorr and Barbosa, 1963, pl. 8) similar to those in the Moeda and Piedade synclines to the east. Although the major syncline developed as a result of compressive forces from the southeast, the marked development of cross folds in the northwest limb and the marked lineation parallel to their axes suggests that a left-lateral shear couple operated during the folding.

The Monlevade area is unique in the region for its series of well-defined medium-scale conjugate synclines and anticlines; all plunge to the northeast or east. In this area the metamorphic grade is so high that most of the Piracicaba Group pelitic rocks have been transformed into gneiss, and much of the Cauê Itabirite is highly magnetitic. Some of the synclines, such as that culminating in Morro Agudo, are closely appressed and isoclinal in the keel zone; others flare out as relatively gentle folds. Intensity of shearing and tightness of folding increases to the south-west, and structures swing to an east-west orientation in the same direction. The folds are broken by two major cross faults, the largest known in the region. Thrust faulting is minor except in the southwest corner, where one limb of the Agua Limpa syncline is overridden by gneissic rock.

RIO DAS VELHAS UPLIFT

The master structure in the Quadrilátero Ferrífero is the Rio das Velhas uplift (Gair, 1962, p. A8). All major synclinal structures except those in the Itabira and Monlevade districts are at least to some extent conjugate to this great structure, which is traceable for 100 km north from the south edge of the Bação complex to near Nova Lima and thence northeast, where it disappears into the granitic rocks of the Caeté complex. This central uplift is the key to the structural development of most of the region.

The Rio das Velhas uplift is about 19 km wide at the narrowest point and widens to about 47 km at the south end, taking the base of the Minas Series as datum, and is even wider at the north end (fig. 4). At the northeast end and the south end, large masses of granitic rock have invaded the general anticlinal structure; at the south end the masses are of two ages, and possibly they are of two ages at the north end. In the main body of the uplift, diabase and metadiabase dikes are known but are not abundant; significant postmetamorphic gabbro masses are not known.

Because of the base of the Minas Series is arbitrarily taken as the edge of the uplift, the metasedimentary rocks of the uplift are Rio das Velhas Series. The Rio das Velhas Series shows at least two ages of folding: the pre-Minas folding discussed on pages A83–A84, and folding which this writer believes is related to the main post-Itacolomi orogeny. As brought out in some detail in the section on stratigraphy, the Rio das Velhas Series for the most part lacks mappable stratigraphic zones and thus intricacies of the structure can be deciphered in few places. Included distinctive mappable lithologies are lenticular; the only mappable throughgoing contact is the base of the Maquiné Group. Most primary sedimentary features were destroyed by metamorphism; hence, tops and bottoms of stratigraphic sections cannot be established.

The foliation in the Nova Lima Group is roughly parallel to the contact with granitic rock around the Bação complex except at the north end, where it strikes across the contact. A band of iron-formation, which crosses the old road from Itabirito to Pico de Itabirito in the northern part of the Bação quadrangle, shows that foliation and bedding are parallel there. Quartzite beds found by A. L. M. Barbosa in the São Bartolomeu quadrangle, on the other side of the Bação complex, indicate the same relation. Probably, the southern part of the uplift was bulged upward by the Bação complex, and the bedding is largely concordant with the contact in this part of the uplift.

In contrast, the foliation of the Nova Lima Group is strongly discordant with much of the contact between the Caeté complex and the Nova Lima Group south of the town of Caeté, but from there northward the foliation is closely or completely concordant with the granite contact. West of Caeté an unmapped quartzite body in the Nova Lima Group is parallel to the contact and concordant with the foliation; there it trends northeast.

The structure on the west side of the Rio das Velhas uplift north of Itabirito is complex indeed as the result of strong pre-Minas and post-Itacolomi folding. In the vicinity of Nova Lima, Honoré Bicalho, and Raposas, abundant bands of iron-formation and other mappable rocks trend northwest and are complexly crumpled; the crumpling is thought to be related to the post-Itacolomi orogeny, as it can be best explained by movement against a buttress to the northwest. Lineation and axial planes of the folds in the Nova Lima Group are generally parallel to the same structures in the nearby Minas Series. These vermiform structures give some hint of the complexities that may be hidden in areas of uniform lithology.

The Mariana anticline, the southeasternmost extension of the Rio das Velhas uplift, is in part a post-Itacolomi structure. However, the writer suspects that pre-Minas granitic rocks of the Bação complex may extend eastward from the outcrop of that complex, hidden under the broad area of Nova Lima Group forming the axis of the Mariana anticline. Such a mass, if continuous with the Bação complex, would have formed a rigid east-west buttress. Such an east-trending granitic mass would explain the sharp bend in the Dom Bosco–Santa Rita synclinal system and the channeling of the major westerly trending thrust faults in the Dom Bosco syncline. Unless such a buried pre-Minas granitic mass exists, the above structures are most difficult to resolve.

VARGEM DO LIMA SYNCLINE

On the east flank of the Rio das Velhas uplift lies the isoclinal overturned east-dipping Vargem do Lima syncline (Gair, 1962, p. A–49). In this structure, the Maquiné Group crops out for about 53 km. This syncline generally trends northwest and swings sharply to the northeast at its north end (pl. 4). The north end plunges south, flattening in the Nova Lima quadrangle. The plunge of the syncline at its south end is not determinable, owing to great shearing in that area and the presence of the overlying fault plate of Minas Series rocks.

Throughout its whole extent, the Vargem do Lima syncline is strongly sheared parallel to its axial plane. Such shearing seems to diminish in intensity to the northwest; at the southeast end, the quartzose rocks were described by Maxwell (written commun., 1962) as cataclasites. In the Capanema quadrangle, shearing is parallel to the many strike faults in the Minas Series in the Conta Historia syncline and, in part, in the Ouro Fino syncline to the east. These strike faults are also parallel to the fault between the Vargem do Lima syncline and the Conta Historia syncline—part of the system called the Fundão fault to the north. Here, the fault is a tear rather than a thrust fault, and its east side has moved northwest. One branch of this fault system was mapped by Maxwell entirely within the Maquiné Group and joins the Fundão fault at the most westerly part of the Serra do Ouro Fino.

The north end of the Vargem do Lima syncline warps sharply to the northeast, and the axial trace trends parallel to that of the Rio das Velhas uplift and to iron-formation beds in the Nova Lima Group mapped by Alves and O'Rourke. One may presume that the fold continues on to the northeast in the Nova Lima Group rocks, to disappear in the Caeté granitic complex near Caeté. Foliation in the Nova Lima Group is parallel to this trend, but the lack of throughgoing mappable horizons precludes tracing of the structure.

The Vargen do Lima syncline is not deflected by the folding which produced east-west structures on the west limb of the Rio das Velhas uplift, folding that was clearly pre-Minas. It is thought that the present form of the Vargem do Lima structure was largely produced by the post-Itacolomi folding, probably contemporaneous with the northwest-trending fold of the Conta Historia and Ouro Fino synclines. A pre-Minas fold, much more open, existed here, because the Minas rocks just to the east overlie Nova Lima Group rocks, not Maquiné rocks.

CONCEIÇÃO-CARAÇA UPLIFT

The Conceição-Caraça uplift lies in the eastern part of the Quadrilátero Ferrífero (pl. 1). Except at its extreme northeast end, where it runs into the Santa Bárbara Gneiss, no granitic rocks are known in this uplift, and in this it is unique in the region. It is bounded to the north by the Gandarela syncline and locally by the Fundão thrust fault, on the east and south by the Santa Rita syncline and its subsidiary folds, and on the west by the Conta Historia syncline. The Nova Lima Group crops out on its north flank and the Maquiné and Tamanduá Groups in the central and southern parts of the structure. Deformation within this uplift is very complex.

The north side of the uplift is occupied by the Nova Lima Group; these rocks trend northeast subparallel to the Gandarela syncline and the structure was named the Conceição anticline by Moore (1969). This structure can be traced to the northeast to the Santa Bárbara Gneiss and the Petí phase of the Borrachudos Granite, both of which have discordant contacts with the Nova Lima Group. Long lenses of iron-formation in the Nova Lima, mapped by Moore, Simmons, and Maxwell, showed that these rocks probably are folded into tight isoclinal folds. Because all top and bottom criteria were destroyed by metamorphism and tight folding, it is not possible to ascertain which of the two folds indicated on plate 1 is the anticline, but it seems more logical to suppose that it is the more northerly, which would make the Nova Lima Group subparallel to the Minas Series in the Gandarela syncline. Simmons indicated that a low-angle unconformity between the Minas and Rio das Velhas Series rocks is present in the area mapped by him. If the south fold were the anticlinal fold, tight pre-Minas folding and a sharp unconformity between the Minas and Rio das Velhas Series would be indicated. As shown above, the Minas–Rio das Velhas unconformity seems to be characteristically low angle in the eastern part of the region, and therefore it is believed that the northern fold is the anticline.

The lack of mappable zones in the Nova Lima Group west of the end of the iron-formation exposure makes it impossible to decipher the detailed structure of the Conceição anticline in that area. Possibly the isoclinal folding in the Nova Lima continues southwestward, but this cannot be proved, and the writer thinks that it may well die out to the southwest, as it did in the Gandarela syncline, the conjugate fold just to the north.

The northeast end of the Conceição anticline is in contact with posttectonic Borrachudos Granite and foliated granitic rocks of the Santa Bárbara Gneiss. The contact with the latter rock is marked by a long foliated greenstone schist intrusive of post-Minas age. (See page A79.) The southwest end of the Conceição anticline butts with fault contact against the Vargem do Lima syncline in the Rio das Velhas uplift.

In the Conceição do Rio Acima quadrangle, Moore (1969) named a fold that lies just south of the Conceição anticline the Capivara syncline. Maquiné Group rocks were thought to have been isoclinally folded upon themselves in this syncline. Because the Cambotas Quartzite of the Tamanduá Group lies immediately to the southeast of the Maquiné Group, in space that should be occupied by older rather than younger rocks if a major syncline exists, this writer believes that this syncline must be a local wrinkle rather than a significant feature. A major thrust fault was postulated by Moore to explain the anomalous relations but this fault was not mapped in adjacent quadrangles, where the contact between the Maquiné and Tamanduá Group rocks was deemed by Maxwell to be sedimentary. Maxwell's interpretation was followed on plate 1. Relations between the Nova Lima, Maquiné, and Tamanduá Groups in the central part of the Capanema quadrangle suggest an anticlinal rather than a synclinal structure; conceivably the axis of the Conceição anticline swings south to this area rather than continuing to the southwest as shown on plate 1. It should be made clear that this area is the least accessible and among the most rugged in the whole region and that exposures are poor. Therefore, it is not surprising that the complex structures resulted in some disagreement.

In the main mass of the Serra do Caraça, the Cambotas Quartzite was folded into tight isoclinal structures, some recumbent, and was sliced into many imbricate thrust plates, probably individually small. It is also cut by many steep faults occupied by mafic dikes. The area is one of great tectonic disturbance. As is evident from the fault pattern, rock failure was primarily toward the west and, in the southwestern part of the structure, toward the northwest (pl. 1). The northwest-trending cross folds on the Santa Rita syncline are responsible for the sinuous south border of the Conceição-Caraça uplift. The west half of the south border is a magnificent dip slope on bare quartzite, some 600–800 m in height, crenulated by minor folds and faults.

The east border of the Conceição-Caraça uplift, one of the more spectacular sights in the Quadrilátero Ferrífero, is a wall of bare quartzite, sloping more than 50° and more than 1,000 m high, cut by crevasses and punctuated by castellated crags (fig. 15). Bedding of the strata is obscured by the intense folding, faulting, and foliation of the quartzite but trends nearly north and dips steeply east at the north end and also probably farther south, where the mountain is too rugged to climb. On the east side, the overlying formations are tightly wrapped around the quartzite and are faulted with strike faults and tightly folded.

The extensive dike system in the Serra do Caraça and the many late tensional faults may well indicate that a large gabbroic body similar in size or larger than that unroofed north of the Serra do Tamanduá may underlie the Serra do Caraça, accounting in part for its uplift.

OTHER UPLIFTS

Because most uplifts around the periphery of the Quadrilátero Ferrífero consist largely of granitic rocks that crop out poorly, lie in great part outside the mapped area, and are of slight economic interest, they were not mapped in detail. Similarities with gneiss domes in Rhodesia and other parts of the world suggest that these gneissic domes grew outward in successive periods of accretion. The areas merit further study.

The uplift west and southwest of the Serra da Moeda may have been similar to the Rio das Velhas uplift. Two sides of the uplift are delineated within the mapped area, but the other two sides were not found in reconnaissance and may have been destroyed by granitization or intrusion, as on the north side of the Serra do Curral. Or, as seems more likely from the stratigraphic evidence, the area may have been one of major erosion during Itacolomi time, and the Minas Series and perhaps the underlying metasedimentary rocks may have been removed then. Alternatively, the keels of the bounding synclinal folds may have been eroded away in post-Itacolomi erosion.

FAULTS

Three main types of faults developed in the region during post-Itacolomi deformation: (1) thrust faults, some intimately related to (2) tear faults parallel to the strike of the rocks, and (3) cross faults. Of these, the first two seem closely related to the earlier compressive stage of orogeny, and the last, to the end stages.

THRUST FAULTS

The south and east sides of the Quadrilátero Ferrífero are intricately cut by thrust and tear faults, in several areas by imbricate sets. Such faults are superposed on the earlier folds and thus indicate their later age. Other thrust faults and fault systems of similar age are found elsewhere in the region but are not nearly as complex or as extensive.

Displacement along thrust faults has nowhere been measured and, because of the lack of known matching elements, cannot be calculated without much more detailed field mapping. Facies changes in stratigraphic units are gradual or erratic and, without fossils, cannot be used with any confidence. At the junction of the Serra do Curral and the Moeda syncline, an abrupt facies change in the Cauê Itabirite was noted by Pomerene (1964) and this feature has been seen elsewhere. Too little is known of the nature and rapidity of such changes to use them as a measure of the distance thrust plates may have moved.

Cumulative westward movement along the south edge of the region perhaps is on the order of tens of kilometers. If the most westerly thrust plate in the Jeceaba and Casa da Pedra quadrangles was torn from the south limb of the Dom Bosco syncline near the west end of that feature, movement there may have been on the order of 7 km. The west- and northwest-trending subsidiary folds in that thrust plate would be expectable where the Dom Bosco syncline swung to the southwest to join the missing limb of the Moeda syncline.

Similarly, the north-striking thrust faults south of the Serra do Caraça may have a cumulative displacement of not less than several kilometers. Part of the westward movement of the Itacolomi and Minas Series was caused by the nearly recumbent overturned folding in that direction, but part was due to transport westward in thrust slices.

The great Fundão fault system is probably the longest single fault in the region. It has been traced southwest from the Florália quadrangle, where it disappears in granitic rocks, to the Rio de Pedras quadrangle, a distance of 48 km. There it veers southeast as a system of tear faults and thrust faults for another 30 km to the axis of the Mariana anticline [8] and thence, as thrust faults, another 10 km to the west, a total extent of 88 km. It very probably joins the major thrust-fault system in the Ouro Prêto and Mariana quadrangles, which swings south and again to the east, bounds to the north the largest block of Itacolomi Series in those quadrangles, and continues out of the region to the eastward as a tear fault. Thus, the system may be more than 110 km long.

The Fundão fault system marks the boundary between the highly faulted area which lies to its east and the relatively unfaulted area that lies to its west. It is thus both a major structural boundary and a major structure in its own right.

The displacement on the Fundão fault itself cannot be proved to be great. Simmons (1968b) stated that a minimum displacement of 500 m would explain all the observed features in the Santa Bárbara and Cocais quadrangles. In the Conceição do Rio Acima quadrangle, Moore calculated the minimum strike-slip displacement along this fault, which there splits into three slices, as 2.4 km. If, as the writer believes, the northeastward-trending part of the Ouro Fino syncline is the result of a 90° bend of this part of the syncline by movement of the upper plate of the Fundão fault toward the west-northwest, the displacement must be in the order of 5 km.

No horizon markers are known to measure displacement along the part of the Fundão fault system between the Serra do Ouro Fino and the axis of the Mariana anticline. The fault is a tear parallel to the strike of the wallrocks in the Rio de Pedras and Capanema quadrangles. The Maquiné Group is faulted against the Itabira Group for much of this distance. The Maquiné rocks to the southwest of the fault trace are very strongly sheared parallel to the fault zone, and much displacement is represented in the shearing. Maxwell (written commun., 1962) remarked on the extreme elon-

[8] Although plates 7 and 8 by A. L. M. Barbosa do not show this fault as continuous across the Sao Bartolomeu and Antônio Pereira quadrangles, Barbosa said (oral commun., 1964) that he thinks it may well be present where not mapped.

gation of many cobbles and pebbles in the Maquiné beds, with axial ratios of as much as 20:1. This northwest-trending shearing diminishes to the northwest. On the northeast side of the tear fault, close northwest-trending faults in the end of the Conta Historia syncline displace the blocks on the southwest side of those faults to the northwest (Maxwell, written commun., 1964).

Farther southeast, in the São Bartolomeu quadrangle, the Fundão fault is a thrust and continues thus to the axis of the Mariana anticline and around the nose, where outliers (klippen) of the basal Minas Series on the Nova Lima Group demonstrate the low dip of the fault plane (fig. 27).

According to the present interpretation, the displacement on the Fundão fault is at least 5 km and is to the northwest or west-northwest. The fault is a thrust where trending across this direction and largely a tear fault where trending parallel to it.

In the Dom Bosco syncline the thrust fault system is imbricate, the sheets piled on one another toward the west and bounded to the north and south by tear faults. No means of deciphering the individual displacement of each fault or the total displacement is known; it is probably large, perhaps more than 20 km. It was suggested that the displacement at the west end might be in the order of 7 km, but most of the total shortening took place in the imbricate system to the east.

The Dom Bosco fault system starts at the east end of the syncline with a fault of great displacement thrusting the Nova Lima Group over the Itacolomi Series. The vertical component of the fault must be at least

FIGURE 27.—Thrust fault, Cauê Itabirite over Moeda Formation, near N. 12,950, E. 6,200, Mariana quadrangle. The Cauê Itabirite here contains disseminated gold and was being removed by hydraulicking 1964, when the picture was taken. The happy geologist is A. L. M. Barbosa, who predicted the position of the fault before it was exposed. At that time few other geologists believed the fault existed there.

2,000 m, but it could be more than 4,000 m. The northern extension is called the Agua Quente fault and is traceable for a distance of 50 km (Maxwell, written commun., 1964). At its north end the Agua Quente fault disappears in the Nova Lima Group argillaceous rocks; at the south it veers abruptly to the east in the Mariana quadrangle as a tear or strike fault, placing in juxtaposition the Nova Lima Group with the Piracicaba Group and cutting out at least the middle and lower Minas Series. Its east end lies beyond the mapped area.

The Agua Quente fault has many branches and splits, some of which reunite with the main fault; others wander off to disappear in the granitic rocks or to turn into strike faults in metasedimentary rocks. Near the pretty hamlet of Agua Quente the fault is subparallel to the tightly squeezed Santa Rita syncline; it cuts out the west limb of this fold from that place on to the north (Maxwell, written commun., 1962). The warm spring at Agua Quente (about 30°C) may represent the surfacing of deeply circulating water along this fault. The displacement cannot be calculated, owing to the complex structure, but the fault juxtaposes pre-Minas rocks with Minas Series rocks for much of its length and has a minimum displacement of several hundred meters in the central and northern parts of its extent. If the east side of the fault is up, as it is farther to the south and as is the regional rule, the missing west limb of the Santa Rita syncline must be below the present surface, possibly thrust beneath the Serra do Caraça or lost in the granitic rocks at depth.

South of the Serra do Caraça a series of other north-trending high-angle thrust or reverse faults lies to the west of, and parallel to, the Agua Quente fault. These faults constitute a system of interbranching faults which all bend to the southeast southward and to the northeast northward. Those bending to the northeast join other faults until only two master faults are left, both of which bend sharply to the northeast and disappear, one as a strike fault, the other as a cross fault that disappears into the Cambotas Quartzite, offsetting the contact only about 75 m. The influence of the Caraça monolith and the Mariana anticline on the trends of these faults seems clear. Most of these faults are parallel to the strike of the beds, and movement on individual faults is difficult to define, owing to irregular pre-Itacolomi erosion in this area. Minimum displacement cannot be less than several hundred meters on most of the faults and may be much more. The north-south faults dip east at moderate to high angles.

Within the Serra do Caraça another intricate thrust-fault system roughly parallels the system just discussed but is not continuous with it (Maxwell, written commun., 1962). As stated above, the Cambotas Quartzite in the Serra do Caraça is intensely deformed, consisting of recumbent folds sliced by thrust faults striking north and dipping 30°–50° E., by other faults striking northwest and dipping northeast, and by still other vertical faults striking east-northeast and east-southeast. All are best developed in the orthoquartzites of the Cambotas Quartzite. They extend into the protoquartzite and subgraywacke of the Maquiné Group, but are neither as numerous nor as prominent there. Only a few of these faults extend into the phyllites and schists of the Nova Lima Group or into and across the Minas Series or the greenstone schist on the east and south sides of the area. Lithology apparently played a part in the development of faults, such structures forming in greatest number in brittle rocks, in fewest number in plastic rocks. It should be added that faults crop out more conspicuously in the bare outcrops of orthoquartzite than in the soil-covered rocks of more mixed composition.

On plate 1 a major thrust fault, marked with queries, is shown a short distance east of the Rio das Velhas. This fault has not been recognized on outcrop. The north end, in the Rio Acima quadrangle, was mapped by Gair (1962, Pl. 2); the part to the south was not mapped by the geologists who worked in those quadrangles. This writer believes that a thrust fault must exist near the location shown because of the strong structural discordance between the east and west sides of the Rio das Velhas valley and because the necking of the Rio das Velhas uplift into an hourglass shape creates space problems that can best be explained by the existence of such a fault.

South of the area mapped by Gair the location of this fault is questionable, for the rocks are homogeneous, horizon markers are absent, and weathering is deep. The fault is visualized as generally following the bedding but cutting across the dip at a low angle, with the east side moving west. It was located on the map by persistant lateral erosion features and, in the Rio de Pedras quadrangle (pl. 6), by the presence of old surficial gold workings which can be followed across that quadrangle for more than 15 km. The gold deposition was at first believed to have been controlled by a particular stratigraphic horizon; no evidence of this was found in the field, and it seems at least equally probable that the gold, which was associated with sulfide mineralization (O'Rourke, written commun., 1960), may have been deposited in a permeable zone along the trace of the postulated fault. In the rest of the region gold mineralization is posttectonic.

Conceivably, the structural discordance is caused by an unconformity within the Nova Lima Group; such an unconformity would be difficult to locate in the homogeneous rocks of that group. The thrust fault solution seems preferable because of the space relations, because it is consistant with the regional structural geology, and because such an unconformity has not been found elsewhere in the region.

To the north and west of the Fundão fault system and the Dom Bosco syncline, only two significant thrust faults are known: that at the junction of the Serra da Moeda and the Serra do Curral, mentioned earlier, and the one just discussed.

Many small thrust faults are to be found throughout the region, faults with displacements measured in centimeters, meters, or very rarely, tens to hundreds of meters. Most of these resulted from local adjustment during the folding. They do not always fall into general areal patterns, as do those discussed above, and they are of only local importance.

TEAR FAULTS

The Engenho tear fault, forming much of the south boundary of the post-Rio das Velhas Series rocks, is a unique structure in the Quadrilátero Ferrífero. It has been traced for about 70 km from east to west and turns to the southwest at its west end (Guild, 1957). The structure branches in several places. The south side moved up sufficiently to cut out most of the post-Nova Lima Group stratigraphic section along most of the trace of the fault; thus, it may be considered to have a minimum vertical displacement of 2,000 m. The horizontal component cannot be estimated; there is little apparent horizontal offset in the Serra do Ouro Branco. The structure is younger than folding and thrust faulting. It is also younger than the emplacement of granitic rocks south of Ouro Prêto and possibly younger than some intrusive granitic rocks near Congonhas. It is certainly older than the diabase dikes, for Johnson (1962) considered that the long dike cutting the Serra do Ouro Branco was emplaced along a branch of this fault.

A large tear fault is well exposed just west of the Mutuca II hematite deposits, a short distance south of Belo Horizonte in the Macacos quadrangle. This fault is part of the rather enigmatic system at the north end of the Moeda syncline (p. A88) and limits the Mutuca II ore deposit. The fault plane has been exposed in several underground workings both in the Mutuca II deposit and the Zoroastro Passos deposit about 4 km to the south and in surface workings at these and other intermediate localities. These workings were opened after mapping of the area by Pomerene.

This north-south fault is postore, has produced a notable unhealed breccia zone in hematite ore, and has juxtaposed the Nova Lima Group against the Itabira Group. At its north end, the fault trace swings to the east and passes into a steep reverse fault with Minas

Series thrust over Rio das Velhas Series (fig. 28). In the Mutuca II area and to the south the fault is nearly vertical; evidently the east side moved north relative to the west side. The horizontal displacement is unknown, but this writer suspects that the Mutuca II ore deposit may once have been contiguous to, or part of, the Capao Xavier deposit, on the west side of the fault some 3 km to the south. That deposit continues under Tertiary and Recent cover not less than 900 m east of the position shown by Pomerene (1964, pl. 2), as revealed by subsequent drilling. Although this fault was considered by Pomerene to swing to the west as shown on plate 1; the writer thinks that it continues to the south as a strike fault, gradually dying out to the southward. It is not exposed south of Feixos.

As discussed in previous pages, part of the Fundão fault should be considered a tear fault, and other thrust faults also merge into tear faults for part of their extension.

CROSS FAULTS

The regional structures are cut by many high-angle cross faults, most of them small but a few of them large. The cross faults seem to fall into two major orientations: those striking nearly at right angles to local structural trends, and those striking between 30° and 45° to those trends. Although some authors have related cross faults to regional stress patterns and have even assigned specific ages to such faults on the basis of their orientation, it is evident from plate 1 and from the individual quadrangle maps of the region that the direction of cross faults is instead controlled by the direction of local fold trends.

FIGURE 28.—Tear fault in the Mutuca II iron-ore deposit, near N. 11,200 E. 3,200, Macacos quadrangle. Iron ore in the Cauê Itabirite is to left of hammer; Nova Lima Group phyllite is to right. At depth this fault dips steeply in the opposite direction.

Thus, most of the cross faults in the west half of the Serra do Curral are nearly at right angles to the strike of the range, whereas a few others are at about 45° to that trend. In the east half of that Serra, most cross faults are between 30° and 45° to the trend, and a few are at right angles. In the Serra do Itabirito most cross faults are at right angles to the local strike, even though that trend varies nearly 90°. In the northern part of the Serra da Moeda, most cross faults approach the perpendicular to the trend, whereas in the southern part, most approach 45° to the trend. Few cross faults were mapped in the north edge of the Dom Bosco syncline; they are at right angles to the fold structure, and they change direction around the even bend at the southwest corner of the Rio das Velhas uplift. The east side of the Santa Rita syncline is cut by cross faults normal to the trend. The same is true in the Monlevade district, where two major cross faults are nearly at right angles to a third, and all are roughly normal to the local structural orientation. The fault systems and cross-fold system in the Santa Rita syncline are possibly the most complex because of the varying strikes of the rocks.

Displacements of most cross faults range from a few meters to perhaps 100 m. Two cross faults in the Monlevade area have displacements of more than 1,000 m; the third more than 2,000 m (Reeves, 1966). Other major cross faults are a fault in the northern part of the Catas Altas quadrangle, on the east side of the Quadrilátero Ferrífero, which offsets the greenstone schist about 700 m; three major cross faults in the Serra do Itabirito that have displacements of perhaps 400–800 m (Wallace, 1965); and two in the Serra do Curral south of Belo Horizonte, both with displacements in the order of 1,000 m. One of the Serra do Curral cross faults was chosen as a site for a water aqueduct through the mountain despite the presence on outcrop of one of the major fault breccias in the region and an obvious major offset of the rocks. The tunnel had been under construction for about 8 years and still was not completed in 1968; the original estimated cost has already been exceeded many times.

Because they are closely related to the structural trends of the major post-Itacolomi folds and in many places cut intrusive granite, the cross faults are the youngest structures to have formed and represent the final adjustment to stresses at the end of orogeny. There is no evidence that they represent regionally directed stress related to a later orogeny.

GEOLOGIC EVOLUTION OF THE QUADRILÁTERO FERRÍFERO

Because some of the reports resulting from this project, as well as other papers on the region, discuss several orogenies, the philosophy underlying the discussion herein must be stated, for the writer only discusses two orogenies in the region, a post-Rio das Velhas orogeny and a post-Itacolomi orogeny. The terms "orogeny" and "epeirogeny" are used in the sense defined by G. K. Gilbert and I. C. Abbe, Jr., as quoted in the glossary of the American Geological Institute (1960, p. 206). Orogeny is "the process of formation of mountain ranges by folds, faults, upthrusts, and overthrusts, affecting comparatively narrow belts * * * while the epeirogenic movements of the earth's crust produce and maintain the continental plateaus and broad depressions which are covered by the sea." Thus, warping of the crust or uplift and erosion without significant folding is not here considered orogeny. An unconformity, even a profound erosional unconformity, need not indicate an orogeny unless accompanied by strong and usually systematic folding. For example, in the interval between the Minas Series and Itacolomi Series sedimentation, uplift was great enough to produce at least 1,000 m of erosion, and warping was strong enough to produce local angular unconformities up to about 12°, but there is no evidence within this region for strong or widespread systematic folding or faulting in this interval. That discordance is therefore considered to be the result of an epeirogenic event in this region.

Naturally, it is completely possible that outside this region evidence may be found for stronger and more systematic deformation. If so, the writer's classification would be wrong on an interregional basis, although still correct on a regional basis. Considering the evidence of the Itacolomi sediments, one must expect that an orogeny might have occurred in that interval outside the area here considered, but neither the site nor the time of this orogeny is now known.

Although orogeny is often accompanied by emplacement of granitic rocks, such emplacement is not a criterion of orogeny unless accompanied by demonstrable major folding (James Gilluly, oral commun., 1966).

Given the uncertainty of interregional correlation of Precambrian stratified rocks, it seems prudent to confine interpretation to the region at hand unless adjacent regions contain compelling and unequivocal arguments bearing on the region at hand. Such unequivocal evidence is to be found in the steady and marked increase in metamorphic grade and the apparent complexity of deformation of the rocks to the southeast of the Quadrilátero Ferrífero, continuing a trend already established throughout the Quadrilátero. This involves all Precambrian rocks of the region and indicates that the center of the post-Itacolomi orogeny lay to the southeast. This orogenic zone has been traced roughly parallel to the coast of Brazil for hundreds of kilometers by many geologists, although the absolute age of the deformation is not well established either in the Quadrilátero Ferrífero or elsewhere.

The question of whether there was one or more orogenies in post-Itacolomi time is subject to more than one interpretation. The writer conceives of the orogeny in the Quadrilátero Ferrífero as the result of gradual building up of directed forces in the subcrust and crust, possibly by deep convection cells. These driving forces were periodically relieved by folding, thrust faulting, shearing, and recrystallization of the rocks. Stress accordingly varied in time with deformation by the modes cited and could be expected also to vary in general direction as the main orogenic belt to the southeast developed. The Quadrilátero Ferrífero is on the fringes of that belt. Strain also varied in local direction as originally plastic rocks recrystallized, as sychronous erosion changed confining pressures, and as granites were formed and intruded, placing buttresses or competent rocks in places where preexisting rocks had been able to fail plastically. Fault planes formed, along which stress could be relieved obliquely, setting up new couples. After local relief of stress, much time may have passed before the active orogenic belt to the east could again build up enough force to initiate another period of active renewed local deformation.

Each of these periods of deformation, which locally may have different directions of strain, might be regarded as different orogenies. In dealing with post-Cambrian rocks with fossil records, this might be profitable in permitting closer analysis. In dealing with metamorphosed and nonfossiliferous Precambrian rocks, the difficulty of separating the sequence of events is naturally enormous. Therefore, it seems more profitable to analyze the total deformation process as parts of a single great and long continuing event than to attempt to fractionate a process the essential features of which are mutually consistent and the temporal details of which are essentially unknowable at this stage of the science. The whole orogeny probably lasted hundreds of millions of years.

The earliest evidence of the structure of the area now occupied by the complexly folded and faulted rocks delineated on plate 1 is the flysch sediments of the Nova Lima Group, overlain by the molasse sediments of the Maquiné Group, both of the Rio das Velhas Series. This sequence indicates that the sediments were deposited in a eugeosynclinal basin receiving a volcanic contribution possibly from an island arc and an aluminous and quartzose fraction from maturely weathered granitic rocks. These sedimentary rocks were then folded, strongly on the west side and less strongly on the east, and were intruded by gabbroic and ultramafic rocks and, later, by granitic rocks in the area of the Bação complex and probably to the southwest, west, and north. The main center of this orogeny was probably to the west and southwest of the Quadrilátero Ferrífero, for there is no persuasive evidence of sharp pre-Minas folding in the eastern part of the region. In the western part of the region folding was generally open but locally rather tight.

The main evidences for emplacement of granitic rocks in and around the region during this orogeny are (1) the age of metamorphic minerals in the Nova Lima Group on the periphery of the Bação complex—2,800 million years (rubidium—strontium determination on muscovite) and only slightly younger within the Bação complex—(2) the breakdown of the normal Minas Series stratigraphic section south of that feature into much more phyllitic rocks than commonly found, and (3) the fact that post-Minas folding was strongly influenced by rigid bodies in this vicinity, to the west of the Serra da Moeda, and to the north of the Serra do Curral.

The degree of regional metamorphism, if any, imposed on the Rio das Velhas rocks during this orogeny is unknown; contact metamorphism along the granitic intrusives certainly occurred, as evidenced by age of the muscovite cited above. There is much difference of interpretation on this point among the many competent petrographers who have studied the rocks of the region, largely because of the lack of unequivocal evidence. The apparent relative simplicity of the pre-Minas folding might, in conjunction with the lack of unequivocal petrographic evidence of pre-Minas regional metamorphism, suggest that the Rio das Velhas rocks were not strongly metamorphosed on a regional basis at this time.

The folded Rio das Velhas rocks were then uplifted, subjected to deep erosion, and peneplaned in this area; west and southwest of the region, and probably to the north, granitic bodies were unroofed. At an unknown time the region was warped, the western side rising, and an area of some relief developed to the west and southwest of the Quadrilátero Ferrífero. Coarse pure quartzose sediments now called the Cambotas Quartzite of the Tamanduá Group were unconformably deposited on the older rocks in narrow lenticular zones along a shoreline. These accumulated to considerable thickness. The general trend of this shoreline was north, but it may have extended as far southeast as São João del Rei and certainly extended far to the north.

Over these sedimentary rocks were deposited offshore clay, silt, and dolomitic and ferruginous deposits of no great thickness and unknown lateral extent. They are preserved only in the east-central part of the region as the upper Tamanduá Group and have not been definitely identified outside this very limited area. The ferruginous deposits were deposited in an oxidizing environment, in contrast to those of the earlier Nova Lima Group iron-formation, which were deposited in a reducing environment. It is not clear whether a retreat of the sea occurred after the Tamanduá sedimentation; the Tamanduá rocks are known only in a relatively narrow zone. This might be due to original sedimentary patterns or to later erosion of much of the original deposits or both. The former seems the dominant control, as the rocks can be traced far to the north and there, too, are narrow in outcrop width compared with length.

Over the underlying rocks, mostly of the Nova Lima Group but also of the Maquiné and Tamanduá Groups, the blanket sandstones and conglomerates of the Caraça Group rocks spread throughout the region. In the west side of the Quadrilátero Ferrífero, these were coarse and thick in the basal section; farther east, to the south, and in the extreme northwest they were thinner and finer and contained more argillaceous material. Thick sequences of claystone, locally graphitic, accumulated on the coarser sediments, indicating westward migration of the shoreline and platform conditions of sedimentation. The claystone sediments gave way to chemical deposition of iron-formation under oxidizing conditions, followed by deposition of mixed carbonate sediments, oxide-facies iron-formation, and dolomitic aluminous sediments. The shoreline was probably far to the west during Itabira time.

Upwarping and partial retreat of the sea followed for a short interval in which limited erosion of the carbonate rocks of the Gandarela Formation occurred, probably largely to the west. Another cycle of local downwarping followed, with the western area that was the source of the sediments being actively eroded once more, contributing to the region coarse black sands mixed with aluminous and ferruginous sediments in shallow-water deposits. Further downwarping continued, with deposition of silty dolomitic sediments followed by well-differentiated fine argillaceous, graphitic, and sandy sediments. Downwarping continued, the platform was incorporated into a geosyncline, and another flood of eugeosynclinal flysch sediments poured into the region, with significant volcanic contributions. The source of these eugeosynclinal sediments is not known; the main eugeosynclinal basin was probably to the southeast, where later orogeny centered. The abrupt change in nature of the sediments must indicate a change in source and a fundamental tectonic change in the borderland.

Here the record of Minas sedimentation ends in this region, for the next recorded event was strong uplift, warping, and erosion of the Minas sediments to depths at least 1,000 m into the last surface of sedimentation. On this surface was deposited the Itacolomi Series.

The Itacolomi Series is a paralic group of sediments, changing rapidly in nature in space and time. Coarse lenticular conglomerates were deposited with fine silts and clean and dirty sandstones. These sediments possibly also came from the west and southwest, for they are generally finer to the northeast, but so little is left in this area that no definite statement as to provenance is possible.

A great thickness of sediments that has now been completely removed from the region was undoubtedly deposited upon the rocks we now find, for the youngest Precambrian rocks now exposed are metamorphosed to the same grade as the oldest. The great erosion that stripped this cover must have taken place during and after the post-Itacolomi orogeny, not only because of the metamorphic evidence cited above, but also because the plastic failure of the pre-Minas, Minas, and Itacolomi rocks during that orogeny indicate considerable depth of burial at the beginning of that orogeny. Herz (written commun., 1966) believes, on the basis of the metamorphic minerals present in the surviving rocks, that their depth of burial must have been 10 km or more, and this writer agrees.

At the beginning of the post-Itacolomi orogeny, the rocks in the Quadrilátero Ferrífero were quite different in nature and distribution than now. The Itacolomi Series rocks were sandstones, conglomerates, and sandy shales. The Minas Series rocks were sandstone, shale, shaly and cherty limestones, limestones, jaspery iron-formation, siltstone, tuffs, and the wackes. Whether the Rio das Velhas Series rocks had been regionally metamorphosed during the pre-Minas orogeny is moot; regardless, there is no unequivocal evidence that on the whole they were generally more highly metamorphosed than now. The main masses of the rock may have been shales or argillites and slightly metamorphosed siltstones and wackes, with the Maquiné Group silty sandstone, silty shales, and subgraywacke. Thus, none of these rocks, except conceivably the Rio das Velhas Series rocks, were then as competent as they are today, and notable thicknesses were composed of incompetent and relatively incompetent sediments. Interlayering of widely varying rock types makes the sediments anisotropic in their response to extenal force. Massive abruptly lenticular quartzose sedimentary bodies also contribute to structural anisotropism.

At that time granitic rocks occupied a much smaller part of the total area of the Quadrilátero Ferrífero than today. The whole area to the east, northeast, and southeast of the Quadrilátero Ferrífero was probably occupied by Rio das Velhas Series rocks overlain by Minas Series and probably shaly Itacolomi Series rocks. The existence of granitic rocks in the Caeté-Cocais uplift or elsewhere to the east, northeast, or southeast is doubtful, although a major granitic body some tens of kilometers farther to the north must have been already exposed, as shown by the nature of the preorogenic sediments to the north outside the Quadrilátero Ferrífero in the Serra do Cipo and the relations of the granitic rocks with the nearly flatlying postorogenic sediments which now roof them near Lagoa Santa and Vespaziano.

The first event in the post-Itacolomi deformation was probably a partial uplift of the Bação complex and the granitic areas to the south and north which had been formed during the post-Rio das Velhas orogeny. This may even have started during the uplift that caused the deposition of the Itacolomi and the younger, now missing, rocks; and it is believed to have occurred very early in the major deformation, because later stresses were all from the eastern quadrants, and the open Dom Bosco syncline could hardly have been formed by stress from this direction. The southern part of the Moeda syncline, contemporaneous with the Dom Bosco syncline, probably started to form at this time also, caught between the Bação granitic rocks and those to the west. These synclines were open folds at this time. Following this event, the gradual buildup of stress from the southeast and east began, and the rest of the Rio das Velhas uplift took shape, channelized at the north end by the S. 60° W.-trending structure at the north side of the region. The Santa Rita syncline, then possibly trending north-northwest or northwest, was outlined, and the eastern part of the Gandarela syncline and the Conceição anticline began to form, their location governed by the thick quartzite mass now exposed in the Serras das Cambotas and do Tamanduá. The west end of of the Gandarela syncline was part of the east flank of the Rio das Velhas uplift structure, and the west end of the syncline was probably a fold open toward the east, shielded from the west and northwest-trending stress by the great mass of quartzite now forming the Serra do Caraça.

Stress from the east became more severe, folds became tighter and steeper, and finally many folds were overturned. Synclinal keels projected deep into the crust; the recumbent folds of the Cambotas Quartzite (then a sandstone?) formed in the Serra do Caraça. The Vargem do Lima syncline was tightly folded in this part of the deformation, probably before the full development of the Conta Historia syncline. The Santa Rita syncline became steep and was tightly folded against the Caraça monolith at the north end and severly overfolded south of that mass. Cross folding, caused by varying directions of stress and strain, began and modified strongly the original fold and the southern part of the Caraça uplift. Cross folding in the Moeda syncline, less intense than that in the Santa Rita Syncline, also occurred. The east end of the Gandarela syncline was tightly compressed against the thick quartzite of the Serras do Tamanduá and das Cambotas. The west end, in the stress lee of the Caraça mass, remained open. The east end of the Conceição anticline was tightly folded also. Crumpling of less competent rocks reached its apogee, and major rock flowage to relative low stress parts of folds occurred. A massive compression of the crust toward the west and northwest resulted.

Temperatures of the rocks increased, in part owing to downfolding, in part to the deformation, and in large part probably to increasing temperatures caused by the subcrustal activity driving the orogeny. Great mountains may have covered the whole area, only the roots remaining today. Recrystallization and the beginnings of the change of the rocks to metamorphic rocks accompanied increasing temperatures. With compaction and recrystallization and unloading by erosion of overburden, quartzite became more brittle and massive, the plastic iron-formation became brittle itabirite, and the argillaceous rocks slate, phyllite, and schist. Failure by folding gradually ceased as the rocks changed their physical characteristics and yielding began to be by fracturing rather than folding.

The northwestward diminution of metamorphic grade in the east side of the region shows that the higher temperatures were to the southeast, toward the orogenic center, but there is no evidence that a significant temperature gradient affecting regional metamorphism existed in the central and western parts of the region, which are at the same metamorphic grade except where modified by intrusive activity. With many local exceptions, stress seems to have diminished to the northwestward, for foliation and shearing diminish in that direction, and the complexity and tightness of folding also diminished in that direction.

More brittle rocks such as quartzite faulted first, and imbricate systems of minor thrust and tear faults such as those in the Serra do Caraça were formed, probably at the same time that nearby less brittle rocks were still failing by folding. Shearing of quartzitic rocks such as the Maquiné rocks in the Vargem do Lima syncline began, probably synchronously with the plastic bowing toward the northwest and overturning of the Rio das Velhas uplift. The isoclinal folding of the Conceição uplift and further relative vertical movement of the southeast and east side of the Caraça mass occurred, possibly with underthrusting at depth of the tightly squeezed north end of the Santa Rita synclinal zone. The ultramafic dikes and sills, now greenstone schist and talc schist, were probably intruded about this time, and metasomatic hematite bodies in the Cauê Itabirite had formed in part during and shortly before this part of the orogeny.

The major direction of strain seems to have been toward the west, and later the north of west, varying from area to area with local lithologic and structural conditions. Thus, when the main epoch of thrust faulting started, the direction of movement in the south area was east to west, guided by the granitic rocks of the Bação complex and those to the south. Between the salients formed by the Mariana anticline and the Caraça-Conceição uplifts, the principal movements were east to west. North of the Caraça-Conceição uplift the great Fundão thrust fault system had a principally northwest movement. The Fundão fault formed after the east side of the Gandarela syncline could yield no more by folding; it broke and the southeast side moved upward and to the northwest. The west end of the Gandarela syncline had been protected by the monolithic Caraça mass and had escaped most of the folding stress; it moved northwestward only enough to bifurcate the axis of the fold, connecting with the Ouro Fino and Conta Historia synclinal structures by relatively low transverse anticlines which formed saddle folds like that at the north end of the Moeda syncline. One saddle fold was formed by the Conceição anticlinal axis; the other by a lower northeasterly trending anticline, probably formed early in the folding.

The monolith of the Serra do Caraça and the isotropic rocks of the Bação complex seem to have channelized the strain to the northwestward on the west side of the Serra do Caraça. Intense shearing in the southeastern part of the Vargem do Lima syncline parallel to the axis of the fold, the formation of northwest-trending strike faults parallel to the axis of the Conta Historia syncline, and the formation of the system of tear faults related to the thrusts to the south and to the Fundão fault attest rock failure on a large scale with the east side of the faults moving northwest. Clearly, the whole block bounded to the north by the Fundão fault and to the west by the tear-thrust system moved to the northwest. The rootless Ouro Fino syncline, at the edge of the upper plate, was twisted to the northeast and refolded on itself toward the low-stress sheltered area behind the Caraça monolith as the upper plate moved to the northwest. Strong imbricate thrust faulting occurred in the sole of the plate where the Fundão fault merged with the southeast-trending tear fault. This northwest couple imposed strong cross folding in the Cauê Itabirite at the southwest corner of the Gandarela syncline.

The Agua Quente thrust fault may well mark the west limb of another large mobile block, in which dominantly pre-Minas rocks were thrust over Minas Series rocks. There is now no way of measuring the displacement along this fault, but the writer believes the fault to be one of the larger faults of the region.

This period of extreme stress and great crustal shortening undoubtedly further depressed the rocks of the synclinal belts, raised rock temperatures still further, and palingenesis may have occurred at depth. Heat foci, perhaps caused by the movement of fluid magma from depth, perhaps by metasomatizing fluids at depth, perhaps both, developed; and metasedimentary rocks of suitable composition were gneissified and granitized in the region of the Bação complex, forming thermal aureoles. Mobile granitic magma was also emplaced here and elsewhere. It is probable that the eastern and northeastern granites and granitic gneisses formed, largely from Nova Lima Group rocks but also from others, at this stage. The granitic gneiss at the north side of the Bonfim dome and the mobile and other young granites on the north side of the Serra do Curral were also formed and emplaced, as included and intruded rocks show crumpling and deformation similar to those unaffected by the granite.

Perhaps owing to increased plasticity of the subcrust and increasing grain size in the metasedimentary rocks, perhaps owing to some other cause such as a natural ending of the orogenic cycle by dying out of subcrustal activity, the generally east to west strain seems to have ended after relief by the large scale thrust faulting, and no further crustal shortening is recorded in the rocks after the thrust-faulting cycle. None of the major faults seem to be significantly folded. The thrust faults are themselves faulted only along the south border, where the great Engenho fault cut off the thrust plates to the south, and others of the many thrust plates in the southern part of the Dom Bosco syncline were cut by east-west faults. During the relaxation of the stresses and in the later period of adjustment, normal faults developed perpendicular to the trends of the major folds and at 30°–45° to those trends. A few cross faults with major displacement developed at this time or later, after the major folding.

Although much of the granitic rock formed during the post-Itacolomi orogeny was foliated generally parallel to the foliation of the adjacent metasediments (possibly a relict foliation), posttectonic unfoliated granitic rocks, with a rubidium-strontium age from feldspars of about 1,000 million years, were also intruded.

A puzzling feature of the granitic rocks of the Quadrilátero Ferrífero is the common presence, particularly in the east side of the region, of biotite with a potassium-argon age of about 475–500 million years, although the strontium-rubidium age of muscovite and feldspar in the same rocks may be twice as old or older. No granitic rock with a strontium-rubiduim age of the feldspars less than about 1,000 million years is yet known.

The geologic map of Brazil published in 1960 by the Divisão de Geológia e Mineralogia of the DNPM, compiled by A. R. Lamego, shows that the coastal Precambrian shield area is composed of rocks which trend about N. 60° E. from São Paulo to southern Espirito Santo, a distance of about 750 km. A northwest-trending fold axis runs from about Cabo São Thomé on the coast through the Quadrilátero Ferrífero and disappears under the posttectonic São Francisco Series (Late Precambrian?) sedimentary rocks to the northwest. North of this fold axis the Precambrian rocks trend to the north for about 1,500 km. The age of this megastructure is not known, but the youngest Precambrian rocks of Brazil (believed by some to be Cambrian in age), the Lavras Series of northern Minas Gerais and southern Bahia, are involved.

The writer suggests as a working hypothesis that this major flexure may date from about 500 million years ago. At the time of this deformation, although no granitic rocks were formed or intruded in the Quadrilátero Ferrífero, the rocks may have been heated enough to cause leakage of argon from biotite but not enough to greatly disturb the strontium-rubidium ratio in the more stable muscovite and feldspars.

Guimarães has shown that a major period of pegmatite formation occurred at about 450 million years ago, which he related to a "Caledonian orogeny"; conceivably this may represent the period of heating and loss of argon from the biotite of the older granitic rocks.

Toward the end of the Paleozoic or early in Mesozoic time, epeirogenic uplift of this region occurred, and the peneplaned surface began to be dissected. Four major uplifts are here recorded by relict erosion surfaces, correlated by King with the Early Cretaceous, Late Cretaceous, middle Tertiary, and late Tertiary. Many minor uplifts occurred between the major uplifts, leaving intermediate erosion surfaces. In this area there is no evidence for faulting or folding during this interval or to the present.

Although it is conventional to relate the diabase dikes with the Jurassic plateau lavas of São Paulo-Paraná, dated by potassium-argon methods as about 135 million years old (Amaral and others, 1966), there is, as of 1966, no firm evidence for this. Because the diabasic rocks are locally intimately related to the major gabbroic intrusives, also undated, it seems probable to this writer that they may be somewhat older, as the gabbroic rocks are in many places very coarse grained and may well have been intruded at notable depth.

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