Gneissic and Igneous Rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 641-B

Prepared in cooperation with the Departmento 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 NORMAN HERZ

REGIONAL GEOLOGY OF THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL

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A study of the age, composition, and origin of Precambrian igneous and ultrametamorphic rocks in the Brazilian shield

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GNEISSIC AND IGNEOUS ROCKS OF THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL

By Norman Herz

ABSTRACT

In the Quadrilátero Ferrifero, granitic and gneissic rocks form bodies that range from dikes to large complexes. The larger bodies form cores of domes or anticlinorial structures, and the granitic dikes intrude metasedimentary and older rocks. Ultramafic rocks, altered to steatite and serpentinite, intrude the early Precambrian rocks; mafic rocks and amphibolite intrude all Precambrian formations. Other igneous rocks include felsic and mafic metavolcanic rocks in the Nova Lima Group, the Gandarela Formation, and the Sabará Formation.

Absolute age determinations suggest at least five thermal events: about 2,700, 1,930, 1,350, 1,000, and 500 m.y. (million years) ago. All but the 500-m.y. event may have been accompanied by granitic intrusion. Ultramafic rocks were intruded before 2,700 m.y. ago. Mafic instrusions include diabase dikes and gabbro plugs and are of several ages. Some are folded in with the Minas Series and have been metamorphosed; others follow late-formed joint systems. The deformed mafic rocks are both pre- and post-Minas; the undeformed rocks are probably correlative with diabase-gabbro to the south which has been dated around 120 m.y., and suggests a sixth thermal event in this area.

Most granitic and gneissic rocks can be grouped into an earlier suite of granodiorite (Group I) and banded gneiss (Group II) and a later suite of granite (Group III) and gneiss (Group IV). Some group II and IV gneissic rock may have originated by ultrametamorphism of sedimentary rocks, and some I and III granitic rock may have crystallized from anatectic melts. Group I granodiorite of the Bação complex and Congonhas district is presumed to be about 2,700 m.y. old; Group II banded gneiss may have developed early in the 1,350-m.y. orogeny and in earlier events. The Group III granites may have formed later in the 1,350-m.y. event, or after it, and the Group IV gneisses may be 1,350 m.y. old and older. Some granitic rocks, such as in the Moeda complex, are not similar to any described suite, do not show any intrusive relationships with metasedimentary rocks, and cannot be dated with any degree of certainty. The differentiation index (normative quartz + orthoclase + albite) for the older Groups, I and II, is 67.1–92.4 and for the younger Groups III and IV, 85.7–96.1. The highest values may be due, in part, to assimilation of quartzo-feldspathic sedimentary rocks.

In the northwestern Quadrilátero Ferrífero, a younger granite and gneiss and an older granodiorite and gneiss are found. The older granodiorite is in the Bonfim dome of the southeastern part of the Brumadinho quadrangle and extends south and southwest outside the Quadrilátero Ferrífero. It is correlated with the well-banded Itabirito Granite Gneiss found north of the Serra do Curral and in the Bação complex. It is medium to coarse grained, has large augen-shaped microcline crystals, and is well layered in biotite- and felsic-rich layers.

The younger granite and gneiss consist of (1) elongate plutons surrounded by metamorphic aureoles, as at Mazagão; (2) crosscutting veins and dikes in the older layered granodiorite and other rocks; (3) a gneiss with one or two very weak foliation planes found in contact with, or enclosed by, the Minas Series, called in part the Souza Noschese Gneiss; and (4) a highly deformed sericite-epidote-chlorite green feldspar gneiss at Morro da Pedra.

The intrusion of both the older and younger granitic rocks led to the development of a metamorphic aureole in the metasedimentary rocks; garnet and staurolite developed against the contact. At some later date, 500(?) m.y., a widespread mechanical deformation and retrograde chlorite-zone metamorphism led to the development of epidote and chlorite, cataclastic textures, and also a group of mixed gneisses that have been mapped together with the younger gneiss. Some of the young granite and gneiss may have been derived by silica-alkali metasomatism as well as anatexis of older rocks. Albite growth aprons and porphyroblasts in gneiss and quarzite near the Serra do Curral and microcline porphyroblasts in gneiss at some distance from the Serra are evidence for metasomatism.

K/Ar age determinations on gneiss and granite show a regular pattern, as follows:

1. Starting about 8 km south of the Serra do Curral, 462 m.y.;
2. At the south side of the Serra do Curral, 550 m.y.;
3. On the north side of the Serra do Curral, in Barreiro, 595 m.y., and in Belo Horizonte, 800–895 m.y.; and
4. In the Prado Lopes quarry, 5 km north of the Serra do Curral, 1,360 m.y.

Near Sete Lagoas, 55 km north of Belo Horizonte, a whole-rock Rb/Sr isochron showed 1,930 m.y. These data suggest that the thermal event causing the argon loss was related to deformation about 450 or 500 m.y. ago at the Serra do Curral and to the south. Sc content of biotite also suggests relatively high temperatures obtained at the Serra do Curral.

Alkali feldspar from both Groups II and IV gneiss are low-temperature, subsolvus types, metamorphic rather than magmatic; their suggested temperatures of formation are about 400°C. Minor elements Rb and Sr suggest that the Group II gneiss is pretectonic or syntectonic, and that Group IV is post-tectonic.

Ultramafic rocks are found as serpentinite, talc schists, and metagabbro intruding schists of the Nova Lima Group in the Rio Acima and Macacos quadrangles. The serpentinite forms a narrow body about 4 km long, bordered by metagabbro; the talc schist is found in two elongate zones that may represent shear zones. Mafic dikes cut pre-Minas rocks, others are folded in with the Minas, and still others cut all previous structures. Mafic dike rocks in the Raposas mine are foliated and cut pre-Minas iron-formation. Other dike rocks that intrude the Minas

Series were folded and metamorphosed in a post-Minas orogeny. Still a third type does not follow any Precambrian structures and commonly is not metamorphosed. This type includes diabase and porphyritic metadiabase that may be related to the 120-m.y. diabase and basalt to the south in São Paulo.

A granitic complex of about 700 square kilometers consisting of a porphyritic granodiorite surrounded by granite gneiss is found west of the central part of the Serra da Moeda. Both felsic rocks are closely related chemically and may have been produced, in part, from anatectic melts. Age determinations suggest that every event that affected the Quadrilátero Ferrífero was felt here: bordering sediments of the Rio das Velhas Series were intruded and metamorphosed before 2,300 m.y. ago; the coarse porphyritic granodiorite was emplaced at 1,985 m.y. and was affected by an event at about 1,320 m.y.; granite gneiss was formed around the periphery of the granodiorite at 975–1,050 m.y.; and a 500–630-m.y. event recrystallized biotite in the granite gneiss and metasedimentary rocks.

The granite gneiss is medium grained, poorly to well foliated, and consists of abundant microcline, quartz, and oligoclase and of some biotite, chlorite, and muscovite. The coarse porphyritic granodiorite contains microcline grains as much as 25 mm long, albite, quartz, and some epidote, chlorite, sphene, and sericite. Alkali feldspars from both the granite gneiss and porphyritic granodiorite in the contact area are low-temperature (about 400°–430°C), subsolvus types. A mixed gneissic rock was formed at the Rio das Velhas Series contact, but only metasomatic effects are seen at the base of the Minas Series. Amphibolite dikes and quartzite lenses that may be remnants of an ancient pre-Minas sequence are also found in the complex. The complex apparently was a gneiss dome that was reactivated in several Precambrian events and acted as a positive area in all post-Rio das Velhas events.

The Bação complex consists largely of the Engenheiro Corrêa Granodiorite and the well-banded Itabirito Granite Gneiss. The gneiss grades into both migmatites and granodiorite. Foliation in the surrounding sedimentary rocks is not everywhere parallel to that of the gneiss. A metamorphic aureole as high as the garnet-amphibolite facies in the Rio das Velhas Series surrounds most of the complex, but the Minas Series shows little effect of thermal contact. Roof pendants, presumably pre-Minas rocks, are of high metamorphic grade. Alkali feldspars from the granodiorite and gneiss are low-temperature (420°–460°C), subsolvus types; minor elements in biotite also suggest relatively low temperatures for the granodiorite. Results on both minerals imply that the whole area was affected by a regional low-grade metamorphism. The beginnings of the complex are about 2,700 m.y. ago, to judge by the age determinations. Subsequent events may have occurred about 1,930, 1,380, 1,040, and 500 m.y. ago, although the last event was largely thermal and its effects were to lower the apparent ages of older rocks.

The grandodiorite is poorly foliated and fine to medium grained. Microcline phenocrysts are scattered through a groundmass consisting of about half plagioclase, An_{21} (some of which are rimmed by K-feldspar), quartz, biotite, and microcline perthite and by accessory muscovite, magnetite, apatite, zircon, and clinozoisite. The gneiss has well-defined alternating felsic-rich and biotite-rich layers. Microcline phenocrysts are as much as 10 mm in diameter; the groundmass consists of plagioclase (An_{10-15}), microcline, quartz, biotite, and clinozoisite. Both gneiss and granodiorite are intruded by granitic dikes or tourmaline-bearing pegmatites, especially around the margins of the complex. Gneiss having a weak planar orientation is interpreted as highly deformed Itabirito type and yields "mixed" K/Ar ages. The Engenheiro Corrêa Granodiorite, however, is considered to be largely igneous, and the Itabirito, largely the result of ultrametamorphism of the Rio das Velhas Series. In later events, other granitic material formed, in part by anatexis, and intruded largely around the borders of the complex in the style of a mantled gneiss dome. Similarity of minor elements and mineralogy suggest that some gneiss yielded an anatectic melt that also makes up granodiorite layers. Some amphibolites found in and near the complex have diabasic texture; others may have originated as lava flows or as "dirty" carbonate-rich sediments.

Granodiorites are common in the Congonhas area in the southwestern part of the Quadrilátero Ferrífero, and in the nearby Serra do Ouro Branco, thin lenses of granitic gneiss are similar to those found farther north. Age data are not conclusive, but they do show that the area was affected by the 500–m.y. thermal event. Alkali feldspar from the granodiorite is a medium-temperature (570°C), subsolvus type and of probable igneous origin; whereas alkali feldspar from gneiss is of low-temperature (420°C), subsolvus, metamorphic origin. The granodiorite that intrudes the Rio das Velhas Series is composed of a granodiorite-tonalite suite and a more potassic leucogranodiorite suite. The leucogranodiorite has a fine- to medium-grained granitoid texture and is similar to the Engenheiro Corrêa Granodiorite. It is generally massive, except near contacts. The tonalite is similar in minor elements to the leucogranodiorite, but has zoned plagioclase, An_{20-32}, and hornblende which the leucogranodiorite lacks. Both are cut by microcline-rich pegmatites similar to those of the southern Bação complex. Country rock at the contact has been metamorphosed to the garnet amphibolite level; elsewhere, the general metamorphic grade is upper greenschist. The mode of occurrence as well as this contact aureole shows that the granodiorite-tonalite suite is of igneous origin; it may be related to the granodiorite of the Bação complex by anatexis.

Granitic dikes found in the Serra do Ouro Branco have paragenetically late and large perthite crystals in a groundmass of partly crushed albite, microcline, quartz, sericite, biotite, and epidote. They are considered to be either tectonically emplaced near fault zones or of autochthonous metasomatic origin.

Mafic dikes intrude all the Precambrian rocks throughout this area. Altered ultramafic bodies are found in the Congonhas district as massive steatite, serpentinite, and amphibolites derived from rocks that ranged from peridotite to gabbro and intrude into the Rio das Velhas Series.

A body of granodioritic gneiss-porphyritic granodiorite, the Caeté complex, lies between Caeté and Cocais. These rocks are medium to coarse grained and are well banded in places. Along the margins of the body, the gneiss appears to grade into quartz-rich metasedimentary rocks. Highly metamorphosed roof pendants are found within the gneiss. Granodiorite found near Santa Bárbara in the northeastern part of the area is massive in places and gneissic in others, and is cut by unfoliated younger granitic veins. The gneisses and granodiorite are correlated with Group II and are cut in places by Group III granite dikes and a Borrachudos Granite stock. Contact effects have been obliterated by the regional low-grade metamorphism, although evidence of Na- and K-metasomatism is seen in late microcline crystals and albite rims on older feldspars.

Dates obtained on biotite from gneiss (690 m.y.) and granodiorite (810 m.y.) are considered mixed. Alkali feldspar analyses from Santa Bárbara show it to be metamorphic, and to have formed at about 420°C.

Field evidence including transitional facies to quartzitic rocks as well as many crosscutting granitic dikes suggest that the gneissic and granodioritic rocks have a mixed origin. Differentiation indices in the eighties and nineties, high normative quartz and low normative anorthite, and high Y, La, and F in some rocks also suggest mixed origins.

Ultramafic rocks and amphibolites are found in the Caeté area. Mafic dikes and plugs are common in the Caraça region and also as elongate intrusives, especially along the eastern Quadrilátero Ferrífero margin.

Granitic and gneissic rocks underlie most of the northeastern part of the Quadrilátero Ferrífero. They are largely of post-Minas age and granitic in composition, and show both gradational and intrusive contacts with metasedimentary rocks. Relict staurolite, garnet, and kyanite in the metasedimentary rocks suggest high pressure and temperature assemblages that were later masked by a regional greenschist metamorphism that produced chlorite, albite, and epidote in the same rocks.

Radioactive ages based on dates on the post-Minas Borrachudos Granite yield 1,230 and 486 m.y. Other dates in this area show 450–545 m.y. Alkali feldspars show indicated temperatures of 380°–400°C in gneiss and 610°C in the Borrachudos. High Rb and Li in the feldspar and high Nb, Li, Rb, and F coupled with low Mg in biotite also suggest high temperatures of formation, under late magmatic or pneumatolytic conditions.

Four varieties of gneiss show varying degrees of igneous and apparent relict sedimentary textures and structures. They consist commonly of granoblastic aggregates of quartz, plagioclase (An_{10-20}), sheared microcline, micas, chlorite, and clinozoisite. Granodiorites range from tonalite to adamellite. The youngest igneous rock, the Borrachudos Granite, is unique in containing fluorite and large porphyritic perthitic feldspar crystals that range in size between 2 and 5 mm. Biotite, almost pure annite, forms elongate unfoliated knots. Pegmatites are absent from the Borrachudos, although present in the granodiorites.

Ultramafic and mafic rocks in the Itabira district are intrusive into the Rio de Velhas Series and include soapstone, serpentinite, and talc schist. Metagabbroic rocks throughout the area are largely amphibolites.

The following igneous cycle was repeated two or more times:

1. High-grade metamorphism, perhaps to granulite facies level;
2. Formation of anatectic liquids and crystallization of granodiorites and gneisses; and
3. Introduction of some liquids of granitic composition and the formation of granites.

A low-grade regional metamorphism, structural deformation and alkali metasomatism associated with thermal gradients occurred one or more times. Temperatures associated with these later events were 380°–430°C; temperatures of earlier, largely igneous events were 570°–610°C.

Tie lines for coexisting feldspars are parallel the Or-Ab join in an anorthite-albite-anorthite triangular diagram, suggesting low metamorphic temperatures. On a normative quartz-albite-orthoclase "residua" diagram, older granodiorites and younger granites fall within a low pressure-temperature trough, the older being more albitic than the younger.

Differentiation indices for the granodiorites and older gneisses range from 67.1 to 92.4, whereas the granites and younger gneisses range from 85.7 to 96.1. Differentiation trends of oxides of the older rocks seem to be similar to igneous rocks elsewhere. The serpentine-steatite rocks are chemically and texturally metamorphosed ultramafics. The later mafic rocks are TiO_2-rich and have quartz in their norms. They are largely metamorphosed or unmetamorphosed rocks of gabbroic to diabasic composition.

INTRODUCTION

This report is one in a series based on geologic investigations in the Quadrilátero Ferrífero since the end of 1946. The program was financed by both the Brazilian Government, through the Departamento Nacional da Produção Mineral (DNPM), and the American Government, through the Technical Assistance Program of the U.S. Department of State. Seventeen geologists did the mapping, 15 from the U.S. Geological Survey and two from the DNPM. The general program was under the supervision of J. V. N. Dorr 2d, in Belo Horizonte, and W. D. Johnston, Jr., in Washington, D.C. The Brazilian part of the program, including support for laboratory services, field assistants, topographic and aerial coverage, was under the supervision of Dr. José Alves, Chief of the Belo Horizonte office of the DNPM, and Dr. Avelino I. de Oliveira, Director of the DNPM, in Rio de Janeiro. Photomicrographs were taken by Dr. E. Ribeiro Filho, University of São Paulo.

Dr. Djalma Guimarães, Chief of the Serviço de Geologia e Geoquímica of the Instituto de Tecnologia Industrial of the State of Minas Gerais, provided laboratories for chemical and spectrographic analysis and also for rock-sample preparation.

This study of the entire area would not have been possible without the full cooperation of the Brazilian and American geologists who worked on the Quadrilátero Ferrífero mapping program. However, since the primary aim of the program was a study of the ore deposits, and because of the limitations of time, the field geologists devoted relatively little effort to the igneous rocks. They provided preliminary maps and reports to me in advance of publication and made available their rock collections and thin sections. In all, more than 1,500 thin sections prepared for other geologic purposes were studied. They also read and discussed the different parts of this report that pertained to their field areas. J. E. Gair and J. V. N. Dorr 2d read various revisions of this report critically, for which I am deeply indebted.

Regional correlations of the granitic rocks were attempted by a few field men and myself, but we were hindered by the limitations of time, the scarcity of fresh rock, and the difficulty of access into areas underlain by igneous rock. Most of this paper is based on the collections, maps, and reports of other geologists, plus study of thin sections, some detailed mapping, and samples that I collected for this and certain other studies. The amount and kind of information available for different parts of the area varies widely, depending on accessibility and what was considered important to the areal mapping. Because of this, some parts of the Quadrilátero Ferrífero are better described in this report than others, and most of the conclusions must be drawn from these better known parts.

PREVIOUS WORK

Some previous workers have described two distinct granitic types, one of which was an "Archeozoic" basement complex, and the other, a later granodiorite (Barbosa, 1949, p. 5, 8–9). In places where the contact between the "basement" and the younger Minas Series is well exposed, it appears to be conformable with bedding in the metasedimentary rocks parallel to foliation in the gneiss (fig. 1). Von Freyberg (1932, p. 21–23) and Guild (1957, p. 11) both described this contact in detail and questioned the age assignment of the "basement" gneiss. In Salto, in the Jeceaba quadrangle, Guild found the uppermost part of the gneiss unusually rich in quartz and differing from the overlying quartzite of the Moeda Formation chiefly in that the quartz was coarser and was associated with muscovite. The later granodiorite was also described by Guild (1957, p. 26–28), who found that it intruded as stocks, batholiths, and dikes into rocks now recognized as both the Nova Lima Group and Minas Series.

FIGURE 1.—Contact between basal rocks of the Minas Series (left) and granite gneiss, near Salto, Jeceaba quadrangle. Apparent bedding of metasedimentary rocks and foliation of gneiss are almost parallel.

Guimarães (1951) regarded the principal period of granite formation to be early Precambrian and the time of mafic intrusions to be later Precambrian. However, he did recognize some granitization and remobilization of earlier formed rocks during later orogenies.

REGIONAL GEOLOGY

Rocks of sedimentary origin in the Quadrilátero Ferrífero have been divided into three series, from oldest to youngest:

1. Rio das Velhas Series, subdivided into two groups, the Nova Lima and Maquiné.
2. Minas Series, subdivided into four groups, the Tamanduá, Caraça, Itabira, and Piracicaba. The Caraça is divided into the Moeda and Batatal Formations; the Itabira, into the Cauê Itabirite and the Gandarela Formation; and the Piracicaba, into the Cercadinho, Fêcho do Funil, Taboões, Barreiro, and Sabará Formations.
3. Itacolomi Series.

The general stratigraphic and structural relations of these rocks have been discussed on a regional basis by Dorr (1969).

Large complex masses of granitic and gneissic rocks intrude these metasedimentary rocks and generally form the cores of domes or anticlinorial structures. Dikes of similar rocks also intrude metasedimentary rocks, and some granitized rock occurs in the axial parts of folds. Some of the complexes, such as the one around Bação (pl. 1), have been thought to be horst structures (Guimarães, 1951, p. 18). Two different types of ferromagnesian intrusions have been mapped, a predominantly ultramafic suite and a gabbroic-dioritic suite. The ultramafic suite is restricted in occurrence, but the mafic suite is found in almost every quadrangle.

GRANITIC ROCKS AND GNEISSES

Granitic complexes are found west of the Serra da Moeda and south of the Serra dos Tres Irmãos (pl. 1); east of the Serro do Itabirito, in the region of Itabirito-Cachoeira do Campo-Engenheiro Corrêa; east of Caeté and north of the Serra do Tamanduá; in the general region and south of Jeceaba-Congonhas do Campo; north of the Serra do Curral and Serra da Piedade; east of Santa Bárbara; and in the general regions of Itabira and Monlevade. Except for certain coarse-grained varieties, granitic rocks throughout most of the area weather relatively rapidly and deeply, and therefore underlie gently rolling hills that are at lower altitudes than the more resistant metamorphic rocks. Structures and textures are preserved in many outcrops of saprolite and thus give an idea of the original mineralogy and rock type. In general, however, mapping and collecting of specimens is difficult; fresh rock is hard to find, and a second-growth jungle vegetation (mato) flourishes on the granite-derived soil. In all probability, future workers in this area, as elsewhere in Brazil, will rely on heavy-mineral suites to make detailed correlations of granite and gneiss.

The granitic and gneissic rocks are assigned to four general types, on the basis of field, petrographic, chemical, and age-determination data. Two of these types, an older, Group I granodiorite, and a younger, Group III granite, appear to be igneous, and two are gneissic (Groups II and IV).

Many gneissic rocks appear to show inherited sedimentary structures; layered gneisses include and grade into quartzite and biotite schist of almost certain sedimentary origin. Parts of the gneisses may have originated by ultrametamorphism of such sedimentary rocks in early Precambrian time. In later orogenies, a palingenetic magma may have been produced and intruded into younger sediments. Chemical evidence for remobilization of older rock in later intrusions is seen in the similarity of trace-element suites of different granitic and gneissic rocks (Herz and Dutra, 1958). Such an anatectic melt would be rich in quartz and alkali feldspar and can be produced from a variety of sedimentary rocks at temperatures of about 700°C (Winkler and Von Platen, 1961). Basement granitic rocks might then appear to intrude sediments that were deposited over them unconformably.

A widespread low-grade greenschist metamorphism accompanied locally by mechanical deformation that produced cataclastic textures (fig. 2) has made it difficult to extrapolate the original mineralogy and rock textures. Resulting assemblages in many gneisses include albite, epidote, and chlorite, all metamorphic in origin. The possibility that some of these gneisses were originally granulites and not granites is suggested by a "granulitic fabric" (Williams and others, 1954, p. 236)—that is, schistosity due to elongated coarse quartz grains alternating with layers of fine-grained quartz and feldspar (fig. 3). In the fine-grained layers, coarse plagioclase porphyroblasts with clinozoisite inclusions and epidote-chlorite knots are present. The plagioclase-clinozoisite pair represents an originally higher calcic plagioclase, and the epidote-chlorite may have been derived from pyroxenes or amphiboles.

In the present classification (below), two Groups, I and II, show granodioritic affinities and are oldest, Group I possibly being older than Group II; Group III has granitic affinities, and is clearly the youngest of the entire area; and Group IV generally appears younger than the first two, but, in places, its relationship to them is not clear.

Group	*Gneiss or granite rock*
I.	Engenheiro Corrêa Granodiorite
II.	Itabirito Granite Gneiss
III.	Young granites such as the Borrachudos
IV.	Younger and mixed gneisses.

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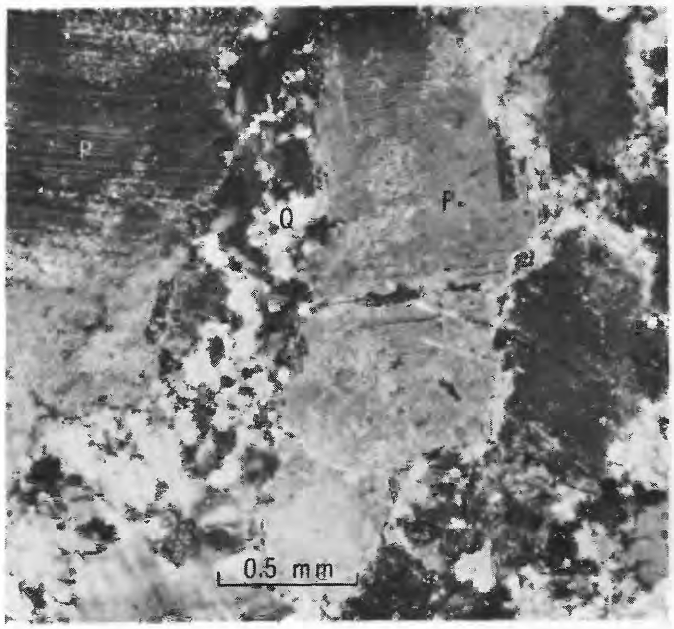


FIGURE 2.—Photomicrograph showing cataclastic texture in granite gneiss from Barreiro, sample, Ha-14-Y. Large plagioclase crystal (P) is broken and partly replaced by fine-grained muscovite and granular clinozoisite. Quartz mortar (Q) fills in around grains. Crossed nicols.

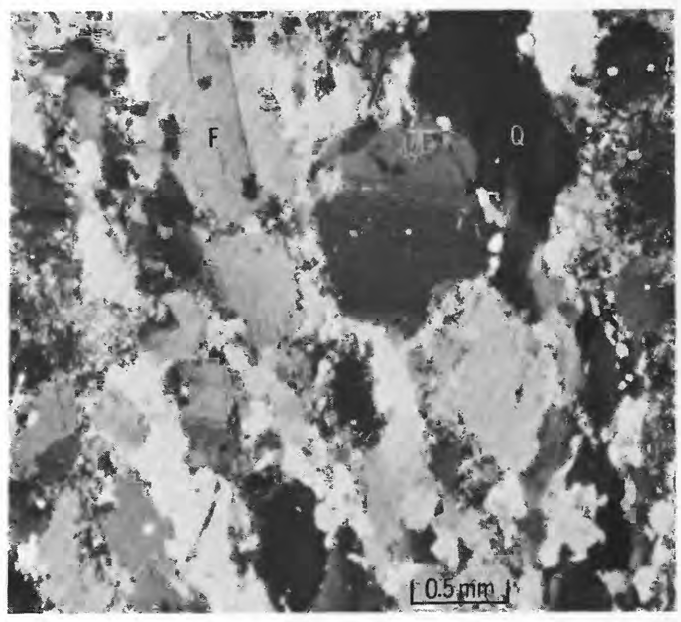


FIGURE. 3.—Photomicrograph showing relict granulitic texture in granitic gneiss from Barreiro, sample Ha-14. Many quartz grains (Q) are elongate, as are feldspar (F), and make up the foliation plane. Other minerals are granular, finer grained epidote, muscovite, and biotite. Crossed nicols.

In addition to these, other distinctive rocks, such as the porphyritic granite of the Moeda complex, have been mapped in limited areas and so cannot be assigned to a group. The rocks of the Monlevade district, including the Monlevade Gneiss of the Rio das Velhas Series and the Bicas Gneiss of the Piracicaba Group (Reeves, 1966), are included with the group of youngest granites and gneisses (Group IV) because similar rocks in Itabira belong to this younger group.

Group I, the Engenheiro Corrêa Granodiorite, appears to be the oldest and has been identified with certainty only within the Bação complex. Granodiorite of the Congonhas area is probably similar to this, and ancient granodiorite must have also been present elsewhere, including the Moeda complex, to judge by the 2,300-m.y. Sr/Rb date for Ha-23 (table 2). These granodiorites were igneous in origin, although some may have formed by a melt of syntectic origin.

Group II includes the Itabirito Granite Gneiss, which in different places, appears to be older, younger, or the same age as the granodiorite. It underlies most of the Bação complex and much of the region north of the Serra do Curral. The gneisses found about 5 km south of the Serra dos Tres Irmãos and 12 km west of the Serra da Moeda, and those near Caeté, Cocais, and Santa Bárbara are probably equivalent. These rocks have well-developed felsic- and biotite-rich layers. In places, they show flow-structures, implying an igneous origin, as at the Prado Lopes quarry in Belo Horizonte. In other places, however, probable granitization features are seen, such as gradational contacts with Rio das Velhas metasedimentary rocks, as in the Rio de Pedras quadrangle, northeast of the Bação complex (J. E. O'Rourke, written commun., 1954). These granite gneisses probably formed, in part, by anatexis of the granodiorite, in part by mobilization and partial melting of ancient sediments.

The Engenheiro Corrêa Granodiorite (Group I), and the Itabirito Granite Gneiss (Group II), and their correlatives compose the older suite of granitic rocks and gneisses.

Group III, the younger granites, such as the Borrachudos Granite of the northeastern Quadrilátero Ferrífero and the Marzagão granite gneiss, north of the Sabará quadrangle, are intrusive and discordant into all other Precambrian rocks. These are the most silicic and potassic, by far; they form stocks that show no planar structures, as at Borrachudos, or small bosses that have a strong foliation, as at Marzagão. They also form discordant unfoliated dikes, as in the older granitic gneiss of Barreiro, and apparently concordant lenticular bodies that show more than one weak foliation plane, as in the Serra do Ouro Branco. These granites are igneous in origin, and their intrusion has thermally metamorphosed or metasomatized rocks of the Minas Series in places. North of the Serra do Curral, pelitic rocks of the Sabará Formation were netamorphosed to staurolite-garnet assemblages. To the south, away from the granite contact, the degree of metamorphism diminishes. Where granite is in contact with quartzitic rocks of the Moeda Formation, for example, west of the Serra da Moeda, metasomatic effects include the development of feldspar porphyroblasts in quartzite and veins of tourmaline and quartz or, perhaps, kyanite and quartz.

Most of the granitic facies that range in composition from granite to quartz-monzonite do not show any tectonic features. The granites are generally coarse grained in the east and show a well-developed linear structure caused by elongate clusters of biotite. These young granites may contain abundant coarse microcline-perthite phenocrysts as much as several centimeters in diameter.

Group IV, younger and mixed gneisses, makes up the largest felsic rock group and include rocks intimately associated with metasediments of the Minas Series, and older Group II gneisses that were mobilized to some degree during later events. These gneisses commonly strike parallel to, and are in contact with, rocks of the Minas Series; away from the Minas Series they are in contact with an older granite or gneiss. They are fine grained to medium grained, and generally have abundant augen-shaped K-feldspar phenocrysts. In the west especially, the Group IV gneiss shows more than one plane of foliation; in the eastern part of the area, the gneiss is well layered. Mixed gneisses are especially common in many places, including the Bação complex, in the Piracicaba Group of the Serra do Curral, and the eastern part of the area.

In a late metamorphism, 500(?) m.y. ago, in the western part of the area, rocks were not remobilized, but metamorphic features, such as crystallization of albite, chlorite, and epidote; development of a weak fracture cleavage; and some rheomorphism took place. In the eastern part of the area, metamorphic grade is higher; the youngest gneisses were locally more completely recrystallized to form biotite, amphiboles, and garnet, and developed a pronounced layering and foliation, with the result that some of them now strongly resemble the older granite gneisses. The younger and mixed gneissic rocks seem to be a result of the mixing of possible anatectic solutions with older rocks or of mechanical deformation of the older rock followed by recrystallization.

MAFIC AND ULTRAMAFIC ROCKS

Small bosses, stocks, and dikes of ultramafic rock that intrude both gneissic rocks and the Rio das Velhas Series have been metamorphosed largely to serpentinite, talc and chlorite schist, steatite, and similar rocks. Mafic rocks, of dioritic to gabbroic composition, occur only as dikes or small bosses and intrude either pre-Minas or Minas rocks; some dikes have been mapped continuously for several kilometers. Several types of amphibolite are found: some may represent metamorphosed lava flows or "dirty" carbonate-rich sediments, but most are metadiabase or gabbro. They occur as dikes and sills in both pre-Minas and Minas rocks.

Mafic and ultramafic rocks weather to a distinctive dark-reddish-brown soil and are most commonly mapped on the basis of this soil. In many areas, serpentinites and similar rocks weather to knobby or blocky outcrops, and fresh rock may be preserved inside a rind of highly weathered material. Some mafic and ultramafic rocks have been mapped only from aerial photographs by study of deep erosional and characteristic vegetation pattern.

MAFIC ROCKS

In the northern part of the Quadrilátero Ferrífero, diabasic and gabbroic plugs, dikes, and sills intrude all Precambrian rocks. Guimarães (1933) has called these rocks collectively amphibolite. In Itabira (Dorr and Barbosa, 1963, p. 46) the mafic dikes show chilled margins and range in thickness from 0.5 to 5 m and may be several kilometers in length. Ophitic texture is seen even in badly weathered dikes. Fresh samples consist of plagioclase, either oligoclase or andesine commonly replaced by clinozoisite, sericite, albite, and quartz; pyroxene is diopside or, in places, pigeonite, commonly altered to tremolite-actinolite or chlorite; accessory minerals are ilmenite, sphene, leucoxene, apatite, and sulfides.

Diorite-gabbro bodies intrude Minas Series and pre-Minas rocks and cut all Precambrian structures. They are here assumed to be correlative with the diabase-gabbro dikes and plugs in the State of São Paulo which have been dated at about 120 m.y., or middle Early Cretaceous (Amaral and others, 1966).

Some diabase dikes seem to be older than those described above and have been folded in with Minas and older sedimentary rocks. In the Raposas mine, beds of pre-Minas iron-formation are cut by folded diabase dikes 15–50 m thick; these dikes are almost completely altered to chlorite schist, and the alteration is least intense near the center of the dikes (Tolbert, 1964, p. 781). Wallace (1965, p. 27) found that some diabase dikes are folded with Minas rocks, but that others follow northeast- and northwest-trending joint systems. Fresh diabase samples had about equal parts of labradorite and hornblende and also accessory pyrite, apatite, biotite, clinozoisite, and magnetite. The folded dikes and associated amphibolites are both pre- and post-Mir as in age, but all are Precambrian in age.

Some amphibolites in pre-Minas metasedimentary rocks may represent metamorphosed gabbroic rocks. These rocks have relict gabbroic textures and a bulk chemical composition that indicate an original gabbro mineral assemblage. An amphibolite in pre-Minas rocks yielded an age of 2,675 m.y. (table 2, DTM–2) which represents recrystallization and suggests that some of these rocks may be older than the 2,700-m.y. orogeny.

Diabaselike rocks of porphyritic texture (figs. 11, 12) in the Ibirité and Catas Altas quadrangles and elsewhere have been metamorphosed. They intrude the Cambotas Quartzite in the Catas Altas and the Minas Series in the Ibirité quadrangles and are considered equivalent to the diabase dikes.

ULTRAMAFIC ROCKS

Ultramafic rocks intrude only early Precambrian formations, except perhaps east of the Serra do Caraça. In the Congonhas and Nova Lima districts, large sills and stocks represent altered peridotites, dunites, and other similar ultramafic rock types. In the Congonhas district, Guild (1957, p. 25) mapped bodies of talc-, antigorite-, and tremolite-bearing rocks in which these minerals show outlines of former olivine and pyroxene crystals. In the Nova Lima district, Gair (1962, p. 44) mapped elongate serpentinite bodies, small metagabbro stocks, and talc schists, which are petrographically similar to rocks in the northeastern part of the area mapped by Dorr and Barbosa (1963).

ABSOLUTE AGE DETERMINATIONS

Most of the granitic rocks of the area have been previously assigned one of three ages, about 2,400, 1,350, or 500 m.y., on the basis of K^{40}/Ar^{40} determinations on micas by the laboratories of the Massachusetts Institute of Technology (Herz and others, 1961). Many ages fell in the range between 1,350 and 500 m.y. and were considered "mixed," the results of a loss of Ar^{40} from mica during an event that occurred 500 m.y. ago.

More recently, K^{40}/Ar^{40} and also Rb^{87}/Sr^{87} ages were determined by Aldrich and others (1964) on micas and feldspars from different parts of the central and west-central Quadrilátero Ferrífero. The U.S. Geological Survey also determined three Rb^{87}/Sr^{87} ages on K-feldspar (table 1). The M.I.T. laboratories determined whole-rock ages from near Sete Lagoas, about 55 km north-northwest of Belo Horizonte (Pinson and others, 1967). All dates determined thus far on samples from the Quadrilátero Ferrífero in different laboratories are given in table 2 and are shown by the histogram in figure 4. Because Rb/Sr ages are less susceptible to change by metamorphism than are K/Ar ages in all minerals studied (Hart, 1964), Rb/Sr ages should be credited more than the K/Ar ages.

TABLE 1.—Rb^{87}/Sr^{87} *age determinations of K-feldspar from granitic rocks*

[Analysts: C. E. Hedge and F. G. Walthall, U.S. Geological Survey. Constants used: $Rb^{87}\lambda\beta = 1.47\times10^{-11}$/yr; Rb^{87} = 0.283 g/g Rb. Rb and Sr determined by mass spectrometric isotope dilution. For sample locations, see table 3]

Sample	Rb^{87} (parts per million)	Normal Sr (parts per million)	$^{*}Sr^{87}$ (parts per million)	$^{*}Sr^{87}/Sr^{87}$ total	$^{*}Sr^{87}/Rb^{87}$	Age (m.y.)
Ha-4	74.0	682	1.18	0.024	0.0159	1,080±400
Ha-10	253	12.2	4.62	.84	.0183	1,230± 60
Ha-28	51.8	54.7	1.27	.25	.0244	1,640±100

*Radiogenic.

Even more precise than one Rb/Sr measurement of a mineral is the whole-rock Rb/Sr technique, in which an isochron is drawn up to show original age. This was done for rocks of the Farnetti quarry, 3 km south of Sete Lagoas and about 55 km north-northwest of Belo Horizonte (Pinson and others, 1967). On the basis of the isochron determination and the histogram showing other mineral determinations within the Quadrilátero Ferrífero, at least five events seem to have taken place:

1. The oldest, about 2,700 m.y., suggested by three Rb/Sr and one K/Ar determination,
2. About 1,930 m.y., shown by the Sete Lagoas whole-rock isochron and one Rb/Sr determination,
3. About 1,350 m.y., suggested by three Rb/Sr and two K/Ar determinations,
4. About 1,000 m.y., suggested by three Rb/Sr and two K/Ar determinations, and
5. The youngest, about 500 m.y., suggested by five Rb/Sr and 15 K/Ar determinations.

A sixth event, at 120 m.y., is suggested by diabase dikes and gabbro plugs similar to dated rocks to the south in the State of São Paulo (Amaral and others, 1966).

TABLE 2.—*Mineral age determinations*

[For sample locations see table 3 and pl. 1]

Sources of data:
(1) Department of Terrestrial Magnetism, Carnegie Institution of Washington. For analytical data, see Aldrich and others (1966).
(2) Massachusetts Institute of Technology, Department of Geology and Geophysics. For analytical data, see Herz and others (1961).
(3) U.S. Geological Survey. Analytical data, table 1.

Minerals and determinative systems used:
K = K^{40}/Ar^{40}
Rb = Rb^{87}/Sr^{87}
b = biotite
m = muscovite
f = K-feldspar

Sample	≥2,300 m.y.	1,640–1,985 m.y.	1,230–1,420 m.y.	975–1,080 m.y.	690–895 m.y.	≤640 m.y.
DTM-3	2,790 Rb/m (1)	1,700 K/m (1)				
2	2,675 Rb/m (1)			975 K/m (1)		
Ha-4	2,400 K/b (2)			1,080 Rb/f (3)		
23 (=DTM-4)	2,300 Rb/f (1)					600 K/b (2). 610 K/b (1). 530 Rb/b (1).
DTM-6		1,985 Rb/f (1)	1,320 Rb/b (1)		850 K/b (1)	
Ha-28		1,640 Rb/f (3)		1,060 K/b (2)		
DTM-1			1,420 Rb/f (1)			495 Rb/b (1).
Ha-16			1,360 K/b (2)			
2			1,340 K/b (2)			
10			1,230 Rb/f (3)			486 K/b (2).
DTM-7				1,050 Rb/f (1)		630 Rb/b (1). 640 K/b (1). 470 K/f (1).
5				975 Rb/f (1)		510 Rb/b (1). 420 K/b (1).
Ha-15					895 K/b (2) 800 K/b (2)	
29					870 K/b (2)	
19					810 K/b (2)	
26					790 K/b (2)	
3					740 K/b (2)	
25					740 K/b (2)	
18					690 K/b (2)	
14						595 K/m (2).
13						550 K/b (2).
DTM-8						545 Rb/f (1).
Ha-11						530 K/m (2).
21						514 K/b (2).
7						500 K/b (2).
33						493 K/b (2).
24						462 K/b (2).
6						460 K/b (2). 450 K/m (2).

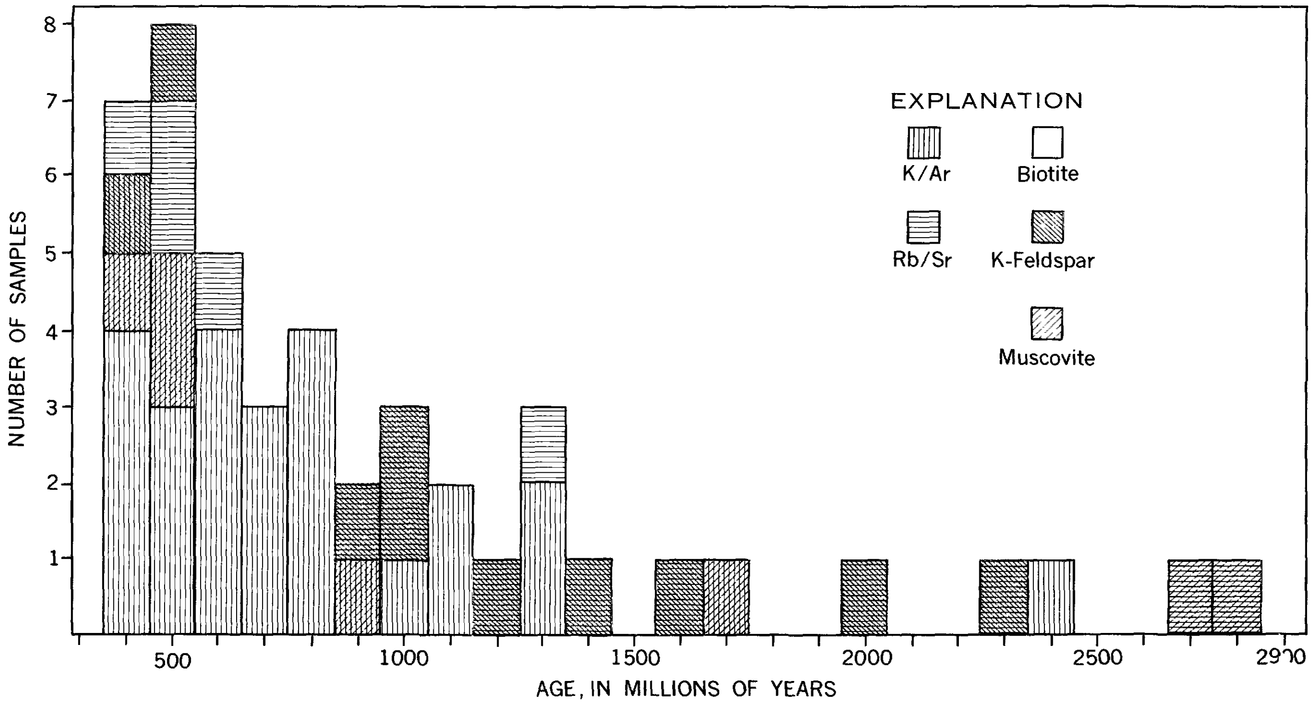


FIGURE 4.—Histogram of age determinations. Based on table 2.

The dates that range from 1,640 to 1,700 m.y. and from 690 to 895 m.y. (table 2) should be considered mixed until more data are accumulated. The older of the two time intervals is represented by only two analyses, and the 690–895 range is based only on K/Ar analyses. The data do show that the Quadrilátero Ferrífero is a "noisy area" and that all older rocks have been affected by each succeeding event. The youngest dated event, which produced some pegmatites, was probably largely only thermal in most of the area, and caused a loss of Ar which lowered the apparent K/Ar ages of many micas.

Based on Pb/U chemical analyses of pegmatite minerals from various parts of Minas Gerais, Guimarães (1958, p. 200) suggested 1,236 m.y. for the close of the Archeozoic; 1,064 m.y. for the post-Minas, pre-Itacolomi orogeny; 800 m.y. for a post-Itacolomi orogeny; 550 m.y. for the close of the Precambrian; 450(?) m.y. for an epeirogenic Taconic orogeny; and 375 m.y. for a Caledonian orogeny.

On the basis of the absolute age determinations, and also field data, the following chronology is proposed:

1. Deposition of Rio das Velhas Series, and perhaps even earlier sediments, older than 2,700 m.y. (DTM–3).[1]
2. Intrusion of ultramafic and also some mafic igneous rocks (DTM–2).
3. Emplacement of a granodiorite (Group I) in the area of the Bação complex (Ha–4), and perhaps also west of the Serra da Moeda (Ha–23) at about 2,700 m.y. Formation of banded gneiss (Group II), in part from alkali-silica-rich anatectic solutions derived from older sedimentary rocks and igneous rocks. Emplacement of granite west of the Serra da Moeda (DTM–6) and northwest of the area around Sete Lagoas about 1,930 m.y.
4. Deposition of Minas Series.
5. Deposition of the Itacolomi Series. (May coincide with the start of 6.)
6. Renewed igneous activity in the Moeda (DTM–6) and Bação complexes (DTM–1, Ha–2), emplacement of granodiorite and granite (Group III) with large xenoliths north of the Serra do Curral (Ha–16), and a postmetamorphic granite (Group III) in the east (Ha–10) at about 1,350 m.y. Much of this granodiorite and granite has felsic- and biotite-rich bands, and, in places, appears to grade into metasedimentary rock (Group IV). The post- or late-tectonic granite shows discordant contacts with country rocks.
7. An event about 1,000 m.y. ago in the Bação complex (DTM–2, Ha–4, Ha–28), and in the Moeda complex (DTM–5, DTM–7) may have produced an anatectic magma (Group III). Intrusion of mafic dikes(?).

[1] Analyses for samples in parentheses are given in table 2.

8. A thermal event about 500 m.y. ago, or perhaps two at 550 and 450 m.y., resulted in the loss of much argon, especially from micas. Pegmatitic intrusions in at least the eastern part of the area (DTM-8).
9. Intrusion of diabase sills and small gabbroic stocks, about 120 m.y. ago, presumably related to those in the State of São Paulo (Amaral and others, 1966).

ANALYTICAL TECHNIQUES

Most chemical analyses shown in this report represent 1-pound separates of fresh rock that were split down from rock samples on the order of 40 pounds collected from outcrops. Locations for all analyzed samples are given in table 3. The major element analyses were done in the laboratories of the U.S. Geological Survey in Washington, D.C., by the rapid chemical methods described by Shapiro and Brannock (1956). Analysts were P. L. D. Elmore, I. H. Barlow, S.D. Botts, G. W. Chloe, M. D. Mack, and H. H. Thomas. Fluorine was determined in some samples by S. M. Berthold, U.S. Geological Survey, Washington, D.C.

TABLE 3.—*Locations and descriptions of analyzed samples*

[Most sample localities are shown on pl. 1; their locations here are given as distance in meters from a corner of the quadrangle. For example, S 100 E 100 would be 100 m south and 100 m east of the northwest corner; N 100, W 100 would be 100 m north and 100 m west of the southeast corner. Samples from outside the Quadrilátero Ferrífero are located on 1:250,000 scale maps of the Conselho Nacional de Geografia or on prominent highways]

Sample No.	Quadrangle	Location		Notes	Where referred to in this report
Ha-2	Itabirito	N 280,	W 6,660	Itabirito quarry, migmatitic granodiorite gneiss.	Tables 2, 8; p. 9, 26; figs. 17, 26*A*, 27.
3	Cachoeira do Campo.	N 4,200,	W 6,200	Banded granodiorite gnêiss	Tables 2, 8; p. 26, 28; figs. 16, 26*A*, 27.
4	Bação	N 720,	W 1,640	Engenheiro Corrêa, weakly foliated layered granodiorite.	Tables 1, 2, 8; p. 9, 26, 27, 40; figs. 25, 26*A*, 27.
5	do	N 5,300,	E 2,200	Saboeira quarry, well-layered granodiorite 5L=light-colored part; 5D=dark-colored part.	Table 8; p. 27, 33; figs. 15, 26*A*, 27.
6	Itabira	S 4, 900	W 2,600	Granodiorite gneiss	Tables 2, 15; p. 42, 44, 45, 47; figs. 23, 25, 26*B*.
7	do	S 3,600,	W 2,450	Mixed gneissic-granitic material, 7P=pegmatite.	Tables 2, 15; p. 42, 44; fig. 26*B*.
8	do	S 4,700,	W 8,700	Borrachudos Granite	Table 15; p. 44, 45, 46, 47; figs. 25, 26*B*.
10	São Gonçalo	N0,	E 2,300	Petí phase, Borrachudos Granite	Tables 1, 2, 14, 15; p. 9, 43, 43, 44, 45, 46, 47, 49; figs. 24, 25, 26*B*.
11	Dom Bosco	N 2,850,	W 3,000	Granite gneiss with K-feldspar porphyroblasts.	Tables 2, 9-10, 11; p. 31, 32, 33, 34; figs. 19, 25, 26*B*.
12	Ibirité	N 1,600,	E 8,000	Poorly layered younger gneiss	Table 4; fig. 26*B*.
13	do	N 2,700,	E 3,200	Poorly layered younger gneiss, K-feldspar porphyroblasts.	Tables 2, 4; p. 13, 16; fig. 26*B*.
14	From northeast corner. Ibirité	N 500,	W 1,050	Older banded gneiss (14-O) cut by unfoliated younger granite (14-Y).	Tables 2, 4; p. 13, 17, 18; figs. 2, 3, 9, 26*A*, *B*, 27.
15	Belo Horizonte	N 6,000	E 3,600	Morro da Pedra, green feldspar younger granite.	Tables 2, 4; p. 13, 18; figs. 25, 26*B*.
16	do	S 2,800,	E 5,100	Prado Lopes quarry, well-banded older granite gneiss; 16P=pegmatite.	Tables 2, 4; p. 9, 13, 15, 18; figs. 5, 25, 26*A*, 27.
18	Cocais, ½	S 0,	W 4,700	Granodiorite gneiss	Tables 2, 12, 10d; p. 36, 37, 38, 39.
19	Santa Bárbara	N 5,100,	W 3,700	Gneissic granodiorite	Tables 2, 12; p. 36, 37, 38, 39, 40; figs. 25, 26*A*, 27.
21	From southwest corner Marinho da Serra.	N 5,000,	W 6,000	Porphyritic (1-3 mm feldspar) granite.	Tables 2, 6, 7; p. 21, 22, 23; figs. 25, 26*B*.
22	Marinho da Serra	S 4,700,	E 2,800	Coarse porphyritic (to 2 cm microcline) granite.	Tables 6, 7; p. 22; fgs. 25, 26*B*.
23	do	S 4,000,	E 4,400	Gneiss at Rio das Velhas granite contact.	Tables 2, 6, 7; p. 6, 9, 21, 22, 24, 25.
24	Casa de Pedra	S 6,350,	E 1,100	Granodiorite gneiss	Tables 2, 10, 11; p. 23, 31.
25	Congonhas	N 650,	E 4,100	Tonalite	Tables 2, 10, 11; p. 31, 33.
26	Jeceaba	S 450,	E 1,300	Granodiorite gneiss	Tables 2, 10, 11; p. 31.
27	do	N 2,900,	E 1,850	Amphibole-bearing granodiorite	Tables 9, 10, 11; p. 31, 32, 33, 49; figs. 17, 25, 26*A*, 27.
28	Itabirito	S 6,010,	W 2,800	Coarsely layered granodiorite gneiss.	Tables 1, 2, 8, p. 9, 26, 27; fig. 25.
29	do	S 6,850,	W 6,050	Granodiorite	Tables 2, 8; p. 26.

TABLE 3.—*Locations and descriptions of analyzed samples*—Continued

Sample No.	Quadrangle	Location	Notes	Where referred to in this report
30	Caeté	S 650, W 5,450	Quartzose older gneiss	Table 12; p. 37, 38, 40; fig. 26*A*.
31	Gongo Sôco	S 5,350, E 4,400	Older gneissic granite	Table 12; p. 37, 40; fig. 26*A*, 27.
32	Fecho do Funil ½	S 5,880, E 3,270	Souza Noschese Gneiss	Table 4; fig. 26*B*.
33	Brumadinho ½	N 1,800, W 6,320	Granodiorite at Alberto Flôres	Tables 2, 4; p. 13, 18; figs. 7, 26*A*, 27.
34	do	N 1,800, W 6,320	Younger unfoliated granite crosscutting Ha–33.	Table 4; p. 13, 17; fig. 26*B*.
35	Brumadinho ½	N 3,200, W 3,400	Granodiorite gneiss	Table 4; figs. 26A, 27.
36	Monlevade	S 4,380, W 4,860	Poorly foliated granitic gneiss	Table 15; p. 43, 44; fig. 26B.
38	São Gonçalo ½	N 2,200, W 2,100	Coarse-grained flaser gneiss	Table 15; p. 42, 43; fig. 25, 26B.
39	Rio Piracicaba	N 7,550, E 4,800	Quartz-biotite gneiss	P. 43.
H–8a–5	Caeté	S 1,200, E 6,700	Asbestos	Fig. 22.
11i	Jeceaba	S 1,100, E 1,680	Salto, porphyritic gneiss	Table 11.
11j	do	S 1,100, E 1,680	Salto, unfoliated granite	Do.
11jI	do	S 1,100, E 1,680	Salto, well-banded gneiss	Table 11; p. 33.
19d	Itabirito, 1:250,000 sheet.	West of Alto de Paiol Novo.	Porphyritic granite	Table 7.
19g	Bonfim, 1:250,000 sheet.	Campo Alegre	Foliated granite	Do.
20c	do	Grota do Vallo	do	Do.
20d	do	82.5 km north of Bomfim.	Felsic granodiorite, abundant granite veins.	Do.
21b	Belo Horizonte, 1:250,000 sheet.	Barreiras	Unfoliated granite	Do.
22h	Itabirito, 1:250,000 sheet.	Just west of Belo Vale.	Coarse porphyritic granite	Table 11.
23a	Casa de Pedra	N 2,420, E 500 Arojado Lisboa.	Well-banded granite	Table 8.
24c	Belo Horizonte-Monlevade highway.	18.5 km east of Av. Pres. Carlos, Belo Horizonte.	Granite, similar to Ha–14	Table 4.
24e	do	Same as H–24c, 30.6 km east.	Foliated gneiss	Do.
24f	do	0.6 km west Sabará road junction.	Unfoliated granite	Do.
25b	Rio Piracicaba	N 5,350, W 4,040	Granite gneiss near contact with Rio das Velhas.	Table 15.
25c	do	N 2,400, W 410	Granite gneiss	Do.
DTM–1	Rio de Pedras	N 2,500, E 3,600	Granite gneiss	Table 2; p. 9, 26.
2	do	N 1,600, E 7,000	Amphibolite, pre-Minas	Table 2; p. 7, 9, 26.
3	do	N 4,100, E 5,100	Mica schist, Rio das Velhas	Table 2; p. 9, 26.
5	Marinho da Serra	S 5,700, E 2,400	Porphyritic granite	Table 2; p. 9, 22.
6	do	S 6,200, E 1,700	do	Table 2; p. 9, 22.
7	From southwest corner of Marinho da Serra.	N 4,400, W 5,800	Gneissic granite	Table 2; p. 9, 22.
8	Rio Piracicaba	S 2,100, W 5,600	Pegmatite	Table 2; p. 10, 42.
A–653	Belo Horizonte	S 2,450, W 230	Banded granite gneiss	Table 4; p. 18,; figs. 26A, 27.
753	Nova Lima	S 2,340, E 600	Metadiabase dike	Table 5; p. 20, 54; fig. 10.
JG–10–55	Rio Acima	N 1,610, E 0	Serpentinite	Table 5; p. 19, 54.
11–55	do	N 1,160, E 580	Metagabbro	Table 5; p. 19, 54.
105–56	Nova Lima	S 1,140, E 1,740	Marzagão granite	Table 4, p. 17; fig. 26B.
J–37	Cachoeira do Campo	N 5,900, E 5,950	Banded gneiss	Table 8.
76	do	N 2,560, W 4,000	Granitic gneiss	Do.
82	do	N 780, W 640	Granite interlayered with Nova Lima.	Table 8; p. 30; figs. 26A, 27.
668	do	N 5,900, E 5,300	Biotite gneiss	Table 8; figs. 26A, 27.
48G12	Bação	N 850, W 1,290	Granodiorite	Table 8.
51G56	São Julião	S 430, W 1,200	Mafic granodiorite	Table 8; p. 27.
G–1	Congonhas	N 2,800, E 1,600	Border zone, gneissic, granodiorite intrusion	Table 10.
3	Jeceaba	N 2,800, E 5,200	Granodiorite	Do.
4	São Julião	N 600 E 700	do	Do.
CM–606	Catas Altas	S 6,130, E 2,590	Porphyritic diabase	Table 13; p. 41.
54P126	Ibirité	S 2,090, E 4,700	do	Table 5; p. 20, 41; figs. 11, 12*A*.
S.B	City of Santa Bárbara quarry.		"Orthogneiss"	Table 12; p. 39; figs. 26*A*, 27.
WM–1–3	Marinho da Serra	S 6,400, E 1,660	Granite gneiss, porphyritic	Table 7.
5	do	S 7,100, E 220	Granite gneiss	Do.
Z–8a	Rio de Pedras	N 2,110, E 4,200	Microcline gneiss	Table 8.
188a	do	N 4,400, E 1,490	Titaniferous biotite gneiss	Do.

Normative minerals of the chemically analyzed granitic rocks were calculated by computer. These minerals are shown in the appropriate tables, as well as the differentiation index (D.I.) (Thornton and Tuttle 1960) of each rock, defined as the sum of normative quartz+albite+orthoclase, and thus a measure of the leucocratic nature of the rock. During the early course of differentiation of a silicate melt, enrichment takes place in quartz, albite, and orthoclase K-feldspar compositions in the liquids, whereas the mafic minerals tend to crystallize out first. Thus, the total amount of the three salic minerals indicates how differentiated the magma source was that produced each rock: the higher the abundance of these minerals, the later rock crystallized. Thornton and Tuttle (1960, p. 671), used Daly's data for average composition of igneous rocks to compute the following D.I. values: alkali granite, 93; granite, 80; and granodiorite, 67.

The D.I. range for the older granodiorites and banded gneisses (Groups I and II) of the Quadrilátero Ferrífero is 67.1–92.4, and for the younger granite-gneiss suite (Groups III and IV) is 85.7–96.1. The younger suite and many of the older have high D.I. values which may be, in part, the result of assimilation of quartzofeldspathic sediments and silica-alkali metasomatism, and should not be attributed entirely to differentiation crystallization from an igneous melt.

Modal analyses were obtained from stained thin sections using a point counter (Chayes, 1949). Thin sections were cut perpendicular to any discernible foliation and lineation. Modal analyses were by J. E. Gair, P. W. Guild, R. F. Johnson, and W. B. Wright, of the U.S. Geological Survey; by E. C. Damasceno, Department of Geology, University of São Paulo; and by me.

Minor element analyses were done in the laboratories of the Instituto de Tecnologia Industrial, Belo Horizonte, M. G., Brazil, by C. V. Dutra, using a grating spectrograph with a 3-meter focal length, Eagle mount, and dispersion of 5 A/mm. The complete technique and accuracy and precision of the analyses are described elsewhere (Herz and Dutra, 1960, p. 82–83).

NORTHWESTERN PART OF THE QUADRILÁTERO FERRÍFERO

Parts of the northwestern Quadrilátero Ferrífero have been mapped and described most recently by Gair (1962), Pomerene (1964), Tolbert (1964), and Simmons (1968a).

Granites and gneisses underlie the area north and south of the Serra do Curral and west of the Serra da Moeda (pl. 1). Because they weather relatively rapidly and deeply, fresh exposures are not common. A few small *lit-par-lit* granitic dikes are found within the Nova Lima Group, and dikes crosscut older gneisses and granite along the northern contact of the Sabará Formation of the Serra do Curral (Gair, 1962). Stocklike bodies of metgabbro border serpentinite along the southern boundary area of the Macacos-Rio Acima quadrangles. Metadiabase dikes cut all Precambrian formations and are widespread.

Gneissic rocks south of the Serra do Curral and west of the Serra da Moeda make up the Bonfim dome (Simmons, 1968a). The dome consists of an outer ring of younger Souza Noschese Gneiss, which has one or two weak planes of foliation, and an inner core of well-foliated and compositionally layered gneiss, that is correlated here with the Itabirito Granite Gneiss. The outer ring is about 7 km wide, and the dome itself extends to the southwest from the Serra do Curral for about 50 km. The foliation strikes north and generally dips steeply; within about 1 km of the margins it parallels the trend of adjacent metasedimentary rocks.

North of the Serra do Curral, in the Belo Horizonte and Nova Lima quadrangles, the granitic and gneissic rocks are similar to the rocks of the Bonfim gneiss dome. Younger gneissic and granitic rocks, which have poorly developed foliation similar to the Souza Noschese Gneiss, are in contact with rocks of the Minas Series in many places. Well-foliated compositionally layered rock similar to the Itabirito Granite Gneiss is generally found away from the Minas Series contacts. These rocks extend the length of the Serra do Curral and to the north, and are in contact with the youngest rocks of the Minas Series. On their north, they are overlapped by the Bambuí Limestone of early Paleozoic or latest Precambrian age.

The older, well-foliated Itabirito-type gneiss and the younger Souza Noschese Gneiss appear to be gradational. Alkali feldspar porphyroblasts and tourmaline-quartz-muscovite dikes are present in the basal quartzite of the Minas Series near its contact with gneiss. Staurolite is developed along the contact between gneiss and the Nova Lima Group in the Brumadinho quadrangle; in Ibirité and adjoining quadrangles, biotite is found along the same contact. In both areas, some higher grade metamorphic minerals have retrogressed to those of the chlorite zone. The retrogressive metamorphism was widespread and also affected the gneisses, granites, and the Minas Series.

On the northern slope of the Serra do Curral, staurolite and garnet have developed in the Sabará Formation near its contact with granite. Near General Carneiro in the Nova Lima quadrangle and Morro da Pedra in Belo Horizonte, the Sabará Formation is intruded by large granite bodies (Gair, 1962, p. 47–48; Pomerene, 1963, p. 33). No actual contacts have been seen between the metasedimentary rocks and the granite, although both crop out within tens of meters of each other on the new road north of Sabará, east of the Rio das Velhas.

Despite the differences in origin and in structural features, all the granitic rocks have been metamorphosed to the greenschist facies and most show some structural deformation. Modal analyses (table 4) show as much as 8.4 percent epidote and 4.9 percent chlorite, and every sample has one or both minerals.

SPECIAL STUDIES

AGE DETERMINATIONS

K/Ar ages have been determined for biotite and muscovite from five samples of gneiss and granite from the northwestern part of the Quadrilátero Ferrífero. North of the Serra do Curral, three of these determinations are increasingly older with distance from the Minas Series. Ha-14 (table 2) from the quarry at Barreiro is in an area largely underlain by the Sabará Formation and has a K/Ar muscovite age of 595 m.y. The gneiss of Morro da Pedra in Belo Horizonte, sample Ha-15, also in the Sabará Formation, has a K/Ar biotite age of 800–895 m.y. (based on two determinations). In the Prado Lopes quarry, nearly 5 km north of the contact of granitic rocks with the Minas Series, sample Ha–16 yielded a K/Ar biotite age of 1,360 m.y. Near Sete Lagoas, 55 km north of Belo Horizonte, a whole-rock Rb/Sr isochron showed 1,930 m.y. (Pinson and others, 1967).

South of the Serra do Curral, sample Ha-13, a gneiss from near the contact with the Minas Series, has a K/Ar biotite age of 550 m.y., and Ha–33, about 8 km farther south, yielded a K/ar biotite age of 462 m.y.

Deformation localized at Minas Series-gneiss contacts was probably responsible for some loss of Ar. However, the progressive increase in age from southwest to northeast, that is, from sample Ha–33 (462 m.y.) to Sete Lagoas (1,930 m.y.), suggests that the event that caused the loss of Ar and the lower ages was centered in a southerly direction and probably related to a 450- or 500-m.y. deformation at, or to the south of, the Serra do Curral. All the ages, except for the one from Prado Lopes, should be considered as "mixed," and as only minimum ages due to Ar loss. The 1,360-m.y. date is considered to be post-Minas; the mixed ages may be due to the largely thermal event about 500 m.y.

ALKALI FELDSPARS

Alkali feldspars separated from a Group IV gneiss, sample Ha–15, and a Group II gneiss, sample 16, were analyzed for major elements and some trace elements (Herz and Dutra, 1966). Some results (in parts per million for minor elements; in percent, for feldspar molecules) are:

Sample	Rb	Ba	Sr	Li	Ca	An	Ab	Or	T° C
Ha-15	650	2, 170	120	7. 0	860	0. 62	10. 21	89. 17	380
Ha-16	276	4, 530	540	1. 0	790	. 56	12. 07	87. 37	420

Both analyzed feldspars have less than 15 percent albite molecule and therefore are considered to be of low-temperature, subsolvus origin (Tuttle and Bowen, 1958, p. 129). The temperatures given obtained sometime during the latest metamorphism and were determined by comparing the albite molecule in alkali feldspar to the albite molecule in plagioclase (Barth, 1956). The high Rb and low Sr in the feldspar of Ha–15 compared to that in Ha–16 suggest that Ha–15 is posttectonic, and that Ha–16 is pretectonic or syntectonic (Herz and Dutra, 1966), which also agrees with our ideas on the origin of the gneiss groups.

MINOR ELEMENTS IN BIOTITE

Some minor elements were determined in biotite of Group IV gneiss, sample Ha–13 from Ibirité, near the Minas contact south of the Serra do Curral, and Group III, young granite, sample Ha–34 from the Brumadinho quadrangle, about 7 km south of the Serra do Curral, in the hope that they would indicate approximate temperature of formation (Oftedal, 1943). Sc content, for example, is highest at low temperatures of formation. The results of these analyses (in parts per million) are (Herz and Dutra, 1964a):

Sample	Co	Ni	Sc	Cr	Nb
Ha-13	28	28	10	39	200
Ha-34	30	19	130	22	150

The high Sc value in Ha–34 suggests a relatively low temperature of formation, and the low amount of Sc in Ha–13, a higher one. These data agree with the K/Ar determinations, which suggest that temperatures of the last deformation were highest nearest the Serra do Curral.

OLDER GRANODIORITE AND GNEISS

The older granodiorite gneiss suite (Group II), in table 4, typically shows a well-developed foliation and compositional layering. It crops out the southeastern part of the Brumadinho quadrangle and extends southward more than 20 km, and southwestward more than 20 km beyond the limits of the Quadrilátero Ferrífero.

378-971 O—70——3

It is a gray medium- to coarse-grained well-foliated granodiorite gneiss of alternating felsic and biotitic layers. Large augen-shaped microcline crystals as much as 2 cm in length occur in a groundmass of smaller crystals of microcline, plagioclase, quartz, and biotite. This rock is similar to that found north of Belo Horizonte and in the Bação complex near Itabirito.

In the northwestern part of the Brumadinho quadrangle, granodiorite gneiss close to the contact with metasedimentary rocks was mechanically deformed and retrogressively metamorphosed during and after the emplacement of younger Souza Noschese Gneiss. Foliation in this gneiss is parallel to that in the rocks of the Nova Lima Group and may be inherited structure preserved during the granitization of these older sedimentary rocks.

TABLE 4.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks from the northwestern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. P, present; N.d., looked for, but not detected]

	Older granodiorite gneiss					Younger granite					Younger gneiss		Older pegmatite
	South of Serra do Curral		North of Serra do Curral			South of Serra do Curral		North of Serra do Curral			South of Serra do Curral		
	Ha-33	Ha-35	Ha-14-O	Ha-16a	A-653	Ha-32	Ha-34	Ha-14-Y	Ha-15	JG-105-56	Ha-12	Ha-13	Ha-16P
Chemical analyses (Weight percent) [Analysts: P. D. L. Elmore and others, U.S. Geological Survey, using method of Shapiro and Brannock (1956)]													
SiO_2	71.4	73.1	73.5	69.4	73.6	75.7	74.0	74.2	72.8	72.2	76.0	72.0	72.3
Al_2O_3	14.6	13.8	14.9	14.6	14.8	13.6	14.1	14.6	14.2	16.0	13.1	13.6	14.9
Fe_2O_3	1.0	.6	.5	.8	.1	.5	.4	.2	.7	.3	.7	1.1	.4
FeO	1.7	1.9	1.2	2.0	1.4	.70	.65	.51	1.0	.88	1.0	2.2	.37
MgO	.72	.63	.44	.68	.38	.30	.20	.10	0.25	.34	.24	.94	.20
CaO	2.0	1.9	1.7	2.1	1.5	.47	.89	.90	1.1	.62	1.0	1.1	1.3
Na_2O	4.8	3.3	4.9	3.2	5.0	3.0	3.6	4.2	3.4	3.3	3.0	3.0	3.0
K_2O	2.1	3.4	2.2	5.1	2.3	4.7	4.9	4.8	5.2	5.2	4.1	4.8	6.8
H_2O	.60	.63	.54	.58	.52	.58	.38	.37	.59	.84	.59	.86	.38
TiO_2	.43	.30	.19	.48	.19	.08	.12	.05	.24	.08	.18	.44	.12
P_2O_5	.12	.10	.08	.26	.04	.03	.02	.01	.06	.12	.06	.14	.06
MnO	.08	.06	.05	.08	.04	.06	.04	.02	.06	.02	.04	.06	.02
CO_2	.06	<.05	.06	.14	<.05	<.05	.36	.12	.23	<.05	.24	.03	.37
F			.02	.06				.00			.03	.07	.00
Total	99.6	99.7	100.3	99.5	99.9	99.7	99.7	100.1	99.8	99.9	100.3	100.3	100.2
Normative minerals (Weight percent)													
Quartz	29.8	35.0	32.0	26.0	31.0	38.5	32.8	29.4	30.8	31.0	40.8	32.0	26.9
Corundum	1.2	1.5	1.7	1.1	1.5	2.8	2.1	1.2	1.7	4.1	2.7	2.0	1.2
Orthoclase	12.4	20.1	13.0	30.1	13.6	27.8	28.9	28.4	30.7	30.7	24.2	28.4	40.2
Albite	40.6	27.9	41.4	27.1	42.3	25.4	30.4	35.5	28.8	27.9	25.4	25.4	25.4
Anorthite	8.8	8.8	7.4	7.5	7.2	2.1	2.0	3.6	3.6	2.3	2.9	3.9	3.7
Enstatite	1.8	1.6	1.1	1.7	.9	.7	.5	.2	.6	.8	.6	2.3	.5
Ferrosilite	1.7	2.6	1.6	2.4	2.2	.9	.7	.7	1.0	1.3	1.0	2.5	.2
Magnetite	1.5	.9	.7	1.2	.1	.7	.6	.3	1.0	.4	1.0	1.6	.6
Ilmenite	.8	.6	.4	.9	.4	.2	.2	.1	.5	.2	.3	.8	.2
Apatite	.3	.2	.2	.6	.1	.1			.1	.3	.1	.3	.1
$CaCO_3$	.1		.1	.3			.8	.3	.5		.6	.1	.8
Total	99.0	99.2	99.6	[1] 99.0	99.3	99.2	99.0	99.7	99.3	99.0	[1] 99.7	[1] 99.5	99.8
Differentiation index	82.8	83.0	86.4	83.2	86.9	91.7	92.1	93.3	90.3	89.6	90.4	85.8	92.5
Percent An in plagioclase	17.8	24.0	15.2	21.7	14.5	7.8	6.2	9.3	11.1	7.6	10.1	13.3	12.7
Modal minerals (Volume percent)													
Plagioclase	42.5	32.2	37.5	23.7	±30	31.5	22.0	19.6	28.5	±20	21.4	24.0	
(Percent anorthite)	(15)	(15)	(14)	(17)	(14)	(14)	(12)		(10)		(14)	(12)	
Potassium feldspar	13.7	28.0	13.2	33.1	±30	15.2	31.1	25.1	32.2	±30	24.3	13.8	
Quartz	29.2	31.3	31.7	23.1	±30	34.5	28.5	32.4	27.4	±20	36.7	30.4	
Biotite	3.3	1.0	7.2	12.0	±10	7.1	4.8	3.0	3.4	P	5.7	12.2	
Muscovite	5.7	4.3	6.3	5.1	P	4.8	9.5	7.4	5.0	±10	6.7	11.1	
Epidote	3.8	1.3	2.2		P	2.7	2.2	8.4	2.1	P	1.9	5.1	
Chlorite	1.1	P	1.9	.6	P	2.1		1.6	1.1	P	4.9	3.0	
Sphene											1.4		
Apatite	.8	P		P	P	.6	P		P		P		
Opaques	.6	P		P	P	1.2	.6	.7	P				
Zircon		P				P	P		P		P	P	
Allanite												P	
Rutile		P		P									
Carbonate	.2	.3		P		.2	1.2	1.6					
Amphibole				2.0									
Tourmaline												.4	

TABLE 4.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gnessic rocks from the northwestern part of the Quadrilátero Ferrífero*—Continued

Minor elements

(Parts per million)

[Quantitative spectrographic determination by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte M.G., Brazil]

Element	Ha-33	Ha-35	Ha-14-O	Ha-16a	A-653	Ha-32	Ha-34	Ha-14-Y	Ha-15	JG-105-56	Ha-12	Ha-13	Ha-16P	H-24c	H-24e	H-24f
Ba	1,300	800	440	1,600	800	390	1,300	430	1,300	560	490	810	1,700	1,300	3,900	1,300
Be	4.3	5.4	2.7	----	1.4	5.8	N.d.	2.0	----	4.3	----	----	1.2	1.2	1.4	2.5
Co	5.3	4.0	3.4	7.9	2.4	1.3	1.3	N.d.	2.8	.9	1.8	4.4	1.3	2.8	N.d.	3.0
Cr	18	5.6	6.8	18	2.7	<.7	.8	2.4	1.6	4.0	.9	2.9	7.5	4.4	2.1	27
Cu	3.2	12	.2	11	.5	.6	14	Trace	1.2	.5	1.6	2.0	Trace	.8	7.6	3.7
Ga	14	16	18	18	17	13	15	16	22	16	15	16	13	16	11	17
La	150	94	30	210	30	14	27	30	170	N.d.	84	94	36	67	N.d.	53
Mo	4.0	N.d.	4.3	----	N.d.	N.d.	N.d.	N.d.	----	N.d.	----	----	N.d.	N.d.	N.d.	N.d.
Nb	20	32	13	27	22	22	13	N.d.	25	11	23	11	N.d.	5.9	13	12
Ni	7.5	4.8	4.6	8.1	2.4	.8	.8	1.8	8.6	2.0	4.5	6.3	2.6	1.9	2.3	3.1
Pb	27	32	32	15	19	36	53	59	37	52	12	10	28	46	20	17
Sc	8.1	5.5	6.5	7.2	4.0	1.0	1.3	2.8	36	3.8	2.6	8.0	N.d.	2.0	N.d.	40
Sn	9.0	N.d.	7.5	45	5.5	12	N.d.	3.9	N.d.	3.7	23	34	N.d.	4.7	3.2	5.1
Sr	250	150	240	380	230	55	220	85	170	100	85	130	260	180	260	340
V	55	24	26	21	12	8.1	11	2.0	7.5	2.7	10	29	13	16	16	18
Y	42	57	13	66	15	83	6.3	10	N.d.	7.1	240	72	5.5	7.1	43	25
Zr	470	400	106	310	140	64	93	47	220	53	152	290	100	160	52	170

[1] Includes 0.1 percent fluorite.

A granodiorite gneiss which is compositionally layered and foliated similar to the granite at Alberto Flôres underlies much of the area north of the Serra do Curral and continues to the west, north of the Serra dos Tres Irmãos (Pomerene, 1964, p. 32). These rocks have been correlated with the Itabirito Granite Gneiss (granodiorite phase) (Guimarães, 1951, p. 18–19). Good exposures are seen in the Prado Lopes quarry north of Belo Horizonte (Ha–16) where the well-foliated rocks are characterized by alternating felsic, hornblendic, and biotitic layers. Microcline augen reach 10 mm in diameter but average 3–6 mm. Plagioclase and other microcline crystals are smaller than this; quartz averages 0.5 mm, and rutilated biotite flakes and amphibole average 0.3 mm in length (fig. 5).

At Prado Lopes, mafic schlieren and xenoliths of amphibolite are common (fig. 6), as are thin crosscutting pegmatites consisting of feldspar, quartz, micas, and black tourmaline. The xenoliths are rimmed by coarse quartz and feldspar, and flow banding has developed around them.

The granodiorite gneiss has been metamorphosed, as shown by the presence of chlorite and epidote; deformed, as shown in many grains by strain and fracturing; and metasomatized, as shown by K-feldspar rims around plagioclase (fig. 7). Near its contact with the Minas Series, foliation is not so well developed and, in many places, for examples, at the Barreiro (Ha–14) and Brumadinho quarries, younger unfoliated or poorly foliated granitic rocks cut the older layered gneisses (fig. 8).

YOUNGER GRANITES AND GNEISS

At least three distinct facies of younger gneiss and granitic gneiss, as well as granite in dikes, are found in the western Quadrilátero Ferrífero. One facies is a poorly foliated gneiss and occurs just south of the Serra do Curral between the older granodiorite and the Minas Series, and is typified by the Souza Noschese Gneiss; another forms large intrusive bodies, such as the Marzagão granite gneiss that may have been responsible for development of staurolite and garnet in the Sabará Formation; and a third is highly deformed sericite-epidote-chlorite gneiss at Morro da Pedra in Belo Horizonte.

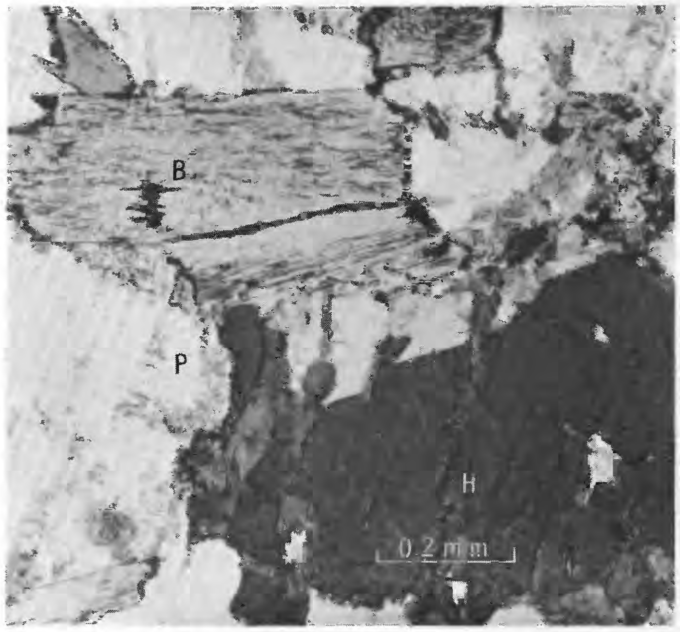


FIGURE 5.—Photomicrograph of oriented rutile needles in biotite (B) typical of the older granodiorite suite. Hornblende (H) grain fractured; plagioclase (P) grains partly replaced by fine-grained muscovite and clinozoisite. Sample Ha–16a.

SOUZA NOSCHESE GNEISS

The Souza Noschese Gneiss forms a body about 6 km in width and 15 km in length in the central part of the

FIGURE 6.—Large xenoliths of amphibolite in banded gneiss, Prado Lopes quarry, Belo Horizonite quadrangle.

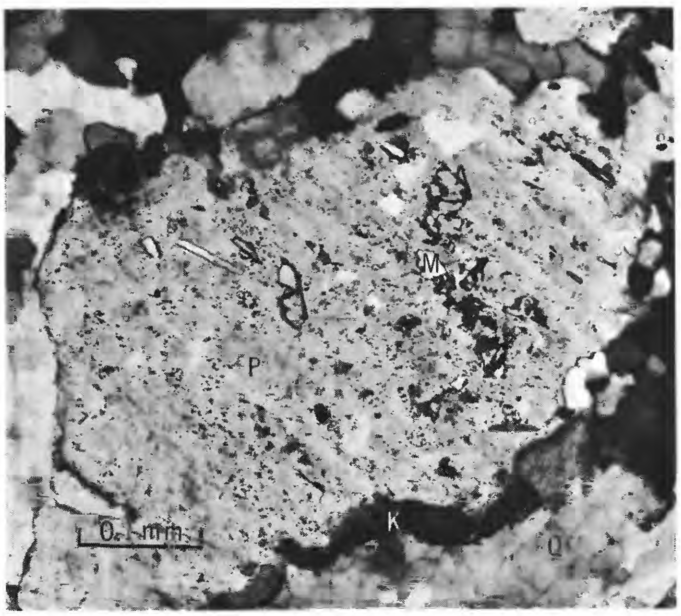


FIGURE 7.—Photomicrograph of plagioclase crystal (P) in older granodiorite gneiss showing partial replacement by clinozoisite (C) and muscovite (M), fracturing and partial filling by vein quartz (Q), and rimming by K-feldspar (stained, K). Sample Ha–33b, Brumadinho, crossed nicols.

A

B

FIGURE 8.—Banded gneiss in the quarry at Barreiro. *A*, General aspect of older granodiorite gneiss Ha–14–0 (darker) cut by thin felsic veins, largely quartz and feldspar, and intruded by younger granite Ha–14–Y (lighted colored). *B*, Detail of lower right-hand corner of *A*.

Brumadinho quadrangle, and it extends south and west out of the Quadrilátero Ferrífero. The gneiss is light gray, fine to medium grained, poorly foliated, and in many places has more than one plane of foliation. It is composed of quartz, feldspar, muscovite, biotite, chlorite in part replacing biotite, and epidote replacing oligoclase. The larger quartz grains are strained, and some form intergrowths with plagioclase. Microcline crystals are as much as 5 mm in diameter and have many inclusions.

Gneiss identical to the Souza Noschese was found near Samambaia (Pomerene, 1964, p. 32) in the Ibirité quadrangle where it is in contact with the base of the Minas Series (sample Ha–13). The Minas Series here is a quartzite conglomerate in which small albite porphyroblasts formed, possibly as a contact effect. Within several meters of the contact, the porphyroblasts disappear.

GRANITE GNEISS AT MARZAGÃO

Granite gneiss is found in the Nova Lima quadrangle intruding the upper Piracicaba Group (Gair, 1962). Small granite gneiss bodies occur as dikes in the Piracicaba Group north of the Serra do Ouro Branco (Johnson, 1962, p. 23). These gneisses are generally light gray, inequigranular, and very thinly layered. The felsic layers are between 2 and 5 mm thick and are separated by thin dark layers. The felsic layers themselves are broken up into irregular augen-shaped areas by anastamosing thin dark layers that are approximately parallel to the plane of foliation.

Epidote and micas in mafic layers are well alined, whereas minerals in the felsic layers are not. Quartz is found in elongated zones, commonly fractured or mosaic textured. Plagioclase is twinned, somewhat altered, and some grains are rimmed by K-feldspar. In some rocks, microcline-perthite in crystals as large as 1 cm appears to be the last mineral to have formed.

Although the younger gneisses appear texturally to be derived from a variety of feldspar- or quartz-rich rocks, mineralogically and chemically the different occurrences are quite uniform. Both analyzed samples (table 4, Ha–14–Y and JG–105), are similarly deficient in accessory minerals, epidote and chlorite, and both have about the same proportions of principal minerals.

GRANITE AT MORRO DA PEDRA

A green feldspar granite forms an elliptical body 700 by 400 meters at Morro da Pedra, in the Belo Horizonte quadrangle; this granite gneiss intrudes a partially granitized staurolite schist of the Sabará Formation (Pomerene, 1964, p. 33). Small dikes of this granite have also been seen at Prado Lopes and elsewhere.

The green feldspar granite is medium grained, poorly foliated, and consists of quartz, feldspar, micas, epidote, and some chlorite, apatite, and zircon. In thin section, quartz has two ranges in grain size, forming both large, irregular shapes, and smaller aggregates of sutured grains. Plagioclase is highly sericitized and replaced by K-feldspar along cleavages, in embayments, and on the rims of grains. Large microcline crystals are irregularly cracked and filled with quartz. Many feldspar grains are bent and fractured. In short, the rock shows evidence of postcrystalline mechanical deformation and metasomatic replacement by Si and K. The green color of the feldspar is distinctive enough that it was used as a mapping criterion.

YOUNGER GRANITE DIKES

Younger rocks of granitic aspect and composition are widely distributed in the older gneisses as crosscutting dikes. Most are less than 1 meter wide (samples Ha–14–Y and Ha–34, table 4 and fig. 8).

Some dikes have sharp contacts, and others grade into the older rocks. Foliation is generally poor, except in the gradational varieties. Feldspars are medium to coarse grained, and quartz is medium to fine grained. Much of the K-feldspar is perthitic and rims plagioclase. Some plagioclase that has sericitized cores is rimmed by clear albite. Larger grains are strained; many smaller grains are sutured or form mortar structures around feldspar phenocrysts.

PETROGENESIS

OLDER GNEISSES

The older gneisses were correlated by their distinctive alternating felsic and mafic layering and well-developed foliation. Certain general conclusions can be drawn about them: (1) Older gneiss with the highest differentiation index (table 4) is found close to, and in contact with, Minas rocks of the Serra do Curral. This gneiss also shows the effects of Na-metasomatism (fig. 9), and has undergone much retrograde metamorphism and deformation. (2) Older gneiss from both north and south of the Serra do Curral has similar differentiation indices, shows evidence of K-metasomatism, and has

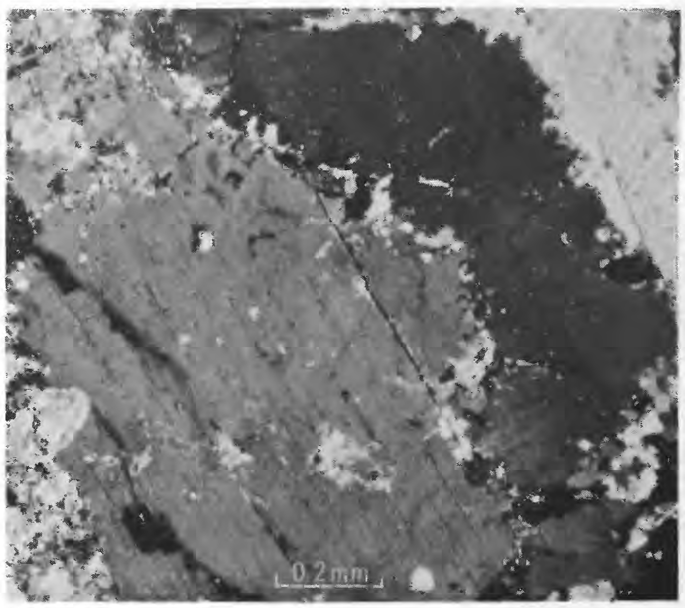


FIGURE 9.—Photomicrograph of plagioclase (gray, center and left part of photomicrograph), with some inclusions and rims of quartz and clinozoisite replaced by more sodic plagioclase (almost black, upper right) which, in turn, is rimmed by quartz. Original grain An_{14}, replacement $<An_{10}$. Sample Ha–14–O, Barreiro, crossed nicols.

undergone comparatively little retrograde metamorphism and deformation.

1. The average differentiation index of older gneiss near the Serra do Curral is 86.7 compared to about 83 for older gneisses several kilometers away from the Serra. The higher index near the Serra is due to higher normative albite. Albite was probably formed in part by retrograde metamorphism, in part by Na-metasomatism, and it is seen as aprons around and through less sodic plagioclase. The higher degree of retrograde metamorphism near the Serra is evinced by abundant epidote and chlorite and by low anorthite content of plagioclase; deformation produced mortar texture and strained crystals.
2. Both Gair (1962, p. 48) and Simmons (1968a, p. 25) noted a second generation of K-feldspar in the older gneisses at distances of several kilometer from the Serra do Curral. Original plagioclase is speckled with sericite, whereas the K-feldspar and albite are fresh. Some K-feldspar replaces plagioclase on rims and in myrmekitic intergrowths. The change from Na-K-metasomatism near the Serra do Curral to only K-metasomatism at a distance of several kilometers suggests the influence of a thermal gradient, perhaps related to later metamorphism and the intrusion of younger granite at the Serra do Curral. Along such a thermal gradient, Na tends to remain in the area of higher temperature, whereas K tends to migrate to areas of lower temperatures (Orville, 1963).

Temperature gradients during the original conditions of formation of the granodiorite gneisses were apparently very different from those of the post-Minas thermal event. Highest original temperature is indicated for the rock at Prado Lopes, about 5 km northwest of the Serra do Curral, by the presence of hornblende as well as the relatively low differentiation index. The minor elements also suggest original higher temperatures and pneumatolytic solutions in rocks away from the Minas contact at the Serra, compared with those in or near the contact with Minas rocks at the Serra:

Average of samples	Content, in parts per million					
	Ba	Co	Cr	La	Ni	Sn
Ha–16, Ha–33; about 7 km from the Serra	1, 450	6. 6	18	180	7. 8	27
Ha–14, A–653; in or near the Serra	620	2. 9	4. 8	30	3. 5	6. 5

The higher Ba, Co, Cr, and Ni in the samples away from the Serra suggest higher temperatures of formation; the higher La and Sn indicate hydrothermal or pneumatolytic activity.

The early history of these gneisses is difficult to reconstruct. Some were truly igneous at some stage of their development and show flow structures (fig. 6), but nearly all gneisses have well-defined quartz- and mica-rich layers that suggest a sedimentary origin (Gair, 1962, p. 48). These rocks most probably represent a mixture of (a) anatectic liquids produced by granitized sediments and older igneous rocks, with (b) added magmatic solutions, and (c) included refractory sedimentary material. Later, they underwent retrograde metamorphism and metasomatism related to the post-Minas orogeny. Temperatures as low as 420°C obtained during that metamorphism.

YOUNGER GRANITES AND GNEISSES

The sequence of younger granites and gneisses includes rocks of apparent igneous origin and rocks derived from older sediments and gneisses. The igneous granites form crosscutting veins in the older gneisses (fig. 8), and also small intrusive bodies, as at Marzagão (Gair, 1962, p. 48) and Morro da Pedra (Pomerene, 1964, p. 33). Younger gneisses are also found on both sides of the Serra do Curral and are distinguished by one or two poorly developed foliation planes.

The younger granites are similar to much of the younger gneiss both mineralogically and chemically. Both have high K and differentiation indices that range from 89.7 to 93.2. Both modal and normative plagioclase is albite-oligoclase.

The effects of low-grade metamorphism as well as metasomatism are as well developed in the younger gneisses as in the older ones. Epidote is abundant, and some gneisses have epidote veinlets as much as a few millimeters in thickness (Gair, 1962, p. 47). Chlorite and albite are also present, which are good evidence for metamorphism at a low greenschist level. Deformation textures, including mortared quartz, bent and broken feldspar crystals, and strained quartz, are most common in samples nearest the Serra do Curral.

The effects of metasomatism are also most marked in samples nearest the Serra do Curral. Growth aprons of albite around plagioclase, as well as fracture fillings of microcline and albite, are seen in thin section. The granite of Morro da Pedra (sample Ha–15) has higher Ba, La, and Zr than other samples (table 4), which suggests the influence of pneumatolytic solutions.

Contacts between the granitic veins and older gneiss are generally sharp, whereas the younger gneiss appears to grade into the older. Contacts of both younger granite and gneiss with metasedimentary rocks are sharp.

South of the Serra do Curral, a possible effect of granitic solutions is the albite crystals that have developed in the basal Minas Series, as well as crosscutting black tourmaline-quartz-muscovite pegmatites.

The younger gneisses are probably derived in large part from the older by metamorphism. In part, they are gneissic equivalents of metasedimentary rocks of the Rio das Velhas Series which are present in some places between the gneiss and the Minas contact. The granitic rocks were a true product of crystallization differentiation, perhaps derived from an anatectic melt produced from the older gneisses during the early part of a post-Minas orogeny. Good evidence for an igneous origin is seen in the field and is apparent from the metamorphic aureole formed where the Sabará Formation is in contact with the granite; staurolite has developed near the contact (Gair, 1962, p. 52).

ULTRAMAFIC AND MAFIC ROCKS

Ultramafic rocks have been mapped in the southwest corner of the Rio Acima and the adjoining Macacos quadrangles (Gair, 1962; Pomerene, 1964). Metamorphosed mafic or ultramafic sills intrude the Rio das Velhas rocks, and diabasic to gabbroic dikes intrude all Precambrian rocks.

Ultramafic and associated rocks of the Rio Acima and Macacos quadrangles occur as a north-trending body of serpentinite (table 5, analysis JG–10–55) about 4 km long, as smaller bodies of metagabbro, and as talc schist. In the field, serpentinite forms small knoblike outcrops, cut by veins of asbestos. It is generally green in color and is composed essentially of antigorite. In thin section, much of the antigorite appears to have replaced olivine, although the norm (table 5) suggests that the primary mineral was orthopyroxene. Small amounts of magnetite, talc, uralitic amphibole (tremolitic hornblende), quartz, and carbonate may also be present.

Metagabbro is represented by analysis JG–11–55 (table 5). According to Gair (1962, p. 45), it is intimately associated with the serpentinite in the Rio Acima quadrangle and is found in two bodies that border the serpentinite mass. It is typically massive, dull green or mottled green and white, unfoliated, and composed largely of uralitic amphibole and clinozoisite and of varying amounts of oligoclase, chlorite, sericite, ilmenite, and leucoxene. Premetamorphic gabbroic and ophitic textures are suggested by patches made up of either fine-grained aggregates of clinozoite or tremolitic hornblende and some chlorite; clinozoisite replaced plagioclase and amphibole, and tremolitic hornblende and chlorite replaced pyroxene.

TABLE 5.—*Chemical analyses, normative minerals, and minor elements of mafic and ultramafic rocks from the northwestern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1]

	A–753	JG–10–55	JG–11–55	54P126
Chemical analyses (weight percent) [Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe, U.S. Geological Survey, using method of Shapiro and Brannock, (1956)]				
SiO_2	48. 8	51. 8	50. 6	50. 4
Al_2O_3	14. 8	3. 4	15. 5	15. 1
Fe_2O_3	2. 1	2. 2	1. 9	1. 5
FeO	11. 9	5. 0	8. 8	10. 4
MgO	5. 7	28. 1	7. 9	4. 2
CaO	8. 9	1. 2	9. 3	7. 1
Na_2O	1. 9	. 04	2. 8	3. 3
K_2O	. 72	. 02	. 48	1. 4
TiO_2	2. 1	. 10	. 41	2. 8
P_2O_5	. 30	. 04	. 08	. 62
MnO	. 23	. 16	. 09	. 19
H_2O	2. 5	7. 6	2. 8	2. 1
CO_2	<. 05	. 07	<. 05	<. 05
Total	100. 0	99. 7	100. 7	99. 1
Normative minerals (Weight percent)				
Quartz	3. 2	4. 0	--------	1. 9
Orthoclase	4. 3	. 1	2. 8	8. 3
Albite	16. 1	. 3	23. 7	27. 9
Anorthite	29. 7	5. 2	28. 3	22. 3
Wollastonite	5. 2	--------	7. 2	3. 7
Corundum	--------	1. 4	--------	--------
Enstatite	14. 2	70. 0	16. 1	10. 5
Ferrosilite	17. 1	7. 5	11. 5	13. 6
Forsterite	--------	--------	2. 5	--------
Fayalite	--------	--------	2. 0	--------
Magnetite	3. 0	3. 0	2. 8	2. 2
Ilmenite	4. 0	. 2	. 8	5. 3
Apatite	. 7	. 1	. 2	1. 5
$CaCO_3$	--------	. 2	--------	--------
Total	97. 5	92. 2	97. 9	97. 2
Differentiation index	23. 6	4. 4	26. 5	38. 1
Percent An in plagioclase	64. 9	93. 9	54. 5	44. 4
Minor elements [Semiquantitative spectrographic analyses by H. W. Worthing, U.S. Geological Survey. Sample 54P126: Quantitative analysis by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte, M. G., Brazil; semiquantitative analysis preceded by an asterisk (*), by H. W. Worthing. Semiquantitative results reported in series 0, 1, 3, 10, etc., in parts per million]				
Ag	0. 3	0. 3	0. 3	--------
B	30	30	100	--------
Ba	300	30	300	890
Be	0	0	0	*1
Ce	0	0	0	*100
Co	30	100	10	33
Cr	100	1, 000	10	51
Cu	30	1	300	24
Ga	30	1	30	22
La	0	30	30	*50
Mo	10	3	0	0. 5
Nb	0	0	0	36
Ni	100	300	30	47
Pb	3	0	100	*70
Sc	10	10	30	31
Sn	0	0	30	4
Sr	300	0	100	360
V	300	100	300	170
Y	30	10	30	70
Yb	3	1	3	*7
Zn	100	0	0	--------
Zr	100	3	3	220

Talc shist is found in two narrow zones as strongly weathered bodies. Some samples are composed of fine-grained talc, having a decussate structure, and dusty iron hydroxides, magnetite, and chlorite. The field evidence suggests that these bodies are alined along shear zones (Gair, 1962, p. 45).

Metamorphosed dike rocks of probable original mafic composition are abundant in the Rio das Velhas Series and are also present in the Minas Series. Tolbert (1964, p. 781) described four parallel metadiabase dikes, apparently intruded along shear zones, cutting beds of iron-formation in the Raposas mine. The dikes range in thickness from 15 to 50 meters; border zones are light green to gray, strongly sheared and foliated, and altered to chlorite schist. Bordering contact metamorphic zones are about 20 meters wide. The central parts of the dikes are dark green, more massive, and fresher, and consist of chlorite, uralitic hornblende, Na-plagioclase, clinozoisite, and carbonate and of accessory biotite, sericite, and opaques.

Some mafic rock intrusive into the Minas Series was folded and metamorphosed in a post-Minas orogeny. Pomerene (1964, p. 35) found that the degree of preservation of the pyroxene in some diabase appeared to be dependent on the zone of regional metamorphism of the country rock. Most unaltered diabase was found within the staurolite zone of the Belo Horizonte and Ibirité quadrangles; toward the south, in the biotite and chlorite zones, pyroxene was uralitized and plagioclase altered to clinozoisite.

Other diabase dikes do not follow any apparent preexisting structures and do not appear to have been affected by the regional metamorphism. They are considered to be posttectonic and may be contemporaneous with Cretaceous basalt in the south of Brazil. These include fine- to medium-grained dikes having a diabasic texture and porphyritic metadiabase containing feldspar phenocrysts as large as 1 by 3 cm. All the fresh dike rocks show varying degrees of deuteric alteration.

The most common variety is fine to medium grained and is represented by sample A–753 (table 5, fig. 10) that weathers pink and yellow brown, which emphasizes its diabasic texture. The unweathered rock is green, fine to medium grained, and consists of pale-green hornblende, chlorite, biotite, and clinozoisite which form thin veins and granular intergrowths with plagioclase.

The porphyritic metadiabase dike rocks have a crude flow structure represented by more or less alined coarse phenocrysts of feldspar set in a dark fine-grained groundmass (fig. 11). In the Ibirité quadrangle, near the Fazenda Rosário (sample 64P126), such dikes intrude banded gneisses and contain feldspar phenocrysts that are almost completely replaced by clinozoisite.

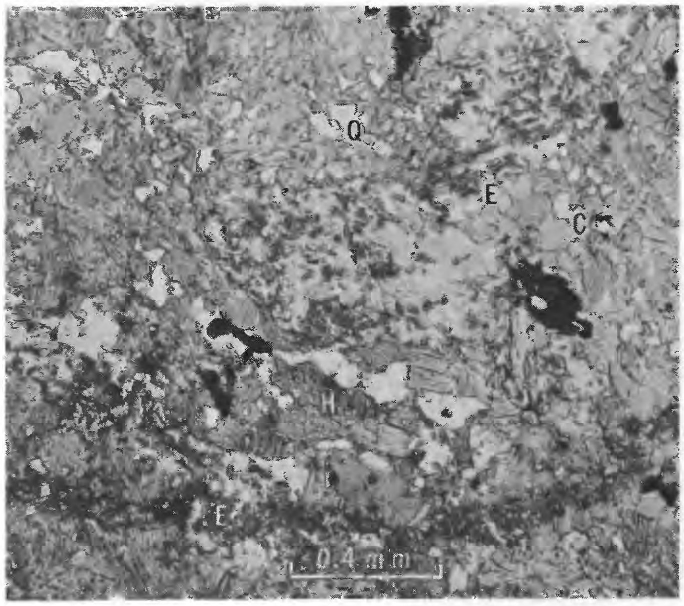


FIGURE 10.—Photomicrograph of metadiabase in which there has been extensive alteration of plagioclase to granular epidote (E) and complete replacement of pyroxenes by hornblende (H) and chlorite (C). Quartz (Q) and opaques (ilmenite?) present. Epidote (E) veinlet is dark streak through bottom of slide. Sample A–753, plane light.

FIGURE 11.—Porphyritic metadiabase near Fazenda Rosário, Ibirité quadrangle.

The mineralogy of the porphyritic dike rock varies in different places (fig. 12). In the rock of Ibirité (sample 54P126), feldspar phenocrysts have a composition of An_{15} or are Carlsbad twins of K-feldspar. The plagioclase has been replaced to some extent by clinozoisite.

Most of the dark groundmass material is chloritized amphibole and actinolitic hornblende. Other minerals in the groundmass include quartz, apatite, sulfides, sphene, and clinozoisite.

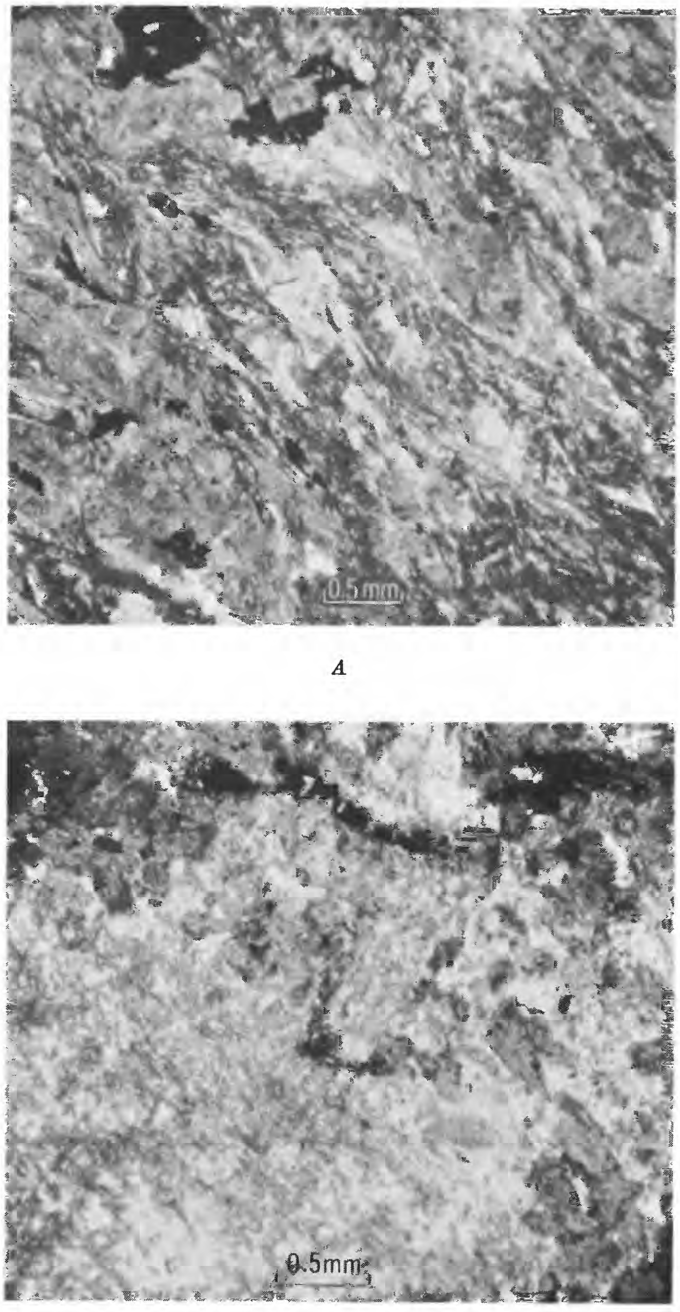


FIGURE 12.—Photomicrographs of porphyritic diabase from Fazenda Rosário, sample 54P126; and from Dom Bosco, sample J-677. (A) Flow structure represented by elongated plagioclase phenocrysts, now largely altered to clinozoisite. Groundmass is fine-grained amphibole and chlorite. Sample 54P126, plane light. (B) Plagioclase phenocryst, largely altered to coarse- and fine-grained clinozoisite. Plagioclase is albite, about An_{10}. Sample J-677, crossed nicols.

WEST-CENTRAL PART OF THE QUADRILÁTERO FERRÍFERO

The west-central Quadrilátero Ferrífero is here considered to be the area west of the Bação complex and includes the granitic complex west of the Serra da Moeda (pl. 1). Diabase and amphibolite dikes and quartzite lenses are also found in the complex.

The complex underlies the lowland east of the Paraopeba River, from Salto in the Jeceaba quadrangle, where it consists of a granodiorite correlated to one found in the Congonhas District (Guild, 1957), to Brumadinho, where it is correlated with the Itabirito Granite Gneiss. The complex covers about 700 sq km; it is 25 km in maximum width and 40 km in length (Wallace, 1965).

Von Freyberg (1932, p. 24–27) and Barbosa (1949, p. 5) considered the gneissic rock of the Moeda complex to be of Archeozoic age. Guild (1957, p. 10) called it basement complex. Wallace, Mello, Sallentien, and Pares (1959) studied a small area in the Marinho da Serra quadrangle and concluded that the gneiss was post-Minas.

Wallace (1965) found that the complex consists of a distinctive granite gneiss predominant in the east, and porphyritic granodiorite, in the west. In many places the two facies are separated by lenses of quartzite that are 4–10 meters thick. A granite gneiss appears again to the west of the porphyritic granodirite, just outside the mapped area.

Von Freyberg (1932, p. 21) and Guild (1957, p. 10) noted that foliation in the gneiss of the Moeda complex and bedding in the basal Minas quartzite of the Serra da Moeda are parallel. This parallelism and the quartz-rich uppermost gneiss suggested to Guild a regolith between the gneiss and the sedimentary rocks. To Wallace, on the other hand, the evidence suggested a gradational zone of varying width (a few to tens of meters) between the two rocks, which he considers a result of granitization.

Cataclastic textures as well as epidote, albite, and chlorite in these rocks are attributed to a late deformation and low-grade regional metamorphism.

SPECIAL STUDIES

AGE DETERMINATIONS

Rb/Sr and K/Ar ages were determined on micas and feldspar from five samples collected on a traverse near the road starting in gneiss at the Minas contact on the west side of the Serra da Moeda (Ha-23), through coarse porphyritic granodiorite, and ending in granite gneiss in the town of Moeda to the west (Ha-21). All ages are discordant; the samples are arranged from east to west:

378-971 O—70——4

Sample	Rb/Sr age K-feldspar	Rb/Sr age	K/Ar age
		Biotite	
Ha–23 (=DTM–4)	2, 300	530	605
DTM–5	975	510	420
DTM–6	1, 985	1, 320	850
DTM–7	1, 050	630	640
Ha–21			514

The age data show that every event that affected the Quadrilátero Ferrífero was also felt here. The oldest date obtained in the Moeda complex, 2,300 m.y., is for a sample of mixed gneiss from the eastern edge of the complex (Ha–23). Most of the sample is probably metamorphosed sedimentary rocks from the Rio das Velhas Series. The coarse porphyritic granodiorite in the core of the complex (sample DTM–6), with phenocrysts as much as 2 cm in diameter, has a 1,985 m.y. Rb/Sr K-feldspar age, which is similar to the Sete Lagoas isochron (Pinson and others, 1967). This rock is surrounded on both east and west by finer grained (1–3 mm diameter) granite gneiss having apparent Rb/Sr K-feldspar ages of 975 to 1,050 m.y.

The coarse porphyritic granodiorite was also affected by an event 1,320 m.y. ago, to judge by the Rb/Sr biotite date. Its central location in the complex shielded it from the 510–630-m.y. event shown by Rb/Sr in biotite of the outer granitic rocks.

ALKALI FELDSPARS

Alkali feldspars separated from a granite gneiss sample (Ha–21) on the west side of the complex and a coarse porphyritic granodiorite (Ha–22) from the contact area with granite gneiss on the east side of the complex were analyzed for major elements and some trace elements (Herz and Dutra, 1966). Some of these results (in parts per million for minor elements; in percent for feldspar molecules) are:

Sample	Rb	Ba	Sr	Li	Ca	An	Ab	Or	T° C
Ha–21	540	1, 330	82	5. 5	570	0. 4	12. 9	86. 7	430
Ha–22	400	1, 120	46	4. 0	570	0. 4	12. 0	87. 6	400

Both feldspar samples have less than 15 percent albite molecule and so are considered low temperature, subsolvus (Tuttle and Bowen, 1958, p. 129). Specific temperatures were derived by comparing the albite molecule in the alkali feldspar to that in plagioclase (Barth, 1956); they probably represent temperatures attained during a late, 500(?) m.y., metamorphism. The types and amounts of minor elements are sufficiently close to suggest a thorough recrystallization under greenschist metamorphic facies conditions, and higher normative anorthite in the coarser porphyritic granodiorite (table 6, sample Ha–22) may be due to an originally higher temperature of formation of that rock.

PORPHYRITIC GRANODIORITE

Coarse-grained porphyritic granodiorite is found in the central part of the Moeda complex, and extends for a distance of about 50 km north-south. To both the east and west, the rock is bordered by a nonporphyritic granitic gneiss. The granodiorite is not found west of the Paraopeba River. Wallace (1965, p. 24–25) considered it to have an igneous aspect, mainly because of randomly oriented phenocrysts and a significant content of xenotime and allanite, as opposed to the granite gneiss which he considered to be a product of granitization. Contacts between the two rock types were not seen during the course of mapping, although they each occur within tens of meters of each other. In some places, quartzite lenses 4–10 m thick separate the porphyritic granodiorite from the granitic gneiss, but generally the contact is obscured by soil or vegetation.

The porphyritic granodiorite is medium gray, consisting of medium-sized to very large light-gray quartz and feldspar phenocrysts in a groundmass of micas, quartz, and plagioclase; sphene is generally abundant. A weak foliation resulting from the parallel orientation of coarse tabular feldspar crystals is seen in hand specimens. Layering of felsic and mafic minerals is poor or lacking, and the orientation of the feldspar is difficult to see in many samples. Plagioclase occurs in grains as much as 3 mm in size; some microcline crystals are as much as 25 mm long and 15 mm wide. Plagioclase and K-feldspar each each make up about a quarter of the rock. Quartz is inequigranular, from 0.3 to 1 mm in diameter, and makes up at least a third of the rock. Some quartz is also in thin veinlets. Epidote, with associated allanite, is very common. Small grains occur within, or on, the rims of the larger plagioclase crystals, and larger grains occur together with biotite. Biotite, in coarse flakes, forms about 10 percent of the rock; some sericite and chlorite are also present (table 6, sample Ha–22). Discrete prisms of sphene, maximum about 0.5 mm, are scattered through the rock. Abundant epidote minerals (2.8 percent), and chlorite (0.9 percent), as well as the composition of the plagioclase (An_9), show that this rock was metamorphosed in the lower part of the greenschist facies.

GRANITE GNEISS

Granite gneiss surrounds the granodiorite of the Moeda complex. On the east side of the complex, the gneiss is in contact with the Minas Series of the Serra da Moeda and trends north for about 30 km in a belt parallel to the Serra. The outcrop width of this belt ranges from 400 m to more than 2 km. The gneiss is

TABLE 6.—*Chemical analyses, normative minerals, and modal minerals of granitic and gneissic rocks from the west-central part of the Quadrilátero Ferrífero.*

[For sample locations, see table 3 and pl. 1]

	Ha–21	Ha–22	Ha–23
Chemical analyses (Weight percent) [Analysts: P. L. D. Elmore, S. D. Botts, and I. H. Barlow, U.S. Geological Survey, using method of Shapiro and Brannock (1956)]			
SiO_2	74. 2	74. 1	76. 2
Al_2O_3	13. 4	12. 4	11. 1
Fe_2O_3	. 7	1. 0	. 8
FeO	1. 1	1. 8	1. 4
MgO	. 25	. 51	1. 1
CaO	. 84	1. 5	1. 2
Na_2O	2. 8	2. 9	1. 5
K_2O	5. 6	4. 5	4. 5
H_2O	. 62	. 60	. 85
TiO_2	. 20	. 42	. 22
P_2O_5	. 08	. 10	. 04
MnO	. 04	. 07	. 06
CO_2	. 23	$<.05$	. 84
Total	100. 1	99. 9	99. 8
Normative minerals (Weight percent)			
Quartz	34. 6	35. 5	47. 7
Corundum	1. 9	. 3	3. 6
Orthoclase	33. 1	26. 6	26. 6
Albite	23. 7	24. 5	12. 7
Anorthite	2. 2	6. 8	. 4
Enstatite	. 6	1. 3	2. 7
Ferrosilite	1. 2	1. 9	1. 7
Magnetite	1. 0	1. 5	1. 2
Ilmenite	. 4	. 8	. 4
Apatite	. 2	. 2	. 1
$CaCO_3$	. 5	--------	1. 9
Total	99. 4	99. 4	99. 0
Differentiation index	91. 4	86. 6	87. 0
Percent An in plagioclase	8. 5	21. 7	3. 1
Modal Minerals (Volume percent) [Microscopist: Samples Ha-21 and Ha-22, E. C. Damasceno, University of São Paulo; Sample Ha-23, Norman Herz. P, present]			
Plagioclase	29. 1	27. 5	6. 8
(Percent An)	(15)	(9)	(14)
K-feldspar	35. 7	20. 8	40. 3
Quartz	27. 3	27. 2	41. 8
Biotite	3. 7	7. 3	11. 1
Muscovite	2. 7	2. 8	9. 4
Epidote	1. 2	2. 8	. 2
Chlorite	. 2	. 9	P
Sphene	--------	. 35	. 4
Apatite	--------	. 35	--------
Allanite	--------	P	P
Carbonate	--------	--------	P
Opaques	P	--------	P
Number of points	803	578	863

poorly foliated to well foliated. In the well-foliated variety, mafic minerals are parallel, and laminae range in thickness from several millimeters to several centimeters. The variation in composition of this rock, according to Guild (1957, p. 10), is quartz, 30–50 percent; feldspar, 30–60 percent; biotite, 5–15 percent; muscovite, as much as 5 percent; and accessory epidote, sphene, and zircon. Quartz and microcline form phenocrysts as much as 3 mm in size.

Sample Ha–21 from the town of Moeda is typical of the gneiss lying west of the granodiorite in the Moeda complex, but it is much finer grained than the granodiorite. The gneiss has a porphyritic inequigranular texture and a weak planar parallelism of biotite flakes, but it is not so coarse grained as the porphyritic granodiorite deeper within the complex. Plagioclase crystals are as much as 2 mm in diameter, and contain inclusions of sericite, epidote, and carbonate; the largest crystals are twinned, and their rims are replaced by K-feldspar. Microcline grains are the same size as plagioclase. Quartz and microcline each comprise about a third of the rock, and plagioclase is somewhat less. Biotite, chlorite, and muscovite round out the mineral assemblage.

On the south side of the Moeda complex, the gneiss is unusually rich in plagioclase (table 10, sample Ha–24) and low in K-feldspar, similar to the granodiorite of the Congonhas area. Plagioclase, An_{13}, forms large crystals as much as 3 mm in diameter, many of which have sutured boundaries and small inclusions of K-feldspar. Quartz and microcline generally are smaller; micas are well alined and form foliation surfaces.

Epidote minerals, chlorite, and sodic oligoclase indicate that the granite gneisses, like the other rocks of the Moeda complex, have been metamorphosed at the greenschist level.

CONTACT BETWEEN THE MINAS SERIES AND BORDER GNEISS

Felsic dikes are common in the area where the Minas Series is in contact with gneiss of the Moeda complex. Within the granite gneiss (Guild, 1957, p. 10) the dikes are rich in silicon and alkalies, and consist of about two-thirds feldspar, largely microcline, but with some oligoclase, muscovite, and about 20 percent quartz. Accessories include biotite, hornblende, and tourmaline.

In the basal quartzite of the Minas Series, tourmaline-quartz veins and kyanite-quartz-muscovite-pyrophyllite veins (Herz and Dutra, 1964b) are common. Away from the contact, kyanite-bearing veins are also present and follow joint sets (Guild, 1957, p. 33). Both kinds of veins are probably due to hydrothermal or pneumatolytic processes that were much later than the original emplacement of the Moeda complex. Contact metamorphism of the Minas Series by the granitic rocks appears to be nil.

An annual gneissic rock (table 6, sample Ha–23) below the base of the Minas Series is composed predominantly of quartz, microcline, and muscovite-sericite. Quartz forms both veins and porphyroblasts. The largest crystals are strained and apparently rimmed by later quartz. Porphyroblasts of microcline are as much as 10 mm in size and contain fractures filled with fine granular quartz. Plagioclase grains are smaller than those of quartz or microcline. Biotite and sericite are abundant, and accessory epidote, sphene, chlorite, and carbonate indicate that this border gneiss has, as has the main granite gneiss, undergone low-grade metamorphism (fig. 13). The large amount of quartz and the porphyroblastic texture of the border gneiss rule out a purely igneous origin and suggest that of a metasomatized quartz-rich rock.

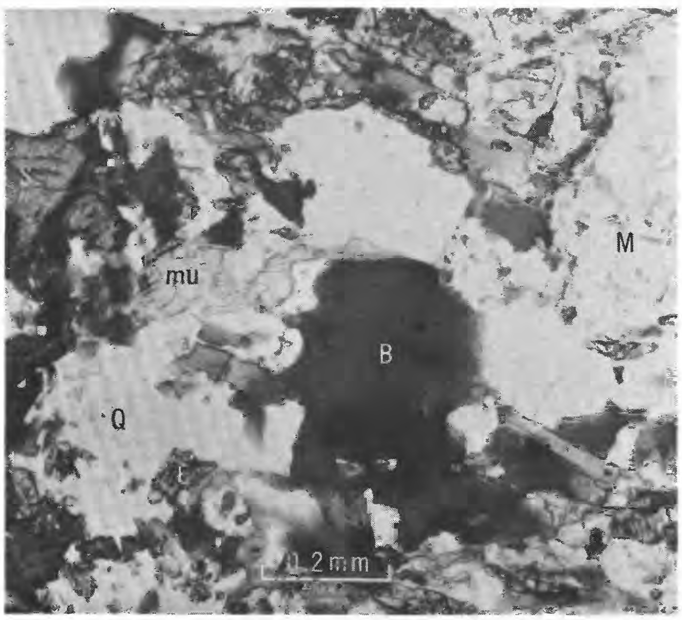


FIGURE 13.—Photomicrograph of gneiss, sample Ha–23, at contact with Rio das Velhas Series, Serra da Moeda. Abundant quartz grains (Q) with spherical inclusions, biotite (B) with pleochroic halos, large microcline crystals (M) containing oriented inclusions of muscovite, large muscovite flakes (mu), opaque minerals, sphene (S), and granular epidote (E).

MAFIC ROCKS

Wallace (1965, p. 27) noted diabase dikes that cut all sedimentary rocks in the area. Some are folded in with the Minas Series, and others fill northeast- or northwest-trending joint systems. Fresh samples consist of about equal parts of labradorite and hornblende and of accessory pyrite, apatite, biotite, epidote, and magnetite. Most of the dikes are completely weathered but retain a diabasic texture.

Some mafic rocks without diabasic texture are found in the granodiorite of the Moeda complex but are too weathered to be thin-sectioned. One occurrence in the Marinho da Serra quadrangle (Wallace, 1965, p. 28) appears to be a plug; it has a strong lineation, and contains some talc.

Autunite-bearing amphibolites have also been found within the complex (J. J. R. Branco, oral commun., 1960).

SUMMARY AND HISTORY OF THE MOEDA COMPLEX

In an effort to see how far the granodiorites of the complex extend, and if rocks correlative with the older Itabirito granites (type II) exist in the general area, R. M. Wallace and I made a reconnaissance west of the Paraopeba River and north of the town of Moeda as far as the Bonfim dome into areas that were not mapped by the USGS–DNPM team. Samples were collected for petrographic and trace-element analysis. This unmapped area was found to be underlain by a well-foliated and layered granite instead of coarse porphyritic granodiorite. In places, dikes of a distinctly younger crosscutting granitic rock were found in the well-layered rock.

Contacts between this layered granite west of the Paraopeba River and the border granite gneiss that surrounds the porphyritic granodiorite of the Moeda complex appear to be gradational. The minor-element abundances of the different rock types (table 7) suggest that the granodiorite and gneiss of the Moeda complex and the rocks to the north and west are not closely related. Although granitic rock petrographically similar to this Moeda type is not found elsewhere in the Quadrilátero Ferrífero, a coarse porphyritic granite is known from Sete Lagoas, about 55 km north-northwest of the Quadrilátero Ferrífero.

The mixed gneiss of the eastern border of the Moeda complex (table 7, sample Ha–23) has the highest Be content of all, which suggests the influence of late-stage pneumatolytic solutions. Most of its other minor elements are much less abundant than they are in the porphyritic granodiorite to the west. The lower minor element abundances can easily be explained if the rock were originally a quartz-rich sediment with attendent low abundances; this would tend to dilute any added higher abundances in igneous solutions.

The trace elements of the crosscutting granite (sample H–21b) suggest that it is derived from a late-stage differentiate of granitic solutions. It has low Ba, but high Cu, Pb, Sc, and Zr compared to the other granitic rocks of this west-central area, which content is typical

TABLE 7.—*Comparison of the minor-element content (in parts per million) of granites and gneisses from the west-central part of the Quadrilátero Ferrífero*

[Quantitative spectrographic determinations by C. V. Dutra Instituto de Tecnologia Industrial, Belo Horizonte, M.G., Brazil. ------ not analyzed for; N.d., not detected]

Element	Moeda complex granodiorite						Foliated granite north and west of Moeda complex				Gneiss of east complex contact	Cross-cutting granite	Average Quadrilátero Ferrífero granite (Herz and Dutra, 1960)
	Ha-21	Ha-22	WM-1-3	WM-1-5	H-19d	Average	H-19g	H-20c	H-20d	Average	Ha-23	H-21b	
Ba	540	720	430	390	480	510	1,300	1,200	900	1,100	360	480	860
Be	2.5	4.0	------	------	2.2	2.9	1.6	1.2	.8	1.2	6.5	2.2	4.1
Co	1.7	3.3	3.0	3.0	1.5	2.5	N.d.	1.3	2.8	1.4	2.0	3.5	3.8
Cr	.7	1.4	7.5	6.8	1.8	3.6	3.3	3.0	4.4	3.6	N.d.	3.1	7.7
Cu	1.6	1.8	3.6	2.6	2.0	2.3	1.8	3.6	3.2	2.9	4	45	11
Ga	12	14	17	16	14	15	11	13	15	13	8.5	19	16
La	75	60	85	68	180	94	20	34	26	27	68	77	76
Mo	N.d.	3.7	------	------	1.7	1.8	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	1.9
Nb	23	28	27	29	17	25	5.6	5.1	5.1	5.3	21	1.9	25
Ni	1.6	2.1	8.6	10	.9	4.6	.8	1.0	2.8	1.5	1.0	2.4	8.3
Pb	56	29	22	110	62	56	24	45	29	33	14	59	26
Sc	3.1	4.2	3.6	3.3	5.2	3.9	1.6	1.6	2.9	2.0	2.0	6.5	6.5
Sn	27	21	------	------	9.5	14	4.7	5.5	6.3	5.2	10	11	25
Sr	71	76	105	110	85	89	240	210	270	240	41	150	160
V	6.8	8.8	41	27	14	20	12	12	20	15	7	18	29
Y	41	120	91	77	160	98	25	6.3	N.d.	10	59	21	82
Zr	190	270	240	210	210	220	74	62	93	76	250	330	220

of the late differentiates of the region (Herz and Dutra, 1960).

The combined evidence of field and laboratory suggests the following chronology.

In earliest Precambrian times (~2,700 m.y.), a eugeosynclinal sequence that included graywacke, arkose, pelite, and volcanic rocks was intruded. In a later event (~1,930 m.y.), the sequence was partly granitized by coarse porphyritic granodiorite and its correlatives (Group I) and also metomorphosed, in many places to the granulite facies level. The border gneiss of the complex (table 7, sample Ha-23) is a remnant of the Rio das Velhas sequence of the first event, although later mechanical deformation and retrograde metamorphism have erased any older high-grade mineral assemblage. Later events produced the granite gneiss around the sides of the coarse porphyritic granodiorite, and the complex developed as a gneiss dome (Eskola, 1949). Intercalated quartzite and amphibolite now found within the complex are probably part of an ancient sedimentary sequence, but they resisted granitization or gneissification because of their chemical composition. The layered granites found to the west and north of the Moeda complex may have been intruded in the same event that caused the granite gneiss. Their well-foliated and layered structure, which suggest a high-temperature origin, and their minor-element content (table 7), indicate that they are correlative to type II, the Itabirito granite type, as well as to granite at Alberto Flôres.

During and after the deposition of the Minas Series, the granodiorites and gneiss of the gneiss dome of the Moeda complex continued to act as a positive area which may have existed since the first post-Rio das Velhas orogeny. How much of the Moeda complex was formed from remobilized preexisting rock, or anatexis, and how much is introduced new material, is difficult to tell. The late granitic dikes certainly passed through a magmatic stage, and the coarse porphyritic granodiorite probably did also. On the other hand, the granite gneiss is texturally more metamorphic than igneous and might in part actually represent an ancient granulite. Feldspar porphyroblasts in the basal quartzite of the Moeda Formation and veins of kyanite-pyrophyllite-quartz-muscovite (Herz and Dutra, 1964b) and quartz-tourmaline in the Caraça Group are the only contact effects displayed in the neighboring Minas Series.

A later event, probably around 500 m.y. ago, led to partial cataclasis of some rocks because of thrusting from the east, caused by an arching and westward migration of the Bação complex (Wallace, 1965, p. 35). A low-grade regional metamorphism to the chlorite zone of the greenschist facies also took place about this time. Temperatures that obtained were about 400°–430° C.

BAÇÃO COMPLEX

The Bação complex is named for the town of Bação around which are many good exposures of granodiorite and gneiss. The complex itself is oval in shape and covers an area of about 27 km east-west by 20 km north-south in the south-central part of the Quadrilátero Ferrífero, west of the Serra de Antônio Pereira and east of the Serra de Itabirito. The eastern part was mapped by Johnson (1962), some of the southwestern part by Guild

(1957), the western part by Wallace (1965), and the northeastern part by J. E. O'Rourke (written commun., 1954). The Bação complex includes the Itabirito Granite Gneiss and the Engenheiro Corrêa Granodiorite of this, and earlier, reports.

Guimarães and Leinz (in Guimarães, 1951, p. 18–19) were apparently the first to recognize the correlation between the compositionally layered granitic rock of Itabirito and that north of the Serra do Curral at Belo Horizonte. They assigned a pre-Algomanian or lower Archean age to both rocks and described them as "gray gneisses" containing white pegmatite, aplitic veins, and ptygmatic folds and rich in biotite and plagioclase. They considered the Bação complex a horst or an old shield. In the northern part of the complex, north of Esperança, in the bed of the Rio das Velhas, especially at the Cachoeira do Bongo, they found beds of feldspathized quartzite which suggested a sedimentary origin for the gneiss. Angular remnants of metabasite and cataclastic texture indicate deformation in the gneiss.

Johnson (1962, p. 19–20) used the term "Itabirito batholith" for the complex, in which he included a granitic orthogneiss, corresponding in part to the Engenheiro Corrêa Granodiorite of this report, and a layered, biotite-rich paragneiss corresponding to the Itabirito Granite Gneiss. The two types grade into each other, and the layered gneiss also grades into migmatites and granitized sediments. Johnson found pegmatite dikes, mafic dikes, and lenses of biotite-garnet schist, as well as pendants of low- to medium-grade schist throughout the complex.

In the granodiorite-metasediment contact area, at the southern edge of the Bação complex, foliation is weak to moderate, and according to Guild (1957, p. 26), bears no relationship to the trend of the metasedimentary rocks adjacent to the contact. In the northern part of the complex, the banded gneiss is gradational into the pelitic rocks of the Rio das Velhas Series (J. E. O'Rourke, written commun., 1954).

A metamorphic aureole surrounds most of the complex. In the São Julião quadrangle, adjacent to the complex, Rio das Velhas sedimentary rocks are metamorphosed to the garnet amphibolite facies and are characterized by staurolite and cordierite (Guild, 1957, p. 29), but the Minas Series shows little, if any, contact thermal effects. In the Dom Bosco quadrangle, the Rio das Velhas Series includes amphibolites near the contact with the complex, yet the equally near Batatal schist has no contact-metamorphic effects (Johnson, 1962, p. 22). The high metamorphic grade of the aureole in the Rio das Velhas rocks is evidence for an original high temperature of intrusion or formation for the granitic rocks in a pre-Minas event.

Quartz and black tourmaline veins that contain some biotite occur throughout the contact area. Wallace (1965, p. 27) found many granodiorite dikes, ranging in thickness from less than 1 to more than 10 meters, both in and bordering the complex. These dikes are somewhat more alkalic in composition than the older granodiorite, and may represent an anatectic melt derived from the granodiorite.

The last thermal event that affected the complex was regional metamorphism at the level of the greenschist facies characterized by epidote and chlorite, especially in the outermost part of the Itabirito granite gneiss (table 8). Cataclastic deformation may have also taken place at this time.

SPECIAL STUDIES

AGE DETERMINATIONS

Mineral separates of muscovite, biotite, and K-feldspar from eight rocks were used for age determinations by Rb/Sr and K/Ar methods (table 2). The ages were not concordant, but certain conclusions can be drawn from them.

All ages obtained in the Quadrilátero Ferrífero are found in the Bação complex, except the youngest date of about 500 m.y. Sr/Rb ages of 2,675 (DTM–2) and 2,790 (DTM–3) m.y. were obtained from mica schist and amphibolite of the Rio das Velhas Series north of the Bação Complex, and a K/Ar age of 2,400 m.y. (Ha–4) was obtained on biotite from granodiorite of the southern part of the complex, near Engenheiro Corrêa. The beginnings of the complex must thus date back at least some 2,700 m.y., but the exact dates of subsequent tectonic events are difficult to obtain.

Thermal events (table 2) may have occurred at 2,700 m.y. (samples Ha–4, DTM–2, DTM–3); 1,670 m.y. (Ha–28, DTM–3); 1,380 m.y. (Ha–2, DTM–1); 1,040 m.y. (DMT–2, Ha–28, Ha–4); and 805 m.y. (Ha–3, Ha–29). The last age, on biotite, was determined only by the K/Ar and is probably mixed; all the other dates may be significant, although from data obtained outside the Bação complex in Sete Lagoas (Pinson and others, 1967) and the Moeda complex, a 1,930-m.y. date is more probable than the one around 1,670 m.y.

ALKALI FELDSPARS

Alkali feldspars were separated from samples Ha–4 (granodiorite) and Ha–28 (layered gneiss) and were analyzed for major and trace elements (Herz and Dutra, 1966). Partial results (in parts per million for minor elements; in percent, for feldspar molecules) are:

Sample	Rb	Ba	Sr	Li	Ca	An	Ab	Or	T°C
Ha–4	240	5,500	618	28	1,790	1.3	14.9	83.8	460
Ha–28	190	3,050	48	5.0	1,570	1.1	13.1	85.8	420

Both feldspar samples have slightly less than the 15 percent albite molecule considered to be the minimum for medium-temperature, subsolvus granites (Tuttle and Bowen, 1958). However, an original higher temperature of formation for both feldspars is suggested by their low Rb and high Ba and Ca, as well as high Sr in Ha–4. The high temperature suggested by the minor elements might be a premetamorphic relict, whereas the low temperature of the albite geothermometer (Barth, 1956) can be explained by their modification under nonequilibrium low-metamorphic-grade conditions.

MINOR ELEMENTS IN BIOTITE

Some minor elements were determined in biotite from Ha–4, a granodiorite from the southern part of the complex, and from a mafic-rich layer of Ha–5, a layered granodiorite gneiss from the western part. It was hoped that the data would provide absolute temperatures of formation(Oftedal, 1943), but, unfortunately, this was not possible. The results of these analyses (in parts per million) are (Herz and Dutra, 1964a):

Sample	Co	Ni	Sc	Cr	Nb
Ha–4	40	53	24	70	nd
Ha–5	60	82	8.2	77	nd

The higher Sc and lower Co, Ni, and Cr in Ha–4 compared to Ha–5 suggest that the granodiorite was recrystallized at relatively low temperatures. This is consistent with the data obtained from analysis of its alkali feldspar. The lack of Nb in either sample rules out a late magmatic origin.

ENGENHEIRO CORRÊA GRANODIORITE

The Engenheiro Corrêa Granodiorite is named for the town [2] in the southeastern part of the Bação quadrangle; Johnson (1962) mapped it as granodiorite gneiss.

A biotite-muscovite granodiorite from Riberão Sardinha, near Engenheiro Corrêa was described by Guild (1957, p. 26–27; table 8, 48G12) and considered equivalent to the granodioritic rocks of the Congonhas area. It has a weak to moderate foliation in the contact zone, and its foliation trend shows no apparent relationship with the bedding or cleavage in the surrounding metasedimentary rocks.

The type Engenheiro Corrêa Granodiorite (table 8, Ha–4) is dark gray and is poorly foliated and layered. It is fine- to medium-grained and is generally equigranular, except for microcline phenocrysts scattered irregularly throughout the groundmass. Groundmass grains average about 0.5 mm in diameter. Plagioclase, An_{21}, makes up almost half the rock and is generally, untwinned or simply twinned; some grains are rimmed by K-feldspar. Microcline and perthite generally make up slightly more than 10 percent of the rock, and quartz, about 30 percent. Biotite averages from 6 to 14 percent; other minerals include muscovite, magnetite, apatite, zircon, and clinozoisite.

Pegmatites and aplitic dikes are retricted to joints and have sharp gradational contacts against the granodiorite. The pegmatites consist of very coarse grained K-feldspar, finer grained plagioclase, quartz, and some muscovite, and are granitic in composition (table 8, sample 51G56b). The pegmatites are low in rare earths, to judge by their lack of the corresponding minerals. The absence of gradational features between the granodiorite and pegmatites suggests that the two rocks were emplaced at greatly different times and temperatures.

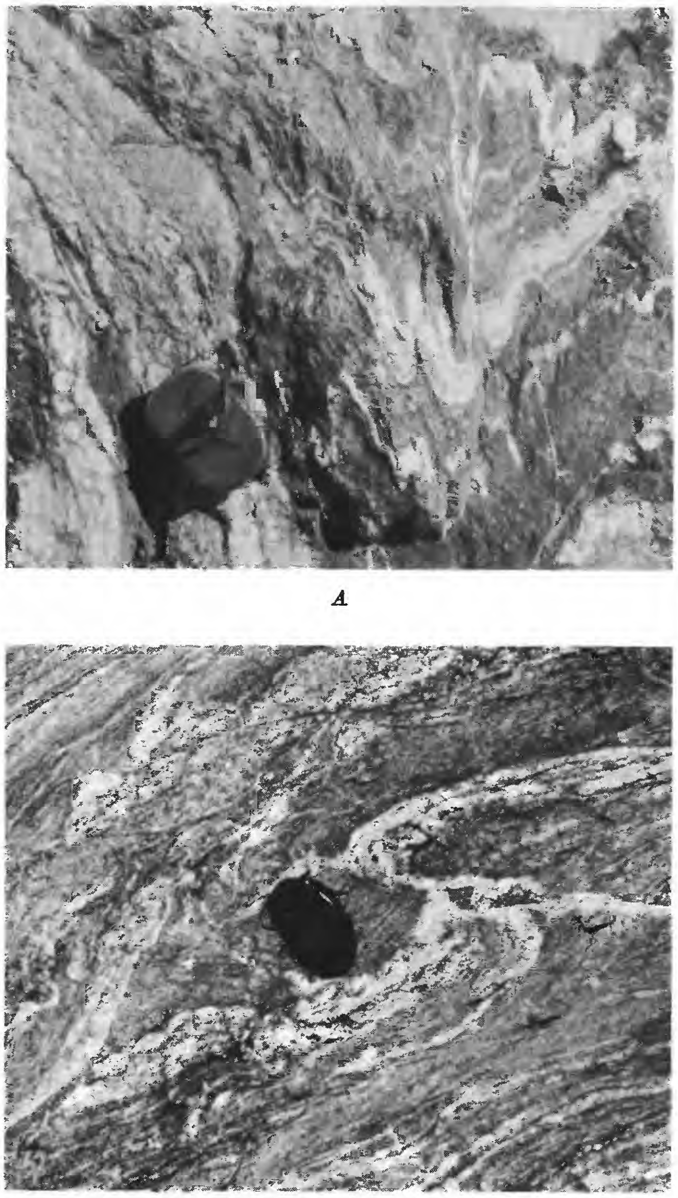
ITABIRITO GRANITE GNEISS

The type Itabirito Granite Gneiss is in the town of Itabirito in the northwestern part of the Bação Complex (fig. 14). Most of the northern, western, and southeastern parts of the complex are underlain by similar rock, as is also the southern margin of the complex south of the Engenheiro Corrêa Granodiorite.

The Itabirito Granite Gneiss grades into granodiorites in some places and into migmatites and granitized sedimentary rocks in others. It is generally medium to coarse grained, well foliated, and compositionally layered by felsic and mafic minerals; it thus resembles gneiss north of the Serra do Curral. Microcline occurs as phenocrysts, averaging 3–6 mm, but they are as much as 10 mm in size. The largest phenocrysts are in the mafic layers. Groundmass feldspars are somewhat smaller, quartz is about 0.5 mm, and biotite is 0.3 mm in size. Some crudely foliated parts of the gneiss consist of grains of crushed quartz and feldspar.

The cores of many plagioclase grains are full of clinozoisite, but the rims are clear sodic plagioclase (An_{10}) (fig. 15). The cores may represent original calcic plagioclase in the granodiorite, and the more sodic rims may be a product of a later event.

[2] The town is also spelled "Engenheiro Correia."



A

B

FIGURE 14.—Banded biotite granite gneiss in the quarry in Itabirito. *A*, Thin mafic and felsic-rich layers alternate. *B*, Contorted folds and fault patterns suggest a migmatitic origin. Large porphyroblasts of K-feldspar are abundant both in mafic and felsic layers.

These banded granitic gneisses vary from granite to granodiorite (table 8), and all have a high proportion of dark minerals, especially biotite, much of which is rutilated. Apatite, zircon, and sphene are common accessory minerals. Pegmatites associated with these rocks consist largely of very coarse K-feldspar, plagioclase, quartz, muscovite, biotite or tourmaline, and sulfide minerals. Tourmaline (schorlite)-quartz pegmatites of uncertain age are found along the southern margin of the Bação complex.

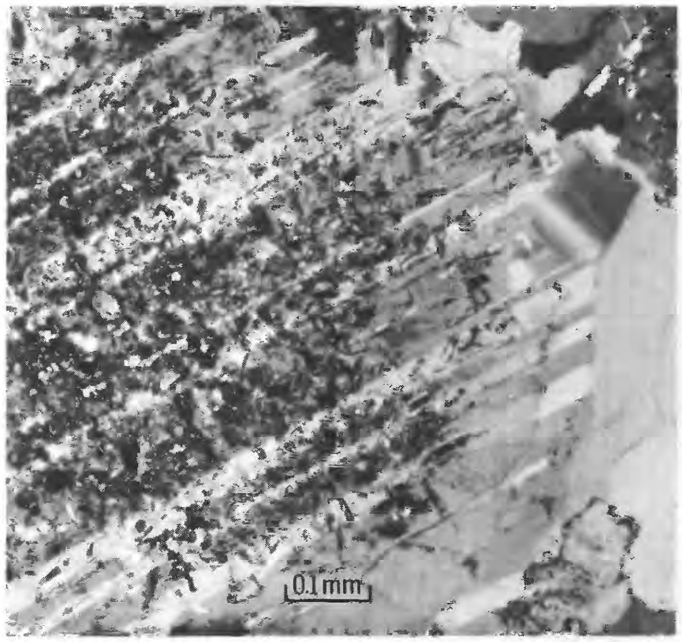


FIGURE 15.—Photomicrograph of partly replaced plagioclase in felsic part of Itabirito Granite Gneiss. Core extensively replaced by clinozoisite and muscovite surrounded by clear rim. Rim has composition about An_{10}; core originally more calcic than this. K-feldspar borders the plagioclase. Sample Ha–5L.

Many rocks within the complex are similar mineralogically to the Itabirito Granite Gneiss; but orientation of biotite is weak, which results in weaker foliation and weaker felsic-mafic-layering. Crushed and mortared quartz and feldspar are seen in thin section. Such rocks as sample Ha–3 from Cachoeira do Campo yield mixed K/Ar ages (table 2). They are interpreted as Itabirito Granite Gneiss that was deformed and metamorphosed in a post-Minas event, and thereby lost some Ar. Microcline and microcline-perthite crystals in this rock range in size from 0.7 to 3.5 mm, and have abundant inclusions of other minerals. Some microcline appears to have replaced both quartz and earlier formed feldspars. Pegmatites near Cachoeira do Campo are crosscutting and also in *lit-par-lit* relation to the gneiss; they are similar mineralogically to those at Itabirito.

Along the southern margin of the complex, a migmatite zone as much as 30 meters wide is a mixture of banded gneiss and felsic granodiorite (Johnson, 1962, p. 22). The migmatite consists of layers of schist 2–3 mm thick and intercalated thin streaks of younger granitic material. In contrast to the contorted migmatite found within the batholith, the layers in the contact area are not crumpled. To the south, the migmatite grades into biotite schist, which suggests that it may well represent, in part, a granitized sediment of the Nova Lima Group.

TABLE 8.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks from the Bação complex*

[For sample locations, see table 3 and pl. 1. ---, not analyzed; P=present; N.d., looked for, but not detected]

	Engenheiro Corrêa Granodiorite							Itabirito Granite Gneiss				Layered gneiss				
												Southern border	Northern border			
	Ha-4	J-668	J-76	J-37	48G12	51G56	[1] 51G56b	Ha-2	Ha-3	Ha-5L	Ha-5D	J-82	Ha-28	Ha-29	Z-8a	Z-188a
Chemical analyses (Weight percent) [Analysts: P. L. D. Elmore, S. D. Botts, I. H. Barlow, M. D. Mack, and H. H. Thomas, using method of Shapiro and Brannock (1956); fluorine, by S. M. Berthold, U.S. Geological Survey]																
SiO_2	72.1	72.0	---	---	---	---	---	74.5	75.1	75.2	63.8	75.1	---	---	---	---
Al_2O_3	15.0	15.6	---	---	---	---	---	14.5	14.0	14.7	15.6	13.7	---	---	---	---
Fe_2O_3	.9	.3	---	---	---	---	---	.1	.4	.5	1.5	.2	---	---	---	---
FeO	1.1	1.3	---	---	---	---	---	.9	.85	.16	4.1	1.1	---	---	---	---
MgO	.52	.56	---	---	---	---	---	.24	.25	.11	1.7	.46	---	---	---	---
CaO	1.8	2.1	---	---	---	---	---	1.3	1.4	1.9	4.2	.80	---	---	---	---
Na_2O	4.7	4.6	---	---	---	---	---	3.7	4.2	4.2	4.3	3.1	---	---	---	---
K_2O	2.6	2.8	---	---	---	---	---	4.3	3.2	3.1	2.1	5.4	---	---	---	---
H_2O	.61	.42	---	---	---	---	---	.41	.42	.43	1.0	.40	---	---	---	---
TiO_2	.24	.24	---	---	---	---	---	.13	.14	.06	1.0	.10	---	---	---	---
P_2O_5	.09	.05	---	---	---	---	---	.05	.02	.02	.30	.04	---	---	---	---
MnO	.06	.04	---	---	---	---	---	.02	.06	.04	.14	.02	---	---	---	---
CO_2	.14	.21	---	---	---	---	---	<.05	.11	<.05	.06	<.05	---	---	---	---
F	.00	---	---	---	---	---	---	---	.03	---	---	---	---	---	---	---
Total	99.8	100.2	---	---	---	---	---	100.2	100.2	100.4	99.8	100.4	---	---	---	---
Normative minerals (Weight percent)																
Quartz	30.4	29.1	---	---	---	---	---	32.9	35.0	34.7	18.3	33.3	---	---	---	---
Corundum	1.7	1.8	---	---	---	---	---	1.5	1.5	1.0	---	1.4	---	---	---	---
Orthoclase	15.4	16.5	---	---	---	---	---	25.4	18.9	18.3	12.4	31.9	---	---	---	---
Albite	39.7	38.9	---	---	---	---	---	31.3	35.5	35.5	36.4	26.2	---	---	---	---
Anorthite	7.5	8.8	---	---	---	---	---	6.1	5.9	9.3	17.1	3.7	---	---	---	---
Enstatite	1.3	1.4	---	---	---	---	---	.6	.6	.3	4.2	1.1	---	---	---	---
Ferrosilite	1.0	1.8	---	---	---	---	---	1.4	1.1	---	4.9	1.7	---	---	---	---
Magnetite	1.3	.4	---	---	---	---	---	.1	.6	.5	2.2	.3	---	---	---	---
Ilmenite	.5	.5	---	---	---	---	---	.2	.3	.1	1.9	.2	---	---	---	---
Apatite	.2	.1	---	---	---	---	---	.1	---	---	.7	.1	---	---	---	---
$CaCO_3$	.3	.5	---	---	---	---	---	---	.3	---	.1	---	---	---	---	---
Total	99.3	99.8	---	---	---	---	---	99.6	[2] 99.8	[3] 100.0	[4] 98.8	99.9	---	---	---	---
Differentiation index	85.5	84.5	---	---	---	---	---	89.6	89.4	88.6	67.1	91.4	---	---	---	---
Percent An in plagioclase	15.9	18.4	---	---	---	---	---	16.3	14.3	20.8	32.0	12.4	---	---	---	---
Modal minerals (Volume percent)																
Plagioclase	44.0	54	56.0	47	53.5	41.1	28.5	22.3	35.5	36	35	37	33.0	36	---	---
(Percent anorthite)	(21)	(±20)	(20)	(±20)	(18)	(±20)	(±20)	(15)	(12)	(12)	(17)	(18)	(9)	(8)	---	---
K-feldspar	14.8	10	6.1	10	11.7	11.3	44.5	37.4	27.8	25	12	12	20.0	15.5	---	---
Quartz	30.4	21	26.0	26	25.1	25.6	26.0	30.1	27.2	29	25	14	22.2	20	---	---
Biotite	5.3	10	11.5	10	5.8	14.4	---	3.7	3.7	5	8	26	9.0	11	---	---
Muscovite	3.3	1	---	3	3.9	7.3	.5	4.4	3.8	2.5	---	3.5	7.5	9	---	---
Epidote, clinozoisite	1.0	P	P	3	---	---	---	1.8	1.4	3	4	P	[5] 7.8	[5] 6	---	---
Chlorite	---	---	---	P	---	---	---	.3	.5	P	---	---	P	P	---	---
Apatite	.6	P	P	P	---	P	---	---	---	---	P	P	---	P	---	---
Zircon	---	P	P	---	---	P	---	P	---	---	P	P	P	---	---	---
Opaque minerals	.4	---	---	---	---	---	---	---	---	---	---	---	P	---	---	---
Tourmaline	---	---	---	---	---	---	---	---	---	---	---	---	P	---	---	---
Carbonate	---	---	---	---	---	---	---	---	.1	---	---	---	.5	---	---	---
Sphene	---	[6] P	---	P	---	---	---	---	---	---	---	P	[6] P	P	---	---
Minor elements (Parts per million) [Quantitative spectrographic determinations by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte, M.G., Brazil]																
Ba	860	940	---	---	---	---	---	1,400	990	700	580	500	1,600	900	900	1,200
Be	3.6	1.3	---	---	---	---	---	---	---	---	---	2.5	N.d.	5.0	---	---
Co	3.0	3.7	---	---	---	---	---	N.d.	N.d.	N.d.	6.7	N.d.	5.2	6.9	6.3	6.9
Cr	3.6	6.8	---	---	---	---	---	1.4	3.1	1.9	12	4.0	2.1	23	9.6	33
Cu	2.3	Trace	---	---	---	---	---	1.2	1.8	7.2	12	1.8	2.6	1.8	6.4	36
Ga	19	18	---	---	---	---	---	21	17	19	22	19	13	7	21	21
La	N.d.	51	---	---	---	---	---	51	N.d.	N.d.	N.d.	N.d.	81	73	102	73
Mo	3.3	N.d.	---	---	---	---	---	---	---	---	---	N.d.	1.3	3.7	---	---
Nb	11	N.d.	---	---	---	---	---	15	9.1	7.0	18	22	11	31	35	49
Ni	4.7	4.4	---	---	---	---	---	2.3	4.0	2.3	20	2.0	2.2	11	14	23
Pb	12	19	---	---	---	---	---	28	21	25	19	45	19	36	21	23
Sc	2.8	6.5	---	---	---	---	---	3.6	3.6	4.2	11	3.8	5.2	7.8	9.1	15
Sn	7.1	4.7	---	---	---	---	---	10	4.7	2.0	10	5.1	28	20	61	61
Sr	300	410	---	---	---	---	---	140	240	190	280	89	72	130	140	200
V	21	27	---	---	---	---	---	8.1	14	7.5	33	8.2	20	31	54	68
Y	11	10	---	---	---	---	---	22	11	23	39	57	42	73	87	87
Zr	105	180	---	---	---	---	---	100	110	59	190	98	250	370	220	300

[1] Granite dike crosscutting granodiorite.
[2] Includes 0.1 percent fluorite.
[3] Includes 0.2 percent hematite.
[4] Includes 0.6 percent wollastonite.
[5] Includes allanite.
[6] Includes leucoxene.

PETROGENESIS AND GEOLOGIC HISTORY

The Engenheiro Corrêa Granodiorite has the highest Na content of the rocks of the Bação complex (table 8) as well as the highest modal anorthite. It has a generally low minor element content, except for Sr, which is high because of the large amount of plagioclase, and La, which may be present in sphene. The normal Itabirito Granite Gneiss (granodiorite phase) has a higher D.I. (differentiation index, Thornton and Tuttle, 1960) than the Engenheiro Corrêa, as well as being high in K_2O and SiO_2. Although both rocks have similar normative anorthite molecule, An_{17}, the Itabirito has lower modal anorthite and a high amount of epidote minerals.

Chemically, the Engenheiro Corrêa is similar to Johannsen's leucogranodiorite (1932, p. 318), because of its comparatively high SiO_2 and Na_2O and low total iron, MgO, and CaO (table 8). Its D.I. of 86.2 is intermediate between those of granite and alkali granite (Thornton and Tuttle, 1960), but mineralogically, the rock is a granodiorite. Conversely, the Itabirito Granite Gneisses range from the granodiorite of Johannsen (1932, p. 318) to granite, with increasing potassium (table 8). The D.I. of the felsic gneisses is 89.4–91.4, and thus, somewhat higher than that of the Engenheiro Corrêa Granodiorite.

Differences in texture between the granodiorite and the gneiss are notable. The granodiorite has a granitic texture and poor foliation, whereas the gneiss has a strong compositional layering, large and paragenetically late microcline (porphyroblasts?), and, in places, exhibits cataclastic deformation. The outer part of the complex is largely gneiss, whereas the interior is granodiorite. In many places there is an apparent gradational relationship between the granodiorite and gneiss as well as between the gneiss and metasediments of the Nova Lima Group (Johnson, 1962, p. 22), which suggests an origin closely linked in time for both the gneiss and granodiorite. The following interpretation is consistent with the field and laboratory data: The Engenheiro Corrêa Granodiorite intruded in a 2,700-m.y. event into Rio das Velhas sedimentary rocks. Many sediments were gneissified, and bedding may be preserved as compositional layering. The similar chemical compositions of the granodiorite and the felsic-rich part of the gneiss attest to conditions of the equilibrium that obtained under the high pressure-temperature conditions. Ultrametamorphism and the formation of anatectic melts from the sedimentary rocks may have taken place at that time.

Mafic layers in the Itabirito Granite Gneiss may represent the more refractory beds or remains of pelitic material of the Nova Lima Group. The biotite of the Itabirito has more abundant minor femic elements than the biotite of the Engenheiro Corrêa (p. B27). which suggests that they may have had different origins.

Some metasedimentary rocks, also of a refractory nature, found within the granodiorite, may represent roof pendants or xenoliths that were metamorphosed to the garnet-amphibolite facies. Elsewhere, as in the northeastern part of the complex sedimentary rocks of a more silicic or feldspathic composition were gneissified or "granitized," and, except for their higher quartz content, were probably mineralogically similar to parts of the granodiorite. J. E. O'Rourke (written commun., 1954) described a transition between the Nova Lima Group and the banded granite gneiss of the Bação complex in the Rio de Pedras quandrangle and considered the entire complex to have originated by granitization of the Nova Lima Group. Most of the Nova Lima metasedimentary rocks today, however, are Fe-Mg-K-rich pelites (Herz, 1962), rather than the feldspathic quartzites that O'Rourke considered as a pregranitized source of the granitic gneiss. Although quartzitic rocks may have been predecessors of much of the gneiss, the granodiorite can better be explained as having an igneous origin.

Guild (1957, p. 27) has cited field relations, in addition to the contact-metamorphic aureole, as evidence for an intrusive origin for the Engenheiro Corrêa Granodiorite: First, the contact of the complex is discordant to the metasedimentary country rock, and second, the granodiorite possesses a weak foliation parallel to the contact in the contact area. In later orogenies, anatectic solutions derived or augmented by the partial fusion of some granodiorite or gneiss moved along channelways opened up during the initial stages of each orogeny. In the 1,350-m.y. post-Minas orogeny, injection of granitic magma largely took place in the peripheral area of the complex. The high amount of minor elements (typically abundant in late-stage granite or pneumatolytic melts) that are present in gneiss of the northern contact, as well as abundant K and Si in the layered gneiss of the southern border (table 8, J–82), do, in fact, suggest late melts.

Granitic dikes and pegmatites may have intruded the complex in the early stages of the 500-m.y. post-Minas deformation. Later, perhaps toward the close of this same event, deformation and widespread greenschist metamorphism affected the complex, especially its peripheral areas and northern outliers. Chlorite, muscovite, and epidote minerals were formed largely in the gneisses (fig. 16), and preexisting feldspar crystals were mantled by sodic plagioclase (fig. 15) or deformed; a mortar texture developed in many rocks. The metamorphism evidently was accompanied by alkali metaso-

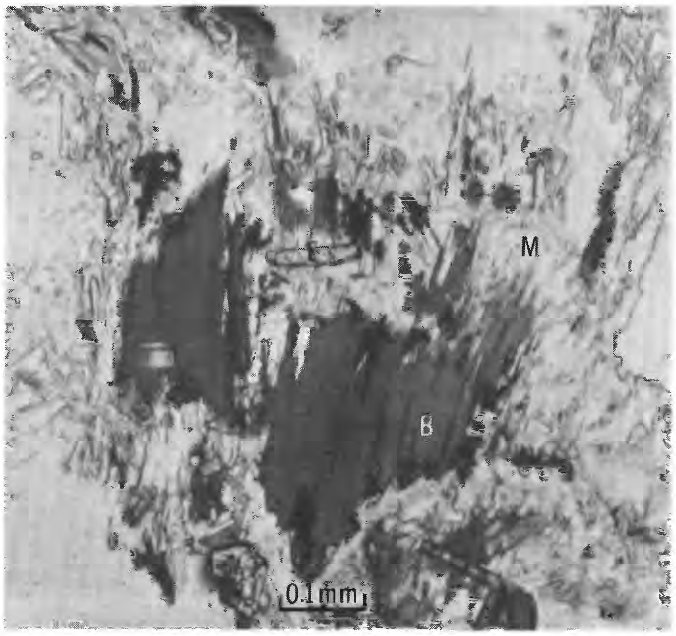


FIGURE 16.—Photomicrograph of Itabirito Granite Gneiss. Replacement of biotite (dark mineral B) by muscovite (M) and epidote (E). Sample Ha–3a, Cachoeira do Campo, plane light.

matism, as indicated by the replacement of biotite by muscovite rather than by chlorite, the partial replacement of plagioclase by muscovite, and the rimming of calcic plagioclase by albite and microcline.

MAFIC DIKES

Both Johnson (1962) and J. E. O'Rourke (written commun., 1954) mapped amphibolite dikes within and near the Bação complex. Many amphibolites retain a diabasic texture, although they consist almost entirely of hornblende and a zoned plagioclase, generally An_{30-40}. Accessories include sphene, leucoxene, pyrite, quartz, apatite, magnetite, and clinozoisite. Many dikes are discordant to all structures and cut both the surrounding metasedimentary rocks and the gneiss.

In the northern part of the complex, J. E. O'Rourke (written commun., 1954) described three types of amphibolites, one similar to the metadiabase dikes of Johnson, and the two others representing possible metamorphosed mafic flows or dolomitic-pelitic mixtures.

No ultramafic rocks are known from the Bacão complex or vicinity.

SOUTHERN PART OF THE QUADRILÁTERO FERRÍFERO

Gneissic and granodioritic rocks of the southwestern part of the Quadrilátero Ferrífero crop out northwest of the Serra das Almas, south of Congonhas and Jeceaba, and south of the Bação complex (pl. 1). The rocks of the first area are a southerly continuation of the Moeda complex. They consist of layered gneiss and grandiorite and have been discussed in the section on the west-central part of the Quadrilátero Ferrífero. The gneisses and granodiorites south of Congonhas and Jeceaba include the most calcic- and mafic-rich felsic rocks of the Quadrilátero Ferrífero. They include a granodiorite-tonalite suite, and their intrusion apparently caused garnet-amphibolite-grade metamorphism in the surrounding country rock. South of the Bação complex, thin granitic and granodioritic dikes and small, apparently concordant, gneissic bodies are found in rocks of the Minas Series and Nova Lima Group (Guild, 1957; Johnson, 1962). Gneisses and granodiorites are also present south of the Engenho fault in the southeastern part of the Quadrilátero Ferrífero (A. L. M. de Barbosa, oral commun., 1960), but these rocks have not been studied in any detail.

Mafic dikes and plugs are exposed throughout the southern Quadrilátero Ferrífero; serpentinized and steatized ultramafic dikes and small stocks are present in the extreme southwestern part.

SPECIAL STUDIES

AGE DETERMINATIONS

K/Ar determinations were made on three samples of biotite and one of muscovite from the southern part of the Quadrilátero Ferrífero. Just northwest of Salto, grandiorite gneiss (table 2, sample Ha–26) was dated at 790 m.y., whereas about 7 km to the north-northwest, deeper within the Moeda complex, a granodiorite gneiss (sample Ha–24) of the Moeda section yields a date of only 462 m.y.

Amphibole-bearing tonalite south of Congonhas, represented by sample Ha–25, was dated at 740 m.y. and therefore is similar in apparent age to the granodiorite at Salto. In the Dom Bosco area, north of the Serra do Ouro Branco, an inclusion of gneiss in the Piracicaba Group of the Minas Series, represented by sample Ha–11, has an age of only 530 m.y.

All the dates from this area are by K/Ar determinations on micas, and need verification by other mineral analyses and methods. With more information, the dates of about 760 m.y. in this area and the Bação complex (table 2) may prove to represent a significant event rather than argon loss at about 500 m.y. The 500-m.y. date, which is taken to represent a widespread greenschist metamorphic event and cataclastic deformation throughout the Quadrilátero Ferrífero, is also represented in this area.

ALKALI FELDSPARS

Alkali feldspar from sample Ha–27, an amphibole-bearing granodiorite from near Jeceaba, and sample Ha–11, a gneiss inclusion from the Piracicaba Group north of Ouro Branco, were analyzed (Herz and Dutra, 1966). Some of these results (in parts per million for minor elements; in percent for feldspar molecules) are:

Sample	Rb	Ba	Sr	Li	Ca	An	Ab	Or	T°C
Ha–11	250	1,560	30	2	290	0.2	14.6	85.2	420
Ha–27	85	5,480	665	2.9	1,720	1.3	22.7	75.7	570

The two feldspars are very different in both composition and origin. Several lines of evidence indicate that Ha–27 was of igneous origin, whereas other features indicate that Ha–11 was of metamorphic origin. The feldspar from sample Ha–27 has more than 15 percent albite molecule and is considered to be of medium-temperature, subsolvus origin (Tuttle and Bowen, 1958). Its indicated temperature of formation, 570° C, using the albite geothermometer, is within the range suggested for igneous granodiorite-tonalite by Barth (1956). The abundant Ca, Ba, and Sr in the feldspar; the lack of metamorphic minerals, such as epidote and chlorite, in the granodiorite; and the associated garnet-amphibolite metamorphic grade of the country rock may be further evidence for an igneous origin. Later greenschist metamorphism, widespread elsewhere in the Quadrilátero Ferrífero, was apparently not effective south of Congonhas.

Sample Ha–11 has less than 15 percent albite and therefore is considered to be of low-temperature, subsolvus origin. The contrast in its minor elements with those in the feldspar of sample Ha–27 also suggests a lower temperature of formation for sample Ha–11. The indicated temperature of 420° C is within the range for the greenschist-facies metamorphic grade, the same grade suggested by the presence of abundant epidote, chlorite, and sericite in the rock.

GRANODIORITE-TONALITE

Two intergradational suites of granodiorite and tonalite (tables 9–11) form batholiths, stocks, and dikes that intrude the Rio das Velhas Series south of the Engenho fault in the Congonhas district (Guild, 1957, p. 26–27). These suites are tentatively correlated with the older granodiorites found elsewhere. The tonalite suite is hornblende bearing and low in potassium, compared with the granodiorite suite. The plagioclase in the hornblendic rocks occurs as hypidiomorphic crystals several millimeters in diameter; in places the crystals have calcic rims (An_{32}) over sodic cores (An_{20}).

The granodiorite has a medium- to fine-grained granitoid texture and, in places, resembles the Engenheiro Corrêa Granodiorite, with which it may be co-

TABLE 9.—*Chemical analyses and normative minerals of gneiss (Ha–11) and granodiorite (Ha–27) from the southern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. Analysts: P.L.D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe, U.S. Geological Survey, using method of Shapiro and Brannock (1956)]

	Ha–11	Ha–27
Chemical analyses		
Weight percent		
SiO_2	72.3	66.2
Al_2O_3	15.1	14.6
Fe_2O_3	.7	1.4
FeO	.76	3.2
MgO	.68	2.3
CaO	.04	3.0
Na_2O	3.3	4.4
K_2O	5.4	2.4
H_2O	1.0	.86
TiO_2	.28	.65
P_2O_5	.06	.23
MnO	.01	.10
CO_2	.02	$<.05$
F	.00	.07
Total	99.7	99.4
Normative minerals		
Weight percent		
Quartz	31.3	20.7
Corundum	3.8	--------
Orthoclase	31.9	14.2
Albite	27.9	37.2
Anorthite	--------	12.9
Enstatite	1.7	5.7
Ferrosilite	.4	3.8
Magnetite	1.0	2.0
Ilmenite	.5	1.2
Apatite	.1	.5
$CaCO_3$	.1	--------
Total	[1] 98.7	[2] 98.3
Differentiation index	91.1	72.1
Percent An in plagioclase	0	25.7

[1] Norm deficient in CaO.
[2] Includes 0.1 percent fluorite.

magmatic. The greater part of the leucogranodiorite is massive, but along the borders of many of the larger stocks, well-oriented schlieren and lenticular or tabular masses of biotite and hornblende lie parallel to the contracts. Xenoliths and roof pendants of ultramafic rocks or Nova Lima metasedimentary rocks in particular are common in or near the border zones.

The tonalite, typified by sample Ha–27 (table 9–11), also seems to be closely related to the Itabirito-Bação rocks. Tonalites more mafic than sample Ha–27 are found to the south, but they were probably contaminated by mafic or ultramafic material during differentiation. Plagioclase in the tonalite is An_{20-32} (Guild, 1957, p. 26) and is zoned with calcic rims over normally zoned sodic cores (fig. 17). The hornblende is pale green and weakly pleochroic. Felsic-rich samples have a medium-

TABLE 10.—*Modal minerals of granodiorite and gneiss from the southern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. Microscopist: (W), Wilna B. Wright, (G), P. W. Guild, (H), Norman Herz, U.S. Geological Survey; (D), E. C. Damasceno, Department of Geology, University of São Paulo. P, present.]

	Granodiorite and tonalite complex south of Congonhas				Granodiorite stock north of Congonhas	Granodiorite gneiss, southern part of Moeda complex		Granite gneiss
	Ha-25	Ha-27	G-1	G-3	G-4	Ha-24	Ha-26	Ha-11
Plagioclase	48.4	50.2	47.3	45.7	47.6	48.5	35.9	17.2
(Percent An)	(23)	(22)	(±25)	(±25)	(±20)	(13)	(25)	(0)
K-feldspar	4.1	10.9	6.4	7.8	16.6	15.7	31.6	32.6
Quartz	16.2	18.3	13.7	21.7	28.7	26.1	30.1	35.3
Biotite	20.8	14.1	23.9	17.3	3.4	4.1	1.4	8.6
Muscovite	P	2.7	P	.4	2.7	4.3	.8	8.0
Epidote	8.4		P	P	P	.8	.3	1.2
Chlorite			P	P				1.8
Apatite	P		P	P	(?)			
Zircon	P	P	P	P	P		P	
Carbonate		P	P	P	P	.2		
Amphibole	2.1	3.7	6.2	1.7				
Sphene		P	P	P				
Opaque			P	P		.3		.3
Number of points	876	1,500				655	1,000	924
Microscopist	(W)	(G)	(G)	(G)	(G)	(D)	(G)	(H)

TABLE 11.—*Minor elements (in parts per million) of granodiorite and gneiss from the southern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. Quantitative spectrographic determinations by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte, M. G. Brazil. N.d., looked for, but not detected]

Element	Granodiorite and tonalite complex south of Congonhas		Granodiorite gneiss, southern part of Moeda complex (arranged north to south)						Unfoliated, crosscutting granite dike, Salto	Granite gneiss
	Ha-25	Ha-27	H-22h	Ha-24	Ha-23a	Ha-26	H-11i	H-11j	H-11jI	Ha-11
Ba	990	1,600	900	720	900	500	710	600	380	450
Be	2.8	5.2	4.0	4.0	1.4	10	2.7	5.4	3.4	
Co	17	7.9	8.8	1.9	4.2	7.9	2.9	3.5	N.d.	2.5
Cr	55	31	11	.7	4.1	48	3.2	12	1.6	1.0
Cu	20	14	11	18	4.4	120	11	5.6	1.6	.6
Ga	18	19	16	16	19	19	12	19	19	16
La	84	62	260	N.d.	14	51	260	100	72	110
Mo	2.3	N.d.	2.0	N.d.	N.d.	4.4	2.7	2.8	N.d.	
Nb	10	20	19	16	7.7	24	10	21	9.8	10
Ni	70	2.9	4.9	1.7	2.0	63	.9	2.0	.8	4.0
Pb	50	29	45	33	31	33	37	48	54	11
Sc	9.8	7.8	9.8	1.3	4.0	29	5.0	6.5	1.3	2.5
Sn	31	7.0	16	14	13	87	9.5	12	7.9	68
Sr	470	580	130	170	160	85	25	120	80	52
V	49	44	56	4.0	23	270	18	28	6.8	6.8
Y	35	24	57	22	7.9	106	130	43	8.7	24
Zr	240	190	350	89	110	210	300	230	110	210

to fine-grained granitoid texture, and the plagioclase is not so strongly zoned as that in the hornblendic varieties (complete modes given in table 10). In some places, border facies are finer grained than interiors of felsic granodiorite masses. Both the tonalite and leucogranodiorite are cut by microcline-rich pegmatites having plagioclase An_{10}, quartz, and some tourmaline and micas, similar to pegmatites found along the southern contact area of the Bação complex.

Country rock of the Rio das Velhas Series near the contact with granodiorite or tonalite north and west of

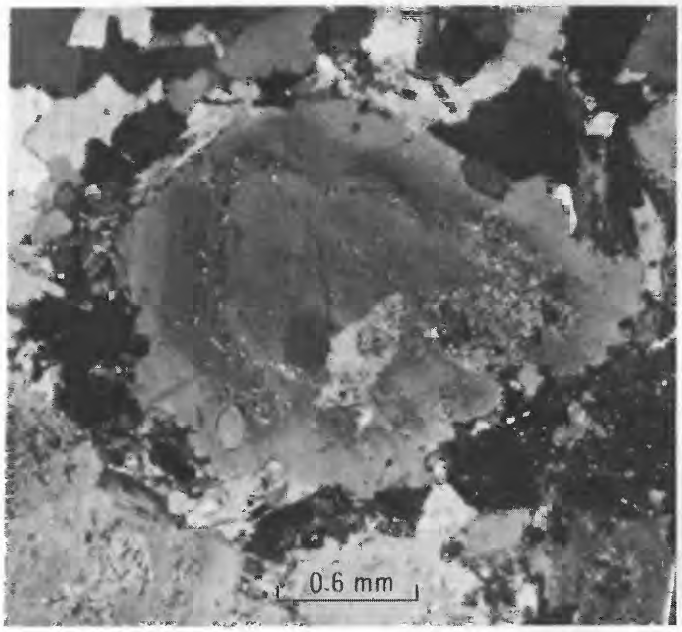


FIGURE 17.—Photomicrograph of zoned plagioclase in granodiorite. Range in composition about An_{20-32}. Some more calcic zones are extensively replaced by clinozoisite. Sample Ha–27, Jeceaba, crossed nicols.

Jeceaba as well as east of Congonhas and south of the Serra do Ouro Branco has been metamorphosed to the garnet amphibolite level. Away from the contact, the general metamorphic grade is at the upper greenschist level.

Minor elements in the Congonhas tonalite-granodiorite suite (table 11, samples Ha–25 and 27) are distinct from other rocks of the Quadrilátero Ferrífero. Femic elements, such as Mg, Co, Cr, and Ni as well as Ba and Sr, are high, which suggests relatively early fractionation from a melt of granitic composition. These elements are even more abundant here than in the maficrich part of the granodiorite of Bação complex (table 8, sample Ha–5D).

Major and minor element abundances in the granodiorite north of Salto show strong similarities to abundances in the Moeda complex (table 7). The coarse porphyritic granodiorite of the Moeda complex was not found here, and the rocks at Salto should be considered as equivalents to the granite gneiss of the Moeda complex.

The late, crosscutting unfoliated granite dike at Salto (sample H–11jI) appears to be similar in its minor-element abundance to the gneiss within the Minas Series south of Dom Bosco (table 11, sample Ha–11).

The mode of occurrence, the metamorphic halo in surrounding rocks, the indicated feldspar temperature, and texture and mineralogy leave little doubt that the granodiorite and tonalite suites of the Congonhas area are igneous. They may be related, in part, by anatexis or by normal magmatism to some of the granodiorite of the Bação complex. The lack of deformation shown by the Congonhas granodiorite has been taken as evidence for a post-Minas or post-Itacolomi age (Guild, 1957, p. 27–28).

SMALL INTRUSIVE BODIES OF GRANITE AND GRANODIORITE

Thin, discontinuous dikes and small irregular bodies of granodiorite and granite are present in the granodiorite complex in pre-Minas, and in Minas rocks south of the Bação complex (Johnson, 1962, p. 23). Sample Ha–11 (tables 9–11) is typical of these rocks. Granitic dikes as much as 10 meters in width and a few hundred meters in length cut the quartzite and phyllite of the Serra do Ouro Branco in the Dom Bosco quadrangle. The granite has sharp contacts with country rock and forms either lenslike, tabular, or irregular bodies (fig. 18). The abundance of these granitic bodies near mapped thrusts (Johnson, 1962) suggests that their emplacement may have been structurally controlled.

FIGURE 18.—Granitic gneiss north of the Serra do Ouro Branco, Dom Bosco quadrangle (N 3,200, W 3,000). Gneiss injects(?) certain folded beds of the Piracicaba Group. Lens cap is on the contact of chlorite-sericite-schist (above) and granitic gneiss (below).

The dikes are layered and consist of tabular ragged-edged perthite crystals as much as 1 cm long in which are abundant inclusions of all the other minerals, in a groundmass of microcline, sericite, quartz, biotite, chlorite, epidote, and albite. Parts of the groundmass are broken and crushed and resemble either quartz-sericite schist or strongly deformed gneiss (fig. 19). The perthite appears to be late in paragenesis; finer grained microcline is definitely last, filling in spaces and partially replacing earlier minerals.

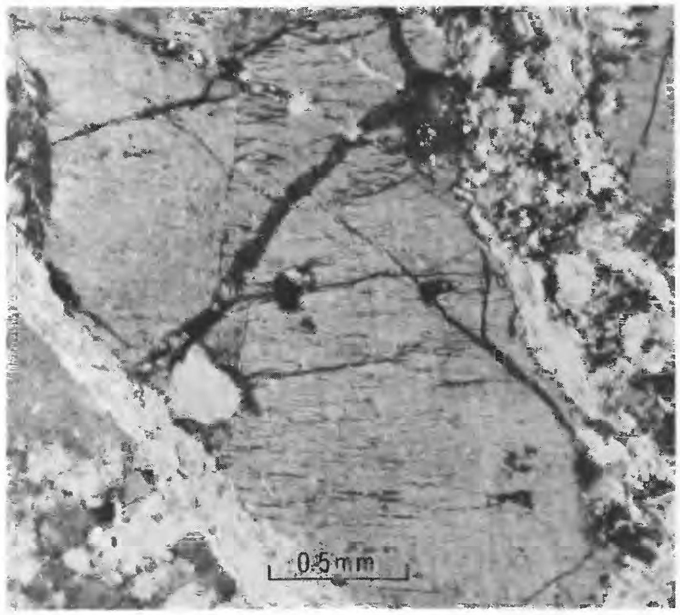


FIGURE 19.—Photomicrograph of a large grain of microcline-perthite in gneiss. Crack filled with fine-grained quartz and sericite and mortar texture in grains bordering the microcline-perthite provide good evidence that deformation followed the metasomatism responsible for the feldspar. Sample Ha–11, Serra do Ouro Branco, crossed nicols.

The position of these dikes in largely overturned anticlinal structures and in a region of thrust faulting (Johnson, 1962) suggests that blocks of granitic rocks may have been picked up and emplaced by a tectonic mechanism. The development of chlorite or biotite in these, and associated, rocks is consistent with such a mechanism of emplacement, which would have taken place under low temperatures and high shearing stress.

An alternate interpretation is that the dikes are partially metasomatized sericite-quartz schist that formed in place. The large microcline crystals must have developed by replacement after regional structural deformation because they themselves are not deformed, although the matrix minerals are sheared and fractured. Alkali-rich solutions would have followed shear planes and metasomatized beds adjacent to such planes. At the present stage of our knowledge of the area, it is not possible to choose between the two interpretations.

MAFIC AND ULTRAMAFIC ROCKS

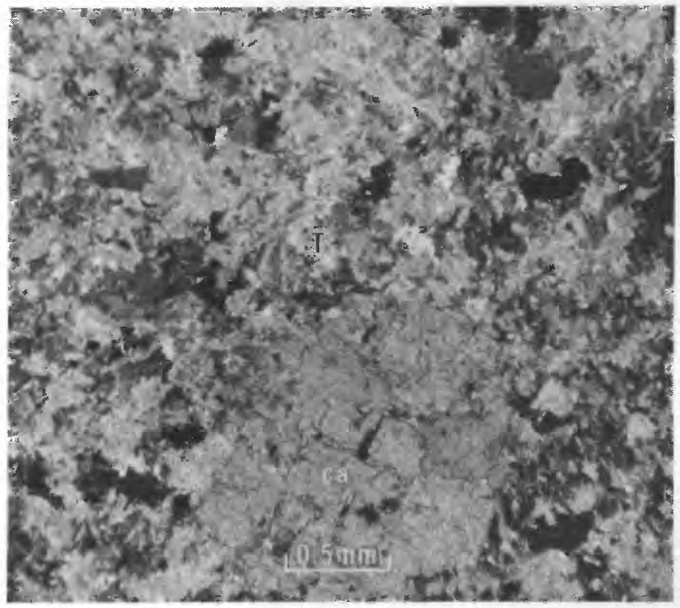
Mafic dikes intrude metasedimentary and granitic rocks throughout the area. Altered ultramafic and gabbro dikes, sills, and small stocks which crop out south of the Engenho fault in the Congonhas district (Guild, 1957, p. 25) and south of the Serra do Ouro Branco (Johnson, 1962, p. 23), are intrusive into the Rio das Velhas Series.

The suite of altered ultramafic rocks of the Congonhas district includes soapstone, serpentinite, talc schist, amphibolite, talc-chlorite schist, talc-chlorite-tremolite schist, and actinolite schist. These rocks probably represent a suite of alpine ultramafic igneous rocks that once ranged from dunite through pyroxenite to gabbro. According to Octávio Barbosa (1949), ultramafic rocks were intruded concordantly into what is now called the Rio das Velhas Series, and both were deformed and foliated together. The granodiorites later intruded around the perimeters of ultramafic rock, which suggests that the ultramafic rocks controlled the emplacement of the granodiorites and so must be older than the granodiorites.

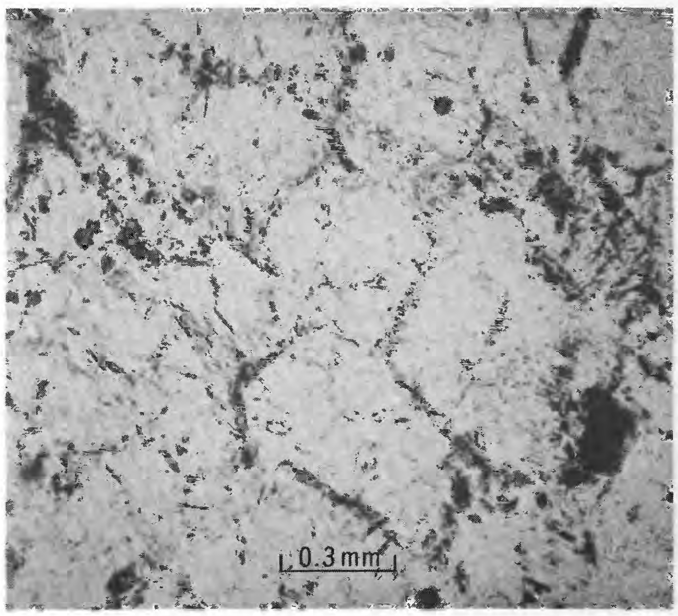
Steatite typically grades into serpentinite. The steatite is massive, and consists of pale-green talc in aggregates of small unoriented plates intergrown with nearly equidimensional clots that average several millimeters across and contain variable amounts of serpentine or a dark-green fine-grained chlorite. The clots of serpentine-chlorite are outlined by dusty magnetite. Ankerite, tremolite, and magnetite are common accessory minerals. The texture of the steatite suggests a medium-grained peridotite having talc pseudomorphous after olivine and antigorite-chlorite pseudomorphous after pyroxene. Magnetite and ferriferous ankerite are common accessories (fig. 20). With an increase in antigorite, the rock grades into serpentinite, which also contains tremolite. The largest steatite mass is a sill in greenschist of the Rio das Velhas Series near Congonhas.

Ultramafic rocks described by Von Freyberg (1932, p. 28) in the Ouro Preto area form a suite similar to that found in the Congonhas area and intrude only rocks of the Rio das Velhas Series, as in the Congonhas area.

Most mafic dikes in the southern part of the Quadrilátero Ferrífero, even those that are badly weathered, have a distinct diabasic texture. In the Ouro Branco and Congonhas districts, fresh rocks are composed chiefly of ferromagnesian minerals and saussuritized albite-oligoclase, but some more calcic plagioclase (An_{30-55}) is also seen (Guild, 1957, p. 28; Johnson, 1962, p. 23). The chief dark minerals are amphiboles, either a deeply pleochroic green hornblende or a nonpleochroic actinolitic hornblende, which make up from 50 to 100 percent of the rock. Amphiboles have been partly altered to chlorite or biotite. Common accessory minerals are ilmenite, leucoxene, magnetite, apatite, and sulfides. In the Congonhas district the mafic dikes range from 10 to more than 100 m in thickness and are as much as several kilometers in length.



A



B

FIGURE 20.—Photomicrographs of altered ultramafic rocks, Congonhas district. A, Sample 49G23. Steatite. Large carbonate grain (ca), opaque minerals, talc (T), and small patches of chlorite (C). Crossed nicols. B, Sample 49G64. Serpentinite. Magnetite grains outline former pyroxene crystals that have been replaced by antigorite. Some talc also present. Plane light.

The mafic dikes in the southern part of the Quadrilátero Ferrífero are younger than the orogeny that occurred in post-Minas time, because they cut all preexisting rocks and structures. Their exact age cannot be fixed in this area, but it is probably about 120 m.y., the same as that of mafic dikes in the State of São Paulo (Amaral and others, 1966).

A dike of metamorphosed porphyritic diabase, similar to that described in the Ibirité quadrangle (Pomerene, 1964, p. 35; table 5), cuts pre-Minas formations south of the Ouro Branco quadrangle (S 300, E 6,400 of southwest corner). It contains about 25 percent phenocrysts including both coarse plagioclase (An_{25}) and K-feldspar in Carlsbad twins. Most of the groundmass consists of partly chloritized amphibole and biotite. Quartz, apatite, opaques including sulfides, sphene, and clinozoisite are accessory minerals. The dike in the Ibirité quadrangle differs in that plagioclase is about An_{15}, and actinolitic hornblende makes up most of the groundmass.

NORTHEASTERN PART OF THE QUADRILÁTERO FERRÍFERO

Granitic gneiss underlies several areas in the northeastern part of the Quadrilátero Ferrífero: one north of the Serra da Piedade; one between the region of Caeté and the Serra das Cambotas, called the Caeté complex in this report; one near Cocais, north of the Serra do Tamanduá; and one east and southeast of Santa Bárbara (pl. 1). They have been mapped by Benedito Alves, in the Serra da Piedade and Caeté quadrangles; by S. L. Moore (1969) in the Antonio dos Santos and Congo Sôco quadrangles; by G. C. Simmons (1968b) in the Cocais and Santa Bárbara quadrangles; and by C. H. Maxwell, in the Catas Altas and Santa Rita Durão quadrangles. Earlier workers described granitic rocks of more than one type and age. Octávio Barbosa (1954, p. 20) pointed out that some granite gneiss of this area is Archean in age, and that it was derived, in part, from pre-Minas sedimentary rocks. Guimarães (1951, p. 37) noted that a granite porphyry cut the Minas Series near Caeté and therefore was post-Minas in age.

Granitic and gneissic rocks in the northeastern part of the Quadrilátero Ferrífero, except the Borrachudos Granite, weather to gently rounded hills and sparse outcrops of fresh rock. The Borrachudos Granite forms bold bluffs of unweathered rock from the northeastern part of the Santa Bárbara quadrangle, northeastward across the northwest corner of the Florália quadrangle, and in the Itabira quadrangle.

The oldest gneisses are granodioritic and correlative to the Group II Itabirito type, they are cut by thin dikes and veins of younger granites which are typical Group III rocks, and they show varying contact effects on country rock from place to place. In the western part of the Caeté complex within the Caeté quadrangle, the border gneiss is unusually rich in quartz and appears to grade into a country rock of pre-Minas quartzite, whereas eastward in the western part of the Gongo Sôco quadrangle (Moore, 1969, p. I26) the contact is either sharp and appears to be intrusive, or it is migmatitic. On the road from Caeté to Barão de Cocais, the contact between the Caeté gneiss and the Rio das Velhas Series is a gradational zone that ranges in width from 30 to 200 meters.

The eastern contact between the Caeté gneiss and quartzite along the Serra do Tamanduá has not been seen (Simmons, 1968b, p. H23), but the trends of the gneiss and the quartzite of the Serra are not parallel. Some quartzite and quartzitic schist along the contact have been partly metasomatized, as indicated by a selvage of tourmaline and quartz in the schist, by albite crystals in the quartzite, and by magnetite in the schist of the upper part of the Tamanduá Group. The age of the Caeté complex, therefore, is clearly post-Rio das Velhas. Because the Gandarella syncline was deformed before the emplacement of the Caeté complex, the age of the complex is also considered to be post-Minas by Moore (1969, p. I27), although this evidence is less certain.

In Santa Bárbara a banded granodiorite gneiss similar to some gneiss of the Caeté complex is cut by a younger granite in which foliation is weak, where present. South, in the Catas Altas and Santa Rita Durão quadrangles, migmatite occurs in places along the contact of the Santa Bárbara gneiss and the pre-Minas sedimentary rocks (C. H. Maxwell, written commun., 1962), but, generally, a weathered chlorite-talc-antigorite dike intervenes between the gneiss and the metasediments.

Most of the metasedimentary rocks in this area are at the chlorite or biotite isograd of regional metamorphism. In places in the gneiss, some epidote and chlorite also indicate low-grade metamorphism. In the Cocais area, Simmons (1968b, p. H 32) reported an andalusite schist, but this is rare and may be a contact effect of a late mafic intrusion. Much gneiss has a mortar texture that may be due to a mechanical deformation that closely followed the metamorphism. This texture, in turn, has been partly modified by a later metasomatism in which K-rich solutions helped form microcline, after which Na-rich solutions formed albite rims on the microcline.

SPECIAL STUDIES

AGE DETERMINATIONS

A K/Ar age of 690 m.y. was determined for biotite from granodiorite gneiss (sample Ha–18) from north of Cocais, and an age of 810 m.y. from gneissic granodiorite (sample Ha–19) from Santa Bárbara (table 2). Both ages are considered minimal and probably represent the loss of Ar in older rocks during a 500-m.y. thermal event.

ALKALI FELDSPAR

Alkali feldspar from the Santa Bárbara sample (Ha–19) was analyzed for major and minor elements (Herz and Dutra, 1966). Some of these results (in parts per million for elements; in percent for feldspar molecules) are:

Rb	Ba	Sr	Li	Ca	An	Ab	Or	T°C
300	1,690	40	38	715	0.5	12.8	86.7	420

The feldspar has less than 15 percent albite molecule and is considered to be a low-temperature, subsolvus phase, and therefore almost certainly metamorphic in origin (Tuttle and Bowen, 1958). Li is higher in this feldspar than in any other one determined from the Quadrilátero Ferrífero, but the abundances of other minor elements, the high Rb and low Ca, Sr, and Ba, agree with the results for metamorphic feldspar. Metamorphism is also indicated by abundant epidote in the sample itself.

CAETÉ COMPLEX

The Caeté complex, a large gneissic complex of essentially granodioritic composition, lies between Caeté and the Serra das Cambotas to the east (table 12, samples Ha–30, 31). The gneissic rocks east of this complex, near the town of Cocais (sample Ha–18) and north of the Serra do Tamanduá, and those near Santa Bárbara (sample Ha–19) tend to be richer in K-feldspar.

Most of the rocks of the Caeté complex are gneissic to porphyritic granodiorites that are light gray, equigranular, and medium grained, and contain about 20–70 percent oligoclase, 20–30 percent quartz, 20–55 percent microcline, and 2–20 percent biotite (Moore, 1969, p. I26); I also found muscovite and sericite generally more than 10 percent. Plagioclase ranges from An_{10-25}, has either no twinning or polysynthetic albite twinning, and is partly replaced by sericite, myrmekitic quartz, microcline, and, rarely, by epidote. Many microcline grains also are partly replaced by a myrmekitic quartz. Most quartz grains are strained, have undulatory extinction, and $2V$ as high as 10°. Some mortared quartz grains are as much as 2 mm in diameter; most are as much as about 1 mm, or about equal to the feldspar. Part of the groundmass consists of a mortar-textured intergrowth of feldspar and fine-grained quartz. Biotite either is shredded and altered to chlorite and epidote or forms large unaltered dusky to olive-gray pleochroic plates. The most common accessory minerals are epidote, apatite, and chlorite.

TABLE 12.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks from the northeastern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. P, present; ---- not analyzed; n.d., not detected]

	Ha–18	Ha–19	Ha–30	Ha–31	S.B. (Morães and Barbosa, 1939)
Chemical analyses (Weight percent)					
[Analysts: P. L. D. Elmore, S. D. Botts, and I. H. Barlow, U.S. Geological Survey, using method of Shapiro and Brannock (1956); fluorine determined by S. M. Berthold]					
SiO_2		72.4	74.8	71.4	74.68
Al_2O_3		14.2	14.2	16.1	13.49
Fe_2O_3		.7	.7	.9	.65
FeO		1.3	.49	.80	.84
MgO		.32	.41	.43	.71
CaO		1.4	.59	1.9	.52
Na_2O		4.3	4.04	4.8	3.70
K_2O		3.9	3.6	2.4	4.45
H_2O		.50	.87	.88	.73
TiO_2		.19	.13	.20	.17
P_2O_5		.06	.03	.08	.01
MnO		.08	.04	.06	.05
CO_2		.38	.36	$<.04$	.05
F		.04	.01	----	----
Total		99.8	100.2	100.0	100.05
Normative minerals (Weight percent)					
Quartz		29.6	36.9	29.6	33.8
Corundum		1.5	3.6	2.3	1.8
Orthoclase		23.0	21.3	14.2	26.3
Albite		36.4	33.8	40.6	31.3
Anorthite		3.9	.4	8.9	2.2
Enstatite		.8	1.0	1.1	1.8
Ferrosilite		1.6	.2	.5	.8
Magnetite		1.0	1.0	1.3	.9
Ilmenite		.4	.2	.4	.3
Apatite		.1	.1	.2	.0
$CaCO_3$		.9	.8	----	.1
Total		[1] 99.3	99.3	99.1	99.3
Differentiation index		89.0	92.0	84.4	91.4
Percent An in plagioclase		9.7	1.2	18.0	6.6
Modal minerals					
Plagioclase	27.2	25	23.6	19	----
(Percent An)	(17)	(13)	(15)	(10)	----
K-feldspar	23.8	17	7.1	7	----
Quartz	33.3	41	44.4	47	----
Biotite	8.0	4	7.1	15	----
Muscovite	5.1	8.5	16.6	12	----
Epidote	2.5	5	P	.5	----
Chlorite	----	----	.6	.5	----
Apatite	P	P	P	----	----
Carbonate	----	P	----	----	----
Tourmaline	----	----	.2	----	----
Garnet	----	----	P	----	----
Opaque	----	----	.2	----	----

[1] Includes 0.1 fluorite.

TABLE 12.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks from the northeastern part of the Quadrilátero Ferrífero*—Continued

	Ha-18	Ha-19	Ha-30	Ha-31	S.B. (Moraes and Barbosa, 1939)
Minor elements					
(Parts per million)					
[Quantitative spectrographic analysis, C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte, M. G., Brazil]					
Ba	900	360	810	1,300	--------
Be	----	----	5.0	4.3	--------
Co	2.0	2.8	1.8	2.5	--------
Cr	.3	1.9	1.0	1.8	--------
Cu	1.9	6.0	3.8	2.4	--------
Ga	14	14	16	18	--------
La	N.d.	N.d.	68	N.d.	--------
Mo	----	----	6.0	4.0	--------
Nb	N.d.	33	15	15	--------
Ni	N.d.	8.2	2.0	1.7	--------
Pb	5.5	7.0	22	27	--------
Sc	2.1	3.0	2.0	1.3	--------
Sn	5.0	15	16	150	--------
Sr	280	110	93	280	--------
V	26	38	5.4	25	--------
Y	6.3	63	54	16	--------
Zr	120	107	89	120	--------

West of Caeté, close to the contact between the Caeté complex and pre-Minas quartzite, the gneiss is typically porphyroblastic (sample Ha-30). Feldspar forms grains as much as 1 mm in length, and quartz, as much as 2 mm in length; the largest grains are mortared. Pleochroic dark-brown to pale-yellow tourmaline is also present. In the field, the gneiss appears to grade through quartzose gneiss into quartzite.

Tourmalinized schist and tourmaline-quartz veins occur along the contact of the complex (Moore, 1969, p. I26). Lenses and dikes of pegmatite within the schist range in width from a few to 60 cm. They consist of coarse feldspar, muscovite, and quartz, and have tourmaline along their margins. Moore thought that the contact of the rocks of the Caeté complex with sericite schist was intrusive and that in places the sericite schist near the contact had been mobilized. Where sericite content is high, the rock is migmatitic and gradational; where chlorite is more abundant than sericite, the contact is sharper.

GNEISS OF COCAIS

The gneiss of Cocais underlies most of the Cocais quadrangle (Simmons, 1968b, p. H23). It is bounded on the south by the Cambotas Quartzite of the Serra do Tamanduá, to the west by a gabbro dike and the Tamanduá Group of the Serra das Cambotas, and to the southeast by the Petí phase of the Borrachudos Granite. It extends at least 20 km north and northwest of the mapped area.

The gneiss of Cocais (table 12, sample Ha-18), is generally light gray where fresh and fine to medium grained. It is granodioritic in composition and consists of quartz, twinned and untwinned sodic plagioclase, microcline, biotite, muscovite, epidote, and minor apatite. Quartz grains are fractured, and vermicular quartz partially replaces feldspar. Some crystals of microcline and plagioclase (An_{17}) are surrounded by rims of clear albite. Biotite pleochroism is similar to that seen in the Caeté gneiss.

The gneiss contains roof pendants of chlorite schist, quartzite schist, and andalusite schist. The chlorite schist roof pendants contain chlorite, biotite, muscovite, quartz, kyanite, ilmenite, leucoxene, and tourmaline; pendants of quartzite schist contain quartz, microcline, oligoclase, biotite, muscovite, and epidote; and pendants of andalusite schist contain biotite, muscovite, chlorite, and quartz. Some plagioclase grains in the quartzite schist have had more than one cycle of growth and are, consequently, characterized by altered inclusion-filled cores and rims of clear albite. Much of the area from Caeté to Cocais underwent mechanical deformation and retrogressive metamorphism sometime after emplacement, as evinced by mortar textures and the presence of epidote, albite, and chlorite. As this retrograde metamorphism is pervasive and widespread, it is difficult to assess the exact effects of the older high-grade metamorphism that was responsible for the gneisses.

The gneiss of Cocais is similar petrographically to the gneiss of the Caeté complex and is assumed to have had a similar origin.

GRANODIORITE GNEISS OF SANTA BÁRBARA

The granodiorite gneiss of Santa Bárbara has been mapped in the southeastern part of the Santa Bárbara quadrangle by Simmons (1968b, p. H24) and in the eastern part of the Santa Rita Durão and Catas Altas quadrangles by C. H. Maxwell (written commun., 1962), and extends east and northeast for unknown distances outside these quadrangles. In the Santa Bárbara quadrangle, a chlorite-talc-antigorite schist is interposed between the gneiss and pre-Minas rocks. To the south, the belt of chlorite antigorite-talc schist ends in the Catas Altas quadrangle, and a transition zone between the gneiss and metasedimentary rocks is occupied by migmatite. This zone consists of layers of schist a few millimeters to a few centimeters thick, alternating with layers of gneiss 1–20 cm thick. In one place (Santa Rita Durão, N 3,100, E 8,800), deformed and shattered garnet crystals as much as 2 cm in diameter in the schist at the contact show a postmetamorphic mechanical deformation. Quartz-tourmaline or quartz-mica veins and veins of bull quartz are also present near the contact.

In the field, the Santa Bárbara granodiorite gneiss appears to be a mixed rock: dominantly well-banded older granodiorite cut by minor unbanded and weakly foliated dikes of a younger granite (fig. 21). The largest grains are of microcline and microcline perthite, but these grains form less than 20 percent of the rock. Plagioclase (An_{13}) makes up 25 percent of the rock. The plagioclase has many inclusions. Quartz makes up about 40 percent, biotite containing acicular inclusions of rutile, 4 percent, muscovite and sericite, 8.5 percent, and epidote, 5 percent of the rock. Apatite, carbonate, sphene, zircon, allanite, and opaque minerals are common accessories.

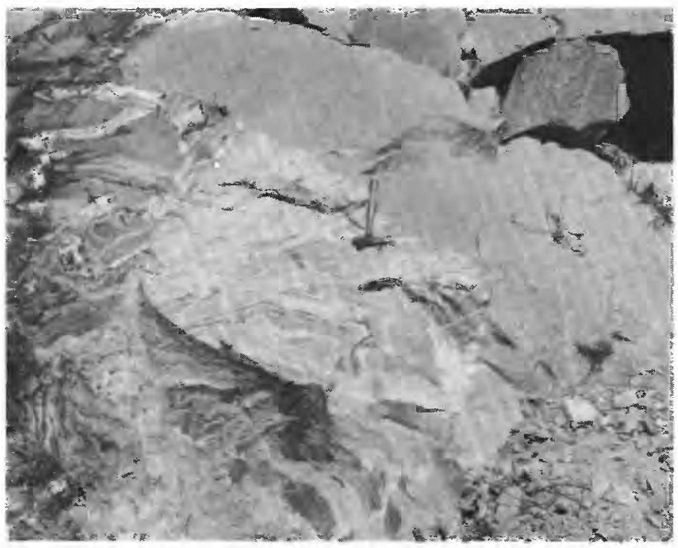


FIGURE 21.—Zone of mixed banded Santa Bárbara granodiorite gneiss and a younger, finer grained unfoliated granite. On Belo Horizonte-Monlevade highway, west of São Gonçalo.

Metasedimentary rocks adjacent to the contact with Santa Bárbara granodiorite gneiss fall within the biotite isograd and contain plagioclase of approximately oligoclase composition. The entire area, however, is in the biotite zone of regional metamorphism, and there is no contact-metamorphic aureole around the Santa Bárbara granodiorite gneiss. The gneiss itself was metamorphosed under the relatively low-grade conditions of the biotite zone, as shown by the presence of epidote and sodic plagioclase (An_{13}).

BORRACHUDOS GRANITE

Borrachudos Granite (Dorr and Barbosa, 1963, p. 42–45) forms bold outcrops in the northeastern part of the Santa Bárbara quadrangle and northeastward in the Florália quadrangle. In those quadrangles it is called the Petí phase and is light gray, coarse grained, has no planar structure, but, instead, a lineation of elongate biotite pods. It is made up of quartz, much in pod-shaped masses; blocky crystals of large untwinned muscovite and chlorite as accessory minerals. The muscovite and chlorite as necessary minerals. The fluorite is interstitial, largely along borders of quartz and feldspar aggregates and makes up as much as 2 percent of the rock.

The undeformed and mineralogically fresh Petí phase was not affected by the pervasive regional deformation and is considered to be a type III, or post-Minas granite. Field relations show it to be post-Rio das Velhas, but nowhere has it been found in contact with Minas sedimentary rocks. This rock is described in greater detail in the section on the extreme northeastern part of the Quadrilátero Ferrífero.

PETROGENESIS AND GEOLOGIC HISTORY

It is apparent that granitic rocks of more than one age and kind are present in this area. The oldest rocks are correlated with Group II, the Itabirito Granite Gneiss, and include the generally poorly foliated gneiss of Caeté and Cocais and the well-layered granodiorite gneiss from Santa Bárbara. These appear to grade into quartzites in places, or to grade through a migmatite zone into metasedimentary schists in other places, which suggests that at least part of the gneiss may have developed by granitization or ultrametamorphism of the Rio das Velhas Series (in the 2,700- and 1,930-m.y. events).

In a later event or events, the gneissic rocks were subjected to a regional low-grade greenschist metamorphism that produced plagioclase of composition An_{10-17} and preceded or accompanied structural deformation. In the 1,350-m.y. post-Minas orogeny, the fluorite-bearing Borrachudos Granite and thin pegmatites were intruded.

The effects of metasomatism and regional metamorphism vary from place to place. The gneisses from the Cocais quadrangle (sample Ha–18) and from Santa Bárbara (sample Ha–19) have considerably more microcline, somewhat more plagioclase and epidote, and less muscovite and sericite than the samples from the Caeté complex. Feldspar in the Caeté gneiss was sericitized during a period of thrusting directed from the south; feldspars in gneisses from Cocais and Santa Bárbara, which were farther from the locus of deformation, were less sericitized.

The abundances of major elements, the amounts of normative anorthite, and differentiation indices (table 12) are similar to those of the gneisses in the western part of the Quadrilátero Ferrífero. Differentiation indices of the Santa Bárbara rocks average 90.2, and the rocks have an average of only 8.2 percent normative anorthite. Sample Ha–30, on the western border of the Caeté complex, has extremely high normative quartz, 36.9 percent, and D.I., 92.0, and only 1.2 percent of normative anorthite. The anorthite is much too low for any normal granodiorite of igneous origin; considering this and the high quartz and D.I., it is possible that this rock originated from a mixture of quartz-rich sedimentary and granodioritic material. Sample Ha–31 from about 2 km within the complex has a D.I. of 84.4 and 18.0 percent anorthite, and may be closer in origin to a purely igneous granodiorite only modified by later metamorphism.

The trace element abundances (table 12) are similar in both the granodiorite of the Caeté complex and that of Cocais. Both have high Ba and Sr, which suggests a high temperature of formation. The low abundance of femic elements, such as Co, Cr, and Ni, is due to a lack of dark minerals in both rocks. Except for high Sn and Pb in sample Ha–31 from the gneiss of Cocais, the minor-element abundances compare favorably with granodiorite from the Bação complex (table 8, samples Ha–4, J–668), and are further evidence that the granodiorites of the western Quadrilátero Ferrífero and from this area have a similar origin.

Minor elements also provide indirect evidence for mixing of residual granitic material with older gneisses and granodiorites. Gneiss of probable mixed origin, sample Ha–30, has unusually high La and Y compared to the other samples from this area; high Y and F (0.04 percent) are present in sample Ha–19 from Santa Bárbara. These elements are typically abundant in residual magmatic liquors (Rankama and Sahama, 1950, p. 518). The field evidence suggests that both rocks are mixtures: sample Ha–30 of older metasedimentary rock and igneous solutions from the Caeté complex, and sample Ha–19, a granodiorite cut by many younger granitic dikes (fig. 21).

MAFIC AND ULTRAMAFIC ROCKS

Serpentinite and talc schist intrude the Rio das Velhas Series and granitic gneisses in the Caeté area (Alves, 1961). Altered mafic dikes, now antigorite schists, amphibolites, or chlorite-amphibole-talc rocks intrude all formations throughout the northeastern region. Postmetamorphic mafic dikes and small gabbroic or diabasic stocks are also present.

A northeast-trending mafic dike occurs in the Barão de Cocais (Simmons, 1968b, p. H25–H26) and Catas Altas quadrangles (C. H. Maxwell, written commun., 1962) between the Rio das Velhas Series to the northwest and the Santa Bárbara gneiss to the southeast. The dike is a continuation of a "greenstone sequence"—metamorphosed ultramafic rocks—overlying, underlying, and apparently interbedded with rocks of both the Nova Lima Group and the Minas Series east of the Serra do Caraça (C. H. Maxwell, written commun., 1962).

In the Serra do Caraça, Moore and Maxwell mapped swarms of mafic dikes that intrude the Cambotas Quartzite and formations above and below. Gabbro plugs, dikes, and sills intrude the Cocais gneiss and Cambotas Quartzite (Moore, 1969; Simmons, 1968b, p. H26–H27). The largest such body is a stock about 1 by 4 km intruding the Cambotas Quartzite on the east flank of the Serra das Cambotas in the northwest corner of the Santa Bárbara and the northeast corner of Gongo Sôco quadrangles.

ULTRAMAFIC ROCKS

The metamorphosed ultramafic rocks in the Caeté quadrangle may originally have ranged from pyroxenite to gabbro. Serpentinite containing penninite-antigorite-magnetite-rutile; talc schists containing abundant colorless amphibole; and asbestos that was mined in places (fig. 22) (Alves, 1961) are commonly found today. The presence of bowlingite, an alteration product of olivine, suggests that some of the serpentinites were originally peridotite.

FIGURE 22.—Photomicrograph of slip and cross-fiber asbestos, near Caeté, sample H–8a–5, crossed nicols.

Other altered mafic and ultramafic rocks in the Caeté area include well-foliated talc schists consisting of talc and chlorite or tremolite, and opaques; chlorite schists containing chlorite, colorless amphibole, epidote, and accessory sphene, quartz, opaques, and zircon; metagabbro, containing saussuritized plagioclase (An_{26}), partly uralitized or chloritized pyroxene, clinozoisite and epidote, opaques, and, in some, serpentine. The similarity in petrographic types and field relations suggest a comagmatic origin with the ultramafic rocks of the Congonhas area.

Ultramafic rocks occur in the Catas Altas and Santa Rita Durão quadrangles in zones of intense shearing. They are shown as a "greenstone sequence" by C. H. Maxwell (written commun., 1962 data) and consist of chlorite-serpentinite-talc-tremolite assemblages with accessory magnetite, pyrite, apatite, and tourmaline. Some small bodies of massive soapstone and foliated talc schists also occur and seem to have replaced some of the chlorite- and serpentine-bearing rocks. An original periodotite is suggested in serpentinite thin sections by relict olivine or othopyroxene in talc aggregates and fine-grained green chlorite clots, probably after clinopyroxene, both set in a groundmass of antigorite.

MAFIC ROCKS

Mafic dikes and plugs are abundant and intrude all other rocks in the Caraça area. The gabbro is unfoliated and intrudes the Borrachudos Granite, the only other unfoliated rock in the region; it is, therefore, considered post-Minas (Simmons, 1968b, p. H27) and probably correlative with diabase in São Paulo dated at 120 m.y. (Amaral and others, 1966). The fresh mafic rocks are medium grained and dark green, and consist of a pale-brown pyroxene (pigeonite?), andesine-labradorite, biotite, magnetite, ilmenite, and leucoxene.

A swarm of dikes is intruded along faults in quartzite and in the rocks above and below in the Serra do Caraça. The dikes have an ophitic texture and are badly weathered; relatively fresh samples have large actinolite crystals, smaller grains of epidote-clinozoisite, and serpentine in a finer grained groundmass of plagioclase (An_{30}), chlorite, quartz, carbonate, and leucoxene. Nearly all the mafic dikes are too badly weathered to allow a determination of original mineralogy.

A long sill-dike consisting of chlorite schist extends for about 12 km northeast through the Santa Bárbara and Catas Altas quadrangles (Simmons, 1968b, H25, H26; C. H. Maxwell, written commun., 1962) and averages 200–500 meters in width. It lies conformably between the Nova Lima Group to the northwest and the granodiorite gneiss of Santa Bárbara to the southeast along much of its length. To the southwest, the body widens into a stock and crosscuts the Nova Lima. It shows strong foliation parallel to its bounding surfaces, but this trends at a high angle to foliation in the Rio das Velhas Series. The dike is almost entirely weathered; a few relatively fresh samples consist of chlorite, talc, and serpentine.

A dike of porphyritic diabase in the Catas Altas quadrangle (table 13, sample CM–606) intrudes the Cambotas Quartzite (C. H. Maxwell, written commun., 1962). The rock is dark green and has phenocrysts of plagioclase, as much as 3 cm in length, that have been largely saussuritized to a mixture of a pure albite and clinozoisite. The plagioclase has albite twinning and many inclusions, among which is ripidolite chlorite ($N_m=1.633$). The groundmass consists of K-feldspar, calcite, opaque minerals, some of which are rimmed by leucoxene, chlorite, quartz, biotite, muscovite, and epidote.

Although the porphyritic diabases of the Ibirité and Catas Altas quadrangles are metamorphosed, both their chemical analyses (compare sample 54P126, table 5 with table 13) and normative minerals are very similar. The differentiation index of the Ibirité rock is 38.1; that of Catas Altas is 41.1. These indices are intermediate between those of basalt and diorite (Thornton and Tuttle, 1960 (p. 671).

TABLE 13.—*Analysis of porphyritic diabase from Catas Altas, sample CM–606*

[For sample location, see table 3 and pl. 1]

Chemical analysis [1] (weight percent)		Minor elements [2]		Normative minerals (weight percent)	
SiO_2	51.5	Ba	1,070	Quartz	9.0
Al_2O_3	13.9	Be*	1.5	Orthoclase	11.8
Fe_2O_3	2.0	Ce*	100	Albite	20.3
FeO	10.8	Co	31	Anorthite	21.3
MgO	3.2	Cr	15	Wollastonite	1.7
CaO	6.0	Cu	21	Enstatite	8.0
Na_2O	2.4	Ga	22	Ferrosilite	13.4
K_2O	2.0	La*	50	Magnetite	2.9
TiO_2	3.1	Mo	.5	Ilmenite	5.9
P_2O_5	.68	Nb	39	Apatite	1.6
MnO	.17	Ni	23		
CO_2	<.05	Pb*	10	Total	95.9
H_2O	3.1	Sc	33		
		Sn	4	Differentiation	
Total	98.9	Sr	290	index	41.1
		V	140	Percent An in	
		Y	79	plagioclase	51.1
		Yb*	7		
		Zr	290		

[1] Analysts: P. L. D. Elmore, I. H. Barlow, S. D. Botts, and G. W. Chloe, U.S. Geological Survey, using method of Shapiro and Brannock (1956).
[2] Quantitative spectrographic results by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte, M.G., Brazil; asterisk (*) indicates semiquantitative analysis by H. W. Worthing, U.S. Geological Survey.

EXTREME NORTHERN PART OF THE QUADRILÁTERO FERRÍFERO

Granitic rocks and gneisses underlie most of the extreme northeastern part of the Quadrilátero Ferrífero, including the Itabira district, and extend to the east and northeast for many kilometers from the Quadrilátero Ferrífero. The granites and gneisses were mapped by Dorr and Barbosa (1963) in the Itabira district, by Reeves (1966) in the Monlevade district, and by me in the Florália quadrangle and southern part of the São Gonçalo quadrangle.

The gneissic rocks here show a stronger layering than those near the Serra do Curral. They also differ in other important respects: the western gneisses are close to granodiorite in composition, whereas many eastern gneisses are more potassic and closer to granite in composition; banded gneiss in the west is largely of pre-Minas age, but much of the eastern gneissic suite appears to be post-Minas, judging by radioactive dating and field data. Much of the eastern gneiss may be derived from Rio das Velhas Series rocks (Octávio Barbosa, 1954, p. 20), and inclusions of itabirite suggest that some is also grantized Minas Series (Door and Barbosa, 1963, p. 42).

Many of the gneissic rocks have intrusive contacts with both the Rio das Velhas and the Minas Series. Pegmatities abound in the contact area of gneiss and metasediments as well as in zones of mixed gneiss and Rio das Velhas rocks. A zone of mixed rock 15 m thick was found about 200 m north of the crossing of Dois Córregos by the old Itabira-Conceição road. Although foliation is concordant in the two rock units, layers in the Rio das Velhas Series appears to trend into the contact in places (Dorr and Barbosa, 1963, p. 41–42). The gneissic rocks there are presently correlated with Groups III and IV. Contacts of the Borrachudos Granite with metasedimentary rocks were not seen, but the granite is postmetamorphic (Dorr and Barbosa, 1963, p. 45) and belongs to Group III.

Most evidence of an original high-grade metamorphic aureole caused by granite intrusions has been destroyed by a widespread low-grade regional metamorphism that produced much muscovite, chlorite, and epidote. However, garnet, staurolite, and kyanite occur in pelitic rocks in the Itabira district, within 200 m of the gneiss (Dorr and Barbosa, 1963, p. 53). Kyanite, staurolite, and almandine garnet are also known in the Monlevade district, but their pattern of distribution is not clear there (Reeves, 1966).

Ultramafic rocks are in the Itabira district and mafic dikes, including amphibolite, occur throughout the area. The ultramafic suite includes soapstone, serpentinite, and talc schist. Some amphibolites have a relict ophitic texture; others are foliated and may represent a welded tuff, or a "dirty" carbonate rock.

SPECIAL STUDIES

AGE DETERMINATIONS

Dates have been determined by Rb^{87}/Sr^{87} analysis of two feldspars and K^{40}/Ar^{40} analysis of three micas from rocks of this part of the Quadrilátero Ferrífero (table 2). K-feldspar from the Borrachudos Granite at the Petí reservoir (sample Ha–10) yielded a Rb/Sr date of 1,230 m.y., and biotite gave a K/Ar date of 486 m.y. The 1,230-m.y. date is a good approximation for the granitic intrusion which took place during the waning phases of the widespread post-Minas orogeny, dated elsewhere as about 1,350 m.y.

A Rb/Sr date of 545 m.y. was obtained on amazonite feldspar from a pegmatite which cuts rocks of the Piracicaba Group in the Rio Piracicaba quadrangle (sample DTM–8). The K/Ar dates of biotite from granodiorite gneiss (sample Ha–6) and biotite gneiss (sample Ha–7) of the Itabira district are 450 and 500 m.y., respectively, and from the Petí phase of the Borrachudos Granite, 486 m.y. All these dates are presently considered to be a result of a thermal event about 500 m.y. ago that caused a loss of Ar. The only igneous activity at that time may have been restricted to the intrusion of pegmatite.

ALKALI FELDSPARS

Alkali feldspars were separated from granodiorite gneiss from Itabira (sample Ha–6), fluorite-bearing Borrachudos Granite at the Petí reservoir (sample Ha–10), and from a granoblastic flaser gneiss from the São Gonçalo quadrangle (sample HA–38), and analyzed for major and some minor elements (Herz and Dutra, 1966). Some of these results (in parts per million for elements; in percent for feldspar molecules) are:

Sample	Rb	Ba	Sr	Li	Ca	An	Ab	Or	T°C
Ha–6	450	2, 320	127	2. 3	715	0. 5	12. 7	86. 6	400
Ha–10	720	90	30	13	430	. 3	34. 7	65. 0	610
Ha–38	330	4, 340	182	3. 2	860	. 6	9. 3	90. 1	380

Feldspars from samples Ha–6 and Ha–38 have less than 15 percent albite molecule and are considered to be a low-temperature, subsolvus phase (Tuttle and Bowen, 1958, p. 129) that crystallized, or was recrystallized, during a post-Minas metamorphism. Their indicated temperatures of 400° and 380° C, respectively, obtained by comparing the amount of albite in plagioclase to that in microcline (Barth, 1956), are about the correct order of magnitude for the greenschist facies of regional metamorphism. Their original temperatures of crystallization, however, may have been much higher; high amounts of Ba and Sr which are present in these feldspars generally concentrate in the earlier formed, higher temperature fractions of a granitic melt.

The alkali feldspar of the Borrachudos Granite (sample Ha–10), with its large proportion of albite molecule, crystallized under hypersolvus conditions, or at high-magmatic temperatures. It was not affected by low-grade regional metamorphism, and so must be later than the post-Minas metamorphism, which agrees with the limited field evidence (Dorr and Barbosa, 1963, p. 45). The minor-element abundance suggests crystallization under late magmatic or pneumatolytic conditions: Rb is more abundant in sample Ha–10 than any other Quadrilátero Ferrífero sample; Li is very high; and the Sr and Ba abundance and ratio are similar to that found in Norway for alkali feldspars from pegmatites (Heier and Taylor, 1959, p. 290).

BIOTITE ANALYSES

Some minor elements were determined in biotite from a granoblastic flaser gneiss (sample Ha–38), and the Bicas biotite gneiss (sample Ha–39), from the Rio Piracicaba quadrangle, and both major and minor elements were determined in biotite from the Petí phase of the Borrachudos Granite (sample Ha–10). The results of the analyses for minor elements (in parts per million) are (Herz and Dutra, 1964):

Sample	Co	Ni	Sc	Cr	Nb
Ha–10	[1] N.d.	6.0	4.6	9.5	670
Ha–38	35	34	32	38	41
Ha–39	59	220	26	250	36

[1] Not detected.

The absolute amount of Sc in biotite is taken to be a geologic thermometer, with highest amounts up to about 1,000 ppm occurring at lowest temperatures of formation (Oftedal, 1943). The low value of Sc in sample Ha–10 thus agrees with the analytical results for the feldspars, which shows that that sample formed at the relatively high temperature of about 610° C. High Nb in this sample also suggests magmatic conditions. The relative amounts of the trace elements are different in each sample, but they do suggest that biotite in the gneisses is not related to that in the granite.

The major elements present in biotite from the Petí phase of the Borrachudos Granite strongly suggest that the rock is a late-stage differentiate (table 14). Although the biotite is partly altered to chlorite, it still contains abundant Nb, Li, Rb, F, and exceptionally low MgO, which is characteristic of pegmatitic biotites or late-stage granitic differentiates (Deer and others, 1962, p. 60).

TABLE 14.—*Partial chemical analysis and optical data of partly chloritized biotite from the Petí phase of Borrachudos Granite, sample Ha–10*

[Chemical analysis by J. J. Fahey; optical data by D. R. Wones, U.S. Geological Survey]

	Percent		Percent
SiO_2	33.38	Li_2O	0.50
Al_2O_3	18.18	Rb_2O	.20
Fe_2O_3	1.05	H_2O	3.29
FeO	30.69	F	.92
Nb_2O_5	.10	Cl	.07
TiO_2	1.71		
MgO	.02	Total	97.86
CaO	.02	Oxygen correction	–.41
MnO	.06		
K_2O	7.6	Total	97.45
Na_2O	.07		

Pleochroism is grayish olive green to grayish yellow green. $n_{y,z}=1.667\pm0.002$; $n_x=1.604\pm0.001$.

GNEISSIC ROCKS

Four varieties of gneiss are found in the Itabira district, but they cannot be mapped separately in the field (Dorr and Barbosa, 1963, p. 37); a granitic gneiss with uncontorted faint to moderate foliation and granitoid texture is most common. It consists of medium-grained granular to granoblastic aggregates of quartz, relatively large angular grains of plagioclase (An_{10-20}), partly sheared microcline, perthite, pale-green muscovite, brown biotite, clinozoisite, and chlorite. The quartz forms 40–60 percent of the gneiss, feldspars form 30–55 percent, and micas generally form less than 15 percent, but, in places, as much as 30 percent. The micas occur separately or interleaved, and muscovite is more abundant than biotite. A second variety of granite gneiss has contorted foliation and is cut by pegmatites of two ages, one contemporaneous with folding and possibly anatectic in origin, and the other, discordant. The two other varieties, quartz-muscovite gneiss and biotite-quartz gneiss and schist are apparently derived largely from sedimentary rocks of the Rio das Velhas Series, whereas the two granitic gneisses are considered igneous in origin. Octávio Barbosa (1954, p. 20) considered these gneisses and schists to be Archean, derived by granitization or metasomatism of the Rio das Velhas Series.

In the Monlevade district, Reeves (1966, p. 10) described the Monlevade Gneiss representing former rocks of the Rio das Velhas Series (table 15, sample Ha–36), and the Bicas Gneiss, a possible highly metamorphosed equivalent of parts of the Elefante Formation of the Piracicaba Group. The Monlevade Gneiss consists mostly of banded feldspathic (granite) gneiss, augen gneiss, and quartz-biotite gneiss interlayered with amphibolite, quartz-mica, staurolite-garnet-schist, quartzite, and itabirite. The Monlevade gneisses are variable in composition and texture; grain sizes vary from fine to coarse; and fine- to medium-grained varieties comprise 90 percent of the formation. Parts of the gneiss contain fine-grained quartz-feldspar layers 1–2 mm thick or more, separated by biotite or hornblende-rich layers. Most of the feldspar is potassic, but some oligoclase is also present. Feldspar augen in the augen gneisses range from a few millimeters to more than 3 cm in diameter in a matrix of biotite, hornblende, and felsic minerals.

The Elefante Formation of the lower part of the Piracicaba Group consists largely of quartz-biotite gneiss, mica quartzite, quartzite, and itabirite. The gneiss member is called the Bicas Gneiss (Reeves, 1966, p. E 21).

Gradational facies between granites and rocks of mixed origin are more common in the eastern part of the Quadrilátero Ferrífero than in the western part, probably because of the generally higher grade of metamorphism in the eastern part. Gneiss and granite are intimately associated and gradational in many places, and are also chemically similar. Three granitic samples (table 15, Ha–6, –8, –10) and two gneisses derived from Rio das Velhas rocks (Ha–7, –36) have differentiation indices ranging from 93.1 to 95.1, indicating a remarkable degree of homogenization.

Pegmatites associated with these rocks in the Itabira district may be pre-, syn-, and posttectonic and are composed dominantly of feldspars and quartz, with some muscovite; the oldest pegmatites also contain calcite and chalcopyrite (Dorr and Barbosa, 1963, p. 46). The pegmatites average only a few centimeters in thickness, but they pinch and swell. Younger pegmatites generally

TABLE 15.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks and pegmatite from the extreme northeastern part of the Quadrilátero Ferrífero*

[For sample locations, see table 3 and pl. 1. ---- not analyzed; P, present; N.d., looked for, but not detected]

Chemical analyses

(Weight percent)

[Analysts: P. L. D. Elmore, S. D. Botts, I. H. Barlow, and G. W. Chloe, using method of Shapiro and Brannock (1956); fluorine determined by S. M. Berthold, U.S. Geological Survey]

	Granitic rocks					Pegmatite	Gneissic rocks		
	Ha–6	Ha–8	Ha–10	H–25b	H–25c	Ha–7P	Ha–7	Ha–36	Ha–38
SiO_2	74.6	74.2	77.8	----	----	72.0	76.3	76.5	71.9
Al_2O_3	14.0	12.7	11.7	----	----	15.0	13.2	11.8	13.3
Fe_2O_3	.3	1.0	.4	----	----	.3	.4	.7	1.0
FeO	.69	1.1	1.0	----	----	.20	.41	1.1	2.1
MgO	.13	.02	.00	----	----	.03	.06	.10	.20
CaO	.83	.80	.71	----	----	.42	.72	.70	1.5
Na_2O	3.7	3.5	3.6	----	----	3.0	3.2	2.8	3.2
K_2O	4.9	5.1	4.1	----	----	7.9	5.0	5.2	4.7
H_2O	.46	.36	.52	----	----	.25	.45	.33	.68
TiO_2	.12	.14	.08	----	----	.02	.03	.10	.45
P_2O_5	.04	.02	.00	----	----	.01	.01	.00	.12
MnO	.04	.04	.04	----	----	.02	.04	.02	.04
CO_2	.34	.13	.06	----	----	.26	.34	.05	.05
F	.04	.37	.52	----	----	.00	----	.16	.14
Total	100.2	99.5	100.5	----	----	99.4	100.2	99.6	99.4

Normative minerals

(Weight percent)

	Ha–6	Ha–8	Ha–10	H–25b	H–25c	Ha–7P	Ha–7	Ha–36	Ha–38
Quartz	33.1	33.7	40.5	----	----	24.1	37.7	38.7	31.6
Corundum	2.1	1.3	1.4	----	----	1.4	2.0	0.8	1.0
Orthoclase	28.9	30.1	24.2	----	----	46.7	29.5	30.7	27.8
Albite	31.3	29.6	30.4	----	----	25.4	27.1	23.7	27.1
Anorthite	1.4	.3	----	----	----	.4	1.4	2.0	5.4
Enstatite	.3	.1	----	----	----	.1	.1	.2	0.5
Ferrosilite	.9	1.0	1.5	----	----	.1	.4	1.3	2.4
Magnetite	.4	1.5	.6	----	----	.4	.6	1.0	1.5
Ilmenite	.2	.3	.2	----	----	----	.1	.2	.9
Apatite	.1	----	----	----	----	----	----	----	.3
$CaCO_3$	.8	.3	.1	----	----	.6	.8	.1	.1
Total	[1] 99.7	[2] 99.0	[3] 99.9	----	----	99.2	99.7	[4] 99.2	98.6
Differentiation index	93.4	93.4	95.1	----	----	96.1	94.3	93.1	86.5
Percent An in Plagioclase	4.4	1.0	0	----	----	1.5	4.8	7.7	16.5

[1] Includes 0.1 percent fluorite.
[2] Includes 0.8 percent fluorite.
[3] Includes 1.0 percent fluorite; CaO deficient.
[4] Includes 0.3 percent fluorite.

TABLE 15.—*Chemical analyses, normative minerals, modal minerals, and minor elements of granitic and gneissic rocks and pegmatite from the extreme northeastern part of the Quadrilátero Ferrífero*—Continued

[For sample locations, see table 3 and pl. 1. ---- not analyzed; P, present; N.d., looked for, but not detected]

	Granitic rocks					Pegmatite	Gneissic rocks		
	Ha-6	Ha-8	Ha-10	H-25b	H-25c	Ha-7P	Ha-7	Ha-36	Ha-38
Modal minerals (Volume percent) [Microscopist: (W), W. B. Wright; (D) E. C. Damasceno; others by author]									
Plagioclase	31	21.5	22.5	----	----	----	25	20	22
(Percent anorthite)	(2)	(6)	(0)	----	----	----	(12)	(11)	(15)
K-feldspar	32	38.9	26.3	----	----	----	25	45	22
Quartz	34	32.2	32.3	----	----	----	43	29	45
Biotite	2	4.8	6.3	----	----	----	45	5	9
Muscovite	P	----	4.5	----	----	----	2	P	P
Epidote	P	1.4	3.0	----	----	----	P	----	----
Chlorite	P	----	1.4	----	----	----	P	----	----
Apatite	P	----	----	----	----	----	P	----	P
Zircon	P	P	----	----	----	----	P	P	P
Fluorite	----	.5	3.7	----	----	----	----	P	----
Opaque (magnetite?)	----	.3	P	----	----	----	----	----	P
Sulfides	----	----	----	----	----	----	----	----	P
Garnet	P	.4	----	----	----	----	----	----	----
Carbonate	----	P	----	----	----	----	----	----	----
Number of points	----	764	765	----	----	----	----	----	----
Microscopist	----	(W)	(D)	----	----	----	----	----	----
Minor elements (Parts per million) [Quantitative spectrographic determinations by C. V. Dutra, Instituto de Tecnologia, Industrial, Belo Horizonte, M.G., Brazil]									
Ba	1,000	450	13	2,500	3,900	900	760	420	1,300
Be	----	----	----	18	1.4	0.8	----	5.0	2.7
Co	N.d.	N.d.	N.d.	9.4	2.8	N.d.	N.d.	1.1	4.7
Cr	1.6	0.8	N.d.	205	2.3	1.1	1.5	0.7	1.8
Cu	.5	4.4	2.0	7.2	5.6	Trace	0.6	6.4	3.5
Ga	14	24	24	22	8.9	16	13	17	14
La	30	230	120	130	N.d.	26	N.d.	170	380
Mo	----	----	----	N.d.	N.d.	2.0	----	1.3	N.d.
Nb	23	57	112	29	N.d.	9.8	21	29	24
Ni	2.0	2.7	4.0	70	2.9	2.0	2.1	N.d.	1.6
Pb	18	33	23	120	19	85	16	59	53
Sc	4.5	N.d.	N.d.	101	N.d.	N.d.	3.8	1.0	7.5
Sn	3.5	17	77	24	N.d.	N.d.	3.8	10	20
Sr	130	42	14	410	280	110	120	25	93
V	6.8	8.1	N.d.	51	14	3.4	1.3	12	20
Y	37	320	200	38	N.d.	14	28	140	±630
Zr	96	410	270	290	36	6.9	107	300	430

crosscut gneiss; older ones have indefinite boundaries and *lit-par-lit* relationships with gneiss, and have been folded with the gneiss.

Pegmatites of the Monlevade district are composed chiefly of quartz and K-feldspar, but they also may have varying amounts of mica, beryl, and phenacite (Reeves, 1966, p. 39). They are small, pinch and swell, and are largely concordant with the Monlevade Gneiss and the overlying Minas Series.

Granitic gneiss is in intrusive contact with all other Precambrian rocks of the Itabira district (Dorr and Barbosa, 1963, p. 41) and is the youngest rock of all, except for the Borrachudos Granite. It was responsible for a metamorphism that produced staurolite and garnet, although most of these minerals were later converted to lower biotite or chlorite zone minerals in a widespread low-grade regional metamorphism.

GRANITIC ROCKS

Granodiorite (table 15, sample Ha–6) and fluorite-bearing granite (table 15, samples Ha–8, Ha–10) are intimately associated with the granite gneisses throughout the Itabira district (Dorr and Barbosa, 1963) and the São Gonçalo and Florália quadrangles; the granite also occurs in the Monlevade district (Reeves, 1966).

The granodiorite is faintly to moderately foliated, and is composed chiefly of quartz and feldspar and of sparse biotite (fig. 23); it appears to grade into the schist and gneisses described above (Dorr and Barbosa, 1963, p. 37). Its compositional range is from tonalite to adamellite with abundant plagioclase (An_{10-20}), varying amounts of microcline and perthite, and less than 15 percent micas, and minor amounts of epidote. Muscovite and green-brown biotite or chlorite and biotite are interleaved in places. The feldspar and quartz are medium-grained, granular to granoblastic. Aggregates of fine-grained quartz and feldspar and coarse crystals of feldspar in a medium-grained groundmass of quartz and feldspar are common. Quartz and feldspar also are intergrown in mosaics.

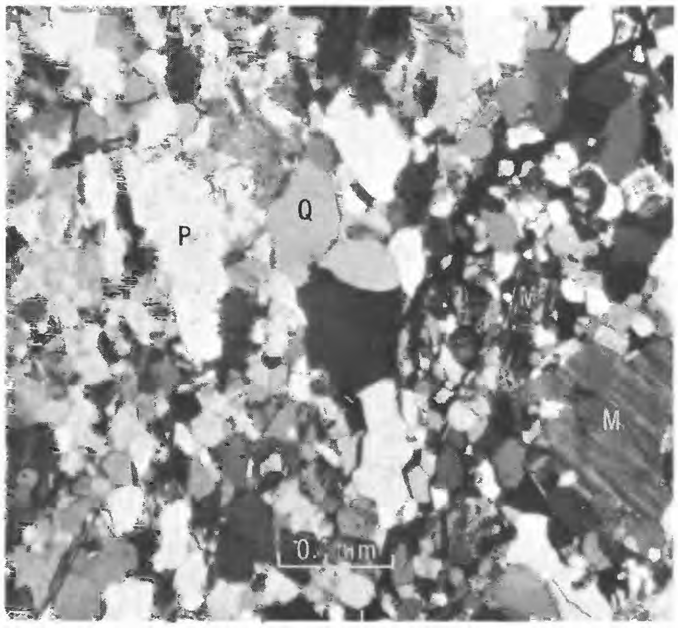


FIGURE 23.—Photomicrograph of granodiorite gneiss, Itabira, consists of quartz (Q), plagioclase with clinozoisite inclusions (P), microcline (M), and biotite. Sample Ha-6, crossed nicols.

The Borrachudos Granite (Dorr and Barbosa, 1963, p. 42) is present in the northwestern part of the Itabira quadrangle and around the Petí dam east of Santa Bárbara. Similar rocks are found in the northeastern part of the Monlevade quadrangle and elsewhere in the northeastern part of the Quadrilátero Ferrífero.

The Borrachudos Granite extends from 20 km northeast to 10 km southwest of the Itabira district in a belt about 5 km wide that passes across the northwestern part of that district. It is massive, unjointed, and forms prominant scarps by which it can be recognized on aerial photographs. The granite is light gray to pinkish gray, coarse grained, and poorly foliated; it has a strong lineation imparted by alined elongate aggregates of biotite. Very close to contacts with other rocks, the Borrachudos may be foliated, but in most places it is unfoliated even near contacts.

In the Itabira district, as far as can be determined, the Borrachudos Granite has sharp contacts with other rocks (Dorr and Barbosa, 1963, p. 44), and contains no inclusions or xenoliths of other rocks. South of the Itabira district in the São Gonçalo and Monlevade quadrangles, the coarse-grained Petí phase of the Borrachudos Granite is similar in appearance and composition to the Borrachudos (compare sample Ha-8, from Borrachudos, with sample Ha-10, from Petí, table 15), but it is not continuous with that rock and has gradational contacts with adjacent foliated granitic and granodioritic gneisses. Near contacts, the Petí phase loses its elongate biotite structure and grades into the bordering foliated gneiss. The transitional rock contains fluorite, a characteristic mineral of the Borrachudos Granite. The presumably sharper contacts in the Itabira district, compared to the gradational contacts near Petí, may be due to differing volatile contents. Compared with the Petí phase, the Borrachudos is "drier" (compare F and H_2O in table 15) and during intrusion would have had a lesser tendency to permeate into the country rock.

These Borrachudos Granites contain abundant blocky porphyritic feldspar, mostly 2–5 mm in size, but with some as large as 10 mm. The feldspars typically are mottled or perthitic. Elongated pods of aggregated quartz or biotite as much as 1 cm in length, and blebs and streaks of fluorite are characteristic (fig. 24). The composition is 45–65 percent feldspar, 30–45 percent quartz, less than 5 percent biotite, and less than 2 per-

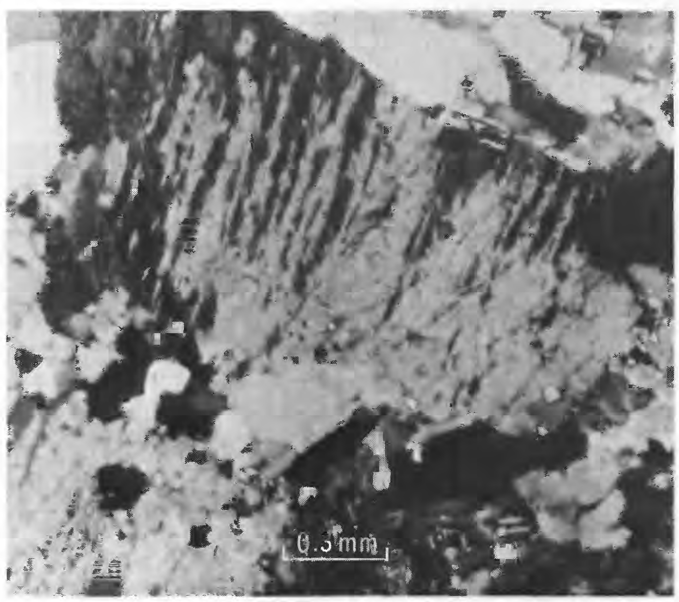


FIGURE 24.—Photomicrograph of Petí phase of Borrachudos Granite. Large inclusions of fluorite occur in mottled perthitic microcline. Sample Ha-10, São Gonçalo quadrangle, crossed nicols.

cent fluorite. Other accessories include muscovite, epidote, chlorite, zircon, carbonate, allanite, and opaque minerals.

The rock varies in composition from granite to adamellite. It contains a dominant phase in which microcline crystals average 1 cm in diameter, and a minor, fine grained phase in which microcline averages half a centimeter across (Dorr and Barbosa, 1963, p. 43). Plagioclase is more abundant than orthoclase in the norm (table 15); so most of the rock is a normative adamellite rather than granite. Sample Ha–8 has 36.2 percent normative plagioclase compared to 30.9 percent normative orthoclase, and sample Ha–10 has 36.6 percent compared to 24.7 percent. The bulk of the perthite, therefore, is probably plagioclase.

Pegmatites are absent from both the Borrachudos and its wallrocks. The lack of joints, the coarse grain sizes, and the mineralogy of the granite suggest that the entire rock is actually a kind of pegmatite in which volatiles were trapped.

PETROGENESIS

Granitic and gneissic rocks of igneous and of mixed igneous-sedimentary origin are present in the extreme northeastern region of the Quadrilátero Ferrífero. The mixed origin for some gneisses has been shown in the field—for example, in the Itabira district where gradational facies exist between gneiss and metasedimentary biotite schist of the Rio das Velhas Series (Dorr and Barbosa, 1963, p. 40). Relict higher grade metamorphic minerals, for example, staurolite, appear to be related to granitic rocks, suggesting a high temperature of emplacement and igneous origin. The present-day similarity of mineralogy and chemical composition of many gneissic and granitic rocks in the area attests to the thoroughgoing nature of the ultrametamorphic or granitization processes responsible for the conversion of metasediments into granitic-appearing rocks.

Of the granitic rocks, the granodiorite and granitic gneiss (sample Ha–6) are intimately related to the gneisses, and the Borrachudos is not. The Petí phase of the Borrachudos Granite (sample Ha–10) is richer in volatile constituents, higher in SiO_2 and lower in Al_2O_3 and K_2O, compared to the type Borrachudos; both normal and Petí phases are unusually rich in fluorine, averaging 0.45 percent.

The minor elements show the close relationship of the Borrachudos Granite and the Petí phase and also suggest that, if the granodiorite was comagmatic, it was formed at higher temperatures than either of them. Ba and Sr decrease from the higher temperature granodiorite of sample Ha–6 to the lower temperature Borrachudos Granite of samples Ha–8 and Ha–10, whereas La, Nb, Sn, Y, Zr, and F increase from sample Ha–6 to samples –8 and –10 (table 15). Ba and Sr are believed to be concentrated early in the differentiation of alkali rock series, and the others mentioned above, late in differentiation (Nockolds and Allen, 1956). The abundant F and Sn even suggest that the later Petí rocks formed during a pneumatolytic stage. The granodiorite and the Borrachudos Granite and associated Petí phase may represent differentiates of the same magma, although the granodiorite intruded earlier, and is probably syntectonic, as it shows some deformation (Dorr and Barbosa, 1963, p. 38); whereas the Borrachudos, judging by its lack of deformational features, is posttectonic.

The minor elements of pegmatites in the gneiss (sample Ha–7P) are much more similar to those of the granodiorite than of the Borrachudos and Petí. This fact suggests that the pegmatites are closely related to the granodiorite and are closer in time to them than to the Borrachudos Granite.

ULTRAMAFIC AND MAFIC ROCKS

Ultramafic rocks are present in the Itabira district, and dikes of probable mafic igneous origin are found throughout the extreme northeastern area. Ultramafic rocks of the Itabira district are considered to be among the oldest igneous rocks in the Quadrilátero Ferrífero, except for metavolcanic rocks interbedded in the Rio das Velhas Series (Dorr and Barbosa, 1963, p. 34). The ultramafic rocks were altered to soapstone, serpentinite, and talc schist. Gabbros and feldspathic peridotites, believed to be younger than the ultramafics, were altered to amphibolite, talc-chlorite schist, talc-chlorite-tremolite schist, and actinolite schist. Foliation in most of the mafic and ultramafic rocks, especially the amphibolites, is concordant to structures in the surrounding pre-Minas rocks.

The soapstone and serpentinite are largely unfoliated and massive, but grade into talc-rich schist near their margins. The soapstone consists of about 99 percent talc and some carbonate and opaques. In places, soapstone has as much as 24 percent by volume of rhomblike holes that range from 2 mm to 2 cm across and may represent former magnesite or other carbonate crystals. Carbonate in veinlets has been identified optically as magnesite-siderite-rhodochrosite containing 75–85 percent of the magnesite molecule (Dorr and Barbosa, 1963, p. 35). The serpentinite contains more than 70 percent antigorite, 5–25 percent talc, and less than 5 percent of carbonate (magnesite 85–90). Accessories include magnetite, pyrite, and chromite.

Amphibolites form sill-like bodies throughout the northeastern part of the Quadrilátero Ferrífero and also irregular stocklike bodies in the Itabira district. Other weathered dikes of mafic origin in the Florália quadrangle appear to be identical with those described in the Barão de Cocais quadrangle (p. B41).

The amphibolite bodies of the Itabira district are of two general types (Dorr and Barbosa, 1963, p. 35): (1) A common variety with a relict ophitic fabric and little or no schistosity, and (2) a less common variety characterized by good alinement of blue hornblende grains and a weak schistosity. Even less common are actinolite-talc-chlorite and tremolite-talc-chlorite schists. The most common amphibolites consist of a blue-green hornblende, 40–60 percent; polysynthetically twinned plagioclase (An_{12-40}) partly replaced by clinozoisite, 20–40 percent; and accessory biotite, leucoxene, quartz, chlorite, sericite, and magnetite. The schistose amphibolite consists of a fine- to medium-grained blue hornblende, 68–80 percent, and plagioclase (An_{15-40}), 10–30 percent. The plagioclase occurs in either untwinned, isolated, equant crystals or irregular aggregates surrounded by hornblende. Clinozoisite and epidote are present; quartz, biotite, leucoxene, apatite, and magnetite generally are minor accessories. The amphibolites are considered to be of metamorphosed gabbro origin.

SUMMARY AND CONCLUSIONS

Absolute age determinations of minerals from the Quadrilátero Ferrífero (table 2; p. B8) suggest five datable events: at about 2,700, 1,930, 1,350, 1,000, and 500 m.y. The older four events were related to granitic intrusions and the formation of gneiss, and the 500-m.y. event was largely thermal, accompanied by the formation of pegmatite.

The granitic and gneissic rocks have been divided into four general groups. Group I includes the Engenheiro Corrêa Granodiorite, which is the the oldest igneous-appearing felsic rock of the region. It first intruded about 2,700 m.y. ago and was partly remobilized or re-intruded in at least the 1,350-m.y. event. Group II includes the banded Itabirito Granite Gneiss, dated the same as I, but also younger and with which it is apparently gradational and interlayered in places, such as the Bação complex. Group III includes the youngest granites of the area which are, as a group, intrusive with, and discordant to, the older Precambrian rocks. They are the most silicic and potassic of all the felsic rocks and are considered to be late or post-Minas tectonism, related to a 1,350-m.y. event and possibly also younger events. Group IV includes the youngest, as well as mixed, gneisses that were either formed or mobilized to some extent in the 1,350-m.y. and younger events. This group is the largest of all the felsic rocks of the Quadrilátero Ferrífero.

In addition, some felsic rocks that have distinctive features have been found in restricted areas, as the porphyritic granite of the Moeda complex, and cannot be correlated with certainty to other rocks within the Quadrilátero Ferrífero. Another coarse porphyritic granite found near Sete Lagoas, about 55 km north-northwest of Belo Horizonte, has been dated at 1,930 m.y. by the whole-rock Sr isochron method (Pinson and others, 1967). The Moeda complex porphyritic granite has yielded a 1,985-m.y. Sr date on K-feldspar, suggesting that the two granites may be comagmatic and related to the same event.

Mafic and ultramafic bodies, ranging in size from thin veins or sills to small stocks or bosses, are also found. The ultramafic bodies intrude only pre-Minas rocks and may have been part of an intrusive cycle of 2,675–2,800 m.y., that included granitic intrusions.

Mafic rocks form sills and dikes and small stocks that intrude all the Precambrian metasedimentary rocks, gneisses, and granitic rocks. They may range in age from the oldest datable events, where they are represented by metamorphosed amphibolite dikes in the Rio das Velhas Series, to about 120 m.y., where they are represented by diabase dikes and gabbro stocks that may be related to the Paraná flood basalts in the south of Brazil (Amaral and others, 1966).

In a general way, the following igneous cycle was repeated two or more times in the Quadrilátero Ferrífero:

1. The original sedimentary and volcanic sequence included some rocks that approximated the composition of granitic gneisses, that is, feldspathic sandstone or arkose. The bulk of the sequence, however, was more mafic and included pelites and basaltic rocks. In an early high-grade metamorphism, granulites may have formed and a layered structure may have been imposed upon some rocks by metamorphic differentiation.
2. Solutions were derived by a partial melting of some original sedimentary rocks. Winkler and Von Platen (1961) found that such a melt would form at about 700°C from rocks containing quartz, alkali feldspar, and biotite, and that the melt would be richer in alkalies and iron than the original rock. This could have taken place in the 2,700-m.y. event in which a regional high-grade metamorphism was developed and again in the 1,930-m.y. event, or in the eastern part of the area during the 1,350-m.y. event.
3. Some liquids of a granitic composition were introduced, but a quantitative estimate of their volume is difficult. The similar mineralogy and chemistry of gneisses and many igneous rocks suggest a closely related origin.

Late regional low-grade metamorphism and structural deformation were imposed upon earlier formed rocks. Mafic minerals were largely changed to chlorite-biotite epidote; the albite content of plagioclase increased as clinozoisite and sericite formed in both the gneisses and granodiorites. During a thermal event, alkali metasomatism, presumably the result of the temperature gradient, also took place, as shown by albite and microcline rims on plagioclase. Many of the gneisses near to the Serra do Curral, for instance, show Na-rich rims on plagioclase, whereas farther away, the rims are K-rich. Most mineralogic changes, however, were due to redistribution of material already present, and presumably only small amounts of silica and alkalies were introduced. Certainly, there are no great differences in composition between rocks showing replacement and those that do not.

Temperatures of recrystallization, calculated by comparing the ab-content of coexisting alkali and plagioclase feldspars (Barth, 1956), referred to elsewhere in this paper, were uniformly low, ranging from 380° to 430°C. The 570°C calculated for the granodiorite of Congonhas (sample Ha–27) and the 610°C for the Petí phase of the Borrachudos Granite (sample Ha–10) may be original temperatures of crystallization.

Other evidence also suggests that temperatures of crystallization or recrystallization were below about 700°C. Compositions of coexisting K-feldspar and plagioclase shown on an orthoclase-albite-anorthite triangular diagram have tie lines that are almost parallel to the Or-Ab joint (fig. 25), except for the tie line for Ha–27. Yoder, Stewart, and Smith (1957, p. 212) have shown that at 5 kilobars water pressure, and about 700°C, plagioclase potassium feldspar tie lines should be parallel to the Ab-Or join; with increase in temperature, the tie lines fan out as the coexisting plagioclase becomes An-rich.

Comparison of the plot of the chemically analyzed older felsic rocks (fig. 26*A* with the younger (fig. 26*B*) on a normative quartz-albite-orthoclase diagram, the "residua diagram" of Tuttle and Bowen (1958), shows that the older are richer in albite and thus "granodioritic" compared to the younger.

The older granodiorite analyses trend from an albite-rich field toward the ternary eutectic of quartz-albite-orthoclase (fig. 26*A*). This is the low-temperature field and the area of maximum concentration of analyses of granites of the world (Tuttle and Bowen, 1958, p. 79). Nearly all such analyses fall within the thermal trough bounded by the 1,000 and 3,000 kg/cm² P_{H_2O} isobars.

In the residua diagram for the younger rocks (fig. 26*B*) nearly all the analyses group within or near the area of maximum concentration of analyses of granites of the world and within the thermal trough shown by the 500 and 3,000 kg/cm² P_{H_2O} isobars. The only exception is sample Ha–7P, a pegmatic which is displaced toward the Or apex. Such uniformity of chemical composition suggest that these rocks were formed in a relatively short period of time, or that all crystalized under similar physical conditions at or near the eutectic at different times. Although the young gneisses in the east have thicker layers and better separation of mafic- and felsic-rich layers than the gneisses of the western Quadrilátero Ferrífero, the rocks are chemically similar in both areas.

Chemical changes accompanying the post-Minas low-grade regional metamorphism are hard to ascertain. Plagioclase tended to break down into albite and epidote minerals at low-metamorphic temperatures, and chlorite formed from biotite, which released some potassium. Part of the Or-enrichment shown in the residua diagram of younger rocks, compared to the world-wide maximum (fig. 26*B*), therefore, may have been due to a K-metasomatism related to metamorphism.

OLDER FELSIC ROCKS (GROUPS I AND II)

Older granodiorite (Group I) was emplaced in the Bação complex and also in the Congonhas district; layered granite gneiss (Group II) intruded, or was developed north of, the Serra do Curral and elsewhere. Parts of Rio das Velhas country rock may have been dissolved into these magmas, or they may have been ultrametamorphosed sufficiently to produce an alkali-silica-rich anatectic melt.

There is evidence that much of the Groups I and II granodiorite rocks were igneous. Flow structures are seen around xenoliths, as in the Prado Lopes quarry (fig. 6), and a high-grade metamorphic aureole occurs in metasedimentary rocks adjacent to the granodiorite in many places. South of the Bação complex, for example, a cordierite-bearing metasedimentary rock borders the granodiorite, and west of the complex, staurolite-garnet metasedimentary rock is abundant. In both places the Rio das Velhas Series shows a high-grade metamorphism, whereas nearby Minas Series rocks are in the chlorite zone, indicating emplacement of the granodiorite before Minas time.

Relations between Group I granodiorite and Group II gneiss vary from place to place. Many small granodiorite dikes crosscut gneiss with sharp contacts and send out *lit-par-lit* dikelets into the gneiss. In other places no such dikes are seen, but granodiorite is *lit-par-lit* in the gneiss. The close chemical and mineralogical compositions of the two rocks in these occurrences suggest that the granodiorite may have formed from an anatectic melt derived from the gneiss.

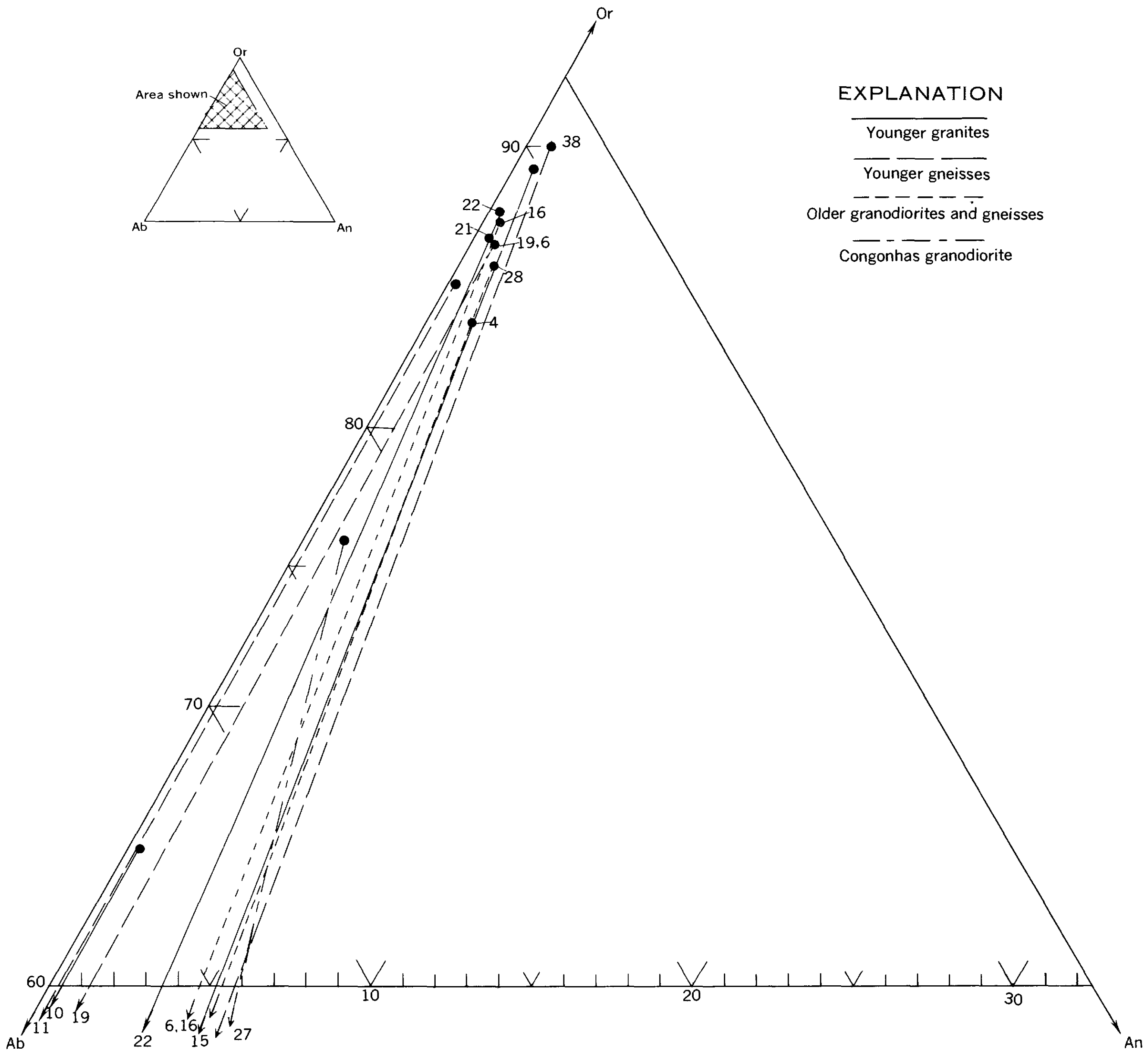


Figure 25.—K-feldspars of the Quadrilátero Ferrífero in a ternary albite-orthoclase-anorthite diagram. Directions of plagioclase tie lines shown. Numbers refer to samples given in table 3.

During the pre-Minas orogenies, large areas of granodiorite were emplaced, granodiorite gneiss was formed, and Rio das Velhas rocks were, in part, assimilated by magma and, in part, metamorphosed to produce assemblages with staurolite-garnet and possibly cordierite-sillimanite. Buttresses formed, composed largely of these gneissic and granodioritic rocks surrounded by Rio das Velhas rocks that were probably too mafic to be "granitized" or converted to gneiss but may have lost their more alkalic fractions by distillation. These buttresses comprise complexes north and west of the Serra do Curral, west of the Serra da Moeda, near Bação and, probably, in the Congonhas area.

In the eastern Quadrilátero Ferrífero, there is no evidence today of such ancient buttresses. If they formed during the earlier history of the area, they were either completely destroyed in younger orogenies or lie at great depths, below the Rio das Velhas Series, and thus are structurally unimportant. The gneisses of the east tend to be rich in potassium, similar to the youngest gneiss in the west.

In post-Minas events, some granodiorite may have

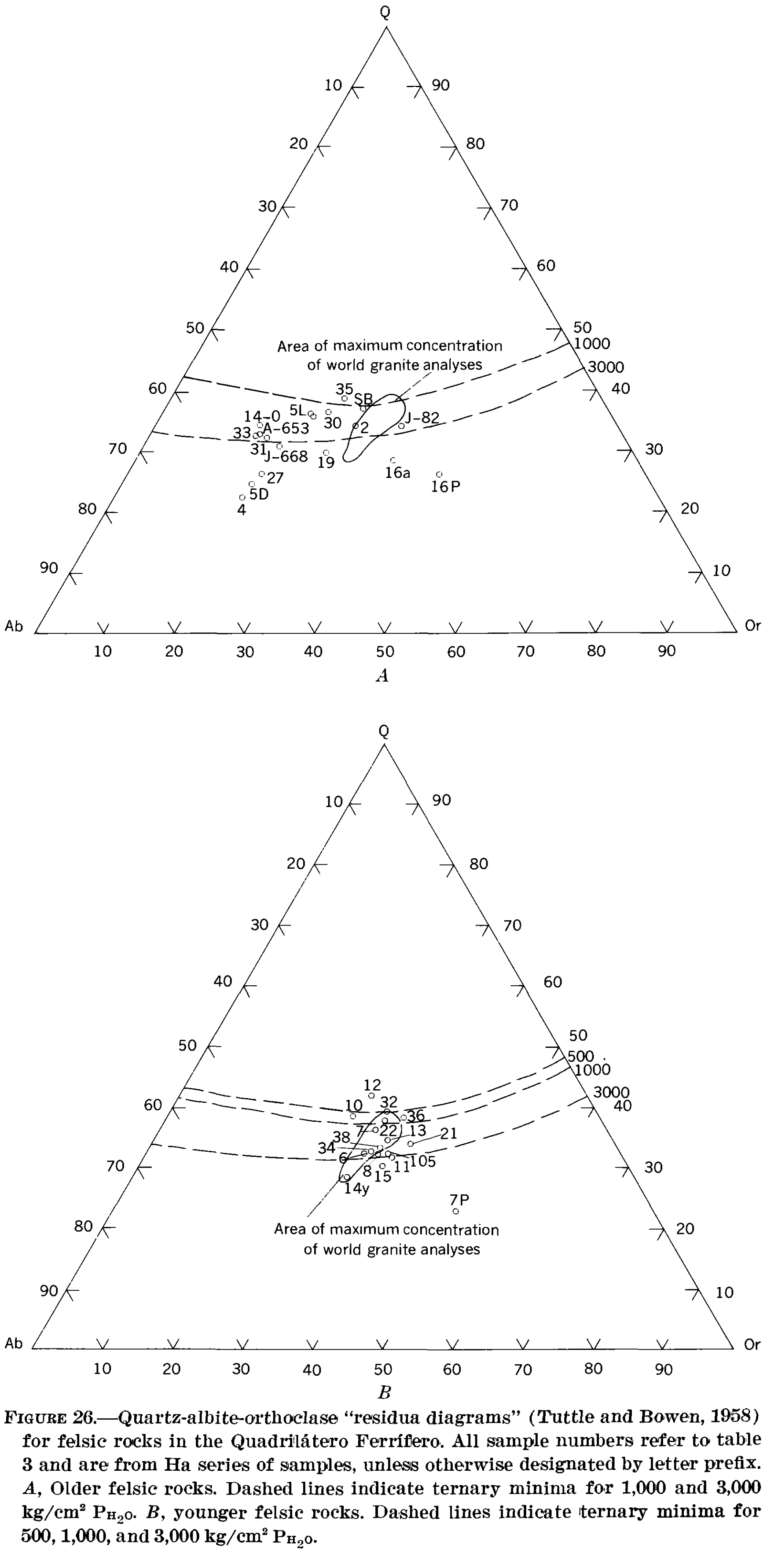


Figure 26.—Quartz-albite-orthoclase "residua diagrams" (Tuttle and Bowen, 1958) for felsic rocks in the Quadrilátero Ferrífero. All sample numbers refer to table 3 and are from Ha series of samples, unless otherwise designated by letter prefix. *A*, Older felsic rocks. Dashed lines indicate ternary minima for 1,000 and 3,000 kg/cm² P_{H_2O}. *B*, younger felsic rocks. Dashed lines indicate ternary minima for 500, 1,000, and 3,000 kg/cm² P_{H_2O}.

produced other anatectic melts, which, in turn, were intruded into older rocks. Such melts would be richer in silica and alkali than the granodiorite, and the younger felsic rocks are actually richer in silica and alkali than the older ones. The last important thermometamorphic event in the area resulted in a general retrograde metamorphism and deformation around the sides of the gneiss buttresses.

A variation diagram for both major and minor elements (fig. 27) of the older granodiorite and gneissic suites (Groups I and II) shows a differentiation trend similar to that found in many worldwide studies of igneous rocks. SiO_2 and K_2O increase with increasing differentiation index, Al_2O_3 shows almost no variation, and the other elements decrease. Na_2O does not vary until the final stages when it decreases. These trends are similar to those for the Lower California batholith as well as the Potosi Volcanic Group of Colorado (Larsen and Schmidt, 1958, p. 29).

The minor elements generally do not appear to vary in a systematic way. Many of them either decrease with increase in differentiation index or do not vary in amount.

YOUNGER FELSIC ROCKS (GROUPS III AND IV)

The oldest date obtained on the younger suite is 1,230 m.y. from the Petí phase of the Borrachudos Granite, which lends support to the idea that most of the younger gneisses (Group IV) and granites (Group III) formed in a post-Minas orogeny of about 1,350 m.y. ago. The granites are largely late- or posttectonic, and the gneisses, syntectonic. The last Precambrian event is dated around 545 m.y. by Rb/Sr on feldspar from pegmatite in the Rio Piracicaba quadrangle and consisted largely of a low-temperature regional metamorphism accompanied by deformation.

In the western Quadrilátero Ferrífero, the younger granites were generally emplaced between the older granodiorite-gneiss buttresses, and the Minas Series, presumably in thrust zones or zones of structural weakness. There is evidence of such a younger intrusion north of the Serra do Curral where staurolite-garnet is found in the Sabará Formation near its contact with granite. West of the Serra da Moeda, albite porphyroblasts in the basal Moeda quartzite formed by metasomatism that possibly was also related to igneous processes. In the eastern part of the Quadrilátero Ferrífero, younger granitic rocks and gneisses are widespread, younger gneisses underlie most of the extreme northeastern region, and high-grade metamorphic facies are adjacent to granite intrusions. The largest discordant granite bodies of the Quadrilátero Ferrífero, the Borrachudos Granite, are in the Itabira and Petí regions.

The same problems of origin and mutual relationships of granite and gneiss apply to the younger as well as the older granodiorite-gneiss suites. In the extreme northeast, Dorr and Barbosa (1963, p. 37), described transitional facies between a granitoid rock of igneous aspect and biotite-rich schistose rock that suggested an anatectic-"granitization" relationship. In the western Quadrilátero Ferrífero, however, discordant dikelets of granite cut older gneiss and instrusive tongues of granite are in the Sabará Formation. Contacts between metasedimentary rocks and the post-Minas granite are generally sharp (Gair, 1962).

In the west, the Group III granites may be largely magmatic differentiates of unknown derivation, and there is no direct evidence for the incorporation of sedimentary material. In the east, on the other hand, preexisting rock could have produced anatectic melts, as suggested by the gradational relationship of metasediments and gneiss in Itabira and Monlevade and by the generally higher metamorphic terrane. High F and Nb, which concentrate in residual magmatic solutions (Rankama and Sahama, 1950), are abundant in the Borrachudos Granite and imply that new material was also introduced.

Most of the post-Minas granite gneiss of the west has been deformed. Two weak foliation planes are commonly seen. Mortar structure and sutured quartz are present, and metasomatic recrystallization is suggested by feldspar grains rimmed by albite or microcline. Much younger gneiss was produced by silica-alkali metasomatism or gneissic structures developed by metamorphic differentiation, near zones of structural deformation or by intrusion of the younger granite. Very little of the younger gneiss in the western part of the Quadrilátero Ferrífero formed by the addition of anatectic liquids since its fine layered structure suggests only original sedimentary or metamorphic processes and a rock that has changed but little. In the east, on the other hand, abundant *lit-par-lit* granite in gneiss has formed a migmatite, suggesting higher temperatures and more thoroughgoing processes of formation.

No variation diagram is shown for the younger granites and gneisses. The younger rocks cover a short interval of D.I. from 85.7 to 96.1 that is entirely within the field of alkalic granite; therefore, no differentiation can be seen.

ULTRAMAFIC AND MAFIC ROCKS

Ultramafic and mafic intrusives that originally ranged from peridotite and pyroxenite to gabbro are now serpentinite, steatite, amphibolite and metagabbro. These intrude only the Rio das Velhas Series and some gneissic rocks and are best developed in the Rio Acima-Macacos quadrangles, the Congonhas district, the Ouro

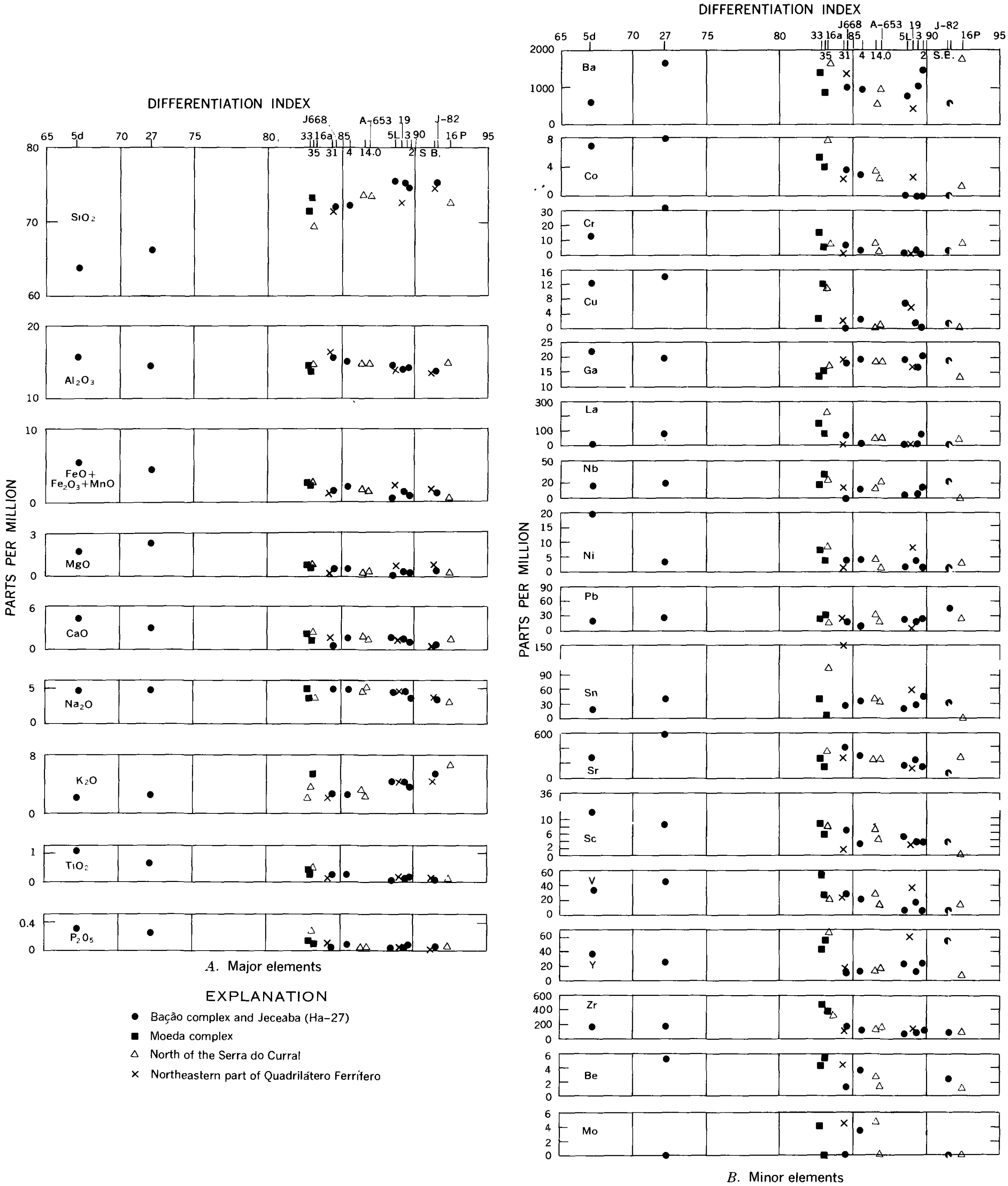


FIGURE 27.—Variation diagram, Groups I and II, older granodiorite and gneissic rocks. Samples are Ha samples unless otherwise designated, and are arranged according to increasing differentiation index (Thornton and Tuttle, 1960).

Preto district, around Caeté, and in the Itabira district. These rocks are pre-Minas, and largely pregranodiorite; in the Congonhas district, there is evidence that some were deformed together with Rio das Velhas Series and later intruded by a granodiorite. Any original contact effects of the intrusions has been masked by later metamorphisms. The oldest dates of the region, 2,700 m.y. and 2,800 m.y., were obtained on amphibolite and schist from the Rio de Pedras quadrangle, north of the Bação complex, and may represent an age of mafic and ultramafic intrusion.

Field evidence shows the larger bodies of mafic and ultramafic rock to be intrusive, and textural evidence of replacement of coarse pyroxenes and olivines by serpentine and talc (fig. 20) also shows a primary igneous rock. Two samples, serpentinite (JG–10–55) and metagabbro (JG–11–55) chosen for chemical analysis because they represent extremes in composition (table 5), have normative minerals suggestive of peridotite and gabbro or diabase, respectively. The metamorphosed ultramafic rock has exceptionally high Co, Cr, and Ni, and is lacking in or has low Ba, Sn, and Sr (table 5), which is additional evidence for an igneous mode of origin for the serpentinite. The gabbro norm suggests an undersaturated mafic alkalic rock containing both orthoclase, 2.8 percent, and olivine, 4.5 percent.

Dikes, plugs, and sills of mafic rocks are found throughout the area, intruding both pre-Minas and Minas rocks. Ophitic texture is seen even in badly weathered varieties and chilled margins have been observed in some dikes (Dorrs and Barbosa, 1963, p. 46). Nearly all have been altered by low-grade metamorphism as well as by weathering. Many of the pre-Minas bodies are now amphibolites, and their origin will be discussed in more detail in the report on metamorphic rocks. Post-Minas mafic rocks may be of two ages, one immediately post-Minas and folded together with the Minas rocks and the other, crosscutting all preexisting structure and correlative with the 120-m.y. old diabase-gabbro dikes and plugs of the State of São Paulo (Amaral and others, 1966). However, both types have saussuritized plagioclase and uralitized pyroxene.

One chemical analysis was obtained of a younger metadiabase (sample A–753) from the Nova Lima quadrangle (table 5). It differs from the older amphibolite metagabbros in having no normative olivine, abundant TiO_2, reflected in high normative ilmenite of 4.0 percent, and is saturated, as shown by 3.2 percent quartz.

Diabase porphyry intrudes pre-Minas sedimentary rocks in the Catas Alttas quadrangle (C. H. Maxwell, written commun., 1963 and older gneiss and the Itabira Group in the Ibirité quadrangle (Pomerene, 1964, p. 35). Chemical and mineralogical similarity suggests that these rocks are related to the younger mafic suite (compare tables 5 and 13). TiO_2 is unusually high in both, trace elements are similar, normative minerals are similar and do not include olivine, and both have wollastonite.

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