Metamorphic Rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil

GEOLOGICAL SURVEY PROFESSIONAL PAPER 641-C

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 metamorphic events that have affected the Precambrian igneous and metasedimentary rocks of the Brazilian shield

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METAMORPHIC ROCKS OF THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL

By Norman Herz

ABSTRACT

The metasedimentary rocks in the Quadrilátero Ferrífero have been divided into the lower Precambrian (pre-2,700 m.y.) Rio das Velhas Series and the middle Precambrian Minas (pre-1,350 m.y.) and Itacolomí Series (pre-1,000, perhaps pre-1,350 m.y.). Five thermal events occurred, four of which may have been accompanied by granitic intrusion or formation. All regional metamorphisms were, in general, Barrovian-type low-grade greenschist facies, either chlorite or biotite isograd except near granitic intrusions where almandine-amphibolite facies conditions obtained and the staurolite isograd was developed. The last thermal event, 500 m.y. was accompanied by pegmatite formation and probable retrograde metamorphism of many of the earlier formed higher grade minerals. In a general way, the metamorphic grade increases to the south and east. Metamorphic aureoles developed around the Bação Complex and the granite north of the Serra do Curral, where the metamorphic grade falls from staurolite isograde adjacent to the granite to the regional chlorite isograde away from it.

In the chlorite zone, the most widespread assemblages developed in pelitic rocks include: chlorite-sericite (muscovite)-quartz, which is by far the most common, and chlorite-sericite (muscovite)-quartz-chloritoid, with or without kyanite. Locally abundant are varieties rich in fuchsite, graphite, carbonate, iron oxides, or tourmaline. Because of the extremely high alumina (average 20.1 percent) and potash (average 4.5 percent) content compared to the low lime (0.15 percent and soda (0.35 percent) content, albite and epidote are not as common here as in low-grade rocks elsewhere. They occur with the chlorite-sericite-quartz assemblage.

With increasing metamorphism, biotite apparently replaces chlorite and sericite. Chlorite changes from an Fe- to Mg-Al-rich variety as metamorphic grade increases, but the compositions of associated biotite also appear to change from Fe- to Mg-rich. Grain size becomes coarser in the biotite zone. Both albite and epidote, as well as spessartite, are found locally. In the upper part of the biotite zone, oligoclase and almandine occur.

Staurolite is generally the highest metamorphic zone present in the area, although sillimanite and cordierite are found in the metamorphic aureole south of the Bação Complex. In this zone, staurolite replaces chloritoid, almandine replaces chlorite and spessartite, and biotite is more abundant, although some chlorite persists. Kyanite is found in this as in all metamorphic zones; oligoclase and andesine occur in places.

With increasing metamorphic grade, the only significant changes in "pure" itabirite are an increase in size of the quartz and hematite and a change from hematite to specularite. Rare accessory minerals in low-grade itabirite are kaolinite, talc, chlorite, and pyrophyllite; as the grade of metamorphism increases, tremolite-actinolite and finally, at the highest grade, cummingtonite-grunerite are found. In dolomitic itabirite, in addition to increase in grain size of magnetite, hematite- specularite, and quartz, with increasing metamorphism, dolomite disappears, diopside and tremolite-actinolite form in medium-grade rocks, and pyroxene, andradite, and cummingtonite-grunerite form in high-grade rocks.

Carbonate rocks generally do not change their mineralogy with increasing metamorphism, although they do become coarser grained. Some tremolite and clinozoisite formed near shear zones; in higher grades cummingtonite also developed.

Quartzo-feldspathic rocks developed suites similar to those in the pelitic rocks, except that plagioclase and microcline are much more abundant.

Amphibolites are found in areas where metamorphism exceeded the greenschist facies. Most of these amphibolites appear to be metamorphosed mafic igneous rocks, although some may be altered "dirty" carbonate rocks. A typical assemblage in these rocks includes hornblende, almandine, andesine, quartz, and some biotite and actinolite.

Major minerals of the Quadrilátero Ferrífero include:

Chlorite.—One of the most abundant minerals of the region, found in all rocks types and in all metamorphic zones. In changing from lower to higher grade rocks, chlorite appears to lose Fe and become more Mg-Al-rich, as well as coarser grained. It occurs with hematite in higher grade rocks; in rocks containing magnetite, biotite of a composition related to chlorite also appears. Chromian chlorite is associated with gold mineralization.

White mica.—Includes mostly muscovite but also some fuchsite and pyrophyllite. No paragonite was found in any rock. Muscovite is one of the most abundant minerals of the area and is found in every rock type, except iron-formation, and in every metamorphic grade. In higher grade rocks, it is coarser grained; in the lowest grade, it is fine-grained "sericite."

Biotite.—Found in medium- to high-grade pelitic schists and in other rock types, but rarely found in low-grade pelites and itabirite. High-Mg biotite is found in carbonate-bearing and

pelitic rocks; high-Fe biotite is usually in amphibolite and greenstone.

Feldspar.—Most abundant in quartz-rich rocks. Orthoclase is found near granite contacts and microcline away from them. Plagioclase, An_{0-35}, occurs with quartz, chlorite, muscovite, biotite, and epidote. Oligoclase and andesine are also found with staurolite, almandine, and hornblende. In most lower grade rocks, plagioclase is either untwinned or twinned in broad bands according to the albite law. In higher grade rocks, some is polysynthetically twinned on the albite law. The An_{10} isograd lies within the biotite zone, albite being toward the chlorite zone and oligoclase being toward the staurolite zone.

Quartz.—One of the most abundant minerals of the area is found in all rock types. With increasing metamorphism it increases in grain size in itabirite from an average of 0.04 mm in the northwestern part of the Quadrilátero Ferrífero to about 0.13 mm in the extreme northeastern part.

Carbonates.—Especially abundant as marble and dolomite and in iron-formation.

Chloritoid.—Found in phyllite and quartzite in the Cercadinho Formation and the Maquiné Group. Chloritoid is iron-rich in phyllite and Mg-rich in quartzite, but both forms are triclinic. Much occurs as rosettes, suggesting that it is postdeformational. Chemical composition of the rocks containing high Al and low Ca appears to play a major role in its formation.

Kyanite.—Found in pelite and quartzite and veins cutting these rocks. It occurs in every grade of metamorphism of rocks having excess Al compared to alkalies. Minor elements are more abundant in kyanite in phyllite than in any other type of occurrence, which suggests that much of the vein kyanite originated as a "recrystallization pegmatite." Much is also postdeformational.

Andalusite and sillimanite.—Rare but have been found in staurolite-zone pelites. Both are generally replaced by sericite and quartz. Andalusite is also found near a diabase dike northwest of Cocais.

Staurolite.—Widespread in pelitic rocks in the innermost aureole around granite contacts and elsewhere in the Itacolomí Series and Piracicaba Group of the southeastern part of the Quadrilátero Ferrífero.

Amphiboles.—Widespread. In low metamorphic grades, actinolite-tremolite is found in carbonate rocks and becomes grunerite-cummingtonite with increasing metamorphism. In pelitic rocks and mafic metavolcanics, low-grade tremolite-actinolite is replaced at higher grades by hornblende.

Pyroxenes.—Rare, but are found in contact-metamorphosed mafic, calcareous, or iron-formation rocks.

Garnet.—Found in a variety of rock types of moderate and high metamorphic grades. In greenschist-grade rocks, it occurs as spessartite; it becomes almandine in the upper biotite zone. Pure andradite is found in contact-metamorphosed dolomitic iron-formation.

Mineral occurrences and assemblages of the Quadrilátero Ferrífero also include epidote, tourmaline, vesuvianite, apatite, talc, sphene, rutile, iron oxides, zircon, sulfides, corundum, topaz, manganese minerals, and cordierite.

Metamorphic temperatures have been determined for the area by dolomite-calcite and dolomite-siderite solid-solution series (400°–500°C); by pyrrhotite-pyrite solid-solution series in the Morro Velho mine (325°C); by the occurrence of diopside in some carbonates (500°C); by albite in plagioclase compared to albite in potassium-feldspar (generally 380°–430°C but 570°C in a granodiorite and 610°C in a posttectonic granite); and by the presence of organic compounds in some phyllites (less than 200°C). Assuming a depth of burial of 10 km or more, these pressure/temperature conditions are consistent with the widespread formation of greenschist-facies rocks.

INTRODUCTION

The Quadrilátero Ferrífero, the most famous iron-mining district of Brazil, is an area of about 7,000 km² in the south-central part of the State of Minas Gerais. The state is named for its wealth of mines, which included in colonial times gold and diamonds as well as iron. The capital of the state, Belo Horizonte, lies in the northwestern part of the Quadrilátero Ferrífero at long 44° W. and lat 20° S. (pl. 1).

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 (hereafter referred to as the DNPM), and the American Government, through the U.S. Geological Survey, sponsored by Technical Assistance program of the Agency for International Development, U.S. Department of State. Seventeen geologists did the mapping, 15 from the U.S. Geological Survey and 2 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, and topographic and aerial coverage, was under the supervision of Ing. José Alves, Chief of the Belo Horizonte office of the DNPM, and Dr. Avelino I. de Oliveira, who was then Director of the DNPM, in Rio de Janeiro.

CLIMATE AND TOPOGRAPHY

The climate is subtropical, consisting of only two seasons, a wet one from November to about February (summer) and a dry one during the rest of the year. The mean annual temperature is about 20°C; the average for summer is only 2° or 3° higher and for winter 2° less. Freezing temperatures are unknown in Belo Horizonte, although some towns situated in deep valleys, such as Ouro Prêto, or high upland places may experience freezing during early winter. The mean annual rainfall ranges from about 1,300 mm in Rio Piracicaba (Reeves, 1966) to about 2,100 mm in Ouro Prêto (Johnson, 1962, p. 4).

Within the Quadrilátero Ferrífero is a great divide, the Serra Geral, part of the Serra do Espinhaço which parallels the Atlantic coast for about 2,400 km. East of the Serra Geral, streams such as the Rio Piracicaba join the Rio Doce and flow east about 300 km to enter the Atlantic just north of Vitória in the State of Espírito Santo. This region is one of abundant rainfall and is called the Zona da Mata because of its formerly extensive forests. West of the Serra Geral, rivers such as the Paraopeba and Rio das Velhas flow north to the São Francisco, which continues northward for about 1,200 km before turning east and entering the Atlantic between the northeastern States of Alagôas and Paraiba. The region west of the Serra is called the Zona do Campo and has sparser rainfall and consequently more open fields with less vegetation.

The Quadrilátero Ferrífero is a generally mountainous area similar in relief to northern New England. Where resistant beds such as itabirite or quartzite crop out, the topography is exceptionally rugged. In most areas underlain by gneiss or granite, such as the Bação Complex and immediately north of Belo Horizonte, gently rounded hills are present. The total relief of the area is about 1,400 m (meters); the lowest part, less than 600 m, is in the east where the Rio Piracicaba leaves the area and the highest is the Serra do Caraça where some peaks are higher than 2,000 m. The maximum relief is found east of the Serra do Caraça, where, between the peaks of the Serra and the valley of the Rio Piracicaba, a 1,000 m drop occurs in 5,000 m.

Ranges held up by iron-formation or quartzite extend north and east and bound the "Quadrilátero." Each range is known by several names, depending on the locality; in this report, only the most important names are used. The northernmost range is called the Serra do Curral, the westernmost, the Serra da Moeda or, in the Congonhas District, the Serra das Almas. In the southwest, the most important range is called the Serra do Ouro Branco and is held up by canga and quartzite. The Serra do Caraça, in the east, is also underlain by quartzite. The Serra do Tamanduá lies in the northeastern part of the area and is underlain by both quartzite and iron-formation.

ACKNOWLEDGMENTS

This study of metamorphic geology 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. 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 studies were examined.

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. Dr. Evaristo Ribeiro Filho, Department of Geology of the University of São Paulo, took the photomicrographs.

Prof. Francis J. Turner read and criticized the manuscript. I profited from many discussions with him on the general metamorphic principles involved, as well as from discussions with the project geologists on specific field relations. I am also indebted to J. V. N. Dorr 2d, who acted as critic on earlier versions, and J. E. Gair, who read and criticized the final version.

PREVIOUS GEOLOGIC INVESTIGATIONS

The State of Minas Gerais has long interested travelers and miners. The first known published reference to its abundant mineral wealth was in 1711; by 1932, Freyberg (1932, p. 331–393) was able to list 976 articles in a bibliography of the geologic literature of the state. Murta (1946) found that about 600 articles on iron and 200 on manganese in Minas Gerais had appeared by 1943. Most early reports, however, were only the results of short reconnaissance visits or studies of specific mines.

The first detailed studies in the area of the Quadrilátero Ferrífero were in 1822 by Von Eschwege, (cited in Freyberg, 1932) who proposed a stratigraphy for the Ouro Prêto area. Towards the end of the last century both Derby and Gorceix published many papers which provided the necessary background for subsequent geologic studies, especially the study made by Harder and Chamberlin (1915) whose stratigraphy is similar to that followed today. They recognized a basement complex and divided and named the Minas Series as follows: Caraça Quartzite, Batatal Schist, Itabira Iron-formation, Piracicaba Formation, and Itacolomí Quartzite.

THIS INVESTIGATION

The author spent the period from January 1957 to August 1961 in Belo Horizonte. During that time, collections made by geologists then working or who had previously worked in the Quadrilátero were studied together with field notes and maps. Supplementary samples were also collected, but, because of the great area involved, the study would not have been possible without the availability of collections and maps made by others.

Some samples are represented only by thin sections and others by small rock chips, but for the great majority of samples cited in the text, both the hand specimen and the thin section were available. Because of the availability of collected material, certain parts of the Quadrilátero Ferrífero may seem to be favored in this report over others. The general descriptions drawn and principles deduced from these samples, however, appear to be universal in application in the area, and the fact that certain localities are mentioned to illustrate a point does not mean that no other places show the same phenomenon.

Laboratory work, largely the study of thin sections and mineral identification, was begun in Belo Horizonte. The time from September 1961 to February 1962 was spent in Washington, where an X-ray diffractometer was available. The report was rewritten and the final stages of the laboratory work were completed during intervals from March 1962 until June 1964, the period during which the author was teaching in the Department of Geology and Paleontology, Faculty of Philosophy, Sciences, and Letters, of the University of São Paulo.

ACCURACY AND PRECISION OF ANALYSES

Chemical analyses by the U.S. Geological Survey and by the DNPM in Rio de Janeiro were done by so-called "rapid methods." Analyses by the DNPM in Belo Horizonte were done by classical chemical techniques. The rapid methods are described by Shapiro and Brannock (1956) and the precision and accuracy of the rapid, as well as the standard methods of chemical analysis are discussed in Fairbairn and others, 1951, and Stevens and others, 1960.

Spectrochemical determinations by C. V. Dutra at the Instituto de Tecnologia Industrial, Belo Horizonte, were quantitative; those by the U.S. Geological Survey in Washington, D.C., semiquantitative. The methods used for quantitative analysis as well as their accuracy and precision are discussed elsewhere (Herz and Dutra, 1960). The semiquantitative analyses are reported either to the nearest number in the series 10, 3, 1, 0.3 or in the series 10, 7, 5, 3, 2, 1.5, and 1. Detection limits for spectrographic analyses are shown in table 1.

ABBREVIATIONS AND LOCATIONS

Many abbreviations are used in the report both in tables and in the text; all of them are listed and explained in table 2.

Sample numbers are all preceded by a letter code. In most cases, the code refers to the geologist who mapped the area and collected the samples. In some cases, I collected samples from a locality described in the field geologists's notes, in which case the geologist's code letter was used. An H is used for other localities collected by me. The letter code used is:

A–	B. E. Ashley
CM–	C. H. Maxwell
G–	P. W. Guild
H–	Norman Herz
J–	R. F. Johnson
JG–	J. E. Gair
M–	S. L. Moore
P–	J. B. Pomerene
R–	G. A. Rynearson
RMV–RRP	R. G. Reeves
S–	G. C. Simmons
W–	A. M. White
W–(with other letters)	R. M. Wallace
Z–	J. E. O'Rourke

Numbers alone or various letters are used by J. V. N. Dorr 2d, A. L. M. de Barbosa, and Benedito Alves.

Quadrangles named in the text are shown on the metamorphic map of the Quadrilátero Ferrífero (pl. 1). Locations within quadrangles are measured in meters from any corner. A location such as N. 1,500, E. 1,700 is 1,500 m north and 1,700 m east of the southwest corner of the quadrangle.

GENERAL GEOLOGY

STRATIGRAPHY

Metasedimentary rocks in the Quadrilátero Ferrífero have been divided into three series, from oldest to youngest, the Rio das Velhas, the Minas, and the Itacolomí. A fourth group of rocks, possibly older than these three, is found as roof pendants or xenoliths, like those near Engenheiro Corrêa, and cannot be mapped in detail. General descriptions of the stratigraphy, as well as of the structure and physiography of the region as a whole, have been written by Dorr (1969). More detailed descriptions on the various quadrangles have been provided by the project geologists (Gair, 1962; Johnson, 1962; Dorr and Barbosa, 1963; Pomerene, 1964; Wallace, 1965; Reeves, 1966; Simmons, 1968a, 1968b; Moore, 1969; and Maxwell, 1972). These subjects are treated in only summary fashion in this report.

OLDEST METASEDIMENTARY ROCKS

High-grade metamorphic rocks near Engenheiro Corrêa form roof pendants and xenoliths (Herz, in

TABLE 1.—*Detection limits in parts per million of spectrographic determinations*

[Column 1, element; column 2, detection limits of quantitative analysis, Instituto de Tecnologia Industrial, Belo Horizonte, analyst: C. V. Dutra; Column 3, detection limits of semiquantitative analysis, U.S. Geological Survey, Washington, D.C., analyst: Helen Worthing; Dash, not analyzed]

1	2	3
Ag	1	0.1
As	--	100
Au	20	10
B	--	30
Ba	2	3
Be	2	1
Bi	--	3
Cd	--	10
Ce	--	100
Co	2	1
Cr	2	3
Cs	--	3,000
Cu	.1	.3
Dy	--	30
Er	--	10
Eu	--	10
Ga	5	1
Gd	--	30
Ge	10	3
Hf	--	20
Hg	--	3,000
Ho	--	10
In	--	1
Ir	--	30
La	30	30
Li	200	30
Lu	--	10
Mn	3	1
Mo	2	3
Nb	30	3
Nd	--	100
Ni	2	30
Os	--	30
Pb	10	1
Pd	--	1
Pr	--	100
Pt	--	3
Re	--	30
Rh	--	3
Ru	--	30
Sb	--	100
Sc	2	1
Sn	10	3
Sr	3	3
Sm	--	100
Ta	200	100
Tb	--	100
Te	--	300
Th	200	100
Tl	--	10
Tm	--	10
U	--	300
V	10	1
W	200	30
Y	10	3
Yb	--	1
Zn	200	100
Zr	2	3

Dorr and others, 1959–1961, p. 99–100). In Ribeirão (Brook) Sardinha, where good exposures are found, thin-bedded quartzose gneiss composed largely of coarse-grained quartz and potassium-feldspar is interbanded with finer grained quartzose and feldspathic gneiss. Quartz makes up 80 percent or more of these rocks; oligoclase, microcline, biotite, muscovite, and clinozoisite complete the assemblage. Garnet-quartz amphibolite is associated with these quartzose gneisses.

TABLE 2.—*Abbreviations used in this report*

ab,	albite	lt,	light
ad,	andesine	mg,	magnetite
ah,	actinolitic hornblende	mm,	millimeter
		mn,	manganese minerals
alm,	almandine garnet	mod,	moderate
am,	amphibole	mu,	muscovite
an,	anorthite	N,	when used as a coordinate, north in meters from SE. or SW. corner of quadrangle.
ap,	apatite		
at,	actinolite		
bi,	biotite		
c,	coarse grained		
ca,	calcite	ol,	oligoclase
cb,	carbonate	on,	olivine
cd,	chloritoid	op,	opaque minerals
cl,	chlorite	or,	oxidation ratio
cm,	centimeter	( ),	accessory minerals
comp,	composition	ph,	phlogopite
congl,	conglomerate	pl,	plagioclase
cr,	cordierite	pp,	pyrophyllite
cu,	cummingtonite	ppm,	parts per million
dk,	dark	psi,	pounds per square inch
DNPM,	Departmento Nacional da Produção Mineral do Brasil	py,	pyrite, or sulfides in general
		pyr,	pyrope garnet
do,	dolomite	quad,	quadrangle
dp,	diopside	QF,	Quadrilátero Ferrífero
E,	when used as a coordinate, east in meters from NW. or SW. corner of quadrangle	qz,	quartz
		qzt,	quartzite
		rd,	rhodochrosite and rhodonite
ep,	epidote	ru,	rutile
f,	fine grained	S,	when used as a coordinate, south in meters from NE. or NW. corner of quadrangle.
fe,	ferruginous		
fm,	formation		
fu,	fuchsite		
ga,	garnet		
gn,	grunerite	se,	sericite
gp,	group	ser,	series
gr,	graphite	si,	sillimanite
gro,	grossularite garnet	sp,	sphene
gt,	goethite	st,	staurolite
hb,	hornblende	ta,	talc
hm,	hematite	tm,	tourmaline
if,	iron-formation	tr,	tremolite
il,	ilmenite	v,	very
ka,	kaolinite	W,	when used as a coordinate, west in meters from NE. or SE. corner of quadrangle.
kf,	potassium feldspar		
kp,	kupferite		
ky,	kyanite		
lc,	leucoxene		
lm,	limonite	zr,	zircon

These oldest metasedimentary rocks are gneisses that were laid down as feldspathic sandstone, arkose, and similar rocks, or they are garnet amphibolite formed from mafic volcanic material, graywacke, and argillaceous dolomite.

The exact relationship of these rocks to the Rio das Velhas Series is not yet known. Tolbert (1962) described a structural and lithologic unconformity within the Nova Lima Group, between rocks of the Morro Velho and the Raposas mines. If this unconformity separates rocks of greatly different ages, then it is possible that the rocks near Engenheiro Corrêa can be correlated with the lower part of the Nova Lima Group (Dorr, 1969, p. A16).

These rocks are pre-2,700 m.y., because they were already metamorphosed at that time (Herz and others, 1961).

RIO DAS VELHAS SERIES

The Rio das Velhas Series is divided into three groups, from oldest to youngest, Nova Lima, Maquiné (Dorr and others, 1957), and Tamanduá (Simmons and Maxwell, 1961). All three groups are separated by unconformities.

The Nova Lima Group is by far the most widespread in the area. It is composed largely of phyllite, mica schist, and quartz-mica schist; minor interbedded rocks are metamorphosed iron-formation, graywacke, subgraywacke, quartzite, conglomerate, metavolcanic rocks, graphitic schist and phyllite, quartz-ankerite rocks, and other metasedimentary rocks. The Maquiné Group is found principally in a broad anticlinorium from the Nova Lima quadrangle southeast to the São Bartolomeu quadrangle and eastward to the Serra do Caraça. It consists of a lower formation, the Palmital, comprised of quartz-sericite schist and interbedded graywacke, sericitic quartzite, and conglomerate, and an upper formation, the Casa Forte, made up largely of quartzite, much conglomerate, and some phyllite and schist. The uppermost group, the Tamanduá, which may actually be lower Minas (Dorr, 1969), underlies the Serra do Caraça, Serra das Cambotas, and the Serra do Tamanduá. It consists of a lowermost quartzite followed by phyllite and quartzite schist, dolomite itabirite, and phyllitic schist.

Metamorphosed equivalents of the Rio das Velhas Series north of the Bação Complex and on the west slope of the Serra da Moeda have yielded dates that range from about 2,300 m.y. to 2,800 m.y. (Herz, 1970), so it must be assumed that the Rio das Velhas Series is older than about 2,700 m.y.

MINAS SERIES

The Minas Series overlies the Rio das Velhas and is separated from it by a profound unconformity (Rynearson and others, 1954). It is younger than 2,700 m.y. and probably older than about 1,350 m.y., as it is intruded by the granite of Petí and metasomatized by that of Moeda, which have yielded dates of 1,230 m.y. and 1,320 m.y., respectively (Herz 1970).

The Minas Series underlies a large part of the Quadrilátero Ferrífero and is made up of, from oldest to youngest, the Caraça Group, the Itabira Group, and the Piracicaba Group (Dorr and others, 1957).

The Caraça Group is divided into two formations, the Moeda (Wallace, 1958) and the Batatal (Maxwell, 1958). Both the upper and lower members of the Moeda Formation are composed predominantly of quartzite and quartzite conglomerate; the intermediate member is a quartz phyllite. The Batatal Formation is largely fine-grained phyllite, in places arenaceous, and some pyrite. Some chert and lenticular beds of iron-formation are intercalated in the upper part of the formation.

The Itabira Group is divided into two formations, the Cauê Itabirite and the Gandarela Formation (Dorr, 1958). The Cauê is itabirite, a metamorphosed oxide-facies iron-formation composed of alternating laminae of quartz and hematite. Locally, dolomitic itabirite or dolomite is interbedded and, in places, amphiboles substitute for part of the quartz. Magnetite commonly occurs in the dolomitic itabirite. A few small lenses of quartzite or phyllite are found. The Gandarela Formation normally consists of dolomite and subordinate dolomitic or siliceous iron-formation and phyllite; in many places, however, phyllite is the dominant rock. In the Dom Bosco, São Julião, and the Catas Altas quadrangles, the Gandarela consists of a greenschist composed largely of chlorite and variable amounts of epidote, quartz, and magnetite.

The Piracicaba Group, overlying the Itabira Group, is divided into five formations. Local erosional unconformities exist between the lower four and the uppermost formation; other unconformities are found below and above the group. The five formations of the Piracicaba Group, from its base, are the Cercadinho (Pomerene, 1958), the Fecho do Funil (Simmons, 1958), the Taboões Quartzite (Pomerene, 1958), the Barreiro (Pomerene, 1958), and the Sabará (Gair, 1958b).

The Cercadinho Formation is composed of ferruginous quartzite overlain by phyllite. The ferruginous quartzite is made up of quartz grains and flaky specular hematite; the lowermost bed is locally conglomeratic. The Fecho do Funil Formation is dolomitic phyllite and argillaceous dolomite, phyllite, and ferreginous quartzite. The Taboões quartzite is a fine-grained translucent quartzite containing irregular brown-stained cavities; in most places it weathers to a friable sand. The Barreiro Formation consists of interbedded phyllite and graphitic phyllite. The Sabará Formation is separated locally from the underlying and overlying formations by erosional unconformities and is a thick series of phyllites, schists, graywackes, subgraywackes, and, locally, metamorphosed tuffs, cherts, and thin iron-formation.

ITACOLOMÍ SERIES

Overlying the Minas Series with angular unconformity is the Itacolomí Series (Barbosa, in Dorr and others, 1959–1961, p. 81–84). It consists largely of quartzite but contains beds of phyllite and metaconglomerate. The quartzites are composed of quartz and muscovite, are generally schistose, and locally grade into mica scists. Hematite varies in amount from traces to quanties sufficient to make the rock a ferruginous quartzite.

No direct evidence bears on the age of the Itacolomí. The maximum angular unconformity between it and the Minas Series is about 15°, which may be the result of epeirogenic upwarp.

AREAL STRUCTURE AND METAMORPHISM

The dominant structural feature of the Quadrilátero Ferrífero is the synclinal ridges of the Minas Series, the outline of which gives the region its name. Many of these ridges are overturned folds having amplitudes from 1 to more than 50 kilometers. The older pre-Minas rocks have been subjected to several deformations and are poorly exposed, so that their detailed structures can only be determined locally in underground mines. The Itacolomí has been folded in the same general structural pattern as the Minas Series.

Five thermal events occurred, four of which may have been accompanied by granitic intrusions (Herz, 1970, table 2). The first datable event, about 2,700 m.y. ago, was a post-Rio das Velhas orogeny. Intrusion is known to have taken place at that date in the present-day area of the Bação Complex and on the west side of the Serra da Moeda, and well-layered gneiss may have formed throughout the area at that time. An event about 1,930 m.y. ago is known only from Lagoa Santa, about 55 km north of Belo Horizonte and the Moeda Complex, and its effects on the metamorphic rocks is not known.

About 1,350 m.y. ago, after the deposition of the Minas and Itacolomí Series, granitic domes were reactivated and intrusion took place throughout the area. This orogeny masked most of the effects of the earlier one and imposed the present structural trends on the region. Synclines striking north and east formed between large anticlinoria of older metasedimentary rock and gneissic domes. Much of the granite of this orogeny may represent anatectic melts produced from the older rocks, judging by a striking similarity in trace elements in both the older and younger granitic rocks (Herz and Dutra, 1958) and by their close association.

After the 1,350-m.y. orogeny, thermal events took place about 1,000 and 500 m.y. ago. The effects of the two later thermal events are difficult to assess. Minor folding and extensive thrust faults and fracture zones modified the structural pattern that preceded them, and pegmatite formed during the 500 m.y. event. Stress appears to have been directed from the general area of the major Precambrian geosynclinal axis, represented today by the charnockite belt of eastern Minas Gerais and Espírito Santo; the deformation thrust rocks such as the Minas Series over the gneiss domes. This resulted in a westward and northward overturning of folds and the formation of thrust faults. Some of these fault zones may have been later filled by granitic rock around the Serra do Curral and Bação Complex and diabasic rocks elsewhere, as in the Serra do Caraça.

NORTHWESTERN PART

The most important structural feature of the northwestern part of the Quadrilátero Ferrífero is an overturned anticline of Minas rocks striking about north 70° E. along the crest of the Serra do Curral. It is the longest linear structure in the Quadrilátero Ferrífero, extending for more than 100 km from the extreme western edge to the Piedade quadrangle.

To the north of the anticline are gneisses which extend the length of the Serra. They are covered to the north by relatively undeformed Precambrian or lower Paleozoic carbonate rocks, pelites, and quartzites. In the contact area of the gneissic and Minas rocks, a possible thrust zone may have been a channelway for younger intrusives.

Toward the west side of the Quadrilátero Ferrífero, the north-striking Serra da Moeda runs into the south side of the Serra do Curral in the Macacos and Ibirité quadrangles. South of the Serra do Curral, and west of the Serra da Moeda, the Bonfim gneissic dome contains a core of gneiss surrounded by younger granitic rocks. Rio das Velhas rocks appear in and around the dome and have about the same low degree of metamorphism as have the Minas rocks, except within a contact aureole in the extreme west where staurolite and garnet have formed in pelitic rocks. Foliation is the dominant planar structure in the older rocks, whereas bedding is dominant in rocks of the Minas Series.

The Rio das Velhas uplift occurs east of the Moeda syncline. It is a northwest- to north-trending anticlinorium made up of Nova Lima rocks on the west flank and Maquiné rocks in the Vargem do Lima syncline to the east of the uplift (Gair, 1962, p. 49). Rocks of the Rio das Velhas uplift have been metamorphosed at least twice. They are now at the greenschist facies, generally within the chlorite isograd but biotite is found in places.

Retrograde metamorphism may have accompanied or followed a deformation some time after the 1,350 m.y. post-Minas orogeny. It is a moot point whether or not the first metamorphism of the Rio das Velhas rocks was a high-grade metamorphism that was masked by late retrograde metamorphism which imposed a widely developed greenschist facies. Foliation or cleavage is generally well developed and bedding is not well shown in the Rio das Velhas rocks (fig. 1), whereas bedding is well preserved in rocks of Minas age.

FIGURE 1.—Photomicrograph, strongly sheared chloritic phyllite, Nova Lima Group, JG–28–55, Rio Acima quadrangle, plane light. Visible foliation plane is a plane of shearing. Chlorite (c) comprises about 80 percent of the rock with lengths as much as 0.1 mm. Flakes penetrate edges of quartz grains. Quartz (q) comprises about 15 percent, both in grains less than 0.1 mm scattered through the chlorite, and in isolated recrystallized augen up to 1 mm. Altered sphene, leucoxene (opaque), and sericite are accessory. This may be a metavolcanic rock, as indicated by the large amount of chlorite and the quartz augen representing phenocrysts.

The greenschist facies is typically shown in fine-grained pelites by the assemblage chlorite-muscovite-quartz, in quartzites by muscovite-hematite-chlorite or chloritoid-chlorite-hematite, and in carbonate rocks by dolomite-quartz-chlorite-muscovite. Locally within the greenschist facies, a higher grade than that bounded by the chlorite isograd is shown by the presence of biotite in pelitic rocks (fig. 2).

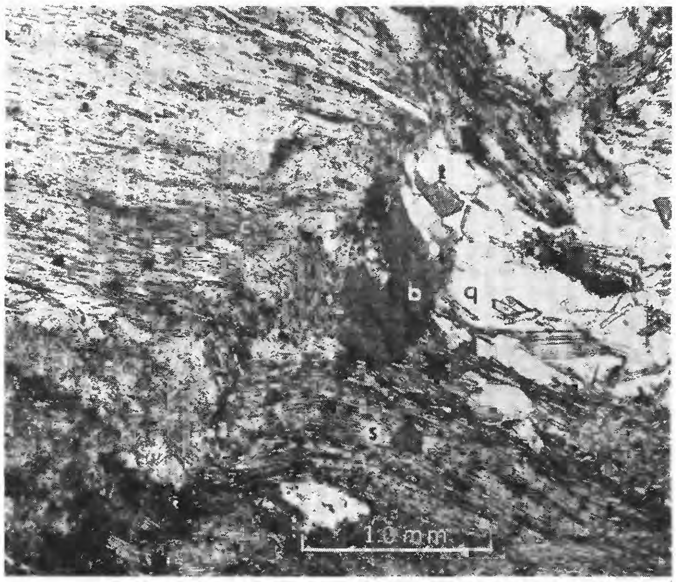


FIGURE 2.—Photomicrograph, schist, Piracicaba Group, J–617, Dom Bosco quadrangle, plane light. Biotite porphyroblast (b), formed in axial planes of shear folds. Quartz (q) comprises about 20 percent of the rock; it forms laminae about 0.5 mm thick in which grains are less than 0.15 mm. Sericite (s) is about 50 percent of the rock, forms bands about 3 mm thick, and is intergrown with chlorite (c) which forms clots, and composes about 25 percent of the rock. Accessories include altered sphene and leucoxene, tourmaline magnetite, and zoisite.

In the Nova Lima, Belo Horizonte, and Ibirité quadrangles (Gair, 1962; Pomerene, 1964), the grade of metamorphism rises north of the Serra do Curral from the chlorite to the staurolite isograd and the rock becomes coarser grained and porphyroblastic as it approaches the granite contact. Chlorite, biotite, garnet, and staurolite isograds appear to parallel both the bedding in rocks of the Minas Series and the granite contact, but some of the higher grade minerals underwent retrograde metamorphism at a later time. Structural complications east of the Nova Lima quadrangle, in the Piedade and Santa Luzia quadrangles, make isograds difficult to map, but high-grade minerals have been found there. West of the Ibirité quadrangle, deep weathering has made mapping of isograds impossible, but Simmons (1968a, p. 31) has found garnet in the Sabará Formation as it approaches the granite contact.

Dynamic metamorphism has affected rocks in the western part of the Quadrilátero Ferrífero in general.

Shearing, largely parallel to bedding planes, strained and fractured quartz grains (fig. 3). Quartz occurs both in fine-grained recrystallized mosaics and in relatively large grains surrounded by mortars of finely

FIGURE 3.—Photomicrograph, strongly sheared phyllite, Nova Lima Group, R–84–52, Itabirito quadrangle, plane light. Foliation is due to shearing of quartz grains and alinement of micas. Sulfides (s) and tourmaline (t) suggest metasomatism. Quartz in irregular, sheared, and recrystallized grains (q), forms about 50 percent of the rock. Muscovite (m) occurs in fine-grained groundmass and in coarser grains with green porphyroblastic biotite (b). Tourmaline (t) is small grained and zoned from brown outside to green inside.

crushed quartz. Belts of extremely fine-grained quartzite, which strongly resemble Arkansas novaculite, extend for several kilometers north of the Serra do Curral in the Ibirité quadrangle (Pomerene, 1964, p. 28) (fig. 4). Feldspathization of the fine-grained quartzite and of Moeda quartzite near Samambaia (Pomerene, 1964, p. 32) occurred in zones parallel to the contact with gneiss, north and south of the Serra do Curral. Feldspathized zones are generally 5 mm to 1 m thick and are attributed to metasomatism by alkali-rich solutions. (See the section entitled, "Alkali Metasomatism.")

Kyanite occurs in quartz veins in aluminous chloritoid quartzite of the Moeda and Palmital Formations in the Gandarela quadrangle and may represent "recrystallization pegmatites" (Ramberg, 1952, p. 252). The Al content of the kyanite may have been largely derived from the country rock (Herz and Dutra, 1964).

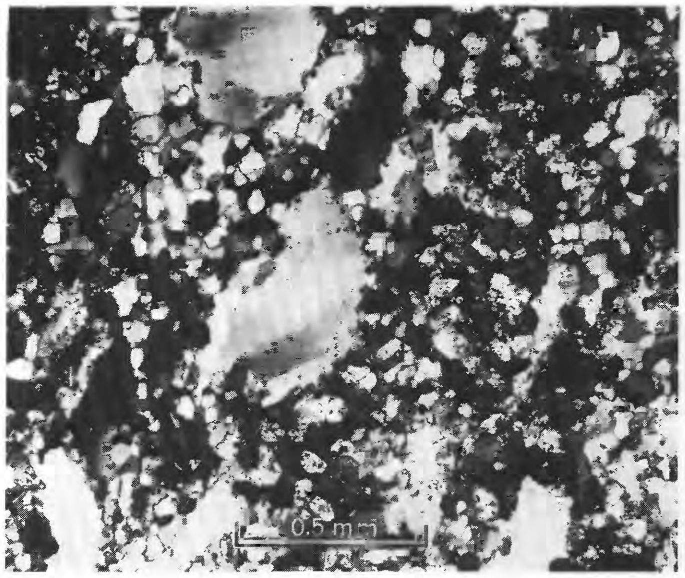


FIGURE 4.—Photomicrograph, quartzite stringer from gneiss, 52–P–206, Belo Horizonte quadrangle, crossed nicols. Rock consists entirely of quartz grains of two sizes and limonite stain. Larger grains may be remnants of clastic grains.

SOUTHWESTERN PART

The Serra da Moeda separates the granitic rocks in the western part of the Quadrilátero Ferrífero from the Moeda syncline, a major structural feature in rocks of the Minas Series, in the southwestern part.

Wallace (1965) has shown the Moeda syncline to be W-shaped in cross section, to have a north trend, and to be bounded by domelike gneissic structures both to the east and west. Rocks of the syncline are metamorphosed to greenschist facies. Toward the southern end, the syncline appears to swing to the east, passing around the south side of the Bação Complex. Structures within the Moeda syncline can be explained as a result of compression between the Bação Complex and the buttress of gneiss in the Moeda Complex to the west (Wallace, 1965, p. 31).

The Engenho fault lies between rocks of the Minas and Itacolomí Series in the São Julião area and the Rio das Velhas greenschist to the south. It extends eastward from the Jeceaba quadrangle (Guild, 1957) to the eastern edge of the Quadrilátero Ferrífero (Johnson, 1962; Barbosa, A. L. M., written commun., 1965). The metamorphism of the area is generally of the greenschist facies but the grade appears to rise in the pre-Minas sediments south of the Engenho fault and also near granitic contacts.

Pelitic rocks in the Moeda syncline typically contain fine-grained assemblages of quartz-sericite-chlorite or quartz-chloritoid-chlorite and accessory hematite or magnetite. Quartzite generally has cataclastic textures. Carbonate rocks are almost entirely dolomite and quartz, but they have accessory chlorite, muscovite, hematite, magnetite, talc, and tremolite or anthophyllite and, rarely, pyrite. Itabirite contains mostly quartz and specularite or quartz, dolomite, and magnetite, but it may grade into schistose itabirite containing either quartz, dolomite, magnetite, and actinolite, or quartz, magnetite, and antinolite.

Metamorphic anomalies in these low-grade rocks appear in the southwestern part of the Quadrilátero Ferrífero, as they do to the north. Northeast of Poço Fundo, for example, fine-grained quartz-muscovite-magnetite phyllite of the Itacolomí Series has porphyroblasts of kyanite, garnet, chloritoid, and muscovite. Guild (1957, p. 38) attributes the porphyroblasts northeast of Poço Fundo and similar occurrences elsewhere to a temporary temperature rise during thrusting.

Kyanite commonly occurs as unoriented ragged grains along minute fractures and as rosettes on bedding planes in quartzite and phyllite of the Minas and Itacolomí Series. Guild thinks the kyanite is hydrothermal in origin, but evidence presented later in this report indicates that it is related to bulk chemical composition and high pressure during metamorphism. (See the section entitled, "Kyanite.")

The grade of metamorphism appears to increase southward from the Engenho fault, but zoning could not be mapped in detail because of poor exposures. Schists rich in plagioclase-quartz-biotite and quartz-hornblende-epidote are common, and a biotite-almandine assemblage was found in Congonhas in a drill hole into schist near a contact with granodiorite. Metamorphism in this area thus appears to be of the upper greenschist and lower amphibolite facies.

Intrusions of granodiorite in the extreme southern part of the area may have caused contact metamorphism; a later, largely deformational, event was responsible for retrograde effects. Near intrusions, sericitic phyllites and schists are coarser grained and contain biotite and almandine, which in some rocks was replaced by chlorite. Deformed ultramafic bodies in the Congonhas district are altered to talcose chlorite amphibole schist and are strongly foliated. Also present in that area is massive steatite containing talc, ankerite, actinolite, amphibole asbestos, and pyrite.

In places along the Minas Series-granite contact west of the Serra da Moeda, a gneissic rock, probably derived from Rio das Velhas sediments, is found. The gneiss contains quartz, microcline, muscovite, oligoclase, biotite, and epidote, and minor calcite, allanite, and sphene. In adjacent basal rocks of the Minas Series, the only contact effects of the granite intrusion are tourmaline-quartz veins and a 5-m-wide feldspathized zone.

BACAO COMPLEX

The Bação Complex is a domelike structure of granitic, granodioritic, and gneissic rocks of more than one age (Herz and others, 1961). The northern part of the complex intrudes metasedimentary rock of the Rio das Velhas Series (J. E. O'Rourke, written commun., 1954). Many large areas of metasedimentary rock occur but are not mapped in the granitic rocks of the Bação Complex and small bodies of granitic rock occur in areas of metasedimentary rock adjacent to the complex. Mappable outliers of granite are common north of the complex (Wallace, 1965).

Metasedimentary rock of the Rio das Velhas is continuous around the west and east sides of the complex. In places along the south side of the complex, Minas rocks are in contact with gneiss, but, in general, a thin septum of Rio das Velhas rocks intervenes (Johnson, 1962; Guild, 1957). The stratified rocks of the Minas Series strike parallel to and dip away from the contact, except at the southwest and southeast corners of the complex.

A metamorphic aureole is present in the Rio das Velhas rocks surrounding the complex. The basal Minas Moeda Quartzite is almost entirely quartz, which may account for its lack of contact-metamorphic minerals adjacent to the complex. On the other hand, the presence of cummingtonite in the Cauê Itabirite at the southeast corner and of pegmatite and quartz-tourmaline veins within the schist of the Piracicaba Group on the south edge of the complex provide evidence that the intrusions affected the Minas to some extent.

The metamorphic aureole is about 500 m wide in Rio das Velhas rocks along the west and southwest sides of the complex (Guild, 1957, p. 39). The freshest examples of contact-metamorphosed pelitic rock in that area occur as float consisting of garnet, staurolite, kyanite, sillimanite, cordierite, quartz, biotite, muscovite, and chlorite assemblages. Float fragments of relatively coarse-grained quartzite and quartz-magnetite itabirite schists also occur along the west and southwest sides of the complex. A metasedimentary gneiss in Ribeirão Sardinha is quartz-plagioclase-(oligoclase - andesine) - garnet - hornblende - sillimanite-biotite. Johnson (1962, p. 26) described similar rocks along the southern margin of the complex and found that assemblages of quartz-andesine-cummingtonite-biotite-garnet occurred in both the contact zone and in xenoliths.

Because the metamorphic aureole is only about 500 m wide, Guild (1957, p. 39) thinks that the intrusion of the granodiorite took place at shallow depths with rapid cooling. Because the area just south of the Bação Complex is much folded and faulted, it is also possible that the aureole originally was thicker but was thinned by thrust faulting. Along the northern boundary of the complex, J. E. O'Rourke (written commun., 1954) concluded that a gradational contact between biotite schist and associated amphibolite and granite gneiss was caused by metasomatism rather than by isochemical reconstitution of minerals under higher pressure/temperature cinditions.

SOUTHEASTERN PART

Essentially the same structures continue eastward from south of the Bação Complex into the southeastern part of the Quadrilátero Ferrífero. In this area, the main part of the Piracicaba Group in the upper part of the Minas Series occupies a synclinorium, which is actually the Dom Bosco syncline (Dorr, 1969) that extends eastward south of the Serra do Ouro Prêto to the eastern limit of the Quadrilátero Ferrífero. Geologic structure south of this synclinorium is extremely complicated and includes many thrust faults along which displacement to the west has occurred (Johnson, 1962; A. L. M. Barbosa, written commun., 1965). An eastward continuation of the Engenho fault and its satellite faults separates Minas and Itacolomí rocks north of the fault zone from Rio das Velhas rocks to the south. The Serra do Ouro Branco, which is composed of poorly sorted quartzites and conglomerates that are tentatively correlated by Johnson with the Caraça Group, may also lie just south of this great fault.

A wide area of Nova Lima phyllite and schist lies east of the Bação Complex and differs from that on the other sides in that biotite apparently is the highest metamorphic isograd. A higher level of metamorphism than the greenschist facies is indicated by the association of oligoclase with biotite. Staurolite-bearing assemblages may have been faulted out by thrusts from the east.

The Serra de Antonio Pereira lies east of the Nova Lima rocks, which comprise the belt east of the Bação Complex. The Serra is underlain by Minas rocks and its structure is much complicated by faulting. Metasedimentary rock of the Rio das Velhas Series appears again in thrust sheets east of the Serra de Antonio Pereira. The whole area is generally within the chlorite metamorphic isograd but biotite appears adjacent to granite in the extreme eastern part of the Catas Altas, Santa Rita Durão, and Antonio Pereira quadrangles.

South and southeast of the Bação Complex, quartz-chlorite-muscovite assemblages are ubiquitous, and some pelitic rocks also contain biotite, chloritoid, or epidote. Albite is comparatively rare. In high-grade pelitic rocks, staurolite and associated garnet and kyanite may have formed by the breakdown of chloritoid. Alkali amphiboles occur in dolomitic itabirite of the Passagem mine (fig. 5) (Guimarães, 1935, p. 23).

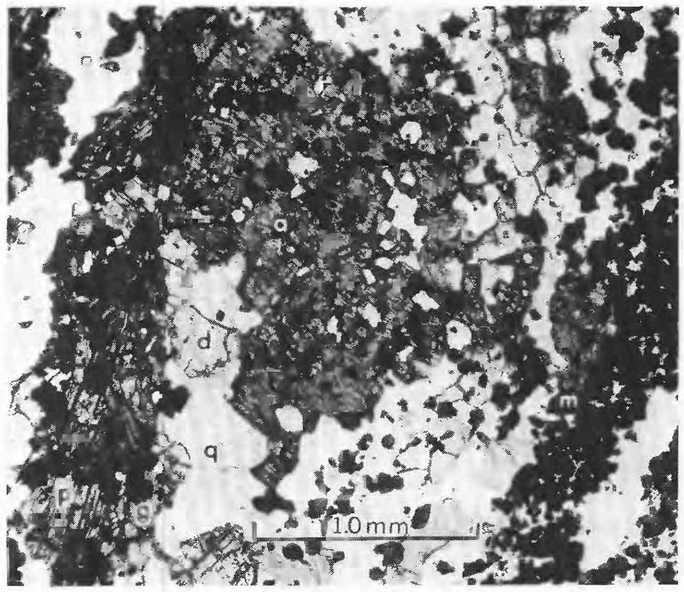


FIGURE 5.—Photomicrograph, amphibolitic carbonate-rich itabirite, Passagem mine, 48–G–130, Passagem quadrangle, plane light. Rock contains well-developed layers of magnetite (opaque, m), dolomite (d), and quartz (q). Large quartz grains are strained. Alkali amphibole (a) up to 1–2 mm, generally prismatic and poikilitic, is abundant along certain layers. It is strongly pleochroic blue-green to yellow-green. Pyroxene (p), (acmite) forms nonpleochroic green grains. Some garnet (g) is associated with the pyroxene.

In Rio das Velhas rocks, the metamorphic grade generally increases near the south edge of the southeastern part of the Quadrilátero Ferrífero and also increases in some folds in that area (pl. 1). The staurolite isograd is common in rocks of the Itacolomí Series in some folds and may have been caused by an increase in temperature and pressure brought on by folding and thrusting. Isograds related to folds has also been observed in regions of Alpine metamorphism (Niggli, E., 1960; Vrana, 1964).

The most common assemblage of the Itabira and Piracicaba Groups in carbonate rocks is dolomite-quartz-muscovite; in schistose carbonates, carbonate-phlogopite biotite-quartz-epidote-chlorite; and in dolomitic itabirite, dolomite-tremolite-quartz-magnetite. Itabirite generally has a simple mineralogy of quartz and hematite or quartz-dolomite-hematite-magnetite, but assemblages containing diopside, epidote, and tremolite have been found in the southeastern part of the Dom Bosco quadrangle. (See table 17.)

Quartzites generally consist only of quartz, muscovite, chlorite, and hematite, but many also have kyanite or chloritoid. Some Itacolomí quartzite has staurolite with or without garnet.

NORTHEASTERN PART

The most important structures in the northeastern part of the Quadrilátero Ferrífero are synclines in metasedimentary rocks of the Minas Series, complex anticlinoria of pre-Minas quartzites, and extensive faults, especially thrust faults. The largest syncline is the Gandarela syncline which is continuous for about 45 km from the Gandarela quadrangle in the southwest to the São Gonçalo quadrangle in the northeast. The pre-Minas rocks appear to have been isoclinally folded and deformed both by pre- and post-Minas deformation. Syntectonic and post-tectonic granitic gneiss occurs along the northern and eastern sides of the area.

Quartzitic rocks of pre-Minas or Minas age make up the Serra das Cambotas and the Serra do Caraça. The Serra do Caraça is cut by a network of north-trending faults, some of which are thrust faults that have low dips to the east. Other faults in the Serra do Caraça trend northwest and generally follow the fault pattern.

Structures in the Rio das Velhas rocks appear to be discordant to Minas structures (Moore, 1969), but, because schistosity or axial plane cleavage is the most obvious planar structure, examples of real discordance are difficult to find.

The metamorphic grade in this area is either of the greenschist or epidote amphibolite facies, except near igneous contacts. The typical assemblage in pelitic rocks is muscovite-quartz-chlorite and locally kyanite. Grain size is generally fine but ranges to coarse. In quartz-rich phyllite of the Nova Lima Group, O'Rourke (written commun., 1954) found plagioclase porphyroblasts with accessory iron oxides, graphite, chloritoid carbonate, and tourmaline.

Quartzites and other quartzose rocks containing muscovite, hematite, kyanite, and chloritoid generally show evidence of cataclasis. Quartz grains are crushed, and larger recrystallized grains form augen. Kyanite is widespread both in thin veins and disseminated in the rock. Most occurrences are in the vicinity of shear zones and may be due to locally high tectonic overpressure (Herz and Dutra, 1964).

Carbonate rocks of the Gandarela Formation in the northeastern part of the Quadrilátero Ferrífero consist mainly of dolomite and quartz. Accessory minerals are chlorite, muscovite, talc, and tremolite. In places, hematite and magnetite are present and the carbonate rock grades into dolomitic itabirite. Although most iron-formation in the area is entirely of granular quartz and hematite, magnetite does occur, especially in dolomitic itabirite. Chlorite and cummingtonite or tremolite are common accessories in dolomitic itabirite and itabirite.

The metamorphic grade increases near igneous contacts, but intense weathering prevents the mapping of contact aureoles. Contact aureoles occur in the extreme north and east parts of the Quadrilátero Ferrífero, near intrusive granitic rock as well as east and southeast of the Serra do Caraça near a metamorphosed ultramafic intrusive sequence. Shattered crystals of almandine-rich garnet as much as 2 cm in diameter occur in chlorite-muscovite schist and phyllite in the extreme eastern part of the area and near granite contacts throughout the area. Original sedimentary rocks adjacent to the ultramafic body contain garnet, staurolite, and kyanite. Magnetite crystals are found in near-perfect octahedra as much as 7 cm in diameter in the Catas Altas quadrangle, as well as large limonite pseudomorphs after pyrite crystals (Maxwell, 1972). Small quartz-tourmaline veins are possibly related to the intense faulting and regional shearing.

Maxwell (1972) described a transition zone of migmatite between pre-Minas rocks and Santa Bárbara gneiss in the eastern part of the Catas Altas and Santa Rita Durão quadrangles and attributed it to pneumatolytic metamorphism. In the Cocais quadrangle Simmons (1968b) found evidence of contact metamorphism of quartzite adjacent to Cocais gneiss north of the Serra do Tamanduá. The zone immediately adjacent to the gneiss contains large potassium-feldspar porphyroblasts and coarse muscovite plus plagioclase Ab_{85-95}, biotite and epidote. Beyond this inner zone is a median zone containing similar porphyroblasts of potassium-feldspar and muscovite, and beyond this is an outer zone of sheared quartzite.

EXTREME NORTHEASTERN PART

The most striking structures of the Itabira and Monlevade areas are synclines of Minas metasedimentary rock bordered by gneiss, granitic rock, or Rio das Velhas metasedimentary rock. Arcuate anticlinal ridges of pre-Minas quartzite occur in the Florália quadrangle. The area was extensively intruded by mafic and ultramafic dikes (Florália-São Gonçalo quadrangles), by sills (Monlevade-Rio Piracicaba quadrangles), and by stocks (Itabira district).

Metasedimentary rocks of the Rio das Velhas Series were metamorphosed to a relatively high grade in both a pre- and post-Minas orogeny. Retrograde metamorphism possibly led to the present widespread muscovite-chlorite-quartz assemblages. Reeves (1966) found evidence that relatively high pressure-temperature conditions existed during a pre-Minas orogeny in which Monlevade gneiss developed from rocks of the Rio das Velhas Series. Layered quartz-biotite gneiss as well as quartz-mica schist show a segregation of lenses of quartz and potassium-feldspar, and paragneiss of the Piracicaba Group of the Monlevade district has quartz-biotite and potassium-feldspar-quartz-biotite layers. Dorr and Barbosa (1963) pointed out that in similar paragneiss in the Itabira area, bedding has generally been eliminated from the original Rio das Velhas rocks, the gneiss has much coarser grain sizes than rocks of the Minas Series, and that hornblende- and biotite-bearing schists are much more common in the paragneiss than in Minas rocks.

No metamorphic aureoles were mapped in this area because of deeply weathered as well as sparse outcrops. It can be seen, however, that the Rio das Velhas pelitic rocks have been more highly metamorphosed than those of the Minas: (1) assemblages of garnet, staurolite, and kyanite may crop out for as much as 200 m in the Rio das Velhas and for only about 10 m in the lowermost Piracicaba (Dorr and Barbosa, 1963, p. 53–54); (2) bedding is no longer visible in most Rio das Velhas pelites, whereas it is seen in all Minas rocks; (3) amphibolites and biotite-rich rocks are seen only in the Rio das Velhas; and (4) the Minas rocks are generally finer grained than those of the Rio das Velhas.

Quartzites of the Minas Series have been recrystallized and have an interlocking mosaic fabric. Coarse-grained muscovite is ubiquitous and biotite, potassium-feldspar, and plagioclase may also be present. Common accessory minerals are zircon, apatite, staurolite, kyanite, garnet, and opaques. Although the mineralogy of iron-formation here is the same as in the western part of Quadrilátero Ferrífero, the iron-formation in the east contains many grains of hematite that exceed 1 mm in diameter, in contrast to iron-formation in the west, where hematite grains average about 0.05 mm. Andradite garnet-grunerite assemblages occur in roof pendants or xenoliths of iron-formation in granitic rocks in the Itabira district.

Hornblende-quartz-plagioclase (oligoclase-andesine) are developed throughout the region, probably derived from metamorphism of mafic rocks rather than from carbonate rocks (which in this district generally preserve their essential carbonate mineralogy and react to metamorphic conditions only by a coarsening of grain size).

MINERALOGY

CHLORITE

Chlorite is one of the most abundant minerals in the metasedimentary rocks of the Quadrilátero Ferrífero. It is found in such diverse rocks as quartzite, iron-formation, dolomite, phyllite, and schist and in different metamorphic environments from the staurolite zone to the greenschist facies.

Chlorite, when associated with muscovite, is generally assumed to represent rocks of the lowest grade of metamorphism, and, together with albite, epidote, and actinolite, it is diagnostic of the greenschist facies (Fyfe and others, 1958, p. 217). In Si- or K-poor rock assemblages, Mg-rich chlorite can be associated with almandine and is stable at temperatures greatly exceeding those attributed to the greenschist facies (Yoder, 1952).

Nelson and Roy (1958) found, on the basis of laboratory investigations, that the stability of chlorite was also a function of crystal structure. At temperatures below about 500°C, two-layered chlorite (or 7 A) is stable; from 500° to 700°C, four-layered (or 14 A) is the stable form. The former is generally finer grained whereas the latter is more perfectly and coarsely crystalline. Because chlorite in higher grade rocks of the Quadrilátero Ferrífero is relatively coarse grained compared to that in lower grade rocks, the high-grade chlorite is probably the four-layered variety.

In the lowest grade rocks, chlorite generally formed from clay minerals of indeterminate composition. In rocks of higher grades, some chlorite persists as a metastable phase; also in places, it appears to be a product of progressive metamorphism (fig. 6).

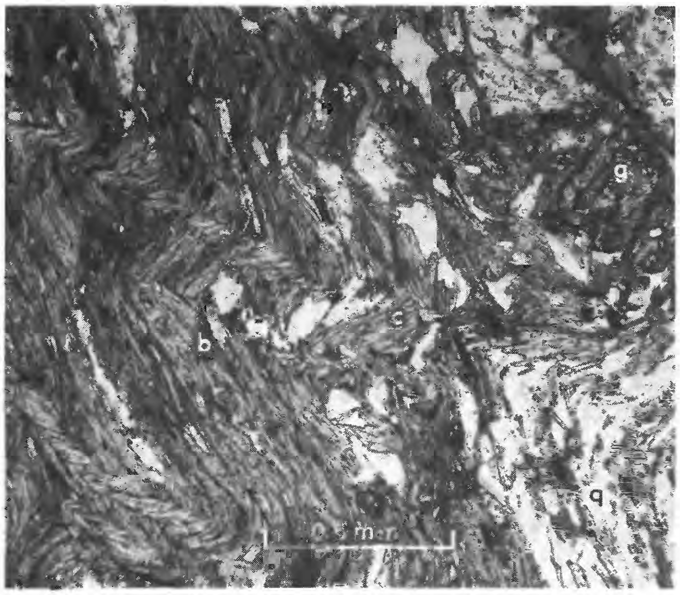


FIGURE 6.—Photomicrograph, schist, Nova Lima Group, near granite contact, R–104–52, Itabirito quadrangle, plane light. Crenulation of interleaved and interbanded biotite (b) and chlorite (c) bands is pronounced. Garnet (g) has snowball structure in places or is fractured, and has kelyphitic, chloritic rims. Quartz (q) recrystallized in elongate grains. Platelike opaque mineral may be ilmenite.

OPTICAL DETERMINATION

In thin section, chlorite is seen either as fine-grained mats in the rock groundmass (fig. 1) or as larger discordant or concordant porphyroblasts that may average 1 mm in diameter. The first is typical of the lowest and intermediate grades of metamorphism found in the Quadrilátero Ferrífero; the second, of the intermediate and highest grades.

The median index of refraction was determined for many chlorite samples in different geologic environments and was used to divide the samples into low-, medium-, and high-iron (tables 3 and 4). Indices below 1.61, including such types as diabantite, pycnochlorite, and penninite, are here called low iron (high magnesia); between 1.61 and 1.63, including diabantite, brunsvigite, and ripidolite, medium iron; and indices above 1.63, ripidolite and brunsvigite, high iron (low magnesia) (from Hey, 1954).

In a general way, depth of pleochroism, in shades of yellow-green to colorless, increases with increasing index of refraction.

TABLE 3.—*Chlorite in low-metamorphic-grade environments*

[Last two columns after Hey (1954); abbreviations explained in table 2]

Assemblage	Rock	n_m	2V, sign	$\frac{Fe\ total}{Fe+Mg}$ in percent	Name
		Low Fe, $n_m < 1.61$			
Do QzCl(mu)(mg)(hm)	Dolomite	1.570–1.600	0 to +10°	5–25	Penninite or pycnochlorite.
Ca QzCl(mg)(hm)	Carbonate-quartzite	1.58	+3°	15	Penninite.
MuQzCl(tm)(hm)(mg)(il)(py)	Phyllite or schist	1.585–1.605	+0 to 10°	15–30	Penninite or pycnochlorite.
MuQzClAb(ep)(hm)(ap)	Phyllite or greenschist	1.570–1.601	+15° to 20°	5–40	Penninite or diabantite.
ClQzEp(mg)(mu)	Greenschist	1.603	+0°	30	Diabantite.
QzHm(cl)	Fe-quartzite	1.575	–low	10	Penninite.
Mn-minerals(cl)	Mn-ore	1.58	+low	10	Mn-clinochlore.[1]
		Intermediate Fe, n_m 1.61–1.63			
MuQzCl(cd)(mg)(tm)	Phyllite or greenschist	1.615–1.626	–20°	50–55	Diabantite or brunsvigite.
MuQzClAb Ep (ca)(sp)(tr)	Greenschist or phyllite	1.622–1.628	+10 to 28°	50	Ripidolite.
MuQzClEp(mg)(hm)(sp)	do	1.618–1.625	–10° to +10°	40–50	Brunsvigite or ripidolite.
QzHm(cl)(mu)(mg)(ca)	Fe-quartzite	1.615	+10°	40	Ripidolite.
		High Fe, $n_m > 1.63$			
MuQzCl(cd)(tm)(ap)(mg)	Phyllite or greenschist	1.630–1.633	±low	55–60	Ripidolite.
MuQzClAb(ep)(mg)(ca)	Subgraywacke	1.649	–low	70	Do.

[1] Probably similar to that described by Hutton (in Winchell and Winchell, 1951, p. 384) which had $n^{\alpha}=1.588$ and MnO=0.14 percent.

TABLE 4.—*Chlorite in higher metamorphic grade environments*

[Last two columns after Hey (1954); abbreviations explained in table 2]

Assemblage	Rock	n_m	2V, sign	Fe total / Fe+Mg in percent	Name
		Low Fe, $n_m < 1.61$			
BiMuQzCl(ol)(ep)(mg)(tm)(sp)	Schist	1.595–1.608	—10°	45	Diabantite.
Do QzMg Cu[1] (ep)(cl)(mu)	Dolomitic-itabirite	1.592	? low	25	Do.
Do Qz Bi[2] (mg)(cl)[2]	Dolomite	1.595	—low	30	Do.
HbAd Qz(bi)(cl)(ep)(sp)	Amphibolite	1.608	?	40	Do.
		Intermediate Fe, n_m 1.61–1.63			
BiMuQbCl(ep)(ap)(sp)(tm)(mg)	Schist	1.610–1.62	—10°	45–50	Diabantite.
BiQzOl Cl[3] (mu)(sp)(op)	do	1.611–1.620	±low	30–45	Ripidolite.
QzOl Cl (mu)(bi)[4] (ca)(mg)	Graywacke	1.617	—low	45	Diabantite.
MuQzOl Kf(cl)(sp)	Quartzite	1.623	?	50	Ripidolite.
QzBiCl[5] Ep Mg (hm)	Greenschist	1.613	?	40	Pycnochlorite.
HBOl/Ad QzBi(cl)(sp)(ep)(op)	Greenschist or amphibolite.	1.620–1.623	—low	45–50	Pycnochlorite or brunsvigite.
		High Fe, $n_m > 1.63$			
BiMuQzCl(mg)	Schist-conglomerate	1.638	?	65	Ripidolite.
MuQzOl Cl(op)	do	1.620–1.630	—low	50	Brunsvigite.
BiMuQzAb(kf)(cl)(ca)(ep)(op)	Greenstone	1.633	0°	60	Ripidolite.
HbOl QzBi(cl)(ep)(mg)	Greenschist or amphibolite.	1.630	—low	55	Brunsvigite.

[1] Partially replaced by ep+cl.
[2] Developed against mg crystals.
[3] Partially replaced by bi.
[4] Partially replaced by cl.
[5] Partially replaced by bi+mg.

CHEMICAL ANALYSES

Chemical analyses were obtained on two samples (table 5), the first of which is from the biotite zone, although it does not have any biotite, and the second, from the chlorite zone. Because of the fine grain size of the chlorite and abundance of intermixed material, separation of pure samples was difficult. The high amount of CaO in both samples suggests either the presence of associated silicates or interlayering with clay minerals (Foster, 1962, p. 2).

Although neither sample was completely pure, certain conclusions can be drawn from the analyses. JG–28–55, from within the biotite isograd, has a lower Fe total/Fe+Mg ratio and a high $Al^{4c}/SiAl^{4c}$ (4c=4 coordination) ratio than J–548 which is within the chlorite isograd. This agrees with observations elsewhere that chlorite stable under conditions of higher metamorphism is generally a Mg- and Al-rich variety. Ramberg (1952, p. 59) postulated the change muscovite + Al-poor chlorite→biotite+Al-rich chlorite +quartz+water with the onset of conditions of the biotite zone. Fawcett and Yoder (1966, p. 378) found that the assemblage chlorite+quartz was stable to about 600° 5kb PH_2O, if the chlorite contained about 23 percent Al_2O_3; Turnock (1960) found that at 2,000 bars pressure synthetic Fe-chlorite broke down at about 100°–150° lower than did Mg-rich chlorite.

TABLE 5.—*Chemical analyses (in weight percent) of chlorite*
[Analyst: Aida Espinola, DNPM, Rio de Janeiro, 1961]

	[1] JG–28–55	[2] J–548
SiO_2	27	32.2
Al_2O_3	22.5	18.7
Fe_2O_3	2.0	14.7
FeO	16.8	12.6
MgO	17.8	10.6
CaO	1.1	.90
H_2O-	.2	.22
H_2O+	12.5	10.46
Sum	99.9	100.4
Median index	1.607	1.615
2V+	±10°	±15°
Color	Pale olive gray	Dark-greenish gray

[1] 11 percent by weight of quartz deducted from original analysis.
Structural formula: $\left[\frac{(Al_{1.49}Fe^{3+}_{0.15}Fe^{2+}_{1.44}Mg_{2.72})}{5.80}\right]\left[\frac{(Si_{2.77}Al_{1.23})O_{9.59}OH_{8.41}}{4.00}\right]$
$Fe^{2+}/R^{2+}=0.35$, Fe (total)/Fe+Mg=0.37
Rock: Nova Lima Group chloritic phyllite; chlorite 80 percent, quartz 15 percent, sphene, leucoxene, sericite.
Location: Rio Acima quadrangle, N.O, E. 800.
Name: ripidolite
[2] Structural formula: $\left[\frac{(Al_{1.41}Fe^{3+}_{1.10}Fe^{2+}_{1.05}Mg_{1.57})}{5.13}\right]\left[\frac{(Si_{3.21}Al_{0.79})O_{11.05}(OH)_{6.95}}{4.00}\right]$
$Fe^{2+}/R^{2+}=0.40$, Fe (total)/Fe+Mg=0.58
Rock: Piracicaba Group, banded ferruginous quartzite-chlorite phyllite; chlorite-phyllite bands have chlorite 50 percent, sericite 30 percent, specularite, quartz.
Location: Dom Bosco quadrangle, N. 4700, E. 1150.
Name: delessite.

ASSEMBLAGES

Chlorite of low metamorphic grade (table 3) was found typically in phyllites, greenstones, quartzites and ferruginous quartzites, dolomite, and fine-grained schists. The most common mineral assemblage throughout most of the phyllitic and quartzitic rocks of the Quadrilátero Ferrífero includes chlorite with sericite and quartz, with or without plagioclase (An_{0-5}) or chloritoid (fig. 18). Hematite is the most common opaque mineral; others are ilmenite, pyrite, magnetite, and limonite. Tourmaline, epidote, sphene, and carbonate are common accessory minerals.

In dolomitic rocks of the Gandarela Formation east and west of São Julião, chlorite is associated with dolomite and quartz; accessory minerals are magnetite, white mica, hematite or limonite, and rarely, rutile. In some carbonate-facies iron-formation in the Nova Lima quadrangle, deep-green chlorite occurs together with quartz, sideritic carbonate, magnetite, and accessory minerals (Gair, 1962, p. 17). A high median index of refraction of about 1.66 shows that the chlorite is iron rich. In ferruginous quartzites, chlorite, hematite, and quartz are accessory minerals; and in greenstones, accessory minerals are epidote, quartz, sericite, and magnetite.

In greenschist, the assemblages are either chlorite tremolite-actinolite-apatite, or epidote (abundant)-white mica-quartz-magnetite-albite-carbonate-sphene.

Chlorite occurs in schists, dolomites, and greenstones in higher grades of metamorphism (table 4), especially in the biotite zone, but also in the garnet zone. In pre-Minas felsic metavolcanic rocks, chlorite appears to have replaced former mafic phenocrysts (fig. 7).

In schistose rocks of moderate grade, as in the Sabará Formation of the Ibirité and Nova Lima quadrangles, chlorite is associated with quartz, biotite, muscovite, and epidote, with or without sodic oligoclase (about An_{15-20}), apatite, and opaque minerals (fig. 14). Microcline where present is abundant. In dolomitic rocks of the Dom Bosco quadrangle, chlorite is associated with quartz, dolomite, magnetite, with or without oligoclase (An_{20}), tremolite, biotite, and muscovite. In greenstone-amphibolite just south of the Bação complex, chlorite is a retrograde metamorphic product derived from hornblende; other associated minerals are sodic andesine (about An_{25-45}), biotite, epidote and sphene.

Chlorite is found in metadiabase throughout the area. In the Ibirité and Capanema quadrangles, where metadiabase porphyry occurs, chlorite is abundant in the groundmass; other minerals are albite (An_0), carbonate, muscovite, biotite, quartz, potassium-feldspar, and minor amounts of epidote, opaque minerals, and leucoxene.

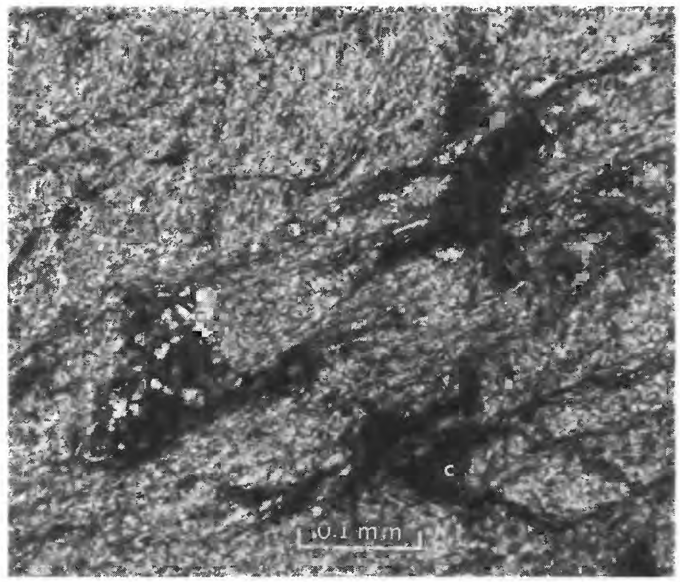


FIGURE 7.—Photomicrograph, sericite phyllite, a possible felsic metavolcanic rock, Nova Lima Group, JG-9-56, Rio Acima quadrangle, crossed nicols. Rock is crinkled and schistose. Sericite flakes (s) recrystallized at a high angle to the strong fracture cleavage, and comprise about 90 percent of rock. Chlorite (c) porphyroblasts may represent former mafic phenocrysts. Small irregular grains of quartz (q) in pockets may represent former amygdules; quartz veinlets (none in slide) are also present in the rock.

A chlorite, presumably high in magnesia, is found in staurolite-garnet schist in the most highly metamorphosed part of the Sabará Formation in the northwestern part of the Quadrilátero Ferrífero. Quartz and muscovite are essential constituents; other minerals include Ca-oligoclase, tourmaline, and iron oxides. The chlorite is fine to medium grained and has persisted as a metastable form through progressive metamorphism. In other samples, it may have developed by retrogressive metamorphism of biotite (fig. 2). A metamorphic assemblage of the apparent high grade south and west of the Bação complex includes chlorite and kyanite together with muscovite, quartz, and magnetite; accessory minerals are garnet and tourmaline.

CHROMIAN CHLORITE

Some chlorite, especially that associated with gold deposits, is unusually high in Cr. In six samples of chlorite from chloritic schist of the Raposos mine, Nova Lima quadrangle, Cr ranges from 0.072 to 0.580 percent; in seven samples from the Morro Velho mine, Nova Lima quadrangle, Cr ranges from 0.022 to 0.31

percent (Tolbert, 1962). One impure sample, from a chloritic schist in the Raposos mine, has a $FeO+Fe_2O_3/FeO+Fe_2O_3+MgO$ ratio of 0.29, and its Al_2O_3 content of 10.9 percent is relatively low. These occurrences are associated with chromian muscovites and are described in greater detail below.

CHLORITE AND BIOTITE

Chlorite commonly is a retrograde phase of both biotite (fig. 8) and hornblende. The relationship between refractive indices of biotite and its associated chlorite is linear, of even slope, and has the indices of the biotite about 0.02 higher than the corresponding indices of chlorite (fig. 9). Thus Mg/Fe ratios of the two minerals vary uniformly and compositional tie-lines would not cross, which suggests formation under approximate equilibrium conditions.

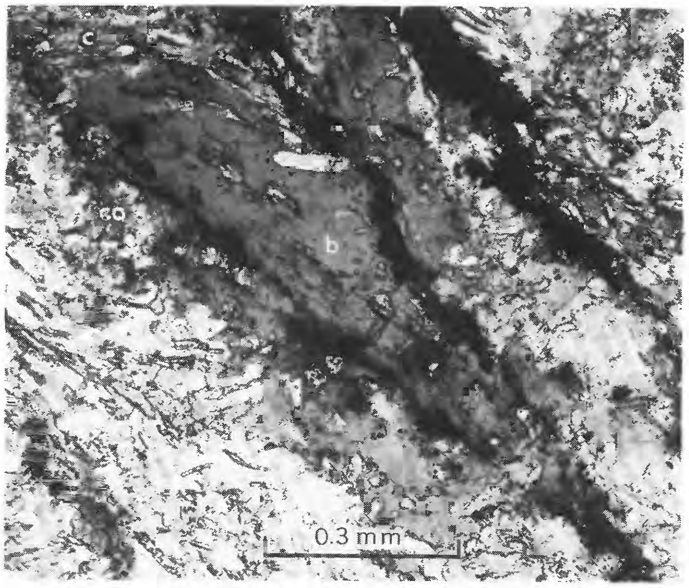


FIGURE 8.—Photomicrograph, chlorite schist, pre-Minas rocks, Z–229A, Rio de Pedras quadrangle, plane light. Shear planes are filled with fine opaque matter and are alined more or less parallel to compositional layering. Quartz and oligoclase are essential minerals; sericite, sulfide, and magnetite are accessories. Large biotite (b) lies across layering, and is cut by shear planes; coarse chlorite (c) is in the "shadow." Large oligoclase grains have irregular quartz inclusions and occur in places, with chlorite, on carbonate (ca).

In many rocks, the partial pressure of oxygen, whose fugacity was buffered by the FeO/Fe_2O_3 ratio, apparently determined whether chlorite or biotite would crystallize. In rocks containing hematite alone, chlorite crystallized readily (fig. 10), whereas, in rocks which have a lower oxygen fugacity and which contain magnetite as well as hematite, biotite also appears to have

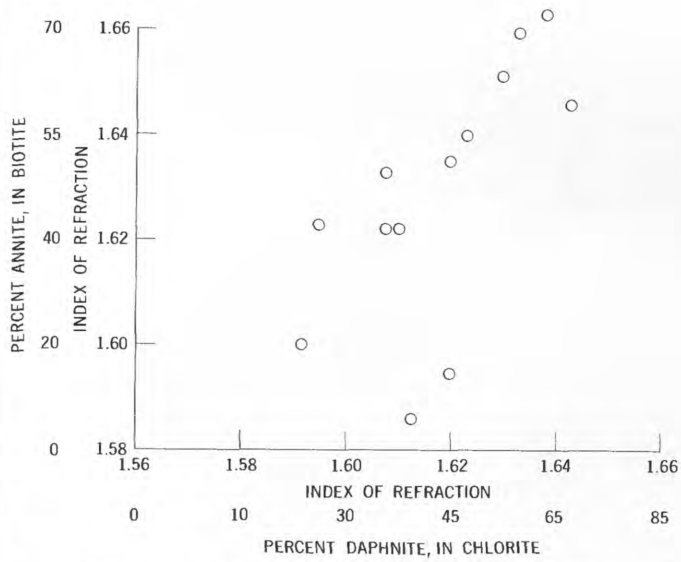


FIGURE 9.—Relations between index of refraction and composition of associated biotite and chlorite. Biotite data (annite) from Eugster and Wones (1958); chlorite data (daphnite) from Winchell and Winchell (1951).

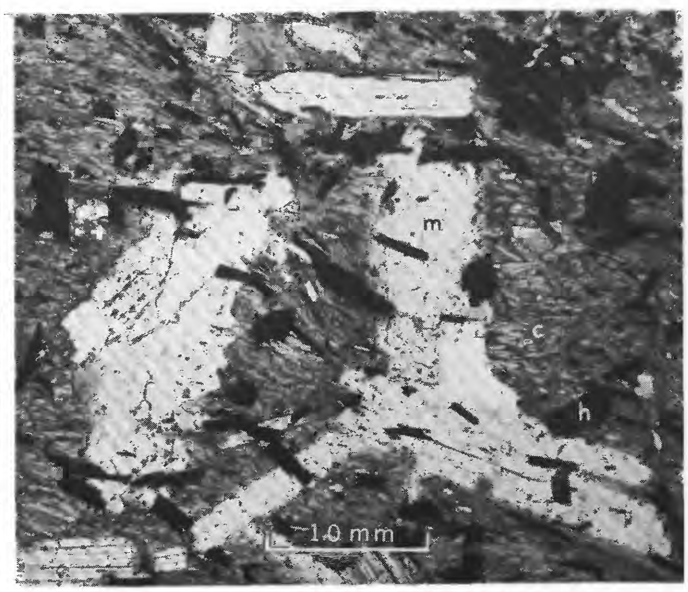


FIGURE 10.—Photomicrograph, greenschist, Itabira Group, near contact with Cercadinho Formation, J–548, Dom Bosco quadrangle, plane light. Bands contain chlorite (c), oriented specular hematite (opaque, h), and crosscutting unoriented coarse muscovite flakes (m). Pleochroic pale-green oriented flakes of chlorite (c) comprise about 50 percent of the rock and form mattes. Specular hematite (about 20 percent) and muscovite (about 30 percent) comprise the remainder of the chlorite-rich bands. Corner of interbedded quartz-magnetite-carbonate bands appear in upper right.

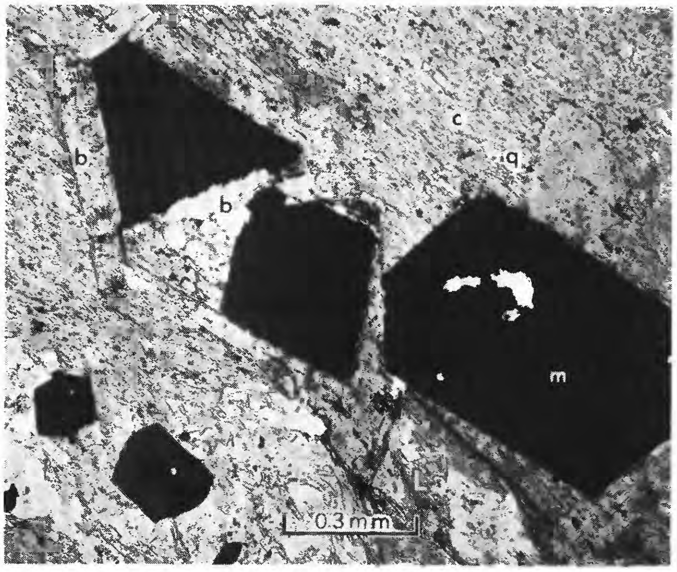


FIGURE 11.—Photomicrograph, greenschist (metavolcanic), Itabira Group, J–543b, Dom Bosco quadrangle, plane light. Fine-grained chlorite (c) comprises 70 percent of the rock; quartz (q) in irregular streaks, lentils, and grains, about 25 percent. Magnetite octahedra (opaque, m) form about 5 percent. Biotite (b) blades were formed by reaction of magnetite and chlorite. Small grains of epidote (not in photograph) are accessory. Some quartz-chlorite lenses (L) appear to be flattened amygdules.

been stable under otherwise similar physical conditions of metamorphism (fig. 2). In places, biotite appears to have formed by contact reaction between chlorite and magnetite (fig. 11).

These observations agree in part with the experimental work of Eugster and Wones (1962) on the stability field of the Fe-rich biotite, annite. They found that at about 430°C and higher oxygen fugacities than determined by the magnetite-hematite buffer, annite was unstable. At lower oxygen fugacities, using buffers that included magnetite but not hematite, annite-quartz-magnetite is a stable association. At higher oxygen fugacities, hematite is stable but annite and magnetite break down.

WEATHERING

Chlorite-rich phyllites and schists are especially susceptible to weathering and occupy topographic lowlands in most places. Chlorite generally alters to a compact clay mineral of indeterminate composition.

WHITE MICAS

"White" micas described in this report are muscovite and sericite, $KAl_3Si_3O_{10}(OH)_2$, the chromian mica, fuchsite, and possibly the aluminum mica pyrophyllite.

White micas are common in almost every type of rock, except iron-formation, and in every metamorphic environment. In low-grade metamorphic rocks, the white mica is generally fine grained, forms mats, and may be associated with chlorite. In high-grade metamorphic rocks, discrete larger flakes occur amidst the fine-grained sericite.

White micas are thus stable from the lowest metamorphic grade to the amphibolite facies, that is, through a range of about 650°C (Ramberg, 1952). Yoder (1959) has shown that at a water vapor pressure of 2,000 bars, corresponding to a depth of about 8 km, paragonite is stable to about 650°C and muscovite, to about 700°C. Between 250°C and 350°C at about 1,000 bars P_{H_2O}, the muscovite polymorphs change from a one-layer monoclinic form (1M) to a two-layer monoclinic (2M) form (Yoder and Eugster, 1955, p. 246).

These relationships were determined in silica-deficient environments, however, and should be considered only qualitative. In quartz-bearing assemblages such as are typical of the Quadrilátero Ferrífero, muscovite should break down at lower temperatures than indicated by Yoder and Eugster to potassium-feldspar + Al_2SiO_5 + H_2O (Turner and Verhoogen, 1960, p. 520).

OPTICAL DETERMINATION

The intermediate indices of refraction of many muscovite micas were determined to see if they varied either with type of rock or grade of metamorphism. According to Winchell and Winchell (1951, p. 368), lower indices are to be expected in aluminum or magnesium-rich varieties and higher indices in ferric-rich varieties. The optical properties, however, were not found to vary systematically in the Quadrilátero Ferrífero, so that muscovite of any given mineral association had variable optical properties from one sample to another.

Of 40 determinations of the intermediate index of refraction of white micas, 11 (or 28 percent) fall between 1.586 and 1.591 and 16 (or 41 percent) fall between 1.598 and 1.605. These indices are within the limits of 1.582–1.610 for B of "normal muscovites" (Deer and others, 1962b, p. 21). Rocks of all types and grades of metamorphism are represented within both the lower and higher groupings.

Fuchsite and other chromian micas were easily distinguished from muscovite in thin section. The indices of refraction are similar, but fuchsite shows pleochroism, generally from colorless to yellowish-green, whereas muscovite has no color.

Pyrophyllite is associated with kyanite in veins, phyllites, and quartz-rich rocks of the Quadrilátero Ferrífero. (See section on "Kyanite.") The 2V's of seven pyrophyllite samples determined on a 4-axis universal stage varied from 52° to 63° and averaged about 58° (Herz and Dutra, 1964). These 2V's are higher than those in muscovite, which are all below 45°.

THE PROBLEM OF PARAGONITE

The appearance of paragonite in metamorphic rocks of the chlorite through kyanite zones probably depends on the bulk composition, especially the $Al_2O_3K_2O/Na_2O$ ratio. Presumably Al_2O_3 should exceed the amount needed to make feldspar, but Na_2O should also be abundant. The pelitic rocks of the Quadrilátero Ferrífero have an unusually high proportion of both Al_2O_3 and K_2O and a low proportion of Na_2O (Herz, 1962); therefore very little, if any, paragonite was formed. Average ratios in the Quadrilátero Ferrífero are $Al_2O_3/Na_2O=8.42$ and $SiO_2/K_2O=12.7$ compared with 9.6 and 16.9, respectively, for worldwide low-grade pelitic rocks (Shaw, 1956, p. 928). The Al_2O_3/K_2O ratio, however, was ideal for the formation of abundant muscovite, and sodium must have gone into both paragonite, held in solid solution with muscovite, and albite, rather than into paragonite as a separate phase.

Because paragonite has been so widely reported in metamorphic rocks (Zen and Albee, 1964, p. 907), a search for this mineral was made by X-ray diffractometer. Mineral assemblages in 12 specimens were determined in the 2θ region from 7° to about 60° (Cu K radiation, Ni filter) (table 6 and fig. 12). In this range, paragonite should yield strong basal reflections at 2θ of about 9.2°, 18.4°, 27.7°, and 47.3° (Zen and others, 1964).

The strong reflections of muscovite in the X-ray diffractograms show that it is well crystallized and that paragonite did not form as a separate phase. In both samples, plagioclase is present, proving that sufficient Na_2O was present to form a distinct mineral phase. Some Na_2O probably did enter muscovite as paragonite in solid-solution, which accounts for the displacement of the muscovite line at about 27° 2Θ from one run to the other.

TABLE 6.—*Muscovite assemblages determined by X-ray diffractometer*

[Abbreviations explained in table 2]

Assemblage	Grain size Muscovite	Rock type	Specimen No. and location
Qz-mu	f	Se qzt-congl	J-533, Dom Bosco quad, N. 2800, E. 900.
Qz-mu-cl-pl-cd-mu	f	Se schist	J-169, Dom Bosco quad, S. 2100, E. 2950.
Qz-mu-An_{18}-cl	f	Se qzt	J-682b, Dom Bosco quad, N. 3250, W. 3000.
Qz-mu-gt	f, c	Qz-se schist	J-625, Dom Bosco quad, N. 4730, W. 3270.
Qz-mu-cl-hm-ky	c	Schist	RRP-235, Rio Piracicaba quad, S. 6350, E. 4250.
Qz-mu-cl-bi-st-(il?)	f	do	54P80, Ibirité quad, N. 9300, W. 5480.
Qz-mu-cl-tm	f	Se qzt	51G173, Jeceaba quad, N. 5800, E. 1750.
Qz-mu-cl-An_8-ca	f	Qz-cb rock	148A54, Nova Lima quad, Morro Velho mine.
Qz-mu-ky-cl	f, c	Ky phyllite	R-56-57, Lagôa Grande quad, S. 4050, E. 1080.
Qz-mu-cl-sp-py	f, c	Qz phyllite	R-84-52, Itabirito quad, N. 4300, E. 2900.
Qz-mu-cl-An_5-hm-ap-tm	f	Qz-se schist	J-211, Dom Bosco quad, S. 2150, W. 5600.
Qz-mu-ky-pp	c	Qz-ky vein	K-7, Lagôa Grande quad, N. 6570, W. 10.

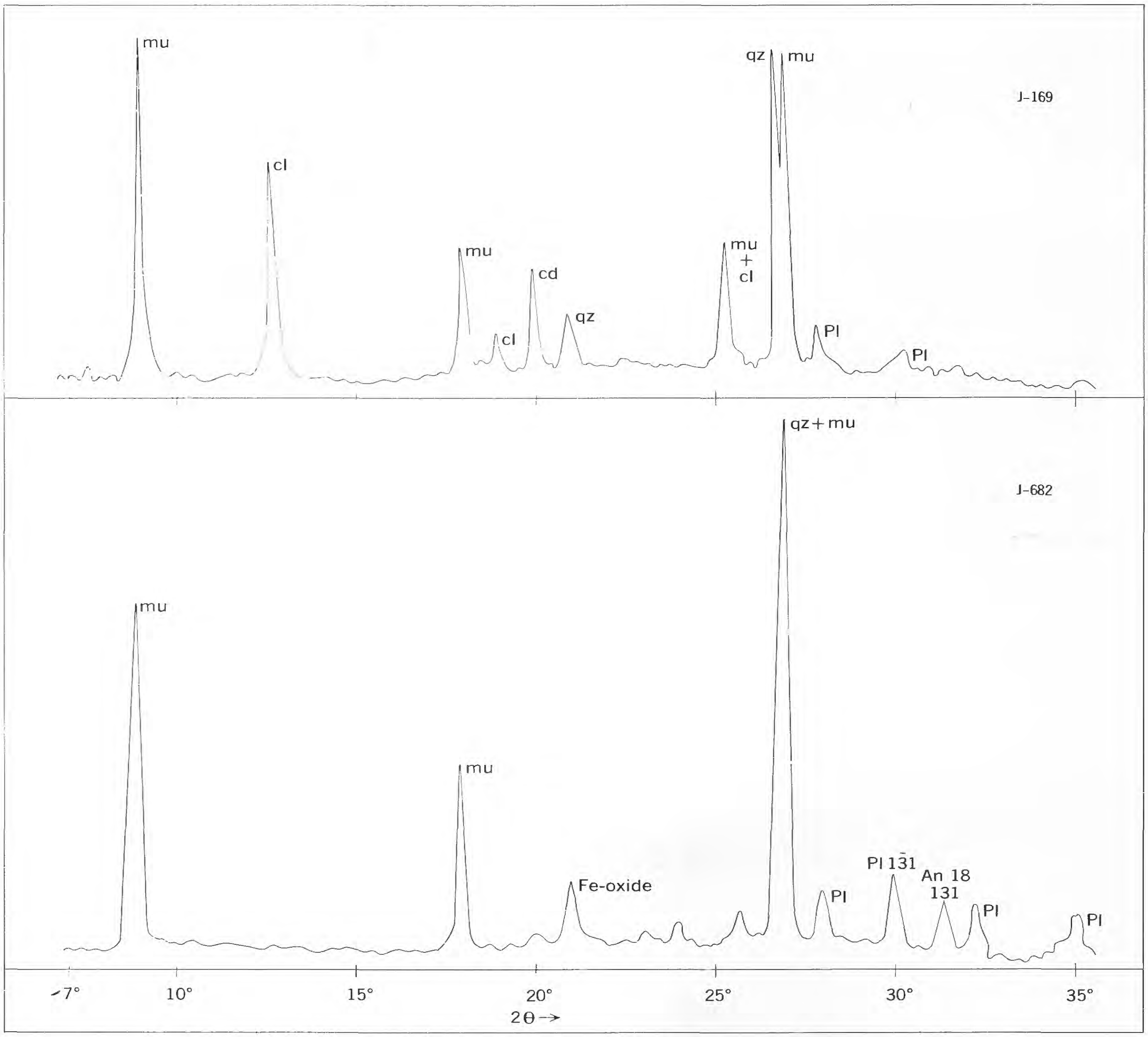


FIGURE 12.—X-ray diffractograms of two muscovite assemblages. Cu Kα radiation, Ni filter, 1° 2θ per minute.

MUSCOVITE ASSEMBLAGES

Throughout the area, fine-grained muscovite (sericite), quartz, and chlorite make up the bulk of the phyllites and low-grade schists. In many low- and medium-grade rocks, muscovite with both a fine and medium grain size is found (fig. 13). In the rocks of highest metamorphic grade, most of the sericite has disappeared and coarse muscovite predominates (fig. 31).

Chloritoid, kyanite, and hematite or magnetite or both are associated with quartz-chlorite-muscovite in some of the low-grade pelitic rocks. Graphite is a common accessory, and epidote, sphene, and tourmaline are rare accessory minerals. In low-grade carbonate rocks, typified by the dolomitic rocks of the

Gandarela Formation in the Dom Bosco quadrangle (Johnson, 1962, p. 14), muscovite is associated with phlogopite and magnetite, and in places with epidote.

At the biotite isograd, sericite combined with available chlorite to form biotite (fig. 3). Most of the fine-grained white mica, however, only recrystallized to coarser grain sizes (fig. 14). Some coarse-grained muscovite near contacts with granitic rocks may be partly the result of metasomatism by potassium-rich solutions.

Assemblages of muscovite-chlorite-quartz have in part given rise to veins of andalusite-muscovite-quartz and corundum-muscovite-feldspar at a granite contact north of Belo Horizonte and Sabará (Pomerene, 1964, p. 36). Because the material is badly weathered, it is difficult to tell exactly what mineral reactions took place, the nature of the feldspar, and whether other minerals also formed. The metamorphic grade here is best described as the lowest level of the pyroxene-hornfels facies (Turner and Verhoogen, 1960, p. 521).

North of Sabará in the Nova Lima quadrangle (Gair, 1962) sericite has broken down to form potassium-feldspar and biotite (fig. 15). In that area and elsewhere, however, some coarse-grained muscovite persists at the highest metamorphic grades reached

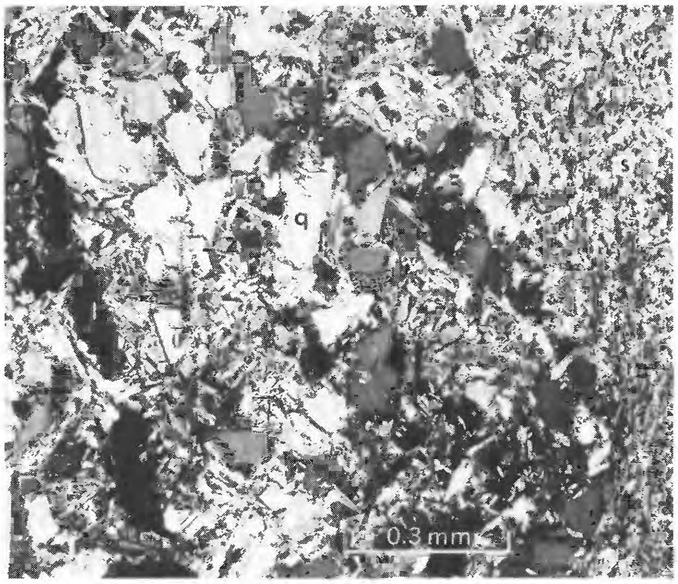


FIGURE 13.—Photomicrograph, sericitic quartzite, Piracicaba Group, near contact with porphyritic gneiss, J–682b, Dom Bosco quadrangle, crossed nicols. Rock is composed almost entirely of quartz (q) and sericite-muscovite(s), and has minor amounts of limonite (opaque, l). Coarser-grained muscovite has two preferred orientations. Limonite may have replaced biotite or chloritoid.

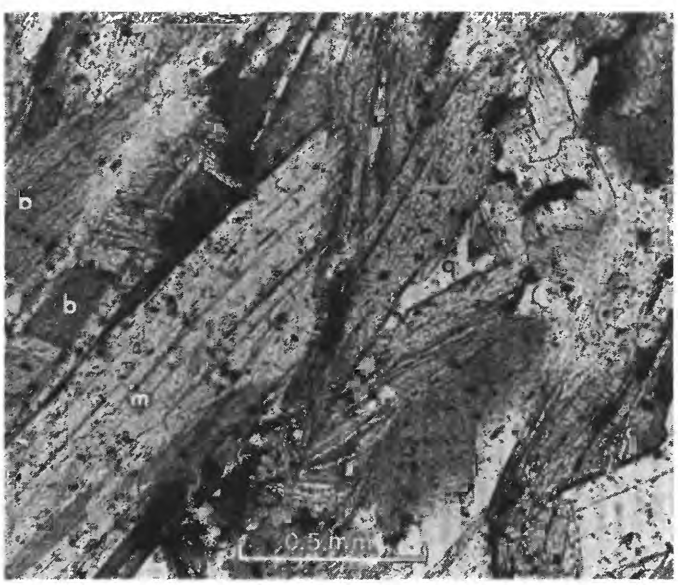


FIGURE 14.—Photomicrograph, pre-Minas schist, near granite contact, Z–82, Rio de Pedras quadrangle, plane light. Rock is well foliated and contains very coarse-grained micas, chlorite, and quartz. Muscovite (m) encloses quartz grains (q) and may replace other minerals. Chlorite (c) is partly replaced by biotite (b). Opaque mineral is magnetite (?).

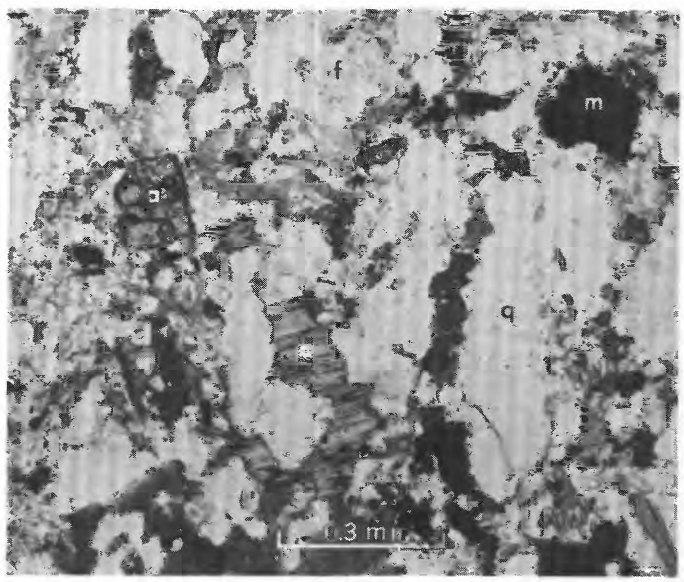


FIGURE 15.—Photomicrograph, subgraywacke, Sabará Formation, JG–81a–56, Nova Lima quadrangle, plane light. Green-pleochroic biotite (b) first appears here on approach to granite contact. Detrital quartz (q) and feldspar (f) occur in a matrix of finer-grained quartz-chlorite-sericite. Porphyroblasts of biotite form in the matrix and contain quartz inclusions. Allanite (a), epidote (e), and magnetite (m) are important accessories.

in the Quadrilátero Ferrífero, which suggests that conditions of the amphibolite facies were nowhere exceeded (Ramberg, 1952, p. 151). The coarse-grained muscovite typically is associated with quartz and: (1) kyanite, with accessory chlorite and garnet; (2) chlorite, calcic oligoclase, and accessory carbonate, magnetite, biotite, and sphene; (3) biotite with or without magnetite or garnet and tremolite.

FUCHSITE

Fuchsite and Cr-rich muscovites have been found in the basal part of the Moeda quartzite near granite contacts, in the Rio das Velhas and Minas Series near fault zones, and in some other quartzitic rocks (Herz, in Dorr and others, 1959/1961, p. 104). Near many of these occurrences, native gold-bearing sulfides of probable metasomatic origin have also been found. The association of fuchsite with these ore minerals strongly suggests that chrome-bearing solutions of metasomatic origin gave rise to the fuchsite. Fuchsite-bearing rocks are most common in the Nova Lima quadrangle and vicinity.

Tolbert (1964, p. 785) studied samples from the hanging wall in the Raposos mine, Nova Lima quadrangle, and found that chromian sericite averages slightly less than 0.5 percent chromium and that chlorite averages 0.3 percent chromium. The indices of refraction of a chromian sericite containing 0.84 percent chromium are: $\alpha=1.565$, $\beta=1.598$, $\gamma=1.600$, and $2V=22°-28°$.

Gair (1962) found that fuchsite was abundant in a wide variety of rocks in the Rio das Velhas Series. The fuchsite is less than 0.1 mm in size in all these rocks and ranges from amounts greater than 15 percent in quartz-sericite schist and phyllite and in carbonate-rich schist to less than 5 percent in metavolcanic schist (table 7).

PYROPHYLLITE

Pyrophyllite, associated with kyanite in veins and in phyllitic and quartzitic country rock, formed by the retrogressive metamorphism of kyanite is discussed further in the section on "Kyanite."

WEATHERING

Rocks rich in muscovite and sericite generally are very susceptible to weathering and tend to form topographic lowlands. The weathering products of muscovite and sericite are clay minerals of indeterminate composition.

TABLE 7.—*Fuchsite assemblages in the Nova Lima Group, Nova Lima and Rio Acima quadrangles*

[After Gair, 1962; abbreviations explained in table 2]

Rock type	Assemblage	Fuchsite, in percent
Qz-se schist and phyllite.	Qz-mu-fu-cb-cl-bi-(ru) (il) (mg) (pl) (ep) (zr).	>15
Quartzites (iron-poor varieties of iron-formation).	Qz-fu-lm-mg-gr-(cl) (mu) (pl) (lc) (op).	>15
Graywacke	Qz-pl-cb-mu-cl-fu-am-ep-lm-(lc) (op) (zr) (ru).	5–15
Carbonate-rich schist.	Qz-ca-mu-cl-fu-bi-(ru) (lc) (op) (gr) (lm) (pl) (tm) (ep) (mg) ap?).	5–>15
Metavolcanic schist	Cl-ep-ah-pl-qz-mu-cb-bi-mg-lc-il-(op) (fu) (lm) (tm).	<5

BIOTITE

Biotite is commonly found in medium- to high-grade metamorphic rocks of appropriate chemical composition. These include pelitic schist, amphibolite, impure layered carbonate rock, greenstone, and carbonate iron-formation. In phyllite and low-grade itabirite, it is rare.

In many areas, as in the southwest part of the Rio Acima quadrangle (Gair, 1962, p. 52), the development of biotite in low-grade rocks is attributed to the thermal effects of nearby mafic intrusives. Where there has been no igneous activity, a spotty occurrence of biotite may indicate early and local development of the biotite regional isograd or incomplete retrograde metamorphism.

The appearance of biotite is taken to represent the middle range of the greenschist facies of regional metamorphism, that is, P_{H_2O}, ±5,000 bars, T±400°C (Turner and Verhoogen, 1960, p. 534) where sericite and chlorite react to form biotite. With an increase in the grade of metamorphism, biotite becomes more deeply pleochroic, acquires higher refractive indices, and presumably is richer in iron (Harker, 1939, p. 217).

According to Wones and Eugster (1959, p. 132), the magnesium-iron ratio of biotite is largely dependent on the oxidation potential during metamorphism. Under relatively reducing conditions, as shown by assemblages containing graphite and magnetite, iron-rich biotite will crystallize; with relatively oxidizing conditions, shown by assemblages containing magnetite and hematite, magnesium-rich biotite forms. Excess silica also reduces the stability field of iron-rich biotite. In the presence of quartz, biotite + quartz ↔potassium-feldspar + hypersthene + water (Ramberg, 1952, p. 152). Because of the normal abundance of water in metamorphic rocks, however, it is not until the granulite facies is reached, at temperatures above 550°C, that the equation tends to go to the right. In the Quadrilátero Ferrífero, biotite was preserved in the most highly metamorphosed rocks of the area because of the abundance of water.

OPTICAL DETERMINATION

The biotite gamma index of refraction was determined in 39 selected samples to determine if the index varies with rock type and grade of metamorphism (table 8). An approximate measure of the proportion of the phlogopite molecule ($KMg_3AlSi_3O_{10}(OH)_2$) was obtained using the curve of Eugster and Wones (1958, p. 194) for synthetic biotites. The biotites were divided as follows:

Name	Mg/Fe ratio	Percent annite	Gamma index of refraction
Low annite (phlogopite).	High	15–35	1.595–1.613
Intermediate annite.	Intermediate	40–55	1.615–1.640
High annite ----	Low	60–75	1.643–1.663

TABLE 8.—*Data on biotite and its assemblages*
[Abbreviations explained in table 2]

Assemblage	Rock	n_m	Pleochroism	Annite (percent)	Number of specimens, rock type, and locality
			Low annite		
Do-qz-mg-(bi) (tr) (mu) (cl).	Carbonate or cb iron fm.	1.60–1.604	Colorless to pale yellow; olive brown.	20–25	2, Gandarela Formation in Dom Bosco quad.
Cl-qz-mu-ep-bi-(mg) (tr) (tm) (sp).	Schist	1.595–1.611	Lt brown to lt olive brown; v pale orange to colorless.	15–35	2, Piracicaba Group in Dom Bosco quad; Nova Lima Group in Rio de Pedras quad.
Cl-qz-ep-bi-mg	Greenstone	1.613	Dk yellowish orange; v pale orange.	35	1, Gandarela Formation (?) in Dom Bosco quad.
			Intermediate annite		
Do-qz-mg-(bi) (cl) (ap)	Carbonate or cb iron fm.	1.621–1.623	Colorless to pale yellow; olive brown.	45	2, Fecho do Funil and Gandarela Formations in Dom Bosco quad.
Qz-cl-mu-bi-an_{8-28}-ep-(ap) (op) (mg).	Schist	1.622–1.635	Grayish olive to mod brown; pale greenish yellow to v pale orange.	45–50	6, Sabará Formation in Belo Horizonte and Nova Lima quads; Nova Lima Group in Nova Lima, Congonhas, and São Bartolomeu quads.
Qz-bi-ga-cr-(si) (op)	Gneiss	1.618	Dark yellowish orange; colorless.	45	1, roof pendant in Bação quad.
Qz-an_{28-35}-bi-st-mu (mg) (ga).	Schist, gneiss	1.616–1.640	Mod olive brown to mod brown; colorless to v pale orange.	45–55	5, Sabará Formation in Ibirité and Nova Lima quads; Nova Lima Series in Rio de Pedras and Bação quads; roof pendant in Cachoeira do Campo quad.
Qz-(cu *or* tr)-bi-ga (mu)	Greenstone	1.615–1.630	Mod brown to v pale orange; dk yellowish brown.	50	2, Nova Lima Group in Cachoeira do Campo quad.
Hb-an_{23-36}-qz-ep-(bi) (cl) (tr) (sp) (ap) (mg) (op).	Amphibolite, schist	1.633–1.640	Yellowish brown to mod brown; colorless to v pale orange.	50–60	4, Amphibolite dikes in Cachoeira do Campo, Marinho da Serra, and Congonhas do Campo quads.
			High annite		
Qz-mu-cl-bi-mg	Schist conglomerate	1.663	Mod brown; v pale Orange.	75	1, Nova Lima Group in Dom Bosco quad.
Qz-mu-bi-an_0-cl-(Kf) (ep) (ap).	Meta-hypabyssal intrusive.	1.660	Olive gray; grayish yellow.	70	2, Meta-hypabyssal intrusive in Ibirité and Capanema quads.
Hb-qz-(an_{14-25}) (ep) (bi) (cl) (tr) (mg) (ap).	Amphibolite	1.643–1.651	Mod brown to yellowish brown; colorless to v pale orange.	60–65	3, Amphibolite dikes in Lagôa Grande and Ouro Branco quads; Nova Lima Group in Cachoeira do Campo quad.

Two-thirds of the determinations fell in the intermediate range; the rest were almost equally divided between low and high annite.

Pleochroism in biotite appears to be dependent both on the degree of metamorphism and on the type of rock. By far the lightest shades found in any of the biotites are in carbonate rocks where pleochroism varies from colorless to pale yellow. The color, pleochroism, and low or intermediate indices suggest phlogopite with a magnesium-iron ratio of about 2:1 (Heinrich and others, 1953).

In low-grade rocks, biotite is interleaved with chlorite and has an olive-brown or grayish-olive to almost colorless pleochroism. At higher grades of metamorphism, pleochroism changes to a light or moderate brown to very pale orange. In amphibolites, biotite generally shows only dark shades of brown. Biotite having these dark shades also has the highest indices, both of which suggest high annite content.

ASSEMBLAGES

The high-magnesium biotites are found principally in carbonate rocks, dolomitic iron-formation (fig. 25), and pelitic rocks in much of the Quadrilátero Ferrífero (table 8, low annite). Biotite is porphyroblastic and developed at comparatively low temperatures of metamorphism at the expense of muscovite (sericite) and chlorite (fig. 15). With increasing metamorphism, biotite comprises foliae of the rock and is commonly interleaved with coarse-grained chlorite or muscovite. High-magnesium biotite also developed as a contact reaction between chlorite and magnetite in greenstone of the Gandarela Formation, Dom Bosco quadrangle (fig. 11).

Biotite having an intermediate iron-magnesium ratio occurs in pelitic rocks, amphibolite, and carbonate rock of both high and moderate metamorphic grade, at which it commonly developed largely at the expense of chlorite (figs. 16, 30, 31) (table 8, intermediate annite). In the rocks of higher metamorphic grade, biotite is one of the last minerals to develop and commonly is the coarsest grained of all. Biotite-rich layers often are also rich in magnetite, whereas nearby layers without magnetite are still chloritic. Apparently higher oxygen fugacities, buffered by hematite, inhibited the development of biotite, for biotite is common in quartz-magnetite-carbonate itabirite, as in the Passagem gold mine, and is absent in the more common quartz-hematite itabirite.

Biotite having a high iron-magnesium ratio occurs both in amphibolite in the eastern part of the Quadrilátero Ferrífero, as in the Monlevade quadrangle, and in greenstone and pelitic rock in the western part of the Quadrilátero Ferrífero (table 8, high annite). The assemblages in which such biotite occurs are identical to assemblages in which biotite having an intermediate iron-magnesium ratio occurs.

Coexisting biotite and chlorite appear to be related chemically. (See fig. 9.) In carbonate rock, chlorite apparently has broken down to form biotite at about the same time that calcite which crystallized in an excess of dolomite molecule changed in composition from dol_3 to dol_7 (table 36). This suggests a temperature between about 400°C and 550°C (Graf and Goldsmith, 1958, p. 232–233).

FIGURE 16.—Photomicrograph, pre-Minas chlorite schist, near granite contact, Z–100, Rio de Pedras quadrangle, plane light. Rock is composed largely of fine- and medium-grained chlorite (c) replaced by porphyroblasts of biotite. Biotite (b) is pleochroic brown and contains inclusions of quartz. Sericite interleaved with chlorite and quartz (q) form abundant elongate grains and pods. Opaques are magnetite and sulfides. Interlayers (not shown) are rich in clinozoisite, quartz, and a colorless amphibole.

RETROGRADE METAMORPHISM AND WEATHERING

Biotite has broken down readily during weathering and dynamic metamorphism to Fe-Mg chlorite, muscovite, and quartz (fig. 24). Near contacts with granitic rocks, as north of the Serra do Curral, hydrothermal solutions may have aided the breakdown of biotite to chlorite, epidote, sericite, and quartz. A penninite chlorite replaced deep-brown pleochroic biotite, typically found in amphibolites, and chlorite plus sericite replaced paler pleochroic biotite typical of schists.

In parts of the Sabará Formation in the Belo

Horizonte and Nova Lima quadrangles, many rocks of high metamorphic grade underwent such retrogressive metamorphism under lower conditions of the greenschist facies (Gair, 1962, p. 52). In addition to biotite breaking down largely to chlorite, staurolite was replaced by sericite and quartz, hornblende by biotite and chlorite, and other amphiboles by chlorite.

FELDSPAR

Plagioclase and potassium-feldspar are not nearly as common in the metamorphic rocks of the Quadrilátero Ferrífero as they are in other Precambrian areas. Albite, An_{0-7}, is considered diagnostic of the greenschist facies (Turner and Verhoogen, 1960, p. 533). In the almandine-amphibolite facies—somewhere in the garnet zone — the composition of plagioclase changes abruptly to oligoclase-andesine An_{15-35} (Turner and Verhoogen, 1960, p. 544). In the almandine-amphibolite facies, microcline may crystallize in rocks containing excess silica, alumina, and potassium. At the highest pressure/temperature conditions of the almandine-amphibolite facies, however, orthoclase crystallizes instead of microcline (Turner and Verhoogen, 1960, p. 549).

POTASSIUM FELDSPAR

Potassium-feldspar was identified optically. Plaid-twinned grains are called microcline; in assemblages of high metamorphic grade, grains that are not plaid-twinned are called orthoclase. Microcline is associated with albitic plagioclase and appears to have developed best in quartz-rich rocks near contacts with granitic bodies, for example, north of the Bação Complex. In such rocks, it tends to form large augen-shaped aggregates. In other quartzose-gneiss, microcline is associated with quartz and muscovite and albite or oligoclase; biotite, tourmaline, chlorite, iron oxides, epidote, and sphene may or may not be present. In rocks in which microcline is abundant, it is medium to coarse grained and hypidiomorphic; otherwise, it is fine grained and granular. In metamorphosed arkose and graywacke, microcline occurs as detrital grains, such as in the Sabará Formation near the southwestern corner of the Belo Horizonte quadrangle.

Orthoclase appears in relatively high-temperature assemblages near contacts between country rock and granite bodies and it increases in amount as muscovite diminishes. In the contact zones north of the Serra do Curral and the Bação Complex, orthoclase occurs in association with quartz, biotite, and oligoclase-andesine and, in places, also with garnet, epidote, magnetite, chlorite, and muscovite. Orthoclase occurs in amphibolite in association with hornblende, oligoclase, and chlorite, most notably in the southwestern part of the São Julião quadrangle.

PLAGIOCLASE

OPTICAL DETERMINATION

Plagioclase was determined largely by measurements of the indices of refraction of cleavage flakes (Tsuboi, in Winchell and Winchell, 1951, p. 280) and in thin sections by measuring the maximum extinction angle in albite twins in the zone normal to 010 (Winchell and Winchell, 1951) on a flat stage or with a 4-axis universal stage (Slemmons, 1962).

ASSEMBLAGES

Plagioclase of composition An_{0-35} occurs in phyllite, schist, and quartzitic rock throughout the area in association with quartz, chlorite, and muscovite. The most common accessory minerals in these assemblages are epidote and biotite; others are potassium-feldspar, carbonate, magnetite, hematite, apatite, sphene, and tourmaline. In many rocks containing plagioclase An_{15-35} and abundant biotite, either muscovite or chlorite may also be present. Rocks containing plagioclase An_{0-10} are common throughout the area and contain muscovite, quartz, albite, and epidote, and, in places, sphene, magnetite, zircon, potassium-feldspar and chlorite.

Quartz and albitic feldspar commonly form myrmekite, indicative of late magmatic or deuteric crystallization (Howell, 1957, p. 195) (fig. 43), but in places plagioclase is the last mineral to form and replaces both quartz and muscovite.

Plagioclase also occurs in rocks of higher metamorphic grade, such as amphibolite or biotite-staurolite schist. In such rocks it ranges from oligoclase to andesine. The grain size of plagioclase generally increases with increasing metamorphism.

In most metamorphic rocks, plagioclase rarely is twinned or else it is twinned in broad bands according to the albite law. Some plagioclase associated with amphibole, staurolite, and garnet, is twinned polysynthetically.

In amphibolite, plagioclase is universally associated with hornblende. Adjacent to the Bação Complex, assemblages include epidote; other associated minerals and corresponding plagioclase compositions are: biotite with An_{20-35}, quartz-biotite with An_{19-37}, quartz with An_{25-59}, and quartz-biotite-garnet with An_{25-30}. Common accessory minerals are carbonate, sphene, ilmenite, leucoxene, apatite, magnetite, allanite, and pyrite.

In schist and gneiss of high metamorphic grade, as in the Monlevade quadrangle (Reeves, 1966), plagioclase, An_{15-35}, is associated with staurolite, biotite, and locally also with garnet, muscovite (most common with more albitic plagioclase), and magnetite.

Roof pendants of schist or amphibolite in the Bação Complex (for example, Cachoeira do Campo quadrangle, S. 2,300, W. 3,700) contain biotite, tremolite or cummingtonite, and plagioclase, An_{52-64}, and, in places, also quartz, epidote, and garnet.

PLAGIOCLASE MAP

A map has been prepared to show distribution of anorthite variation in plagioclase (pl. 1). In most of the area, albite is the dominant plagioclase in metasedimentary rocks away from igneous contacts and even in rocks near granite contacts in the western part of the Serra da Moeda. Albite near granite contacts may be due, in large part, to alkali metasomatism activated by a steep thermal gradient. The occurrence of albite at a distance from granitic bodies suggests metamorphism in the greenschist facies.

Plagioclase more calcic than albite is closely related to relatively high-grade thermal metamorphism at many igneous contacts in the northern and eastern parts of the Quadrilátero Ferrífero and in the area of the Bação Complex. In the Bação Complex oligoclase and andesine also occur in roof pendants.

Oligoclase-andesine occurs in the area northeast of the Bação Complex, largely within the Vargem de Lima syncline, and especially in rocks of the Maquiné Group. This feldspar appears to be a direct product of a post-Minas isochemical metamorphism. Some assemblages include biotite and kyanite which, together with oligoclase-andesine, suggests that pressure and temperature conditions exceeded those of the greenschist facies. Oligoclase and andesine in rocks of the Nova Lima Group southwest of the town of Nova Lima may be a product of contact metamorphism adjacent to mafic and ultramafic intrusive rocks.

RETROGRADE METAMORPHISM AND WEATHERING

By retrograde metamorphism, calcic plagioclase becomes unstable and changes to clinozoisite, muscovite, and sodic plagioclase. This is well shown in the biotite gneisses and schists of the Morro da Pedra type near Belo Horizonte (Pomerene, 1964, p. 33).

Both plagioclase and potassium-feldspar weather to matted mixtures of muscovite and kaolinite(?) throughout the Quadrilátero Ferrífero. Potassium-feldspar, however, is relatively more resistant and survives where plagioclase has been completely altered.

QUARTZ

Quartz is one of the most common minerals in the metamorphic rocks of the Quadrilátero Ferrífero. It ranges from trace amounts in some carbonate rock and iron ore to more than 90 percent in quartzites. No special metamorphic significance is attached to its presence except that it indicates that reactions proceeded in an environment of excess SiO_2.

Quartz of detrital or chemical origin (as chert) formed part of the original sedimentary deposits of the region, and quartz amygdules or phenocrysts occur in metavolcanic rocks (fig. 7). Much clastic quartz underwent cataclastic deformation and recrystallization, as seen by undulatory extinction, mortar structure, and sutured boundaries, and chert was recrystallized. The higher the degree of metamorphism, the coarser the grain size (James, 1955, p. 1462). Original sedimentary textures have been partially or completely destroyed in most rocks, but are well preserved in some quartzite and carbonate rock.

Original grain boundaries, however, have been obliterated in quartzite that was engulfed by granite, such as in that intercalated with gneiss north of the Serra do Curral in the Belo Horizonte and Ibirité quadrangles (Pomerene, 1964, p. 28). Quartz in general has a mosaic texture and grains generally range from 0.01 to 0.1 mm, averaging about 0.03 mm (fig. 4). Quartz grains as large as 1 × 0.3 mm, however, are found in similar quartzite south of the contact of granite with the Piracicaba Group; the grains are characterized by subangular or sutured boundaries and undulatory extinction. Quartz veins are exceptionally numerous in the contact area.

The geologists of the DNPM–U.S. Geological Survey project agree that quartz interbeds in the Cauê Itabirite, and possibly also in some Rio das Velhas iron-formation, are of chemical origin (Guild, 1957, p. 46, figs. 5, 15–17). Fine-grained mosaic-textured quartz laminae range from 0.5 to 10 mm in thickness (fig. 17).

The grain size of quartz in itabirite is related approximately to the degree of metamorphism and increases generally to the east. In the northwestern part of the Quadrilátero Ferrífero, which is mainly in the chlorite zone, quartz ranges in grain size from 0.01

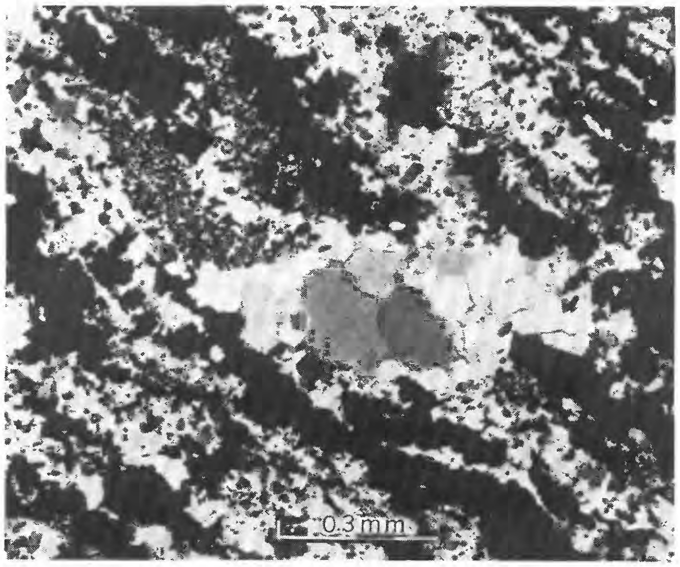


FIGURE 17.—Photomicrograph, itabirite, 54–P–42, Macacos quadrangle, crossed nicols. Layers rich in quartz and iron oxide alternate. Very fine grained inclusions of carbonate occur in some quartz.

to 0.086 mm (table 9). In the extreme northeast, in the biotite and higher zones, grains range from 0.04 to 0.4 mm and have angular boundaries in an equigranular granoblastic fabric (Dorr and Barbosa, 1963, p. 19). Northeast of the Itabira district, even higher metamorphism has resulted in a coarse-grained gneissic itabirite. In all these occurrences, quartz is coarser grained than either hematite or magnetite, which may be a reflection of its greater ease of recrystallization under metamorphic conditions.

TABLE 9.—*Grain size of quartz in itabirite*

General area of Quadrilátero Ferrífero	Quadrangle	Range in grain size	Average	Reference
NW	Fecho do Funil	0.01–.06	0.04	G. C. Simmons (1968a).
NW	Ibirité-Belo Horizonte.	.02–.086	.03–.04	Pomerene (1964).
SW	Congonhas district.	.01–.1	-------	Guild (1957).
North-central.	Nova Lima	.05–.15	-------	Gair (1962).
South-central.	Dom Bosco	.05–.40	.13	Johnson (1962).
NE	Itabira	.04–.4	-------	Dorr and Barbosa (1963).

CARBONATES

Carbonate minerals are widespread in the area. They comprise the bulk of some beds in the Gandarela (Dorr, 1958) and Fecho do Funil Formations (Simmons, 1958) and are also widely distributed in the Cauê Itabirite (Dorr, 1958) and the Nova Lima Group (Dorr and others, 1957). They are accessory minerals in arkose and graywacke of many formations, in schists and phyllites, and in metamorphosed mafic rocks.

No special metamorphic significance is attached to the carbonate minerals. They persist at all rock temperatures under moderate or high confining pressures that prevent the escape of CO_2. In coexisting calcite and dolomite, the amount of dolomite in solid solution in calcite is temperature dependent, increasing with increases in temperature. (See section on "Metamorphic Temperatures.")

The only obvious effect of progressive metamorphism in calcitic rocks of the Quadrilátero Ferrífero is an increase in grain size. Amphiboles formed in carbonate rocks of sufficient original clayey and siliceous material, presumably at low or moderate temperatures, and with $P_{CO_2} > P_{load}$ so that CO_2 could diffuse from the environment and allow reactions such as calcite + magnetite + quartz + water = actinolite + hematite + CO_2. In the development of most, if not all, amphibolites from "dirty" carbonate rocks, however, some carbonate persisted even at pressure/temperature conditions that permitted the development of pyroxene (table 17). Clay minerals generally reacted to form mica, but the carbonate minerals apparently did not entirely react with the silicates.

OPTICAL DETERMINATION

Calcite and dolomite were identified, where possible, on a flat stage in thin section using optical criteria (Deer and others, 1962c, p. 243). Ankerite is the assumed carbonate if grains are stained by iron hydroxides.

Gair (1962, table 3) determined by immersion methods the carbonate minerals in 61 samples from the Rio das Velhas Series of the Nova Lima and Rio Acima quadrangles. These samples were divided as follows:

1. Siderite, 24 samples, only in banded iron-formation.
2. Dolomite, variety magnesiodolomite, 18 samples, in the quartz-carbonate rock "lapa seca" (barren rock), with accessory sericite, chlorite, and feldspar; in sericitic or fuchsitic phyllite; in dolomite.
3. Ankerite, varieties ankerite-ferrodolomite, and ferrodolomite, 14 samples, largely in quartzose or banded iron-formation but some in lapa seca or other carbonate rock, with accessory chlorite and sericite.

4. Calcite and calcite magnesiodolomite, five samples, in graywacke, fuchsitic schist, and quartzose and banded iron-formations.

X-RAY DETERMINATION

Thirteen samples were selected for x-ray diffractometer study and were run initially at 1° 2θ per minute in the region of about 25° to 34° 2θ (table 10). Three of the samples had both calcite and dolomite and were rerun at 1/8° 2θ per minute in the region of about 28.8° to 31.5° 2θ to determine the precise peaks.

MINERALS AND ASSEMBLAGES

The types of rock that contain significant amounts of carbonate minerals are dolomite, dolomitic iron-formation, ferruginous quartzite, phyllite, and schist (table 10). Calcite or dolomite commonly are associated with quartz and in places also with hematite, magnetite, tremolite-actinolite, phlogopite-biotite, muscovite, chlorite, epidote, and graphite. Phlogopite-biotite is best developed in rocks of the Nova Lima, Itabira, and Piracicaba Groups that also have some magnetite (fig. 11).

Carbonates form minor secondary minerals in graywacke, schist, metavolcanic rock, gneiss, and amphibolite throughout the area. In such rocks they are commonly associated with quartz, plagioclase, hornblende, chlorite, biotite, muscovite, epidote, potassium-feldspar, garnet, and vesuvianite.

The retrograde metamorphism of ultramafic rock produced carbonate, talc, and serpentine, and in places also tremolite, magnetite, and pyrite. Soapstone in the Itabira district consists of as much as 25 percent magnesite or its weathering products (Dorr and Barbosa, 1963, p. 34). Most of the magnesite has been weathered away, leaving rhomb-shaped holes, 2 mm to 2 cm in diameter, that are lined by dark-brown iron hydroxide.

Under conditions of temperature higher than chlorite zone or low CO_2 pressure, tremolite (fig. 25) or cummingtonite developed in carbonate-bearing, magnetic, hematite-poor iron-formation, as in the São Julião quadrangle (Guild, 1957, p. 15). At the highest grade of metamorphism in the area, carbonate coexisted with diopside, actinolite, specularite, magnetite, and quartz in the Gandarela Formation, Dom Bosco quadrangle (Johnson, 1962, table 4).

TABLE 10.—*Mineral assemblages from carbonate-rich rocks, detetermined by X-ray diffractometer* (Cu Kα *radiation,* Ni *filter*)

[Abbreviations explained in table 2]

Carbonate mineral	Average grain size, mm	Assemblage	Rock type	Formation	Specimen No., quadrangle, location if known
Calcite	0.1–0.2	Ca-mg-tr; ph-qz-cl	Carbonate itabirite	Itabira Group	J–543–55, Dom Bosco, E 1150, N 4690.
Calcite + dolomite	.02–.1, max .3	Ca-do-ph; qz-ep-mg-cl	Carbonate-mica shist.	Gandarela Formation.	J–134–55, Dom Bosco, W 460, S 870.
Do	.02	Ca-do-mg-hm-qz; ka	Carbonate itabirite	do	Z–549, Gandarela, W 4870, N 6590.
Do	.05–.01	Ca-do-qz-bi; mg-ap	Quartz carbonate, ca as large as 0.3 mm in gash vein.	Fecho do Funil Formation.	J–390, Dom Bosco, E 6070, S 6830.
Dolomite	.1–.2, max. 4	Do-qz; cl	Carbonate-quartz vein. Cuts "lapa sêca"	Nova Lima Group	JG–107a–56, Nova Lima, Morro Velho mine.
Do	.03–.2	Do-at; qz-cl	Altered ultramafic Quartz carbonate	Intrudes Nova Lima Group.	54P64, SW corner Rio Acima.
Do	.x–x.	Do-qz-py-cl		Itabira Group	48G63, São Julião, quarry SE of Vigia, 5900 W, 6900 N.
Do	.01–.2	Do-qz- mu) (hm) (ep) (cl)	Dolomite	Gandarela and Fecho do Funil Formations.	JG–165–56, E 1020, S 5070 and A–6553, S 1720, E 6210, both in Nova Lima; SQ157, E 4590, N 3610, and M–79a–57, W 3540, N 6100, both in Gongo Sôco; J–328, W 4170, N 6600, and J–622–55, E 4810, N 6230, both in Dom Bosco.

WEATHERING

The carbonate minerals decompose very readily at the surface. Rocks consisting originally of almost pure dolomite have generally been altered to a soft brown material, "splash rock" (Guild, 1957, p. 41–43). Contacts between fresh and altered rock are sharp. Analyses show that the splash rock is composed almost entirely of SiO_2, Al_2O_3, Fe_2O_3, and generally has some manganese locally and some phosphorus.

CHLORITOID

Chloritoid is widely distributed in the Quadrilátero Ferrífero. It occurs principally in a wide belt in the Moeda syncline (Herz and Dutra, 1964, table 1), in the lower part of the Cercadinho Formation in the southern part of the Quadrilátero Ferrífero (Johnson, 1962, p. 17, A. L. M. Barbosa, written commun., 1965), and in the Palmital Formation in the central part of the Quadrilátero Ferrífero (fig. 18).

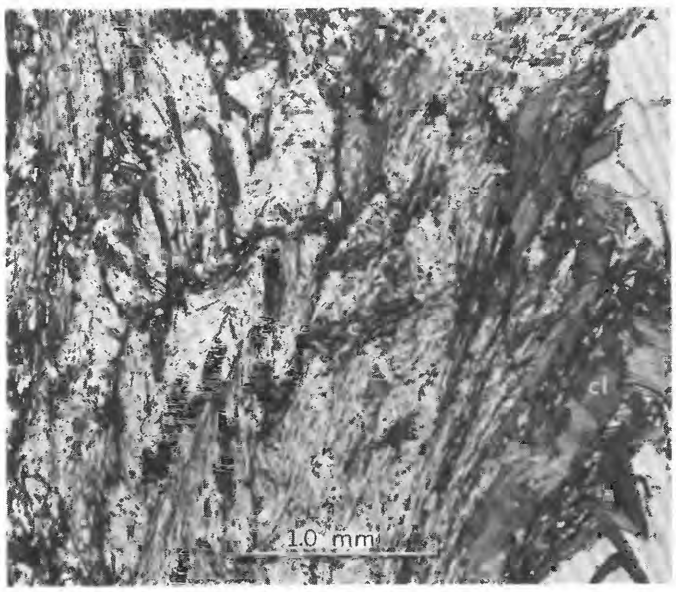


FIGURE 18.—Photomicrograph, chlorite-sericite-chloritoid schist, basal Piracicaba Group, J–169, Dom Bosco quadrangle, plane light. Chloritoid (c) formed largely parallel to fold axes. Chlorite (cl) adjacent to sheared quartz vein. Most of the rock is sericite, bent muscovite flakes, quartz, plagioclase (not in slide), and magnetite.

Chloritoid occurs in emery, pelitic schists, and impure quartzites. It develops in rocks having a wide range in percentage of SiO_2, having high Al_2O_3, and having low CaO (Tilley, 1925). With increasing CaO, epidote develops instead of chloritoid. Chloritoid forms in both the chlorite and biotite-almandine zones of regional metamorphism; at pressures and temperatures higher than those of these metamorphic zones, chloritoid, muscovite, and quartz react to form staurolite, biotite, and water. At pressures between 4,000 and 8,000 bars and temperatures of 545° ± 20°C, Hoschek (1967, p. 152) found that chloritoid breaks down in a reversable reaction with aluminum-silicate to form staurolite + quartz + water.

In quartzite of the Palmital Formation, stress was of little influence in the crystallization of chloritoid. Chloritoid crystallized late, commonly in radiating groups or aggregates rather than with a preferred orientation, as would be expected of crystals formed under stress (fig. 19), a condition which has been considered necessary by some authors (Deer and others, 1962a, p. 169).

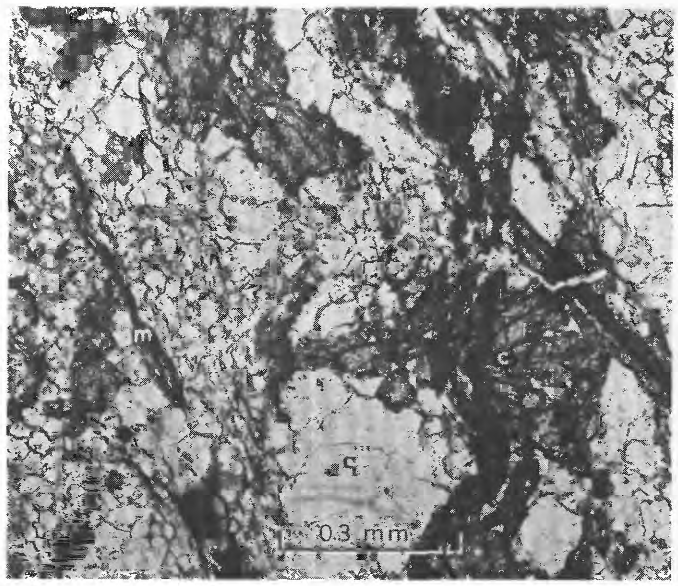


FIGURE 19.—Photomicrograph, chloritoid quartzite, Palmital Formation, Z–346, Rio de Pedras quadrangle, plane light. Chloritoid (c) forms rosettes and isolated prismatic grains. Large clusters of medium- and coarse-grained subangular quartz (q) makes up the bulk of the rock. Muscovite (m), stained by limonite is abundant.

Halferdahl's (1961, p. 99) experimental results also indicate that total pressure has little influence on the formation of chloritoid. Up to about 700°C, higher pressures necessitate higher temperatures for the formation of chloritoid. Thus, the effect of shearing stress is to raise the pressure locally and, if not accompanied by a rise in temperature, to inhibit the crystallization of chloritoid.

OPTICAL DETERMINATION

Chloritoid was generally identified in thin section by its distinctive pleochroic formula in shades of deep greenish black: medium bluish gray/light bluish gray, grayish yellow green/very pale blue, and blue green/colorless. In some quartzite of the Palmital Formation, magnesium-rich chloritoid is light green and is nonpleochroic.

Chloritoid has generally developed in phyllite and schist of the Cercadinho Formation and impure quartzite of the Maquiné Group and Cercadinho Formation. It formed by progressive metamorphism from indeterminate clay minerals at pressure/temperature conditions of the greenschist facies and persisted under higher pressure/temperature conditions, as shown by its presence in some rocks that also developed staurolite. A probable reaction for the development of chloritoid in aluminum-rich rocks (Halferdahl, 1961, p. 123) is montmorillonite + chamosite = chloritoid + quartz + vapor, which takes place in pelitic or lateritic sediments under sedimentary conditions, that is, temperature below about 400° and pressure under about 1,000 bars.

Some authors consider stress to be an important factor in the development of chloritoid. Read (1957, p. 361–362) found that chloritoid occurred largely in special dislocation environments, such as shales compressed between stiff competent bands. Shearing stress was widespread in the area south of the Bação Complex, and chloritoid developed (fig. 18). Here, regional stress from the south or southeast faulted or thrust metasedimentary rocks against the Bação (granitic) Complex. The development of chloritoid in basal Piracicaba phyllite, however, must have also been due to a sensitive chemical control because elsewhere, as west of the complex, chloritoid developed in similar beds without extreme shearing stress.

Chloritoid in pelitic rocks and ferruginous quartzites has $n\beta$ of about 1.725, which is within the iron-rich range shown by Halferdahl (1961, p. 89); that from the Palmital Quartzite has $n\beta \sim 1.718$ (inferred from table 12), which is within the range of magnesium-rich chloritoid, as is the birefringence of about 0.005 (Halferdahl, 1961).

Chloritoid grains vary considerably in size from fine grained in rocks in which it is not abundant to about 0.7 mm long in those in which it is an essential mineral. Gair (1962, p. 32) found that chloritoid is especially abundant in the Casa Forte Formation; there it ranged in grain size from less than 0.1 to about 2 mm.

X-RAY DETERMINATION

Three chloritoid samples were selected for X-ray (table 11) and chemical (table 12) analysis: two from the Piracicaba Group of the Dom Bosco quadrangle and one from the Palmital Formation of the Rio de Pedras quadrangle. One object of the X-ray study was to determine if the chloritoid polymorph was triclinic or monoclinic. Halferdahl (1961) could find no essential difference in geologic environment, composition, or optical properties in the two polymorphs, although both Niggli, von E. (1960, p. 135) and Vrana (1964, p. 130–132) found that in Alpine environments, the monoclinic form occurs in the higher pressure/temperature of the chloritoid zone.

Halferdahl suggested three reflections for distinguishing the triclinic form within the range of 2θ's studied: 34.71°, 42.69°, and 49.94° which correspond respectively to *hkl*'s of $1\bar{1}2$–$\bar{1}12$, 310, and $2\bar{2}1$–203–$\bar{2}21$–113. The first and last reflections, which are the strongest, were found in all samples; the 42.69° reflection was found only in Z–346A. All samples are clearly triclinic; in fact, none of the reflections used by Halferdahl (p. 82) to distinguish the monoclinic form were found.

TABLE 11.—*X-ray data on chloritoid*

[Analysis by X-ray diffractometer. Z-346A analyzed by Maria H. Falabella, DNPM, Rio de Janeiro; other samples analyzed by David R. Wones and Norman Herz using Fe–K radiation, Mn filter, at ½° 2θ/minute. The results of these analyses are compared to Halferdahl's on a triclinic chloritoid from Quebec]

Z–346a		Z–346b			J–367			J–434b			Quebec			
dÅ	I	2Θ	dÅ	I	2Θ	dÅ	I	2Θ	dÅ	I	2Θ	dÅ	I	hkl
---	---	22.7	4.92	6	22.85	4.89	8	23.15	4.82	--	22.77	4.449	1	002
---	---	---	---	--	----	---	----	24.35	49.59	5	24.10	4.640	1	200, 110
4.46	100	25.1	4.46	10	25.15	4.45	10	----	---	--	24.87	4.498	10	$11\bar{1}$, $20\bar{1}$
---	---	---	---	--	----	---	----	----	---	--	25.15	4.449		002
---	---	---	---	--	----	---	----	----	---	--	29.49	3.806	3	201, 111
---	---	---	---	--	30.5	3.68	1	30.5	3.68	2	----	----	--	---
---	---	---	---	--	----	---	----	----	---	--	31.15	3.608	1	$11\bar{2}$, 202
3.25	7	34.5	3.27	4	34.5	3.27	2	34.55	3.26	2	34.71	3.247	[1]6	$1\bar{1}2$
---	---	---	---	--	----	---	----	----	---	--	----	----	--	$\bar{1}12$
2.97	25	38.1	2.97	10	38.2	2.96	10	38.1	2.97	5	38.14	2.965	8	003
---	---	---	---	--	----	---	----	----	---	--	38.69	2.924	2	202, 112
2.75	4	40.9	2.77	1	40.9	2.77	1	39.85	2.84	2	40.92	2.771	4	$20\bar{3}$
2.69	7	42.2	2.69	2	42.25	2.69	2	42.1	2.70	2	42.12	2.696	7	$0\bar{2}1$, $\bar{3}11$
2.67	7	---	---	--	----	---	----	44.4	2.56	2	42.69	2.661	[1]3	310
2.46	15	---	---	--	45.65	---	2.50	4	----	--	45.32	2.514	1	021, $\bar{1}13$
---	---	46.5	2.45	3	46.5	2.45	4	46.5	2.45	3	46.45	2.45	9	022, $\bar{3}12$
---	---	47.6	2.40	2	47.6	2.40	1	----	---	--	47.63	2.399	5	311
---	---	---	---	--	48.3	2.37	2	----	---	--	48.28	2.369	3	$40\bar{1}$, $22\bar{1}$
---	---	---	---	--	----	---	----	48.6	2.35		49.31	2.322	1	400, 220
2.28	15	49.95	2.29	1	49.7	2.30	1	49.9	2.30	1	49.94	2.295	[1]5	$2\bar{2}1$, $\bar{2}21$, 203, 113
2.24	5	---	---	--	----	---	----	----	---	--	50.78	2.259	3	222, $40\bar{2}$

Key: Z–346a, b—Palmital Formation, chloritoid quartzite, cd-qz, Rio de Pedras quadrangle.
J–367—Piracicaba Group, chloritoid quartzite, cd-qz-lm, Dom Bosco quadrangle.
J–434b—Piracicaba Group, chloritoid quartz, cd-qz, Dom Bosco quadrangle.
Quebec—Halferdahl, table 15. Only those lines shown that lie within the 2θ region were studied.
[1] Lines considered diagnostic of triclinic form.

TABLE 12.—*Partial chemical analyses (in weight percent) of chloritoid*

[Analyst: Aida Espinola, DNPM, Rio de Janeiro]

	Z–346	J–367	J–434b
SiO_2	25.0	25.0	25.0
Al_2O_3	37.1	37.5	39.6
FeO	19.8	23.2	20.0
Fe_2O_3	3.1	2.6	3.2
MgO	7.5	2.0	3.6
CaO	Tr.	2.1	0.81
H_2O^+	7.04	7.60	7.68
H_2O^-	0.16	0.05	0.12
Ti	Present	Present	Present
F—	Absent	Absent	Absent
Cr	Do.	Do.	Do.
	99.7	100.1	100.0

Sample descriptions: Z-346 nα=1.714, nγ=1.722; no pleochroism; color dusky yellow to blue-green. 22.7 percent quartz by weight deducted and analysis recomputed to 100 percent. Chloritoid-quartzite, Palmital Formation. Rio de Pedras quad, 6,350 E., 13,350 N.

J-367 nα=1.719, nγ=1.729; pleochroic pale blue; color dusky blue-green. Full of opaque inclusions; 9.4 percent quartz by weight deducted and analysis recomputed to 100 percent. Chloritoid-quartzite, Piracicaba Group, Dom Bosco quad, 7,300 E., 10,750 N.

J-434b nα=1.715, nγ=1.724; pale pleochroism; color dusky yellow to grayish olive. Full of opaque inclusions; 21.1 percent quartz by weight deducted and analysis recomputed to 100 percent. Chloritoid-quartz rock, Piracicaba Group, Dom Bosco quad, 1,000 E., 9,350 N.

CHEMICAL ANALYSES

Heavy liquids and a Frantz magnetic separator were used to separate three chloritoid samples from chloritoid-rich rocks for chemical analyses (table 12). The samples were checked optically for purity and two were found to be full of opaque inclusions of an unknown composition (figs. 20, 21) and all had substantial amounts of quartz. The X-ray diffractometer showed only quartz and chloritoid, and yielded no information on the opaque inclusions.

The two samples from the Piracicaba Group are typical iron-rich chloritoids, and the sample from the Palmital Formation is unusually rich in magnesium, which is substantiated by its low index of refraction. The Piracicaba samples apparently have more than the 0.50 percent CaO, suggested as the maximum in pure chloritoid (Halferdahl 1961, p. 53), possibly because of the inclusions.

FIGURE 20.—Photomicrograph, quartz-sericite-chloritoid schist, lower Piracicaba Group, J–341, Dom Bosco quadrangle, plane light. Chloritoid (c) comprises 25 percent of the rock; quartz (q) about 40 percent; muscovite and stained limonite-sericite (m) about 30 percent.

Whole rock sample No. J–341, a chloritoid phyllite from the Piracicaba Group of the Dom Bosco quadrangle, was analyzed (table 21) to see if it falls within the chemical limits set by Tilley (1925) and other authors for chloritoid-bearing rocks. It is a green schist containing about 40 percent quartz, 30 percent sericite and muscovite, 25 percent chloritoid, 5 percent chlorite and minor magnetite, and, except for alumina, falls within the range given by Tilley: SiO_2 from 30 to 80 percent, CaO trace to 0.5 percent, and Al_2O_3 from 10 to 16 percent. The chloritoid phyllite from the Dom Bosco quadrangle contains 22.1 percent Al_2O_3 and in this respect is similar to chloritoid-kyanite schists from Slovakia, which have 17.41–20.83 percent Al_2O_3 (Vrana, 1964, p. 129).

The unusually high Al_2O_3 is also reflected in a low Fe_2O_3/Al_2O_3 ratio of 0.12. Williamson (1953) found that the most common Fe_2O_3/Al_2O_3 ratio containing chloritoid or staurolite is 0.40 and the lowest known value for chloritoid alone is 0.18 from a chloritoid-sericite schist in the Alps. Sample J–341 meets the chemical requirements determined by Halferdahl (1961) for chloritoid-bearing rocks, that is, excess Al_2O_3 and more FeO+MnO than either MgO or Fe_2O_3.

ASSEMBLAGES

In phyllites, chloritoid is typically associated with quartz, muscovite, and chlorite and with minor amounts of limonite, apatite, pyrite, magnetite, ilmenite, and hematite (figs. 20, 21). In one sample from the Dom Bosco quadrangle (J–172–55, S3080, W2540) which has almost 50 percent chloritoid, the only associated minerals are quartz, tourmaline, and hematite. In the Casa de Pedra and São Julião quadrangles and elsewhere, chloritoid was found with quartz, chlorite, and graphite, or quartz, sericite, magnetite, and very small amounts of chlorite. In phyllitic rocks of the Piracicaba Group, the volume of chloritoid ranges from about 30 to 60 percent and, in one sample from the Ouro Prêto quadrangle (2,000N, 1,400W), forms more than 90 percent of the rock.

Where chloritoid occurs in quartzites of the Piracicaba Group (fig. 21) and the Palmital Formation, it is abundant, as much as 30 percent, and commonly is completely replaced by limonite.

In Cercadinho phyllite of the Moeda syncline (K–2, table 13), chloritoid is associated with kyanite, muscovite, and quartz, and, in places, also with pyrophyllite. In impure Itacolomí quartzite near Casa de Pedra (K–4, table 13) chloritoid, is associated in addition, with garnet (almandine) and magnetite (Herz and Dutra, 1964, p. 1304). Although the pair chloritoid-kyanite has been taken to represent high-grade metamorphism elsewhere (Halferdahl, 1961, p. 115), in the Quadrilátero Ferrífero, as in Alpine metamorphics

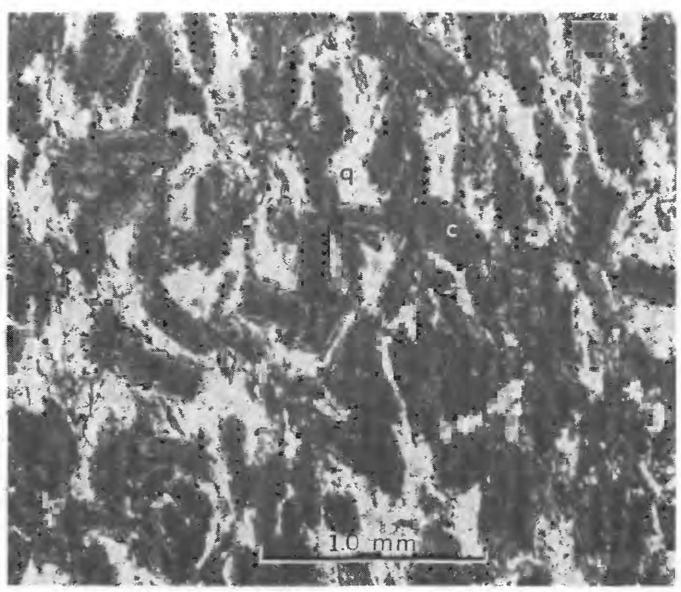


FIGURE 21.—Photomicrograph, chloritoid-quartz rock, Piracicaba Group, J–434b, Dom Bosco quadrangle, plane light. Chloritoid (c) comprises 60 percent of this rock and up to about 75 percent of some adjacent beds. Many grains have preferred orientation and slight bluish pleochroism. Quartz (q) composes about 40 percent of the rock. Magnetite is an accessory mineral.

(Vrana, 1964, p. 135), the pair is found in rocks of the greenschist facies of the chlorite or biotite zones.

In the Nova Lima Group north of Itabirito, chloritoid is associated with quartz, muscovite, biotite, and pyrite in the biotite zone of metamorphism. Chloritoid is found in the Piracicaba Group near Ouro Prêto (A. de Barbosa, oral commun., 1960) in rocks of the staurolite zone, where it developed by retrograde metamorphism of high-grade minerals or persisted as a relict low-grade mineral. Typical assemblages in the almandine or staurolite zones near Ouro Prêto and Congonhas do Campo contain chloritoid, muscovite, chlorite, staurolite, minor quartz, and, in places, garnet and pyrite.

RETROGRADE METAMORPHISM AND WEATHERING

In many retrograded rocks formerly of high metamorphic grade, chloritoid and the ore minerals have been the last to develop. Chloritoid evidently replaced staurolite, garnet, and other minerals.

Chloritoid is very resistant to weathering in both quartzites and phyllites. In quartzites, it is commonly stained and partly replaced by hydrated iron oxide. Halferdahl (1961, p. 56) found that chloritoid from many parts of the world had similar coatings which could be removed only with hot concentrated solutions of ammonium citrate.

In phyllite of the Cercadinho Formation in the Serra do Itabirito, chloritoid associated with kyanite has been extensively replaced by a chlorite mineral of positive sign and a median refractive index of 1.622.

KYANITE [1]

Kyanite is the only polymorph of Al_2SiO_5 found in any quantity in the Quadrilátero Ferrífero. It appears in veins and disseminated in phyllites of the Cercadinho Formation, in quartz veins cutting quartzites along the western side of the Serra da Moeda, in the Serra do Caraça, and elsewhere. In the Itabira Group of the Congonhas district it is found in quartz veins cutting iron-formation or manganese-rich rocks. It developed in response to both low- and high-grade metamorphic conditions in rocks having excess Al_2O_3.

In general, pressure/temperature conditions for kyanite, andalusite, and sillimanite are believed to be high pressure and moderate temperature for kyanite, low pressure and low temperature for andalusite, and moderate pressure and high temperature for sillimanite (Turner and Verhoogen, 1960). Experimental work to determine the triple point of the Al_2SiO_5 polymorphs (Clark, 1961; Bell, 1963) suggests that high pressures of about 8 to 10 kilobars, equivalent to a depth of about 30 km is necessary for the stable crystallization of kyanite at temperatures that would obtain under regional metamorphism. Newton (1966), however, found in hydrothermal experiments that kyanite was stable at 3–5 kilobars pressure and temperatures of 450°–550°C, conditions that might prevail during medium-grade metamorphism.

Kyanite is typically developed in aluminum-rich rocks of the almandine-amphibolite zone of regional metamorphism (Turner and Verhoogen, 1960, p. 551) and, once formed, can persist to the highest metamorphic conditions of the eclogite facies. In rocks of the greenschist facies having excess SiO_2 and Al_2O_3 and deficient K_2O, however, kyanite can also develop in association with quartz-albite-epidote-almandine (Turner and Verhoogen, 1960, p. 539).

In rocks of obviously low metamorphic grade, such as fine-grained quartz-chlorite phyllite, the occurrence of kyanite may be due to a combination of ideal chemical composition and high pressure. This is suggested by the facts that such rocks are characterized by an unusually high Al_2O_3 content (20.4 percent in sample J–211, table 21, as an example) and contain kyanite in or near the troughs of synclines, as between the Serra da Moeda and the Serra do Itabirito, and in the syncline east of Casa de Pedra (pl. 1).

Kyanite is always one of the last minerals to crystallize and occurs in grain sizes from fine medium in phyllites to very coarse in veins. In some veins, kyanite is as much as 15 cm long, but the largest crystals are commonly bent or broken.

The basal Cercadinho Formation, which has more kyanite than any other rock within the chlorite and biotite zones of metamorphism, may have originated as a saprolite from which most of the alkaline earths and the alkalies, except K_2O, were leached out. Kyanite formed both in the matrix and in veins cutting this formation, especially in the troughs of synclines, as noted above, where the tectonic overpressure evidently was greatest (Clark, 1961). During a later metamorphic phase, under lower pressures, much of the vein kyanite was formed.

Kyanite is found in higher metamorphic conditions of the almandine and staurolite zones of metamorphism, where such muscovite and nearly all the chlorite broke down and helped form biotite or potassium-feldspar plus more kyanite.

Because kyanite is so widespread in different metamorphic environments of the Quadrilátero Ferrífero, a special study was made of the chemical, unit-cell, and optical characteristics of selected samples; this

[1] Much of this section has been taken from Herz and Dutra, 1964.

TABLE 13.—*Kyanite sample description*
[Abbreviations explained in table 2]

Sample number	Locality (quad and location)	Description of mineral	Inclusions	Occurrence and associated minerals	Collector
K–1	Lagôa Grande S3300, E2060.	Pale blue; as large as 2 cm.	Qz, pp	In veins with qz, pp rosettes, mu. Cuts Cercadinho phyllite. Cl isograd.	R. M. Wallace
K–2	Lagôa Grande S4050, E1080.	Dark gray; as large as 0.8 mm.	Qz, pp, op (some hexagonal and platy), parallel to ky prism, generally irregularly shaped.	In Cercadinho phyllite with cd-mu-cl-qz.	Do.
K–3	Catas Altas N2100, E4600.	Very pale blue, as large as ±1 cm.	Qz, pp	In veins with qz, pp rosettes, mu. Cuts Rio das Velhas phyllite. Bi isograd	C. H. Maxwell
K–4	Casa de Pedra N5400, E10,200.	Very pale blue core, dull white rim; as large as ±2 cm.	Qz; Mn film on some grains.	In veins with qz, pp. Cuts Itacolomí qz-mu-mg- phyllite with ky-ga-cd-mg-porphyroblasts.	P. W. Guild; see Guild, 1957, p. 29.
K–5	Capanema N4275, E1620.	Moderate blue or bluish green; as large as ±2 cm.	Qz	In veins with qz. Cuts Maquiné quartzite. Bi isograd.	C. H. Maxwell
K–6	Itabirito N6570, E30.	Elongate dark prisms as large as 1 cm.	Similar to K–2	In Cercadinho phyllite with mu-cl-qz. Most ky has parallel orientation, some in rosettes.	N. Herz
K–7	Lagôa Grande N6570, W10.	Pale blue; as large as ±2 cm.	Qz, pp	In veins with qz, pp, mu. Cuts Cercadinho mu-cl-ky-qz phyllite.	R. M. Wallace
K–8	Itabirito N5020, E550.	Very pale blue, as large as ±4 cm.	Qz, pp	In veins with qz, pp, mu and phyllite breccia. Cuts brecciated Cercadinho mu-cl-ky-qz-phyllite.	N. Herz
K–9	Casa de Pedra N6400, E5400.	Pale to moderate blue, as large as ±15 cm.	None	In veins with qz. Cuts Moeda qz-mu-cl±fu quartzite and phyllite. Nearby tm veins and granite contact. Cl isograd	N. Herz; see Guild, 1957, p. 12.
K–10	Capanema N6170, W490.	Light greenish gray; as large as 8 cm.	Qz, pp	In veins with mu, qz, pp. Cuts Cercadinho ferruginous qzt and phyllite. Bi isograde.	C. H. Maxwell
K–11	Capanema N6170, W490.	Small, dark, elongate prisms; smaller than 1 mm.	Mu	In fine-grained Moeda or Rio das Velhas phyllite. Bi isograd.	Do.
K–12	Capanema N7110, E1450.	Fine needles in dark-gray phyllite, smaller than 1 cm.	Qz, cl	Forms rosettes on foliation plane of phyllite of Moeda Formation. Has appearance of fibrolite. Bi isograde.	Do.

is presented in greater detail in Herz and Dutra (1964). For this report (table 13) 12 samples were selected from low-grade metamorphic environments. Four are from phyllites, four from veins cutting the phyllites, and four from veins cutting quartz-rich rocks.

OPTICAL DETERMINATION

Kyanite was recognized in thin section by its prismatic form, high relief, inclined extinction, and positive elongation. Indices of refraction and other optical data (table 14) were determined for the 12 samples selected for the special study. The indices were determined with immersion liquids having an 0.005 interval and using sodium-light. 2V and Z∧C determinations were made with a 4-axis universal stage on grain mounts.

There is no correlation between the optical and the chemical data, nor between the optical data and modes of occurrence. The total variation in the optical data is so small as to fall within the limits of precision of the determinations.

CHEMICAL ANALYSES

Six major elements were determined in four samples (table 15). CaO, MgO, and MnO were also sought in these analyses, but they were found to be below the limit of sensitivity of wet chemical methods.

Part of the high Fe_2O_3 and minor-element abundance of sample K–2 from a phyllite can be attributed to the platy opaque inclusions in the grains (noted in table 13). In general, the analyses reveal the same element abundance shown by Deer, Howie, and Zussman (1962a, p. 139) for kyanite elsewhere in the world.

TABLE 14.—*Optical data of kyanite*

Sample number[1]	N_α	N_β	N_γ	2V°	Z∧C°
From phyllites of the biotite and chlorite zones					
K–2	1.708	1.716	1.720	82	29.5
–6	1.710	1.718	1.722	80	29
–11	1.710	1.719	1.724	80	29
–12	1.707	1.715	1.720	80	30
From veins which cut the phyllites					
K–1	1.710	1.719	1.724	79.5	29.5
–2	1.710	1.718	1.722	79.5	27.5
–7	1.714	1.722	1.727	80	28.5
–8	1.711	1.720	1.726	79.5	27.5
From veins which cut quartz-rich rocks					
K–4	1.709	1.717	1.722	79	30
–5	1.713	1.722	1.727	79	29
–9	1.711	1.719	1.724	78	30
–10	1.710	1.719	1.724	77	29.5

[1] Samples described in table 13.

TABLE 15.—*Chemical analysis of kyanite*

[Analyst: Fernando Peixoto, Instituto de Tecnologia Industrial, Belo Horizonte; 6.4 percent quartz by weight deducted from K–1, 6.8 percent from K–2, and 2.7 percent from K–3; n.d., not detected; Tr., =trace]

	K–1	K–2	K–3	K–9
Chemical analyses				
SiO_2	37.3	36.7	36.9	37.77
Al_2O_3	62.0	61.5	62.6	61.70
Fe_2O_3	.63	1.51	.37	.50
TiO_2	n.d.	.18	n.d.	Tr.
K_2O	.10	.06	.04	.18
Na_2O	.03	.04	.10	.43
Sum	100.1	100.0	100.0	100.58
Composition on the basis of 20 oxygen				
Si	4.03	3.96	3.97	4.070
Al	7.89	7.82	7.94	7.836
Fe^{3+}	0.52 } 8.03 (Al through Mg)	.117	.032	.039
Ti	—	.013	—	—
K	.013	.007 } 7.99 (Al through V)	.005 } 8.00 (Al through V)	.026
Na	.007	.007	.019	.091 } 8.007 (Al through V)
Mg[1]	.065	.011	—	.008
Zr[1]	—	.003	—	—
Ca[1]	—	.002	—	—
Cr[1]	—	.005	.002	.006
V[1]	—	—	—	.001

[1] Values from spectrographic data.

SPECTROGRAPHIC ANALYSIS

Twenty-eight minor elements were sought in each kyanite sample by spectrographic analysis; 10 elements, however, were always below the detection limits (given in parts per million in parenthesis), and so are not reported in table 16: Ag (1), Au (20), Pb (10), La (30), Li (200), Mo (10), Ta (200); Th (200), W (200), and Zn (200).

There is little difference in abundance of the minor elements in kyanite in phyllites of the chlorite and biotite zones of metamorphism (compare K–2 and K–6 to K–11 and K–12, table 16). The appearance of biotite or garnet in one group of rocks and chlorite in another may be as much a function of bulk chemical composition as it is of temperature and pressure. Kyanite, for instance, shows a dependence on the original bulk chemical composition and is developed only in rocks with high Si, Al, and Fe_2O_3. Minor elements, such as Cr, Fe, V, Mg, Zr, K, Ca, Ti, and Na are relatively abundant in both the country rock and the kyanite and may have had some nucleating effect on the kyanite (compare with table 5, Herz and Dutra, 1964).

Minor elements that are abundant in both country rock and in kyanite disseminated in phyllite are generally less abundant in vein kyanite (table 16), except for magnesium in samples K–1 (2,400 ppm) and K–8 (3,300 ppm). The vein kyanite may represent a continuation of the crystallization of the kyanite in the phyllite itself. The kyanite veins thus may be similar to the "recrystallization pegmatites" of Ramberg (1952), as suggested by the fact that the veins are restricted to rocks that contain disseminated kyanite.

ASSEMBLAGES

In the Quadrilátero Ferrífero, kyanite is always associated with quartz (fig. 22) and nearly always

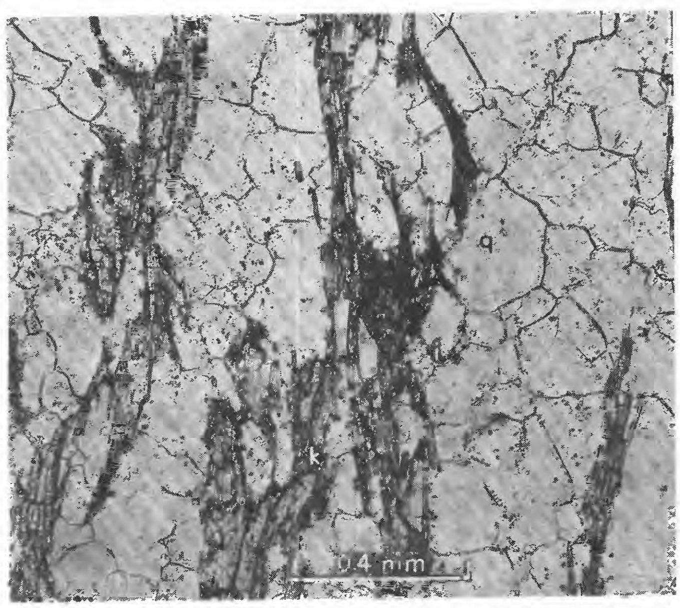


FIGURE 22.—Photomicrograph, kyanite quartzite, lower Piracicaba Group, H–103, São Julião quadrangle, plane light. Rock consists entirely of large subangular grains of quartz (q), alined elongate prisms of kyanite (k), and iron oxides (i). The alined kyanite imparts a foliation to the rock.

TABLE 16.—*Spectrographic analysis of kyanite in parts per million*
[Analyst: C.V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte. Nd., no data]

	Ba	Be	Ca	Co	Cr	Cu	Ga	Ge	Mg	Mn	Nb	Ni	Sc	Sn	Sr	V	Y	Zr
Samples in phyllites of the biotite and chlorite zones																		
K–2	7	Nd.	130	3.5	350	10	31	Nd.	420	8	35	25	4	24	16	95	25	330
–6	9	Nd.	250	Nd.	190	13	21	Nd.	280	14	34	13	Nd.	38	15	140	39	170
–11	9	Nd.	64	Nd.	600	1.9	13	Nd.	97	13	Nd.	39	10	Nd.	Nd.	330	19	19
–12	3.1	Nd.	130	Nd.	410	3.7	49	Nd.	750	7	64	20	5.5	58	8.5	190	31	380
Samples in veins which cut the phyllites																		
K–1	Nd.	Nd.	7	Nd.	63	4.0	14	72	2,400	7	Nd.	3.6	Nd.	Nd.	Nd.	34	Nd.	3
–3	2	Nd.	~1.5	Nd.	140	13	27	Nd.	65	3	Nd.	~1.5	Nd.	Nd.	Nd.	65	Nd.	~1.5
–7	2.7	Nd.	14	Nd.	130	3.2	30	44	72	4	Nd.	Nd.	Nd.	Nd.	Nd.	44	Nd.	~1.5
–8	4.4	Nd.	60	2.4	120	6.4	16	67	3,300	14	Nd.	9	Nd.	12	Nd.	35	Nd.	~1.5
Samples in veins which cut quartz-rich rocks																		
K–4	10	Nd.	110	~1.5	51	16	33	31	140	[2] 420	Nd.	41	Nd.	Nd.	Nd.	30	Nd.	52
–5	27	Nd.	150	13	2,200	3.2	16	Nd.	160	86	Nd.	27	~1.5	Nd.	19	500	Nd.	13
–9	14	2.2	64	Nd.	470	1.9	19	Nd.	280	35	Nd.	Nd.	Nd.	Nd.	19	95	Nd.	10
–10	2.7	Nd.	7	Nd.	29	2.2	33	15	990	56	Nd.	4.4	Nd.	Nd.	Nd.	16	Nd.	3
Limits of detection of elements (in ppm)																		
	2	2	2	2	2	1	5	10	5	3	30	2	2	10	3	10	10	2
rÅ of elements																		
	1.43	0.33	0.99	0.72	0.63	0.72	0.62	0.50	0.66	0.60	0.69	0.69	0.81	0.71	1.16	([1])	0.92	0.79

[1] V^{3+}=0.74Å; V^{5+}=0.59Å.
[2] Probably largely Mn stain on grains.

with muscovite. In the chlorite zone or the lower part of the greenschist facies, assemblages are as follows:

(a) quartz-kyanite
(b) quartz-muscovite-kyanite
(c) quartz-muscovite-kyanite-pyrophyllite
(d) quartz-muscovite-kyanite-chlorite-(pyrophyllite)
(e) quartz-muscovite-kyanite-chlorite-(chloritoid)-(pyrophyllite)
(f) quartz-muscovite-kyanite-garnet-chloritoid-(magnetite)

Assemblages (a), (b), and (c) are typical of veins; (d), (e), and (f) of phyllite.

At a higher metamorphic grade than the lower greenschist facies, biotite replaces chlorite, or staurolite replaces chloritoid, and garnet or tremolite may also be associated with kyanite, quartz, and muscovite (table 17). Such kyanite assemblages of higher metamorphic grade than the greenschist facies are found in the Cercadinho Formation or the Itacolomí Series of the Itabira, Nova Lima, Casa de Pedra, Bação, and São Bartolomeu quadrangles at about the same horizon as lower grade kyanite-bearing phyllites are found. In the Itabira district, kyanite forms as much as 20 percent of some "granitic gneisses" (Dorr and Barbosa, 1963, p. 40).

RETROGRADE METAMORPHISM AND WEATHERING

Kyanite generally persists during weathering and is even found unaltered in a saprolite derived from phyllite in the Lagôa Santa region. During retrograde metamorphism, kyanite commonly was partly replaced by pyrophyllite (fig. 23). Small flakes of pyrophyllite replace kyanite initially around the edge of crystals and along cleavages; as replacement advances, the kyanite crystals become ragged and the pyrophyllite better crystallized.

ANDALUSITE AND SILLIMANITE

Andalusite and sillimanite are uncommon in the Quadrilátero Ferrífero. One or the other occurs in pelitic rocks near granitic contacts north of the Serra do Curral, bordering the Bação Complex, in the Itacolomí area, and in possible roof pendants in the Cocais granite.

Elsewhere in the world, andalusite is known from contact metamorphic aureoles (Turner and Verhoogen, 1960, p. 509 ff). It forms under temperature/pressure conditions of the albite-epidote hornfels facies and is stable into the higher temperature pyroxene hornfels facies. Immediately adjacent to granitic contacts, it gives way to sillimanite, which is generally taken to represent the highest temperature conditions of the almandine-amphibolite facies of regional metamorphism (Turner and Verhoogen, 1960, p. 544 ff). Once sillimanite forms, it is stable into much higher metamorphic conditions.

Other rocks of the area which may have contained andalusite or sillimanite are now completely weathered

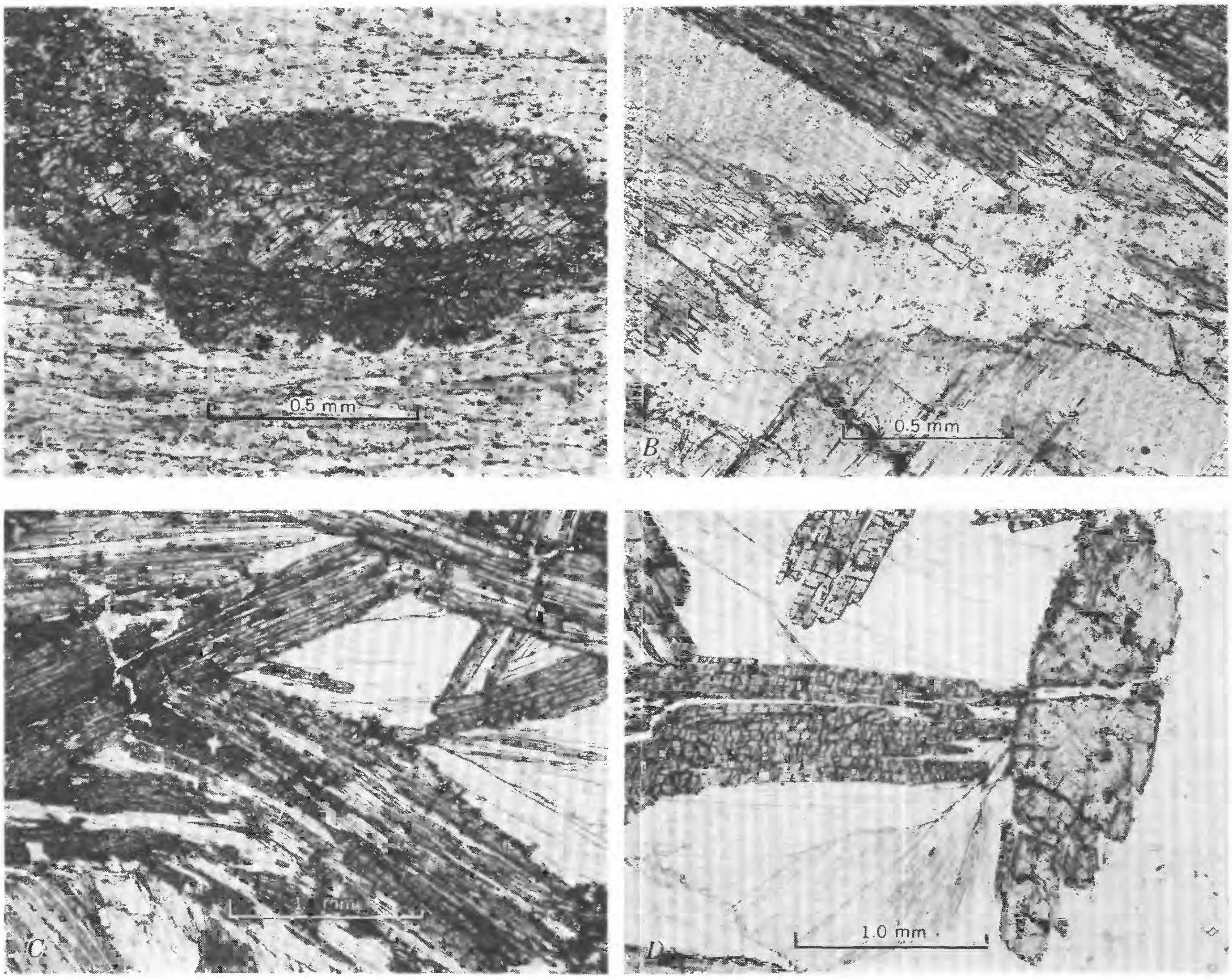


FIGURE 23.—Photomicrographs of kyanite remnants. *A*, remnants of kyanite in chlorite-sericite-quartz phyllite (Herz and Dutra, 1964, figs. 1–4). Kyanite partly replaced by a micaceous material that may be pyrophyllite. Plane light, sample from near K–2. *B*, early stages of replacement of kyanite by pyrophyllite in a quartz-kyanite vein. Pyrophyllite follows fractures and cleavages in kyanite. Plane light, K–7. *C*, stages of replacement of kyanite by pyrophyllite. Plane light, K–9. *D*, well-crystallized pyrophyllite in rosettes and filling fractures in kyanite. Plane light, K–9.

to saprolite, so no general conclusions as to mode of occurrence of these minerals can be made.

ANDALUSITE

Andalusite and staurolite formed together just south of the Bação Complex; both were later replaced by fine-grained micaceous minerals. Andalusite and garnet are associated in the area of Itacolomí; they tended to be replaced during retrograde metamorphism by a mixture of sericite, chlorite, and limonite.

Andalusite in pelitic rocks of the Nova Lima Group in the Macacos quadrangle has been largely replaced by quartz and sericite. Fresh andalusite occurs in veins together with quartz and white mica in the staurolite zone in the Belo Horizonte quadrangle (Pomerene, 1964, p. 36). The andalusite crystals which weather out of the rock are as large as 4 by 7 cm and evidently are associated with now-weathered feldspar and corundum veins.

Andalusite, pleochroic green-yellow and thus possibly manganese-rich (Deer and others, 1962a, p. 133), developed in schist near a diabase dike 5 km northwest of Cocais (Simmons, 1968b). The complete assemblage includes andalusite-biotite-muscovite-chlorite-quartz-ilmenite-leucoxene. Field relations are not clear, but Simmons, (1968b) believes that this assemblage formed in an inclusion or roof pendant in the Cocais gneiss.

Fresh sillimanite is rare. Guimarães (1935, p. 24) found sillimanite associated with quartz, magnetite, and biotite in a Passagem-mine drill core which cut schistose dolomite interbedded with other dolomitic and amphibolitic itabirite.

Guild (1957, p. 38) found sillimanite in garnet-cordierite gneiss in the contact zone of the Bação Complex near Engenheiro Corrêa. Sillimanite occurs as fine needles in the cordierite altered to mats of sericite (fig. 30).

Sillimanite may also have formed in quartzose rocks in the southeastern part of the area near Itacolomí and elsewhere along the southern contact of the Bação Complex and later was replaced by sericite. Other possible associated minerals which were partly or completely replaced evidently included garnet, clinozoisite, biotite, and magnetite. Kyanite appears to have replaced sillimanite in the Capanema quadrangle in the eastern part of the Quadrilátero Ferrífero and elsewhere (K–12, table 13). This is evinced by the frequent occurrence in some schists and phyllites of thin interlacing needlelike crystals, typical of the variety of sillimanite called fibrolite, that optically, are kyanite.

STAUROLITE

The development of staurolite in this area appears to be controlled both by special chemical composition and metamorphic environment. It is abundant in the Sabará Formation north of the Serra do Curral, near the contact of a granitic intrusion. Along the southern and western margin of the Bação Complex, staurolite is commonly found in pelitic schist of the Nova Lima Group near a contact with granite. Staurolite also occurs in the Nova Lima Group in the Brumadinho quadrangle; in the northeastern part of the Quadrilátero Ferrífero in the Piracicaba Group in the Itabira and Monlevade quadrangles; and in the Itacolomí Series and Piracicaba Group in the southeastern part of the Quadrilátero Ferrífero.

The development of staurolite from chloritoid under progressive metamorphic conditions has been discussed in the section on chloritoid.

Staurolite is taken to represent the lowest pressure/temperature conditions of the almandine-amphibolite facies and the higher grade part of the almandine zone of regional metamorphism; it is developed typically in pelitic assemblages (Fyfe and others, 1958, p. 229). With higher pressure/temperature conditions than those of the almandine zone or the lower part of the almandine-amphibolite facies, staurolite breaks down to quartz and kyanite or to sillimanite and almandine (Turner and Verhoogen, 1960, p. 551).

Williamson (1953) states that an Fe_2O_3/Al_2O_3 ratio of about 0.40 in the rock is critical for the formation of chloritoid or staurolite; staurolite alone formed in a rock with a ratio of 0.24. The ratio, however, for sample A–4953 (table 21), a staurolite-garnet-mica schist from the Nova Lima quadrangle, is only 0.22. In all probability, the principal control for the development of staurolite is a very restricted pressure/temperature stability field in rocks of the correct chemical composition (Deer and others, 1962a, p. 158).

Refractive indices were not obtained for staurolite because of the very slight total range in indices and also because the relationship of optical properties to chemical composition is not known (Deer and others, 1962a, p. 157).

Staurolite was easily recognized in thin section by a pale-yellow or colorless to golden-yellow pleochroism, high refringence, and moderate birefringence. All large crystals, that is, 1–2 mm, as well as many of the smaller ones have a porphyroblastic sieve structure (fig. 24).

Staurolite is almost always associated with biotite, quartz, and muscovite. It averages 0.5 to 2 mm in size, generally is almost idiomorphic, poikilitically encloses quartz, and cuts chevron folding of the micas (fig. 31).

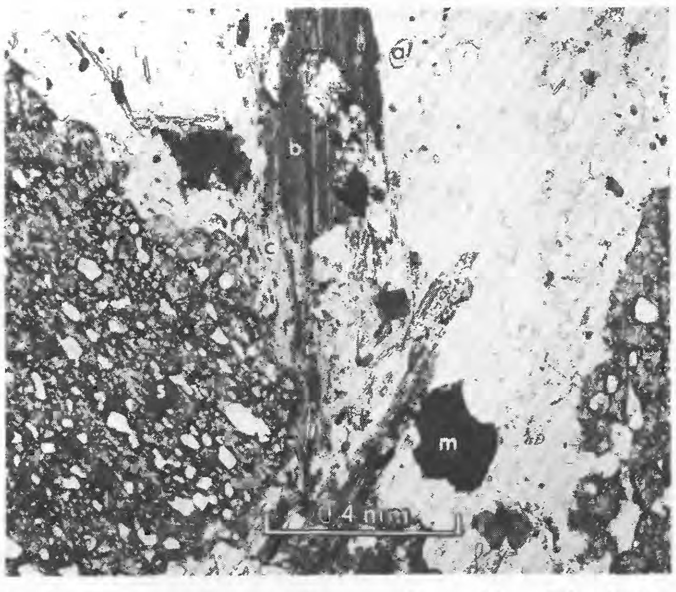


FIGURE 24.—Photomicrograph, staurolite schist, Sabará formation, 54–P–80, Ibirité quadrangle, plane light. Large poikilitic porphyroblasts of staurolite (s) with numerous inclusions of quartz and chlorite. Biotite (b) in part replaced by chlorite (c). Groundmass consists of quartz and muscovite. Magnetite (m) apatite (a) and garnet (not shown) are accessories. Staurolite, in left side of photograph, appears to have been replaced by biotite, and this, in turn replaced by chlorite.

Large amounts of garnet, chlorite (derived retrogressively from biotite, staurolite, or garnet), and tourmaline, and relatively small amounts of sodium-plagioclase and magnetite, occur in staurolite schist of the Sabará Formation north of the Serra do Curral (Gair, 1962, p. 41).

Staurolite commonly has been replaced by chlorite, muscovite, and quartz, and in some of the same rocks biotite is also replaced by chlorite. Chlorite in many rocks, however, does not appear to have developed either from staurolite or biotite. (See section on "Chlorite.") Staurolite in places has been replaced by chloritoid in rocks also containing quartz, muscovite, and chlorite. In general, however, the relations between staurolite and chloritoid are not clear.

Staurolite is present in heavy mineral concentrates from saprolite (R. E. Wallace, oral commun., 1960), and staurolite schist of the Sabará formation has been mapped on the basis of coarse grain size and distinctive crystal form preserved in saprolite.

AMPHIBOLE

Amphiboles are widely developed in the area. Actinolite-tremolite occurs in carbonate rocks and in dolomitic iron-formation of low metamorphic grade (fig. 25). At higher metamorphic grades, the grunerite-cummingtonite-kupferite series formed in dolomitic iron-formation, especially in the Congonhas area, at Brumadinho, north of the Serra do Curral near Sabará and Santa Luzia, in the Passagem mine, and south of the Bação Complex. Wherever metamorphism was sufficiently high to allow the formation of an aluminum-rich amphibole, hornblende or actinolitic hornblende developed in probable original argillaceous-rich carbonate rock or mafic igneous rock (fig. 26). Anthophyllite developed in talc- and chlorite-bearing dolomite east of São Julião (Guild, 1957, p. 16).

Tremolite-actinolite is common in magnesium schists in the lower part of the greenschist facies (Turner and Verhoogen, 1960, p. 534). It persists to the amphibolite facies but becomes rich in aluminum and slightly pleochroic.

Hornblende developed during the almandine-amphibolite facies metamorphism of mafic of calcareous rocks. At higher grades than almandine-amphibolite, hornblende pleochroism changes from shades of greenish-blue to greenish-brown, and presumably becomes richer in aluminum (Deer and others, 1963a, p. 304). Grunerite-cummingtonite is commonly formed in iron-rich rocks (fig. 28) and cummingtonite-kupferite in magnesian-rich rocks of the almandine-amphibolite facies. Minerals of both the hornblende and cummingtonite series are found in the highest grade of metamorphism, the eclogite facies.

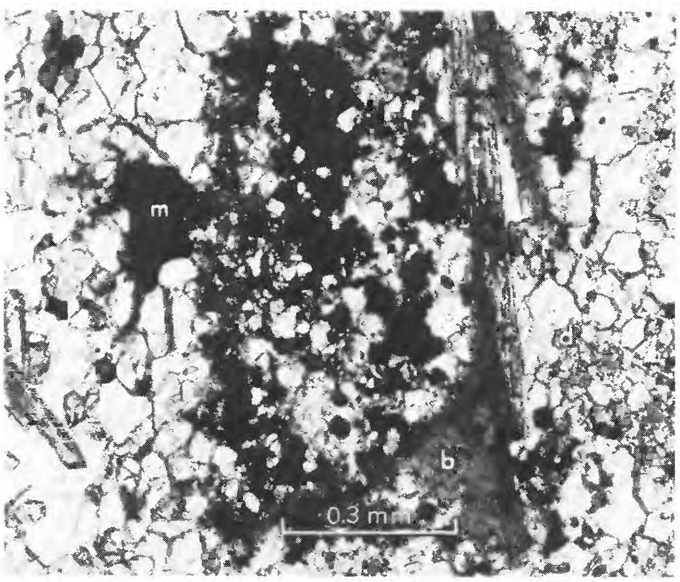


FIGURE 25.—Photomicrograph, dolomitic iron-formation, Itabira Group J-543. Dom Bosco quadrangle, plane light. Dolomite (d) in layers 1 mm thick, comprises 60 percent of the rock; magnetite (m) about 20 percent; and tremolite (t) about 20 percent. Biotite (b) is cut by and interleaved with tremolite.

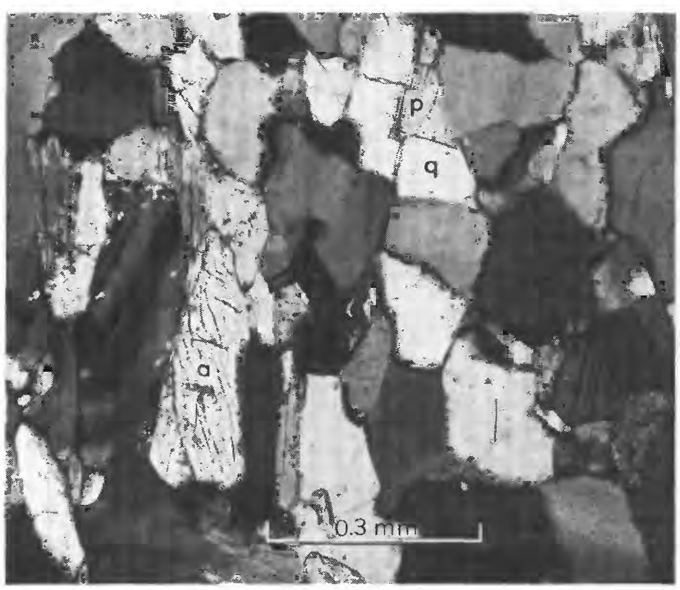


FIGURE 26.—Photomicrograph, pre-Minas quartzite, near granite contact, R-66-54, Bação quadrangle, crossed nicols. Quartz (q) occurs in large subangular grains; strained plagioclase about An_{70} (p) is twinned; amphibole (a) is weakly pleochroic hornblende.

OPTICAL DETERMINATION

The amphiboles were classified by their combined optical properties. The calcium-rich amphiboles were distinguished from each other primarily by pleochroism. Tremolite-actinolite was identified by an absence of, or low, pleochroism, comparatively low indices of refraction, and low birefringence. The alpha index for the tremolite-actinolite generally is between 1.62 and 1.63, and the gamma index, between 1.635 and 1.656. Actinolitic hornblende has a pale-green pleochroism and slightly higher indices of refraction, with alpha ranging from 1.62 to 1.64 and gamma, from 1.64 to 1.66. The pleochroism of the hornblende is from shades of yellow-green to blue-green to olive-green and indices of refraction range from 1.629 to 1.660 for alpha and from 1.656 to 1.690 for gamma. Actinolite of the greenschist metamorphic facies, however, may have a deep bluish-green pleochroism which is indistinguishable from that of hornblende of higher metamorphic grades (Turner and Verhoogen, 1960, p. 534). Such actinolite has a low Al_2O_3 content and is generally distinguished from hornblende only by its association with other minerals of lower metamorphic grade.

Minerals of the cummingtonite series have either pale straw maximum pleochroic absorption or none and indices of refraction are about the same as the indices of hornblende. Many specimens are multiple twinned on (100) and nearly all have a higher birefringence than actinolite.

ASSEMBLAGES

Actinolite is associated with dolomite, or quartz, muscovite, and epidote in carbonate-rich or quartz-rich rocks of low metamorphic grade (table 17). Biotite, kyanite, and garnet in association with the above minerals evidently indicate metamorphism at higher temperatures than those represented by the lowest grade assemblages. Higher grade is also indicated by an aluminum-rich actinolite together with andesine-oligoclase, quartz, epidote and biotite; muscovite, garnet, and hornblende are also seen in places.

In highly metamorphosed rocks derived from argillaceous dolomite, mafic igneous rock, or carbonate iron-formation, tremolite crystallized in equilibrium with hornblende, biotite, quartz, magnetite, and apatite or with diopside, quartz, specular hematite, magnetite, and carbonate. The size of tremolite-actinolite crystals generally increased with increasing degree of metamorphism.

Tremolite-actinolite is relatively uncommon in the low-metamorphic-grade carbonate rocks of the western part of the area. Tremolite occurs in dolomite and dolomitic itabirite at Fecho do Funil in the Brumadinho quadrangle (Guimarães, 1951, p. 54) and near Riberão da Colónia in the southern part of the Dom Bosco quadrangle (Johnson, 1962, p. 15). In both places high values of P_{H_2O} relative to P_{CO_2} must have facilitated the development of tremolite, whereas elsewhere a high P_{CO_2} must have been maintained in pore fluids during metamorphism. Near the edge and within the Bação Complex, aluminous actinolite and hornblende occur in schists and metamorphosed mafic dikes.

Hornblende is present in amphibolite and in metadiabase dikes throughout the region, in mafic xenoliths (fig. 27), in correlatives of the Itabirito granite (Pomerene, 1964, p. 33), and in metamorphosed carbonate and pelitic rocks. Amphibolite derived from carbonate rock or mafic dike rock is most common near Itabira (Dorr and Barbosa, 1963, p. 35–37) and Monlevade (Reeves, 1966, p. 13, 19) in the eastern part and in the southwestern part of the Quadrilátero Ferrífero. The most simple, but not the most common, assemblage, consists of hornblende, epidote, and quartz, and, in places, chlorite or biotite and other accessory minerals (table 18). A much more widespread assemblage typical of rocks high in aluminum and alkaline earths consists of hornblende, plagioclase An_{15-35}, quartz, epidote, biotite, chlorite, and almandine-rich garnet or microcline.

Hornblende occurs as discrete prisms in quartz-amphibolites and consists of ragged uralitic crystals having pale pleochroism derived from pyroxenes in metamorphosed mafic igneous rocks. The grain size of hornblende appears to have no relationship to degree of metamorphism, although large poikilitic crystals are developed only at the highest degrees.

An unidentified fibrous amphibole occurs in some graywackes of the Nova Lima Group in the Rio Acima quadrangle (Gair, 1962, p. 23) and is attributed to admixtures of volcanic material in the original sediment. Assemblages of hornblende and pyroxene are further discussed under pyroxenes.

The grunerite-cummingtonite-kupferite series is developed in carbonate rock and iron-formation in the amphibolite and higher metamorphic facies. The assemblage in carbonate rocks is cummingtonite or kupferite, dolomite, quartz, and commonly, magnetite (table 19). In dolomitic iron-formation near granitic intrusives, or in roof pendants or xenoliths of iron-formation, grunerite occurs with quartz, magnetite, and garnet or biotite and chlorite. The grunerite iron-

TABLE 17.—*Assemblages containing actinolite-tremolite or actinolitic hornblende*
[Abbreviations explained in table 2]

Assemblage	Rock type	Amphibole data	Location, formation
Tr-mg-qz-(hm) (cl) (tm) (ta) (ep).	Dolomitic itabirite.	Indices=1.623, 1.629, 1.632; clusters of fibers as large as ± 1 cm.	Congonhas district (Guild, 1957, p. 15), Dom Bosco quad; Gandarela Formation.
Tr-cl-qz-ep-mu-(bi) (cb) (sp) (tm) (zr).	Qz-amphibolite	Indices=1.630, 1.656; pleochroism is lt green to colorless.	Rio de Pedras, Bação, Gandarela quads; Nova Lima Group, Gandarela Formation.
Tr-bi-qz-mu-ep-(ky) (ga) (gr) (cl).	Schist	Colorless; partly replaced by chlorite.	Dom Bosco, Ouro Prêto quads; Nova Lima Group.
Ah-qz-an$_{24-48}$-ep-(bi) (ga) (hb) (py) (il) (lc).	Qz-amphibolite, schist.	Indices=1.620 to 1.638 (α), 1.644 to 1.659 (γ); pleochroism = lt green to colorless.	Bação, Cachoeira do Campo quads; Nova Lima Group.
Tr-dp-cb-qz-hm-mg	Carbonate iron formation.	Indices=1.625, 1,645; pale blue.	Dom Bosco quad; Gandarela Formation.

TABLE 18.—*Assemblages with hornblende*
[Abbreviations explained in table 2]

Assemblage	Rock type	Amphibole data	Location, formation
hb-an$_{14-35}$-qz-ep-(bi) (cl) (mg) (cb) (mu) (sp) (hm) (zr) (lc).	Largely amphibolites, also metadiabase, mafic xenoliths in granite.	α indices = 1.639–1.660, γ indices = 1.656–1.690; pleochroism = dusky yellow green to yellow gray or shades of deep green.	Bação, Belo Horizonte, Caeté, Cachoeira do Campo, Dom Bosco, Itabira, Itabirito, Marinho da Serra, Monlevade, Nova Lima, Ouro Branco, Ouro Prêto, Rio Acima, São Bartolomeu quads; and Congonhas district; sills, dikes, xenoliths, Nova Lima and Gandarela equivalents(?).
hb-an$_{12-20}$-ep-cl-ga-(kf) (mg) (bi) (cb) (ap) (sp) (tm).	Amphibolite, metadiabase.	α indices = 1.629–1.660, γ indices = 1.659–1.690; pleochroism = deep blue green to yellow green	Same as above.
hb-qz-ep-(bi) (cl) (cd) (ap) (mg) (tm).	Amphibolite	plechroism = deep green; α index = 1.660, γ index = 1.690.	Itabira, Ouro Prêto, Rio Acima quads, Congonhas district; sills, dikes.
hb-pl-dp-bi-(ep) (se)	Mafic xenolith	Deep green pleochroism.	Belo Horizonte quad.

TABLE 19.—*Assemblages with grunerite-cummingtonite-kupferite*
[Abbreviations explained in table 2]

Assemblage	Rock type	Amphibole data	Location, formation
Cu-cb-qz-mg-(hm)	Dolomitic itabirite.	α indices = 1.650 to 1.653; γ indices = 1.678 to 1.684.	Brumadinho, Passagem quads, Congonhas District; Itabira Group.
Cu-cb-qz-ga-rd-(etc)	Mn-silicate-carbonate protore.	"Asbesti-form."	Lafaiete District (Dorr and others, 1956).
Kp-cb-qz-mg-(hm)	Dolomitic itabirite.	α index ~ 1.65, γ index ~ 1.69; pale straw color.	Congonhas district.
Gn-qz-mg-(bi) (cl)	Itabirite	Colorless prisms, 0.15 to 0.77 mm.	Nova Lima quad, Sabará Formation(?).
Gn-qz-ga-mg-dp	do	do	Santa Luzia quad, Sabará Formation(?).
Gn-qz-ga-mg-ep-(se)	do	Dark yellow green to dark green, $Z \wedge c \sim 10°$.	Itabira, Itabira Group xenolith in granite.

formation is best developed in Itabira and north of the Serra do Curral in the Santa Luzia and Nova Lima quadrangles near the contact with the youngest granite. The kupferite-cummingtonite rock occurs in the Brumadinho and Congonhas areas and near Passagem.

South of the Quadrilátero Ferrífero, in the Lafaiete area, an asbestiform manganoan cummingtonite is developed in a sedimentary silicate-carbonate protore of manganese associated with rhodochrosite, spessartite, rhodonite, graphite, quartz, and other accessory minerals (Dorr and others, 1956, p. 291).

RETROGRADE METAMORPHISM AND WEATHERING

During retrograde metamorphism, hornblende is replaced by biotite or chlorite or both, and other amphiboles are replaced largely by chlorite.

The amphiboles are unstable during weathering. In saprolites apparently derived from amphibole-rich rocks, amphiboles have been completely replaced by clay minerals but original structures are commonly preserved.

PYROXENE

Pyroxenes are uncommon in metamorphic rocks of the Quadrilátero Ferrífero. The few occurrences are in contact metamorphosed, mafic or calcareous rock or iron-formation, especially xenoliths. Some pyroxene assemblages occur in apparently anomalous locations away from areas of known igneous activity; some of these occurrences, however, are believed to be related to unexposed intrusive rocks.

Pyroxene, generally diopside, is formed in association with hornblende by the metamorphism of calcareous or mafic rocks at the highest temperatures of the amphibolite facies. In the higher temperature granulite facies, diopside is associated with hypersthene (Turner and Verhoogen, 1960, p. 548–555).

Diopside occurs in minor amounts in mafic xenoliths or layers in the granite gneiss north of the Serra do Curral, typically in assemblages consisting of abundant hornblende and sericitized plagioclase, plus minor biotite (fig. 27). The diopside crystals range in size from about 0.2 to 0.4 mm and have sharp contacts with hornblende, but they are embayed by feldspar.

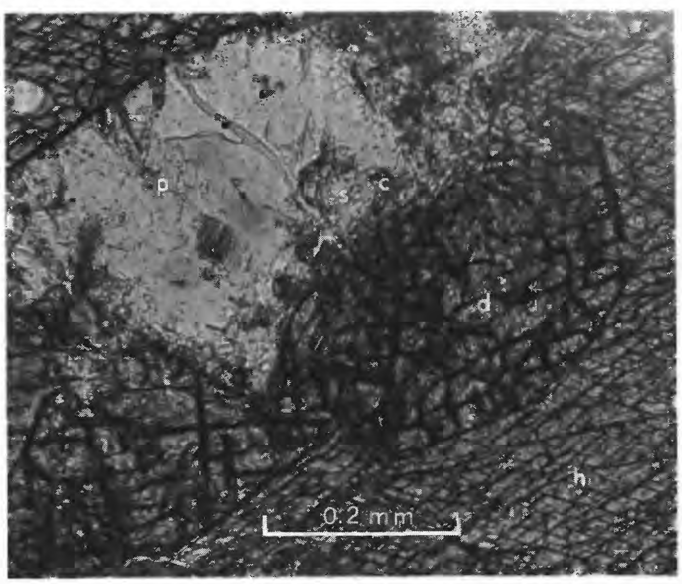


FIGURE 27.—Photomicrograph, mafic xenolith in granite gneiss, 53–P–34A, Belo Horizonte quadrangle, plane light. Hornblende (h) comprises about 50 percent of the xenolith; plagioclase (p) forms about 40 percent and is replaced in part by clinozoisite (c) and sericite (s). Diopside (d) has straight boundaries against hornblende, but frays into plagioclase.

In the Passagem gold mine a pale-green pyroxene, probably acmite-diopside, is associated with cummingtonite, quartz, magnetite, and dolomite in magnetic dolomitic itabirite (fig. 5). There is no apparent reason for a higher grade of metamorphism at Passagem. The pyroxene grains are as much as 1 to 2 mm in length and are concentrated in thin laminae. Alternating laminae rich in magnetite, quartz, carbonate, amphibole, and tourmaline have subhedral grains ranging in size from less than 0.01 to more than 0.2 mm.

North of the Serra do Ouro Branco, diopside and actinolite occur in banded specular hematite and quartz-magnetite-carbonate iron-formation of the Piracicaba Group. The diopside is pale green, averages about 0.04 mm in diameter and forms aggregates; its n_α of 1.690 suggests hedenbergite$_{35}$. The chemical composition of the iron-formation (sample J–687–1, table 32, no. 13) could have been derived from dolomitic itabirite that recrystallized under moderate temperatures and resulted in a loss of CO_2.

Some highly metamorphosed dolomitic itabirite, as in Santa Luzia, contains layers of compact andradite garnet (fig. 28) but is otherwise identical to the rocks described above.

In mafic igneous rocks and xenoliths that contained pyroxene, pale-green uralitic hornblende and chlorite have formed by retrograde metamorphism, and, under the subtropical weathering conditions, pyroxene has broken down readily to chlorite or clay minerals.

GARNET

Garnet is widely distributed in rocks of medium and high metamorphic grade. It is abundant in pelitic and metavolcanic rocks of the Sabará Formation along the northern slope of the Serra do Curral; in the Rio das Velhas Series bordering the Bação Complex and, within it, in roof pendants and xenoliths; in amphibolite, quartzite, and schist in the Ouro Prêto area; in the southern part of the Congonhas district; in the Monlevade and Itabira Districts; and elsewhere in the eastern part of the Quadrilátero Ferrífero.

The pyralspite garnets (pyrope-almandine-spessartite) plus grossularite are the most important in metamorphic rocks, although grossularite-andradite is well developed in impure calcareous rocks and iron-formation metamorphosed at moderate or high grades (Deer and others, 1962a, p. 86). Spessartite crystallizes in manganese-rich rocks in the lowest part of the greenschist facies (Turner and Verhoogen, 1960, p. 537). In the upper greenschist, the epidote-amphibolite, and the amphibolite facies, the almandine molecule is a significant part of the garnet; in the granulite and eclogite facies, the pyrope molecule becomes an important constituent of garnet. Grossularite is an important constituent in metamorphosed pelitic rocks and mafic igneous rocks. Refractive index generally increases and the unit cell edge shortens in the series from Mn- to Fe- to Mg-rich garnet with increasing metamorphism (Sriramadas, 1957).

OPTICAL DETERMINATION

Indices of refraction and unit cell edges were determined for selected samples of garnet (table 20). The reflections used for the cell-edge calculation were at 2θ angles of about 30°–31°, corresponding to (400); 34°, corresponding to (420); and 38°, corresponding to (422).

The index of refraction and the cell edge allow a determination of garnet composition but, unfortunately, not a unique one. In the absence of chemical data, certain arbitrary assumptions must be made in order to use the determinative curves of Sriramadas (1957). According to a statistical study of chemical analyses by Wright (in Deer and others, 1962a, p. 85) the garnet molecules present in biotite schist and amphibole schist are generally almost only almandine, pyrope, and grossularite, and in contact metamorphosed calcareous rocks, they are andradite and grossularite. It is assumed that the garnets in this study are similar to those of Wright's world-wide sample and therefore, depending on the rock type, only the curves of Sriramandas for those molecules mentioned herein have been used.

ASSEMBLAGES

In rocks of low to moderate metamorphic grade in the Belo Horizonte, Itabirito, and Brumadinho quadrangles, garnet is associated with quartz and muscovite in the Sabará formation and the Nova Lima Group. It is invariably euhedral, poikilitically encloses quartz and opaque minerals, and has a great range in grain size, from 0.05 to about 0.5 mm. Chlorite and magnetite are common accessory minerals; biotite is a less common accessory in rocks containing little or no chlorite. In the upper Piracicaba Group in the Casa da Pedra quadrangle (at N5700, W2100) chloritoid, magnetite, pyrite, and zircon form another accessory assemblage.

In rocks of the lowest metamorphic grade, garnet, probably spessartite, associated with quartz, chlorite, sericite, and limonite is now represented only by its manganiferous weathering products. In places, spessarite evidently made up a large part of the rock, as in Piracicaba phyllite of the Jeceaba quadrangle (Guild, 1957, p. 19), where it composed 25 percent. In greenschist of the Rio das Velhas Series in the Congonhas quadrangle, Guild reports that spessartite intercalated with quartz composes about 60 percent of the rock. Quartz and pale amphibole are present in the garnet-rich layers.

Dorr and Barbosa (1963, p. 53) identified spessartite in rocks of the Piracicaba Group in the Itabira quadrangle but considered it hydrothermal in origin, related to nearby manganese deposits. According to Miyashiro (1953), manganese-rich garnet is typical of a low-pressure metamorphism, which is consistent with a hydrothermal origin and also explains why spessartite garnet, in general, is rare in the Quadrilátero Ferrífero. High-pressure minerals such as kyanite, on the other hand, are common.

Because of the relatively high pressure/temperature conditions that obtained within the contact aureole of the Bação Complex in the Itabirito, Dom Bosco, and Cachoeira do Campo quadrangles, euhedral garnet developed in association with biotite, quartz, and chlorite in pelitic rocks (fig. 6). Five garnets from pelitic rocks of the Bação Complex are within the compositional range, pyr_{23-30}, alm_{55-66}, gro_{5-19}. The size of garnet averages about 0.5 mm in such rocks, but may be as large as 1 mm or more. In some rocks, chlorite is the same grain size as biotite and appears to have developed at about the same time. In others, chlorite is finer grained than biotite and forms kelyphitic rims around garnet. Other possible mineral assemblages with garnet-biotite-chlorite include andesine-oligoclase, microcline, magnetite, tourmaline, carbonate, sulfides, apatite, ilmenite and zircon. In some chlorite-free rocks, garnet, biotite, and quartz are associated with plagioclase, about An_{70}.

These mineral associations are typical of the almandine zone of regional metamorphism and the garnet in such rocks should be almandine-rich (Turner and Verhoogen, 1960, p. 533). Almandine-rich garnets, alm_{55-57}, were found in samples of pre-Minas rock R–46–54 (table 20), in the Bação quadrangle and in J–45–55 and J–750 of the Cachoeira do Campo quadrangle (table 20).

Near the southern edge of the Bação Complex, pre-

TABLE 20.—*Garnet assemblages and physical properties*
[Abbreviations explained in table 2]

Specimen	a_0[1] (A)	Index	Assemblage	Rock type	Garnet composition [2]	Location
R–46–54	11.569	1.782	Ah-an_{26}-qz-ga-bi-ep-op	Rio das Velhas qz-am-ga schist.	$Pyr_{26}alm_{55}gro_{19}$	Bação quad, N480, E5620.
R–124–54	11.527	1.792	Qz-an_{35}-bi-ga-st	Rio das Velhas qz-bi-ga schist.	$Pyr_{28}alm_{66}gro_{6}$	Bação quad, N730, W3780.
J–45–55	11.552	1.786	Qz-an_{40}-cu-ga-bi-op	Roof pendant of pre-Minas schist.	$Pyr_{30}alm_{56}gro_{14}$	Cachoeira do Campo quad S2260, W3680.
J–399	11.602	1.792	Hb-qz-an_{25}-ga-mg	Amphibolite dike in gneiss.	$Pyr_{12}alm_{62}gro_{26}$	Dom Bosco quad, S1340, E3550.
J–750	11.556	1.788	Ah-qz-bi-mu-ga-il	Rio das Velhas qz-am-ga schist.	$Pyr_{28}alm_{57}gro_{25}$	Cachoeira do Campo quad, N3550, E120.
JG–86–56	11.580	1.797	Qz-mu-ga-st-pl-mg-cl [3]	Sabará formation qz-ga-st schist.	$Pyr_{14}alm_{67}gro_{19}$	Nova Lima quad, S140, E4250.
51–G–154	11.547	1.793	Qz-bi-mu-ga-si-cr-op	Qz-bi-ga gneiss.	$Pyr_{23}alm_{65}gro_{12}$	Bação quad, N680, W4580.
H–24n	12.051	1.882	Qz-gn-mg-dp-ga-hm	Banded gn-dp-ga iron-formation.	$Andradite_{100}$	Near Santa Luzia on Monlevade-Belo Horizonte highway.

[1] Analyzed with x-ray diffractometer, CuKd radiation, at 0.5° 2θ/minute from 2θ 26°–42°.
[2] Pyr=pyrope, alm=almandine, gro=grossularite
[3] Retrogressive.

Minas rocks of probable mafic-volcanic origin were metamorphosed in the lower part of the almandine zone; these rocks also form roof pendants in the complex. A garnet from amphibolite in this area has the composition $pyr_{12}al_{62}gro_{26}$. Garnet in these rocks ranges in size from fine grained to 15 mm, and is associated with quartz, colorless tremolite-actinolite or cummingtonite, biotite, and in places chlorite, muscovite, epidote, oligoclase-andesine, magnetite, pyrite, and carbonate. In the Itabira quadrangle (Dorr and Barbosa, 1963, p. 15), chlorite schist of possible metavolcanic origin in the Rio das Velhas Series contains prismatic garnets as much as 15 mm in length.

Garnet is associated with quartz, actinolitic hornblende, and almost invariably with andesine or calcic oligoclase, An_{22-50} (as in J–399, Dom Bosco quadrangle, table 20) in mafic volcanic rocks metamorphosed at the highest pressure/temperature conditions of the almandine-amphibolite facies. Accessory minerals include epidote, magnetite, carbonate, biotite, apatite, chlorite, and pyrite. The garnet has about the same range in index of refraction and grain size as in the lower grade tremolitic rocks. Such garnet-bearing amphibolites also occur in the Nova Lima quadrangle (Gair, 1962, p. 42) and in the Monvelade area (Reeves, 1966, p. 13).

At the same level of metamorphism—the upper part of the almandine-amphibolite facies—in pelitic rocks, garnet is associated with staurolite, or rarely with kyanite, as south and west of the Bação Complex (R124–54, table 20) and north of Sabará (JG86–56, table 20). The garnet-staurolite assemblage also includes biotite, quartz, muscovite, and in places chlorite, andesine, magnetite, apatite, and ilmenite (fig. 30). The grain size of garnet is generally coarse, as much as 7 mm.

A sillimanite-garnet-cordierite-biotite-quartz-muscovite assemblage occurs in the contact zone of the Bação Complex, in the southern part of the Bação quadrangle (51–G154, table 20). Kyanite-garnet with quartz and muscovite is found in schist and quartzite in contact metamorphic aureoles in the Itabira District (Dorr and Barbosa, 1963, p. 53) and around the Bação Complex (Bação quadrangle, N420, E5790).

Pure andradite garnet, grunerite, and diopside crystallized in iron-formation that was engulfed by granite in the Itabira, Santa Luzia, and Nova Lima quadrangles (H–24n, table 20). In the occurrence in the Santa Luzia quadrangle, garnet forms massive layered aggregates, 0.1 to 0.5 mm in width, that generally enclose a thinner layer of magnetite (fig. 28).

In the Itabira quadrangle, andradite occurs in banded quartz-magnetite-grunerite-epidote-muscovite-iron-formation with no associated pyroxene. Much of this garnet is in discrete euhedral grains averaging 0.06 to 0.15 mm.

RETROGRADE METAMORPHISM AND WEATHERING

Garnet commonly retrogresses to chlorite, but in many rocks kelyphitic borders of chlorite preserved garnet grains from further retrograde effects (fig. 6).

Garnet is rarely fresh in outcrops, and typically is replaced by hydrous oxides of iron or manganese. The field identification of spessartite-rich garnet was almost always based on the presence of manganese decomposition products pseudomorphous after dodecahedral garnet. Most decomposed garnet, however, has been replaced by hydrous iron oxides, suggesting a high proportion of original almandine molecule.

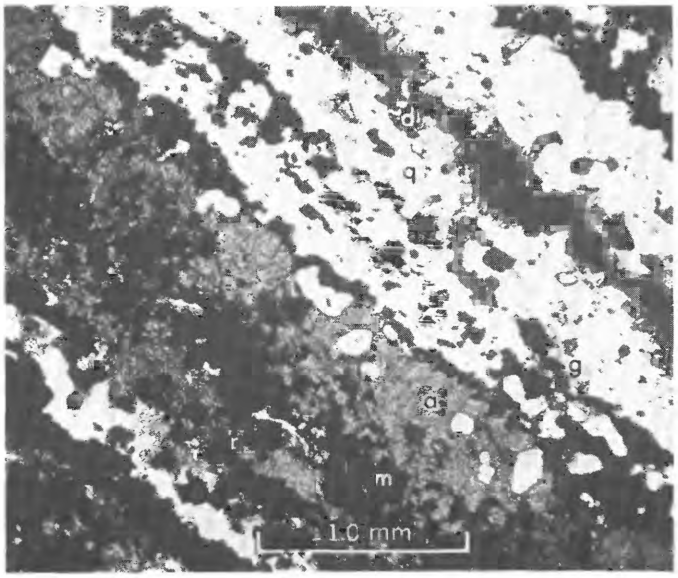


FIGURE 28.—Photomicrograph, garnetiferous iron formation, Itabira Group(?), in roof pendant in granite, H–24n, Santa Luzia quadrangle, plane light. Layers of almost pure andradite garnet (a), quartz (q), specularite (s), and magnetite (opaque, m) occur. Grunerite (g) and diopside (d) appear between the other minerals.

EPIDOTE

Epidote minerals, including zoisite and clinozoisite, are common in both the greenschist and the amphibolite facies of regional metamorphism. Epidote is a common minor constituent of "dirty" carbonate rocks, carbonate iron-formation biotite- and plagioclase-bearing phyllite and graywacke. At low metamorphic temperatures, it forms in lime-rich rocks instead of anorthite if Fe^{3+}/Al is sufficiently high (Ramberg, 1952, p. 51) Plagioclase cannot take up more than 0.5–1.0 percent of Fe_2O_3 whereas epidote can have over 20 percent. This figure suggests that more Fe^{3+} than Al may actually be found in octahedral sites in the lattice of some epidotes (Deer and others, 1962a, p. 199).

Epidote can form by prograde reaction in the greenschist facies, the upper limit of which has been defined (Ramberg, 1952, p. 140) by the reaction, calcite + chlorite + quartz = actinolite + epidote + H_2O + CO_2. Epidote commonly also forms by the retrogressive metamorphism of an anorthite-rich plagioclase in an excess of water – anorthite + H_2O = epidote + silica + alumina. Epidote then is a diagnostic mineral in both the greenschist facies, in the assemblage quartz-albite-epidote (Turner and Verhoogen, 1960, p. 533), and epidote-amphibolite facies. In the Quadrilátero Ferrífero, epidote formed both in prograde and retrograde reactions in rocks of the correct chemical composition, presumably with a high Fe^{3+}/Al ratio and abundant Ca and in a favorable physical environment.

Epidote in metamorphosed mafic rocks and quartz-rich sediments has a generally low index of refraction and birefringence and no pleochroism, all of which suggest a high percentage of the calcium aluminum molecule (clinozoisite). The alpha index in such epidote generally ranges from about 1.710 to 1.715. In metamorphosed carbonate iron-formation and amphibolite, the epidote is pleochroic, from pale yellow to very pale green, and birefringence and the alpha index are generally much higher, the alpha index averaging about 1.725 to 1.730. The alpha index suggests a composition of about 20 percent or more of pistacite, the Fe-rich component (Winchell and Winchell, 1951, p. 449). The pleochroism also indicates richness in iron.

The epidote minerals are widely developed in chlorite-quartz greenstones and phyllites of low metamorphic grade, carbonate-rocks, carbonate iron-formation, and all rocks containing albite. In metamorphosed mafic and ultramafic rocks, epidote is associated with plagioclase or chlorite. These associations have been described in some detail in the sections of chlorite, carbonates, and feldspar. Epidote comprises as much as 20 percent of greenschist of the Nova Lima Group in the Dom Bosco and Casa de Pedra quadrangles (Guild, 1957, p. 20–22); other major constituents are chlorite and quartz, and, in places, muscovite, magnetite, hematite, and sphene are common accessories. These rocks invariably contain layers alternately rich in quartz and chlorite. Fine-grained aggregates or discrete grains of epidote as much as about 0.3 mm in size are largely restricted to the chlorite-rich layers.

In rocks of higher metamorphic grade—the almandine-amphibolite facies of Turner and Verhoogen (1960, p. 544)—epidote is largely restricted to hornblende-bearing amphibolite (table 18) derived from mafic intrusive rock and to metamorphosed carbonate-grunerite iron-formation (table 19).

Epidote forms thin veins, averaging about 0.3 mm in width. In the staurolite zone in the Ibirité quadrangle, the veins cut gneiss and oligoclase biotite schist, but the epidote has no evident reaction relationship with the plagioclase and so may owe its origin solely to calcium metasomatism related to the nearby granitic intrusion.

Allanite commonly grades into epidote in amphibolites of higher metamorphic grade, such as those north of the Bação Complex, and 1 km east of Caeté (B. Alves, oral commun., 1961). The allanite is metamict and isotropic and occupies the central parts of very fine grained granular epidote-appearing aggregates.

Under weathering conditions, epidote minerals readily break down into indeterminate clay minerals.

TOURMALINE

Tourmaline of apparent metasomatic origin is disseminated widely in quartzite and schist or concentrated in veins that border granitic or gneissic rocks. Tourmaline of some quartz-tourmaline veins extends beyond the vein walls into the country rock. Many beds and lenses consisting of nearly pure tourmaline occur in pelites of low and medium metamorphic grade. Tourmaline of probable detrital origin, or derived from boron-rich sediments is also widely disseminated in phyllites and other metasedimentary rocks.

Tourmaline near granite contacts is commonly accepted as evidence of boron metasomatism, especially when the granite itself has been tourmalinized (Turner and Verhoogen, 1960, p. 575). In low-grade pelitic rocks, the evidence for origin is not clear, and Goldschmidt (1954, p. 288) has postulated that tourmaline was derived from a mobilization of chemically precipitated boron that was present in the sediments. Frondel and Collete (1957) synthesized tourmaline under conditions that ranged from 350°C and 2,000 bars to 550°C and 700 bars. This great range in temperature and pressure and the related tendency of tourmaline to persist to the highest grades of metamorphism eliminates it as a metamorphic index mineral.

Tourmaline was identified by pleochroism and indices of refraction (Winchell and Winchell, 1951, p. 465). Grains having a pale-yellow pleochroism and n_0 below about 1.65 are called dravite, the magnesium-rich tourmaline; those having pleochroism in shades of brown or green and having n_0 above 1.65 are called schorlite, the iron-rich tourmaline. Elbaite, the lithium aluminum-rich tourmaline has about the same indices of refraction as dravite, but has a much weaker pleochroism, colorless pink or pale blue to colorless, which was not seen.

Both dravite and schorlite occur near granitic contacts throughout the Quadrilátero Ferrífero in medium- to coarse-grained prismatic crystals, commonly forming rosettes in veins with quartz and, rarely, sulfide. Schorlite, the most common variety, is intergrown with minor amounts of quartz in pods and lenses in phyllite.

Slender needles of dravite of apparent metasomatic origin occur both disseminated and locally concentrated in the basal quartzite of the Moeda Formation of the Jeceaba and Casa de Pedra quadrangles (Guild, 1957, p. 12). The disseminated grains are slightly pleochroic in shades of yellow and $N_e=1.620$; the concentrated grains are pleochroic yellow to brown or pink to green and $N_e=1.630$.

Other tourmaline of possible metasomatic origin is contained in Cercadinho ferruginous quartzite, associated with kyanite and talc, in the Santa Rita Durão quadrangle (C. H. Maxwell, 1972); in phyllite of the Nova Lima Group (fig. 29); in the Batatal Formation in the Itabira District; and in the Cauê Formation and rich hematite ore at Pico de Itabirito (Dorr and Barbosa, 1963).

Tourmaline of probable detrital origin is a common accessory mineral in rocks of the Piracicaba Group in the Dom Bosco quadrangle and is especially abundant in quartz-chloritoid phyllite containing also magnetite, apatite, and sphene (Johnson, 1962, p. 17).

In almost all its occurrences, tourmaline was one of the last minerals to crystallize. Tourmalinite veins in areas where there is no known nearby granite body are attributed to boron-rich hydrothermal fluids. As far as can be determined, metamorphism had no effect on the occurrence of tourmaline. The importance of the type of country rock, however, can be seen at Salto in the Jeceaba quadrangle and in the southern

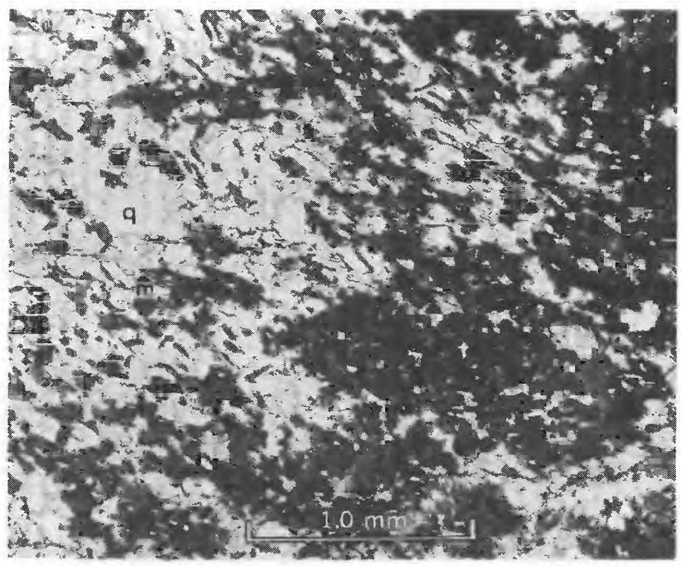


FIGURE 29.—Photomicrograph, quartz-tourmaline schist, Nova Lima Group, JG 88b–56. Nova Lima quadrangle, plane light. The rock is moderately foliated and composed essentially of quartz (q) and tourmaline (t). Well-alined muscovite (m) comprises about 3 percent of the rock. Hydrated iron oxides replace an earlier mafic mineral or sulfide. Tourmaline was the last mineral to crystallize.

part of the Bação Complex where tourmaline veins darken in color and the tourmaline evidently changes composition in passing from granitic rock or quartzite into phyllite (Guild, 1957, p. 12). The composition change must be from magnesium-rich dravite in the quartz-rich or granitic rock to iron-rich schorlite in the phyllite. Similar chemical changes also occur in kyanite (table 16).

Tourmaline is resistant to changes by metamorphism or weathering and has been recovered in heavy mineral residues of gneissic saprolite (Wallace, 1965).

OTHER MINERALS

Vesuvianite.—Vesuvianite occurs in minor amount in carbonate-bearing graywacke of the lower part of the Sabará Formation from the Belo Horizonte quadrangle (N1570, E2260). The associated minerals are quartz (about 50 percent), biotite (about 35 percent), and accessory plagioclase (about Ab_{90}), carbonate, magnetite, and epidote.

Apatite.—Apatite is common in amphibolite and metamorphosed mafic intrusive rock and other rocks that contain amphibole, as well as schists that are rich in muscovite or biotite. It is invariably prismatic, fine grained, and disseminated in the more mafic layers of the rock.

Talc.—Talc is found in metamorphosed ultramatic rocks, carbonate rocks, and in and near iron-formation. Fine flakes of talc of probable hydrothermal origin are commonly disseminated in siliceous parts of the Cauê Itabirite. In the Itabira district, for example, talc is the only visible "impurity" other than iron hydroxides in a rock made up of specular hematite and granular quartz (Dorr and Barbosa, 1963, p. 19). The talc is flaky green and tan, forms plates as large as 10 mm, and is concentrated largely on surfaces between the dominantly quartzose and the dominantly ferruginous layers. Talc veinlets in quartzite of the overlying Piracicaba Group follow bedding planes and joints and are attributed to the same solutions that were responsible for talc in the itabirite.

Sphene and rutile.—Sphene is common in amphibolite and mafic pelitic rock of all metamorphic grades. Grains range widely in size and are largely altered to leucoxene (fig. 1).

Fine needlelike inclusions of rutile occur in biotite and chlorite in gneiss, greenschist, and impure dolomite of the Gandarela Formation, as an accessory mineral in schist, phyllite, and quartzite of the Palmital Formation; and in vein quartz.

Hematite, magnetite, maghemite, and ilmenite.—Minor amounts of iron oxide are present in all types of rock and at all grades of metamorphism. Hematite is the major constituent of much itabirite; magnetite and maghemite are more abundant in carbonate-rich itabirites than in siliceous itabirites. Magnetite appears to be more abundant in rocks containing biotite and hematite in rocks containing chlorite.

Hematite ranges in grain size throughout the area from 0.05 mm in some itabirite to almost 1 m in the Cercadinho Formation in the Itabirito quadrangle (Wallace, 1965, p. 19). It is generally found in tabular plates or irregular grains. Magnetite occurs in euhedral grains, from fine grained in most rocks, to 7 cm in greenstone in the Cata Altas quadrangle (Maxwell, 1972). In places in itabirite, ragged magnetite grains are partially replaced by hematite (Pomerene, 1964, p. 42, for example).

Ilmenite is generally fine grained and identified in thin section by its leucoxene alteration products. It is a common accessory mineral in amphibolite and pelitic rock of the Nova Lima Group.

Zircon.—Zircon is widely distributed in minor amounts. It appears to be most common in amphibolite, but also occurs in schist and quartzite.

Sulfides.—Pyrite is disseminated in phyllite, dolomite, amphibolite, and other rocks. Other sulfide minerals are more common in veins in association with carbonates and quartz. In the Nova Lima quadrangle, gold-bearing sulfides are associated with "lapa seca," a rock consisting largely of quartz and dolomite or ankerite (Gair, 1962, p. 56).

Corundum.—Blue corundum is associated with deeply weathered feldspar in veins in the Belo Horizonte quadrangle (Pomerene, 1964, p. 36). Veins of andalusite-muscovite-quartz are associated with those of corundum and feldspar.

Topaz.—Topaz is associated with euclase and quartz crystals as large as 20 cm in a belt that parallels the Cercadinho Formation in the Ouro Prêto and Dom Bosco quadrangles (Gorceix, 1881; Derby, 1901). It is not known whether the minerals are in pegmatites or directly in phyllite. Pebbles of topaz also occur in streams near the village of Germano, in the Santa Rita Durão quadrangle in the eastern part of the Quadrilátero Ferrífero (Maxwell, 1972). The pebbles apparently are derived from the Cercadinho Formation and may be related to a large fault zone.

Manganese minerals.—Cryptomelane, polianite, psilomelane, pyrolusite, and manganite occur in manganese ores in the Quadrilátero Ferrífero and all are believed to be secondary and to be derived from manganese-rich dolomitic rocks (Dorr and others, 1956).

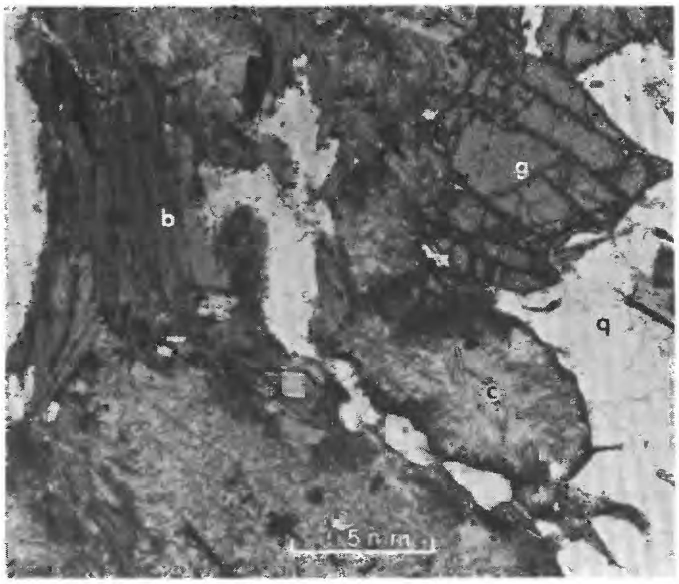


FIGURE 30.—Photomicrograph, garnet biotite cordierite gneiss 51-G-154. Bação quadrangle, plane light, strained quartz (q), biotite (b), dark yellowish-orange to colorless garnet (g). Most of the cordierite (c) is replaced by mica or clay. Sillimanite forms fine needles in the altered cordierite.

Cordierite.—Highly altered cordierite was identified optically in thin sections of quartz-almandine garnet-muscovite-biotite-sillimanite-cordierite schist from the contact zone south of the Bação Complex (51-G-154, table 20). According to Fred Barker, U.S. Geological Survey (oral commun., 1965), the cordierite strongly resembles altered cordierite found elsewhere in thin sections and is similar to that illustrated by Schreyer and Yoder (1961) (fig. 30). Sillimanite is an alteration product of the cordierite and is diagnostic of altered cordierite (Winchell and Winchell, 1951, p. 470).

PETROGRAPHY

PELITIC ROCKS

LITHOLOGY

CHLORITE ZONE

By far the most common types of rocks in the Quadrilátero Ferrífero are chloritic phyllite and schist of low metamorphic rank. They occur in all quadrangles and in almost every formation. Fuchsitic schists or graphitic phyllites are locally abundant, as are varieties rich in carbonate minerals, iron oxides, or tourmaline.

Grain sizes range from extremely fine, below the limit of optical resolution, to coarse grained. Where the grain size is medium coarse, muscovite and chlorite are well alined and the rock is strongly foliated. Nova Lima phyllites are largely gray green or green when fresh but weather to pinkish, red, maroon, or buff (Gair, 1962, p. 9). The Batatal Formation phyllite is light or dark gray (Maxwell, 1958, p. 61) and some other phyllites have merely been described as varicolored.

In most rocks of the Minas Series, bedding is apparent, whereas in parts of the pre-Minas it has been destroyed by shearing, retrogressive metamorphism, and phyllonitization (figs. 1 and 3; Wallace, 1965, p. 9). Phyllonitization is indicated by the recrystallization of elongate grains of quartz parallel to foliation planes (Williams and others, 1954, p. 207). Augen-shaped masses of quartz having serrated boundaries between grains and small folds in micas around the augen are taken as evidence of cataclasis. In rocks of the Minas Series, however, most quartz grains are equant and provide no evidence of cataclastic origin.

The most common mineral assemblage in the phyllitic rocks consists essentially of quartz, chlorite, and muscovite plus accessory iron oxides, tourmaline, carbonate minerals, and graphite. In rocks with a low ratio of K_2O: Al_2O_3 chloritoid also is developed (fig. 19).

Most of the pelitic rocks of the Quadrilátero Ferrífero are relatively high in Al_2O_3 and K_2O (tables 21, 32), and unusually low in CaO. Low CaO is typical of all Precambrian pelitic rocks, and is explained by the lack of lime-secreting invertebrates which are responsible for fixing lime and CO_2.

These pelitic rocks have one of the highest Al_2O_3/Na_2O ratios of any rocks in the world (Herz, 1962, p. 77) which indicates a mature sedimentary source. Sodium is easily leached from soils whereas aluminum generally remains, and neither is likely to be added or subtracted after deposition (Pettijohn, 1957, p. 103). The high Al_2O_3 is also accompanied by comparatively low SiO_2, which suggests that the original sediment was enriched in clay and impoverished in silt and so was extremely fine grained.

Comparatively few rocks in this area have higher soda and concommitantly lower alumina and potash, which leads to development of albite or oligoclase. Elsewhere in the world, plagioclase-bearing rocks are much more common, suggesting that pelitic rocks of the Quadrilátero Ferrífero were derived from areas undergoing intensive tropical weathering.

Most of the sodium-rich, feldspar-bearing phyllite

TABLE 21.—*Chemical analysis in weight percent of pelitic rocks* (*Herz, 1962*)

	Z–842	Z–597	J–84b	J–211	J–341	J–682b	BP–1	A–4953
SiO_2	56.1	61.6	62.4	57.3	58.6	61.9	68.8	60.0
Al_2O_3	18.8	24.5	19.2	20.4	22.1	19.7	17.0	18.7
Fe_2O_3	3.5	1.0	1.7	10.1	2.7	1.7	3.9	4.1
FeO	6.6	.1	3.1	1.2	5.8	2.4	.34	4.7
MgO	5.0	1.7	2.8	.66	2.2	3.9	.49	2.4
CaO	0	0	.12	.18	.13	.03	.01	.73
Na_2O	.1	.2	.32	.40	.26	.20	.18	1.1
K_2O	4.2	6.2	4.9	5.7	3.2	5.4	3.6	3.0
TiO_2	.3	.4	.62	.70	.75	.24	.63	.75
P_2O_5	.06	.09	.06	.16	.09	.05	.05	.14
MnO	.03	0	.02	.02	.16	.02	.02	.14
H_2O	5.0	3.8	3.9	2.8	4.1	4.4	3.6	3.2
CO_2			< .05	< .05	< .05	< .05	< .05	< .05
	99.7	99.6	99.1	99.6	100.1	99.9	[1] 100.1	99.0

[1] 1.5 percent organic matter.

Sample descriptions: Z–842. Rio das Velhas Series (Nova Lima Group?), slate. Opaque in thin section except for fine-grained angular quartz (<0.01 mm). Gandarela quadrangle, 11,100 N., 5,300 E. Analyzed by Cassio Pinto, D.N.P.M. Belo Horizonte; collected and described by J. E. O'Rourke.

Z–597. Batatal Formation, slate. Opaque in thin section except for fine-grained quartz (<0.01 mm). Gandarela quadrangle, 9,950 N., 5,700 E. Analyzed, collected, and described by same persons as sample Z–842.

J–84b. Moeda Formation, quartz-sericite phyllite. Coarse muscovite and sericite, 57 percent; quartz, 33 percent; limonite, 5 percent; chlorite, 2 percent; tourmaline, and other minor minerals 3 percent. Cachoeira do Campo quadrangle, 500 N., 12,600 E. Analyzed by P. L. D. Elmore, S. D. Botts, M. D. Mack, and H. W. Thomas, U.S. Geological Survey, Washington, D. C. (rapid rock analysis); collected and described by R. F. Johnson and Norman Herz.

J–211. Piracicaba Group, quartz-sericite phyllite. Quartz, 40 percent (<0.1 mm); sericite, 45 percent (<0.2 mm); chlorite, 5 percent; magnetite, apatite, tourmaline. Dom Bosco quadrangle, 7,400 E., 11,700 N. Analyzed, collected, and described by same persons as sample J–84b.

J–341. Piracicaba Group, quartz-sericite-chloritoid phyllite. Quartz, 40 percent (0.02–0.04 mm); sericite, 30 percent; chloritoid (late in paragenesis), 25 percent; chlorite, 5 percent; muscovite (1.5mm, late in paragenesis), magnetite. Dom Bosco quadrangle, 11,500 E., 11,600 N. Analyzed, collected, and described by same persons as sample J–84b.

J–682B. Piracicaba Group, quartz-sericite phyllite. Quartz, sericite, chlorite, muscovite, limonite (near granitized rock). Dom Bosco quadrangle, 3,250 N., 10,500 E. Analyzed, collected, and described by the same persons as sample J–84b.

BP–1. Piracicaba Group, Barreiro Formation, fine-grained graphitic phyllite. Ibirité quadrangle. Analyzed by P. L. D. Elmore, I. Barlow, S. D. Botts, and G. Chloe, U.S. Geological Survey, Washington, D. C. (rapid rock analysis); collected and described by G. C. Simmons.

A–4953. Sabará Formation, staurolite schist. Quartz, muscovite, biotite, some replaced by chlorite, late staurolite, garnet magnetite. Nova Lima quadrangle 2100 E., 11.600 N. Analyzed by same persons as sample J–84b; collected and described by B. E. Ashley and Norman Herz.

and schist occur in the Sabará Formation (Gair, 1962, p. 41), the Nova Lima Group (Dorr and others, 1957, p. 18), and the Moeda quartzite. A volcanic origin for the feldspar-rich beds of the Nova Lima has been proposed (Dorr and others, 1957) on the basis of composition and mineral associations. Simmons (1968b) concluded that a saprolite on the Nova Lima Group in the Barão de Cocais area is a metavolcanic rock because it is rich in relict feldspar laths, has no quartz, and weathers to a dark-brownish-red material. A volcanic origin for these rocks is reasonable considering that soda is generally low in the bulk of the other phyllites of sedimentary origin.

Feldspar porphyroblasts in metasedimentary rocks near granite contacts as in the basal Moeda Formation of the Macacos quadrangle are probably of metasomatic origin. The porphyroblasts are small and generally full of inclusions of quartz. The amount of feldspar decreases markedly within a short distance of the contact, suggesting that feldspar was related to potassium- and sodium-metasomatism controlled by a thermal gradient bordering the granite intrusion (Orville, 1963).

Minor elements in the pelitic rocks (table 22) are present in about the same proportions as they are in metasedimentary rocks the world over (Herz and Dutra, 1960, table 6).

BIOTITE AND HIGHER ZONES

BIOTITE SCHISTS

Biotite schist occurs widely in the Nova Lima Group and in the Sabará Formation, north of the Serra do Curral, and throughout the southern and eastern parts of the region. The appearance of biotite marks increasing temperature conditions over the chlorite zone.

Biotite schist is generally dark colored and has one or more well-developed foliation planes, the principal one being generally parallel to compositional layering. The biotite is generally coarse grained and is either lepidoblastic, forming part of the schistosity, or porphyroblastic. Augen structures are seen in which micas wrap around quartz-feldspar aggregates. The biotite is commonly interleaved with muscovite and chlorite; the three minerals may have grown together, biotite may have replaced chlorite or muscovite or biotite may have been replaced, especially by chlorite. The three minerals, together with quartz and accessory epidote and magnetite, are the most commonly found assemblage (fig. 14). In biotite schist of the Nova Lima Group, the common accessory minerals are carbonates, albite, epidote, graphite, and iron oxides. Elsewhere, assemblages include quartz-oligoclase-muscovite-biotite-epidote plus accessory tourmaline and

TABLE 22.—*Semiquantitative spectrographic analysis (in ppm) of minor elements in pelitic rocks*

[Analyst: Helen W. Worthing, U.S. Geological Survey, Washington, D.C., 1958. See table 1 for detection limits; table 21 for sample descriptions. Nd. no data]

	J84b	J211	J341	[1] J682b		A4953
As	Nd.	100	Nd.	Nd.		Nd.
B	1,000	300	300	30		30
Ba	1,000	300	300	3,000	(1,400)	1,000
Be	3	1	3	3	(5)	1
Ce	Nd.	Nd.	Nd.	100		Nd.
Co	10	10	10	10	(4)	10
Cr	300	300	300	30	(2)	300
Cu	30	3	10	10	(4)	30
Ga	30	30	30	30	(12)	30
La	30	30	30	100	(307)	Nd.
Mo	Nd.	10	10	Nd.	(2)	10
Nb	Nd.	Nd.	Nd.	100	(15)	Nd.
Ni	100	100	100	100	(6)	100
Pb	3	10	3	3	(30)	10
Sc	10	10	10	3	(5)	10
Sn	Nd.	Nd.	Nd.	3	(16)	Nd.
Sr	100	300	30	100	(24)	300
V	300	300	300	100	(21)	300
Y	30	30	30	30	(83)	30
Yb	3	3	3	3		3
Zr	100	300	100	300	(260)	100

[1] Values in parentheses are quantitative results by M. da S. Peres, Instituto de Tecnologia Industrial, Belo Horizonte.

magnetite, and quartz-oligoclase-garnet-biotite with accessory chlorite, potassium-feldspar, magnetite, and hematite.

GARNET AND STAUROLITE SCHISTS

Garnet-bearing and staurolite-bearing schists of high metamorphic grade are present in the Nova Lima and in the Piracicaba Groups (fig. 31) adjacent to large granitic bodies, for example, around the Bação Complex; north of the Serra do Curral (Gair, 1962, p. 52); in the Monlevade quadrangle (Reeves, 1966); the Itabira quadrangle (Dorr and Barbosa, 1963, p. 53); the Brumadinho quadrangle (Simmons, 1968a, p. 31) in the Congonhas district (Guild, 1957); and in the Ouro Prêto district (A. L. M. Barbosa, written commun., 1965).

North of Sabará a typical assemblage consists of quartz, muscovite, biotite, chlorite, and staurolite plus subordinate oligoclase, magnetite, and garnet (Gair, 1962).

These schists are generally dark colored, and their foliation planes are crinkled. Folia consist of alined flakes of mica and chlorite separated by quartz seams. Some samples have a micro-augen structure, in which blades of mica wrap around quartz grains or aggregates. Porphyroblasts consists of sieve-structured staurolite and garnet and of biotite. Most garnet is partially or completely replaced by iron oxides, and most staurolite, by silica, clay minerals, or sericite.

Sample A–4953 (table 21) is a typical garnet staurolite schist from north of Sabará. It is chemically similar to low-metamorphic-grade pelitic rocks except

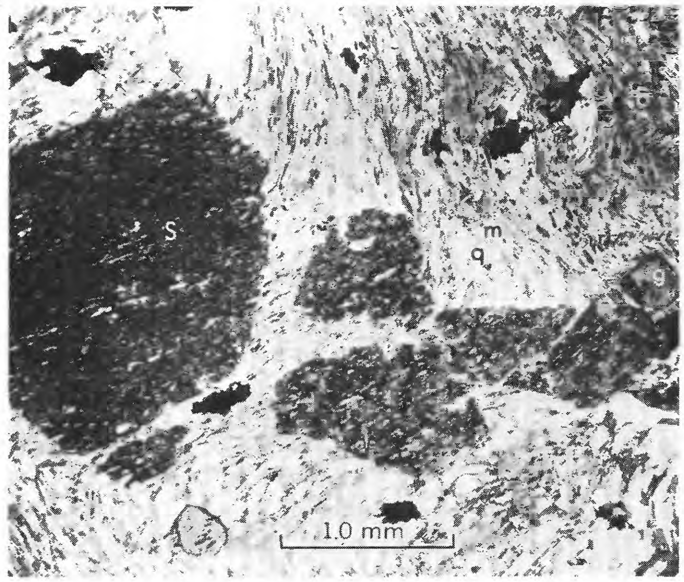


FIGURE 31.—Photomicrograph, staurolite schist, Sabará Formation, A–4953, Nova Lima quadrangle, plane light. Rock is strongly schistose and crinkled, composed essentially of quartz and muscovite, and has staurolite porphyroblasts. Staurolite (s) is poikilitic, and has a moderate yellow to grayish-yellow pleochroism. Quartz grains (q) have sutured boundaries. Muscovite (m) is tightly crinkled. Biotite (b) is partly replaced by chlorite. Small euhedral almandine-rich garnet (g) cuts foliation. Magnetite is common, especially inside quartz pods.

that it has somewhat higher sodium, which allowed plagioclase to crystallize. Minor elements in both the schist and the low-grade rocks (table 22) are of about the same order of magnitude, suggesting that metasomatism did not significantly change the chemical composition of the rocks. If this is so, then the higher sodium in the schist, which is still within the values given for common shales (Pettijohn, 1957, p. 344), may be fortuitous.

BIOTITE GNEISS

Pre-Minas biotite gneiss grades into, or is closely associated with, amphibolite, feldspathic gneiss, and biotite schist and has generally been mapped as "granitic" rock. Biotite gneiss in the Piracicaba Group, on the other hand, is not gradational into other types of rock and so is easily differentiated in the field. In the Itabira district, pre-Minas gneiss has been described as a specific petrographic type in a "granitic gneiss" complex but was not separated in mapping (Dorr and Barbosa, 1963). In the Monlevade district especially, gneiss poor in potassium-feldspar corresponds stratigraphically to beds of the Piracicaba Group and has been named the Bicas Gneiss (Reeves, 1966).

The Bicas Gneiss of the Monlevade district is light gray, granoblastic with fine- to medium-grained crystals, and has a granular texture. Biotite flakes comprise a strong planar orientation and elongation of quartz grains forms a weak lineation. A typical specimen (as Ha–37, table 27) is about half quartz and a quarter biotite; other minerals are plagioclase, about An_{30}, epidote, garnet, apatite, and zircon.

Rocks interbedded with biotite gneiss in the Monlevade and Itabira Districts contain magnetite and abundant coarse muscovite, which commonly lies at an angle to the foliation plane (as Ha–39, table 27). Variations in the relative proportions of minerals, and the addition in places of chlorite and potassium-feldspar, give rise to other types of gneiss.

Biotite gneiss and quartz-rich schist in the Nova Lima Group and Sabará Formation in the northwestern part of the Quadrilátero Ferrífero is medium grained, with or without strong foliation shown by micas (Gair, 1962, Pomerene, 1964). Quartz is slightly elongated and forms granoblastic mosaics and angular grains. These rocks grade into granitic gneiss and quartzite.

Two samples of biotite gneiss from the Monlevade District (Ha–37, 39, table 27) are similar except for the presence of coarse muscovite and correspondingly high K_2O in sample 39 and a lack of muscovite in sample 37. These gneisses are far richer in minor elements that have more of an affinity with late-stage phases of granitic intrusion, such as La, Nb, Sn, and Be, than are the other high-grade metamorphic rocks (table 28). The gneisses contain about the same amount of the basic elements, Co, Cr, Ni, V, and Zr, as the average pelitic rock.

Gneisses that are closely associated with granitic rocks are discussed in the report on igneous and gneissic rocks.

METAMORPHISM

Compared to others elsewhere, the pelitic rocks of this area have about average amounts of SiO_2, total iron, MgO, TiO_2, P_2O_5, MnO, and H_2O (table 23); somewhat above average amounts of Al_2O_3 and K_2O; and far below average amounts of CaO, Na_2O, and CO_2.

Assuming that the regional metamorphism led only to a loss of water and CO_2 and no significant changes in gross chemical composition, the regional average of 20.1 percent Al_2O_3, which contrasts with about 15–17 percent Al_2O_3 in average shale (Pettijohn, 1957, p. 365), suggests that an unusually large amount of residual clay was mixed with the original sediment.

The average pelitic rock of the Quadrilátero Ferrífero is also similar to typical residual clay (of analysis 4, table 23) in having a high oxidation ratio (Chinner, 1960, p. 187) (54.5 and 59.5, respectively) and abnormally low CaO and Na_2O. These data suggest that the source of material for the pelitic rocks was deeply weathered residual oxidized and leached soil low in alkalies and high in bauxite. The Al_2O_3/Na_2O ratio of 57 is intermediate between Nanz' (1953) ratio of 125 for pelitic rocks associated with orthoquartzites and 11 for pelites associated with immature sediments, such as graywackes, and is a further indication of a mature provenance for the rocks of the Quadrilátero Ferrífero.

Shales having more than 5 percent of K_2O constitute only about 5 percent of all shales (Pettijohn, 1957, p. 369). The average pelitic rock in the Quadrilátero Ferrífero has 4.5 percent K_2O; three samples contain more than 5 percent K_2O (table 21), as well as low CaO and Na_2O, in common with other high-potassium shales. A high potassium content in pelitic rocks is generally attributed to a reaction between clay minerals and sea water (Pettijohn, 1957, p. 370) so that, although all alkalies may have been leached during the predepositional weathering, potassium and magnesium can be restored on the ocean floor. Calcium, on the other hand, is normally regained in post-Precambrian sediments by addition from organic precipitation; the low value for CaO in the rocks of the Quadrilátero Ferrífero, as well as in the Precambrian rocks of Nanz', study, is attributed to the lack of biochemical processes in ancient seas. Soda is not nor-

TABLE 23.—*Average chemical analyses (in weight percent) of pelitic rocks in the Quadrilátero Ferrífero and elsewhere*

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	60.8	58.10	56.30	55.07	59.6	62.58
Al_2O_3	20.1	15.40	17.24	26.14	18.7	18.09
Fe_2O_3	3.6	4.02	3.83	3.72	1.7	1.60
FeO	3.0	2.45	5.09	2.53	4.8	5.07
MgO	2.4	2.44	2.54	.33	2.8	2.18
CaO	.15	3.11	1.00	.16	.4	.16
Na_2O	.35	1.30	1.23	.05	1.1	.81
K_2O	4.5	3.24	3.79	.14	4.7	3.68
TiO_2	.55	.65	.77	1.03	.86	.87
P_2O_5	.09	.17	.14	.11	.17	----
MnO	.05	---	.10	.03	.06	----
H_2O	3.7	5.00	3.69	10.39	4.6	4.18
CO_2	.05	2.63	.84	.36	----	.3
Sum	99.3	99.95	100.00	100.11	[1]99.8	99.5

Key:
(1) Average of 8 analyses (6 for H_2O and CO_2) (from table 21) of pelitic rocks, Quadrilatero Ferrífero.
(2) Average shale (Clark, 1924) quoted in Pettijohn (1957, p. 344); average of 27 Mesozoic and Cenozoic and 51 Paleozoic samples
(3) 33 Precambrian slates (Nanz, 1953, p. 57)
(4) Residual clay from gneiss (Goldich, 1938, quoted in Pettijohn (1957, p. 344)
(5) New Zealand argillites, average of 10 analyses (figured from Read, 1957, p. 28)
(6) Average of 7 low-grade pelitic rocks. Littleton Formation, New Hampshire (Shaw, 1956, p. 929)

[1] Includes 0.3 C.

mally restored on the sea bottom and so is very low in shales derived from maturely weathered sediments.

The dark-green and gray colors of these sediments suggest that they were deposited in a reducing environment (Pettijohn, 1957, p. 359). In such an environment, plus alkaline conditions, kaolinite would be unstable and other clay minerals such as illite and chlorite would form (Grim, 1953, p. 356). Presumably, the chief constituents of the detrital-silt fraction were bauxitic minerals accompanied by some quartz.

Authigenic changes and compaction may have produced illite and chlorite, hydrated aluminum oxide, quartz, and some iron oxides. Aluminum hydroxides were converted into clay micas and kaolinite on the sea bottom. Noll (1936) found that a combination of alkaline conditions, and a molecular ratio K_2O/Al_2O_3, of 0.2 to 0.37 was needed for such a clay-mica reaction. The pelitic rocks of the Quadrilátero Ferrífero have a K_2O/Al_2O_3 ratio of 0.24, and, from such indications as the oxidation ratio, formed in a reducing environment. It would not have been unusual for some kaolin to have formed under these conditions, as it does in many marine sediments (Grim, 1953, p. 355). Kaolinite develops by reaction between aluminum hydroxides, such as boehmite and silica at temperatures as low as 250°C and pressures of 41 atmospheres in sediments having a molecular ratio of SiO_2/Al_2O_3 of over 4:1 (Noll, 1936).

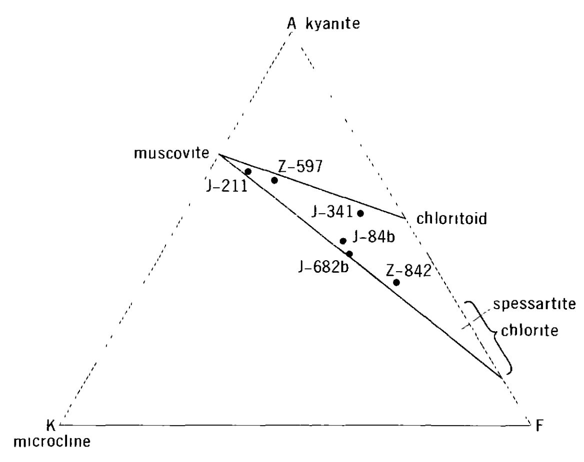


FIGURE 32.—Low-grade AKF diagram representing pelitic rocks of the Quadrilátero Ferrífero. $A=Al_2O_3+Fe_2O_3-(Na_2O+K_2O)$, $K=K_2O$, $F=MgO+FeO+MnO$. Numbers next to points are sample numbers. See Eskola, 1939, p. 347 for a complete description of the AKF diagram's construction.

In places, especially in rocks of high metamorphic grade from thermal aureoles around granitic intrusions, a high K_2O content may be due to potassium-metasomatism (Orville, 1963). The coarse muscovite of the Itacolomí quartzite (A. L. M. Barbosa, written commun., 1965) and the feldspar porphyroblasts in the basal Moeda Formation of the Ibirité quadrangle for instance are attributed to metasomatism. In these rocks, microscopic evidence has shown that potassium-rich minerals formed at the expense of nonpotassic minerals. In the average potassium-rich pelite of low metamorphic grade in the Quadrilátero Ferrífero, on the other hand, there is no such microscopic evidence of substitution, as for example, of muscovite for chlorite. The amount of K_2O furthermore, apparently is not related to either geographic position, or to structural position, making it unlikely that granite intrusions were necessarily a source of potassium-rich solutions. It should be noted that Precambrian pelitic rocks the world over have, in general, a higher K_2O content than do younger pelites (Nanz, 1953).

LOW-GRADE METAMORPHISM

Equilibrium mineral assemblages for rocks of different chemical composition in the greenschist facies can be shown in an AKF diagram (figs. 32, 33).

The most abundant minerals are quartz, sericite (muscovite), and chlorite, which places these rocks in the quartz-muscovite-chlorite albite subfacies of the greenschist facies (Turner and Verhoogen, 1960, p. 536). By chemical composition the rocks are within the muscovite-chloritoid-chlorite field of the AKF diagram. They have an average K_2O content of 4.8 percent; with lower K_2O, for example, 3.2 percent in J-341 (table 21), the rocks also contain chloritoid.

Many pelitic rocks that are richer in Al_2O_3 and lower in K_2O than the average pelite of the region also contain kyanite, which is shown at the A apex of both AKF diagrams; these rocks plot in the uppermost part of the AKF diagram.

The microcline-muscovite field of the AKF diagram is not known in the area. Although the pelitic rocks are rich in K_2O, considering the world average (table 23) they are alkali-deficient relative to Al_2O_3. Consequently, the formation of potassium-feldspar and albite were inhibited whereas the growth of muscovite was promoted.

At temperatures of about 200° or 300°C (see p. 71) to 400°C and pressures of 2,000 bars or higher, depending on the tectonic overpressure in local structures, chlorite and muscovite crystallized from the clay minerals. Epinormative minerals for pelites of low

TABLE 24.—*Epinormative minerals of low metamorphic grade in pelites that contain no chloritoid or carbon (Barth, 1959)*

Molecular percent			Accessories, apatite and ilmenite		White micas muscovite, paragonite		Chlorite amesite, antigorite		Quartz
SiO_2	71.5		--	--	24.0	1.2	3.4	0.3	42.6
Al_2O_3	14.4	16.0			12.06	.6	3.4	--	---
Fe_2O_3	1.6								
FeO	2.7			.5			6.8	.4	
MgO	5.0	7.7							
CaO	.1		.1		----	--	--	--	---
Na_2O	.2		--	--		.2	--	--	---
K_2O	4.0		--	--	4.0		--	--	---
TiO_2	.5			.5	----	--	--	--	---
P_2O_5	.0		--	--	----	--	--	--	---
MnO	.0		--	--	----	--	--	--	---
Sum	100.0		1.1		42.0		14.3		42.6

metamorphic grade that contain no chloritoid or carbon (Barth, 1959) were calculated from the chemical analyses (table 24) and these are identical to the modal minerals, suggesting that chemical equilibrium was attained during metamorphism. The epinorm has 42.6 percent quartz, 42.0 percent muscovite, 14.3 percent chlorite, and 1.1 percent accessories. For the calculations it was assumed that all K_2O was in muscovite and all Na_2O in paragonite as muscovite solid solution. (See p. 71.)

Of the chlorite-muscovite-quartz phyllites described chloritoid also formed in those containing less than about 4 percent K_2O and excess Al_2O_3 and relatively low CaO. Halferdahl (1961, p. 123) found that chloritoid formed from a mixture of clay minerals such as kaolinite, gibbsite, and chamosite and then remained stable at elevated pressures (above about 7,000 bars) to temperatures of 700°C.

There are certain similarities in chemical analyses of chloritoid-bearing rocks (all molecular ratios): (a) $Al_2O_3/Fe_2O_3+FeO+Mgo+MnO$ ratios are greater than one; (b) both numerator and denominator of (a) are greater than the sum of K_2O+Na_2O+CaO; (c) there is excess Al_2O_3 after figuring muscovite and chlorite in the norm; (d) FeO+MnO are greater than MgO, and (e) FeO+MnO are greater than Fe_2O_3 (Halferdahl, 1961, p. 109–111). All these conditions are met for sample No. J–341 (Herz, 1962, p. 76), so it can be assumed that the appearance of chloritoid in that rock is also a function of its chemical composition.

The chloritoid-bearing and the muscovite-chlorite-quartz phyllites must have had a similar provenance because the two types of rock are interbedded and gradational both vertically and laterally.

A manganese-rich variety of garnet may have been abundant in some rocks of the lowest greenschist facies but, unfortunately, is represented today only by manganese oxide weathering products and a general dodecahedral form. Although restricted in occurrence, it is locally abundant and formed large crystals.

MEDIUM-GRADE METAMORPHISM

Most of the minerals formed in alumino-potassic phyllites under greenschist conditions are stable at higher temperatures, especially if high temperatures are accompanied by very high load pressure. Sericite recrystallizes as coarse flakes of muscovite and chlorite tends to become coarser. Biotite may replace sericite or chlorite in a reaction which apparently involves a change from an Fe-rich chlorite to one rich in Al and Mg, at the expense of muscovite and quartz.

The crystallization of biotite must have taken place within a narrow pressure/temperature range in rocks that had sufficient K (of the AKF diagram) but had more F and less A than the more aluminous rocks in which chloritoid or kyanite crystallized. Osberg (1952, p. 104) found that biotite also appeared in Vermont in greenschist of low metamorphic grade that is relatively rich in F and poor in A.

No analyses plot below the muscovite-chlorite join in the AKF diagram representing low-grade metamorphic rocks (fig. 32) and, similarly, none of them have biotite. Biotite-bearing rocks such as H–39 fall near the muscovite-biotite join, in the A deficient field in the AKF diagram representing high-grade metamorphism (fig. 33). Although biotite occurs in some rocks that are in the chlorite zone and that contain plagioclase of composition An_{0-10} it is much more common in rocks that have been metamorphosed above the chlorite isograd and that contain plagioclase with an anorthite content of more than 10 percent.

Biotite-bearing pelitic rocks in the Quadrilátero Ferrífero are characterized by assemblages of biotite-muscovite-quartz and belong to the quartz-albite-epidote-biotite subfacies of the greenschist facies (Turner and Verhoogen, 1960, p. 537). Apparently the great excess of Al over alkalies and Ca in the Quadrilátero Ferrífero inhibited the crystallization of both feldspar and epidote, which are common in pelitic rocks elsewhere.

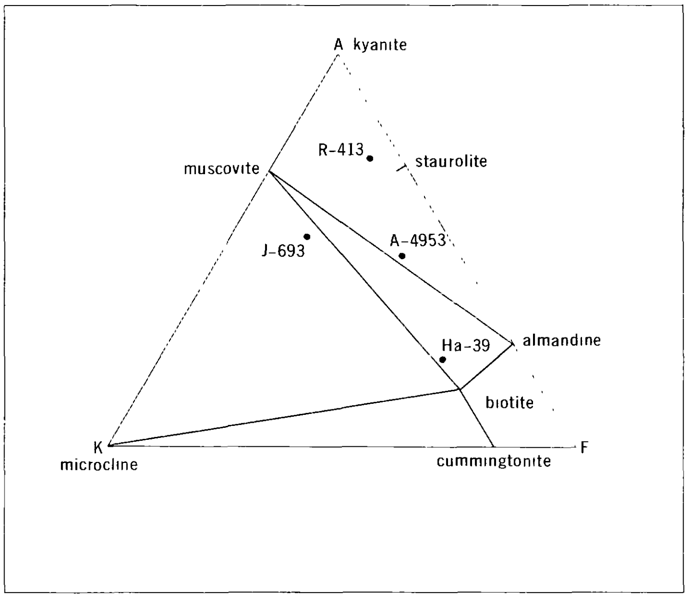


FIGURE 33.—High-grade AKF diagram representing pelitic rocks of the Quadrilátero Ferrífero. $A=Al_2O_3+Fe_2O_3-(Na_2O+K_2O)$, $K=K_2O$, $F=MgO+FeO+MnO$. Numbers next to points are sample numbers. See Eskola, 1939, p. 347 for a complete description of the AKF diagram's construction.

In some rocks, almandine appears with biotite which has been taken by some to indicate the greenschist, and by others, the amphibolite facies (Turner and Verhoogen, 1960). Most garnet in this area, however, is also associated with staurolite, hornblende, or oligoclase-andesine, and sillimanite near Engenheiro Corrêa, as well as with biotite, and so formed in the amphibolite facies. In only a few specimens where albite is also found can garnet be considered to represent the quartz-albite-almandine subfacies of the greenschist facies. Almandine is typically associated with amphibole in metamorphosed mafic dikes and with staurolite and biotite in pelitic rocks in the Quadrilátero Ferrífero. In the western part of the Quadrilátero Ferrífero, garnet associated with biotite is a very high-almandine variety having a restricted range in composition of almandine$_{56-66}$ pyrope$_{23-30}$ grossularite$_{6-25}$ (table 20).

HIGH-GRADE METAMORPHISM

The most important differences between pelitic rocks of low and high metamorphic grades are the presence of staurolite instead of chloritoid and almandine garnet instead of chlorite and spessartite garnet (figs. 32, 33). Biotite is coarser and more abundant than in rocks of lower metamorphic grades. A typical suite from the innermost metamorphic aureole of the Sabará Formation adjacent to the granite contact, north of Sabará (analysis A-4953, table 21) contains staurolite, biotite partly altered to chlorite, garnet, muscovite, quartz, and magnetite. The staurolite-bearing schist is chemically quite similar to the lower-grade chlorite-muscovite-quartz (-chloritoid) phyllite, but may have more CaO and Na_2O and less K_2O. The schist, however, has less CaO and about the same amount of K_2O as Clark's average shale and is similar to Nanz' average Precambrian slate (table 23, column 2 and 3, respectively).

The breakdown of chloritoid may have taken place in this area by two reactions (Halferdahl, 1961, p. 123):

Chloritoid + kyanite = staurolite + quartz + vapor

Chloritoid + quartz = almandine + staurolite + vapor

Experimentally these reactions take place at temperatures below about 675°C and at pressures of about 9 kilobars. Staurolite, however, probably also formed at the expense of chlorite in much the same way that garnet did, with chlorite becoming richer in Mg and Al and poorer in Fe.

Mineral assemblages formed by high-grade metamorphism of pelitic rocks here are typical of the staurolite-almandine subfacies of the almandine-amphibolite facies of Turner and Verhoogen (1960, p. 545). Compared with such rocks of high metamorphic grade elsewhere in the world, the high-grade pelitic rocks in the Quadrilátero Ferrífero have little plagioclase. The assemblage, quartz-staurolite-almandine-muscovite-biotite, is most typical of such rocks in the Quadrilátero Ferrífero, whereas elsewhere oligoclase-andesine is common and biotite may be missing. Again, as in the low-grade metamorphic facies, this is best explained by the abundance of the chemical components of A and F, and the relatively small amount of K in the Brazilian pelitic rocks (fig. 33). A diagrammatic representation of the changes during progressive metamorphism is shown in figure 34. Areas enclosed by each mineral are approximately proportional to volume present in assemblages.

CARBONATE-RICH ROCKS

Carbonate minerals occur widely in the Quadrilátero Ferrífero especially in the Gandarela Formation of the Itabira Group (Dorr, 1958, p. 63), in part of the Fecho do Funil Formation of the Piracicaba Group (Simmons, 1958, p. 65), in lenses and as carbonate-rich iron-formation in the Cauê Itabirite and the Nova Lima Group. The most common carbonate rocks of the

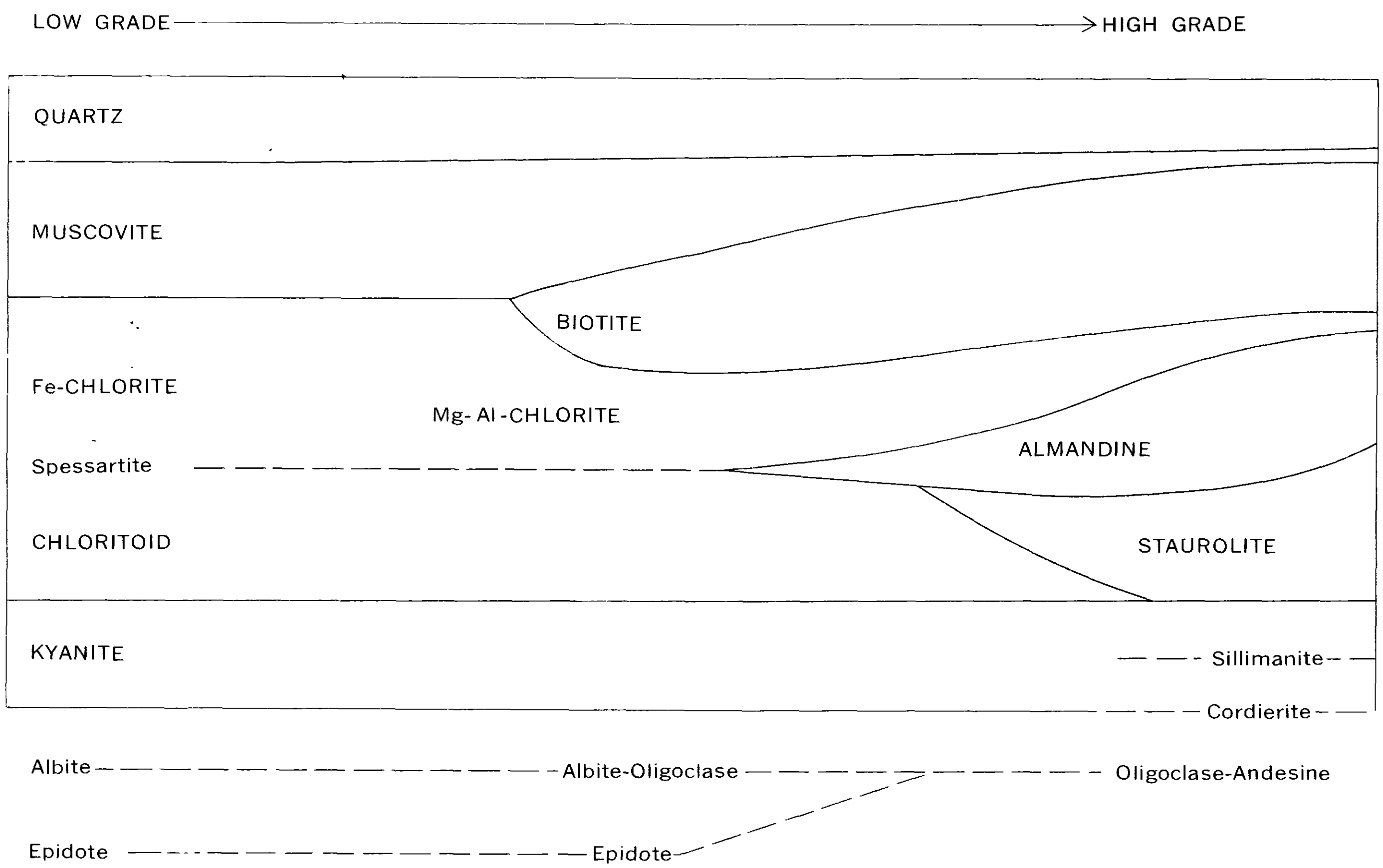


FIGURE 34.—Progressive metamorphism of pelitic rocks in the Quadrilátero Ferrífero area (θ, with hematite).

area are dolomite or calcitic dolomite (following Pettijohn, 1957, p. 418).

The carbonate rocks of the Minas Series have generally much less accessory minerals than those of the Rio das Velhas Series. In addition, they are thicker, mappable units rather than gradational or lensatic as in the Rio das Velhas. This contrast suggests that organic processes may have become more effective by about 2,300 m.y., allowing the formation of relatively clean and persistent chemical carbonate precipitates under large shallow marine areas.

Many fresh carbonate rocks from the Quadrilátero Ferrífero have CaO/MgO ratios that average 1.45 to 1.7 (table 25), indicating nearly pure dolomite. Compared to rocks elsewhere in the world, they are rich in manganese and to a lesser extent in iron (table 25). The average world value for $MnO/FeO+Fe_2O_3$ in carbonate rocks is 0.040, (Graf, 1960, p. 25); except for one analysis, carbonate rocks of the Quadrilátero Ferrífero average from 0.18 to 0.39. In dolomite-rich rocks, laminae of dolomite, magnetite, and talc(?) are about 1 to 5 mm in thickness.

The thickest carbonate beds are in the Gandarela Formation; they are interbedded with and gradational into iron formation (Dorr, 1958, p. 63).

Some thick dolomitic beds may contain very complicated minor flowage structures (Wallace, 1965, fig. 25). Intraformational conglomerate in the Gandarela Formation of the Gandarela quadrangle consists of angular and subrounded to rounded fragments of dolomite, quartzite (chert?), and quartz in a matrix of fine dolomite (J. E. O'Rourke, written commun., 1954).

Dolomite in the Fecho do Funil Formation is dark brown to dark gray and contains much calcite (fig. 35); the purer dolomite of the Gandarela Formation is light gray or green but the upper parts of the formation are light yellow or red (O'Rourke, written commun., 1954). The size of dolomite grains averages about 0.02 to 0.05 mm; muscovite, phlogopite, quartz, epidote, chlorite, iron oxides (especially magnetite) and amphiboles (largely tremolite) are accessory minerals. The micas generally form discrete flakes and quartz very fine grains scattered throughout the groundmass. Where relatively pure dolomite grades

TABLE 25.—*Chemical analyses (in weight percent) of carbonate rocks*

	1		2		3a		3b		4		5a		5b	6		7		8		9
	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range		Average	Range	Average	Range	Average	Range	
SiO_2	10.3	1.9–24.5	7.0	0.10–17.2	0.15	0.15	3.2	1.7–4.4	35.1	19.3–45.2	8.7	0.60–24.7	0.80	4.6	1.5–13.2	3.9	1.0–7.3	2.0	0.46–2.91	11.66
Fe_2O_3	6.6	1.2–17.3	2.2	.8–3.6	2.2	.8–3.6	19.9	13.1–31.6	24.9	1.0–54.2	5.2	1.3–10.7	.5	3.9	2.0–7.0	2.7	.9–5.9	1.5	.57–3.08	3.63
Al_2O_3	.5	.3–1.0	.4	.1–2.2	.3	.1–.4	.5	.5	21.6	.12–39.2	1.0	.08–2.79	-----	.6	nil–1.8	.9	.1–1.8	4.4	2.09–7.19	1.03
CaO	26.7	19.2–32.7	28.8	24.7–31.0	30.1	29.6–30.4	8.0	5.4–9.3	----	-----	26.6	23.6–29.5	54.0	29.8	26.7–39.0	38.5	28.7–50.9	29.5	27.24–31.92	26.30
MgO	16.5	8.4–20.4	18.4	13.0–20.8	20.6	20.1–20.8	6.8	4.3–8.1	----	-----	16.9	11.8–19.5	Tr.	17.9	16.8–21.7	10.8	1.4–18.9	18.8	17.81–19.88	18.09
MnO	2,6	.06–10.9	.4	.1–1.2	1.0	.9–1.2	21.8	19.3–23.9	2.3	0–10.8	1.8	0.3–4.2	2.3	.95	.22–2.28	.5	.02–2.2	.06	[1]	----
Ign. loss	38.3	26.9–45.7	42.9	37.9–46.6	46.0	44.8–46.5	24.5	18.4–30.0	10.1	3.0–13.5	39.8	31.7–43.1	42.4	42.4	39.0–45.1	42.8	40.9–48.4	43.9	40.90–45.75	39.03
P_2O_5	----	----	----	----	----	----	----	----	.06	0–.14	.01	Tr.–0.02	Tr.	-----		-----		-----	-----	Tr.
Sum	101.5	----	[2]100.1	----	100.4	----	84.7	----	94.1	-----	[3]100.0	-----	100.0	100.2		100.1		100.2	-----	[4]99.74
CaO/MgO[5]	1.6	----	1.6	----	1.5	----	1.2	----	----	-----	1.6	-----	-----	1.7		3.6		1.6	-----	1.45
MnO/Fe_2O_3[6]	.39	----	.18	----	.45	----	1.10	----	.09	-----	.35	-----	-----	.24		.19		[1].03	-----	----

Key:
1. Average of six dolomites, Dom Bosco quadrangle (Johnson, 1962). Analyst: Cassio M. Pinto, DNPM, Belo Horizonte.
2. Average of 17 dolomites, Gongo Sôco quadrangle (Moore, 1969). Analyst: same as 1.
3. Gongo Sôco quadrangle (Moore, 1969). Analyst: same as 1.
   a. Average of four unweathered dolomites.
   b. Average of three weathered dolomites associated with a.
4. Average of seven weathered dolomites, Congonhas district Guild, 1957, p. 43). Analyst: same as 1.
5. Gandarela quadrangle (J. E. O'Rourke, written commun., 1954). Anaylst: same as 1.
   a. Average of five dolomites.
   b. Calcitic limestone (1).
6. Average of six "marbles" from the Gandarela Formation, Lagôa Grande quadrangle (Wallace, 1965, p. 17).
7. Average of seven "limestone and dolomite" from the Fecho do Funil Formation, Marinho da Serra Quadrangle (Wallace, 1965, p. 19).
8. Average of three analyses of dolomites from Antonio Pereira, Burnier (average of three analyses), and Rodrigo Silva (Cunha and others, 1949).
9. Average of two analyses from Ilha Tavares, Santa Bárbara (Cunha and others, 1949).

[1] Average of three Burnier samples.
[2] Average sulfur content is 0.03; range is 0.02 to 0.07.
[3] TiO_2=0.
[4] TiO_2=Tr.
[5] Average CaO/MgO for dolomite is 1.4.
[6] Average of world values for MnO/Fe_2O_3 in carbonate rocks is 0.040 (Graf 1960, p. 25).

into phyllite or itabirites, a compositional layering of dolomite and quartz-mica or iron minerals and carbonate is developed.

The dolomite grains generally have sharp, nearly planar boundaries. Some rare unit rhombs may be present, but most of the planar faces are probably irrational (F. J. Turner, written commun., 1962). All quartz grains are rounded and apparently detrital in origin.

Dolomite commonly replaces quartz in magnetite-chlorite itabirite (Guild, 1957, p. 15). Where dolomite is only an accessory mineral, it is found in the quartz-rich layers; the iron oxides and some chlorite comprise alternate layers.

"Lapa sêca" in the Nova Lima Group (table 26) consists predominantly of poorly layered quartz and dolomite or ankerite and accessory muscovite, albite-oligoclase, chlorite, magnetite, and other minerals (Gair, 1962). Quartz and carbonate commonly form fine-grained mosaic intergrowths. Other important units of the Nova Lima Group include iron formation, consisting of quartz-siderite-magnetite and accessory chlorite, muscovite, feldspar, and sulfides (Gair, 1962, p. 17).

No significant mineralogical change took place during the progressive metamorphism of most of the carbonate sediments. Inasmuch as metamorphism took place under a presumed depth of burial of 10 km or more, the effective total pressures prevented a breakdown of the carbonate minerals and the release of CO_2. Carbonates that were relatively rich in Ca recrystallized into coarse-grained marbles. In the more Mg-rich carbonates, dolomite recrystallized as fine- to medium-grained crystals which commonly show irrational planar faces (F. J. Turner, written commun., 1962). Presumably much of iron and manganese entered dolomite as mixed crystals of ankerite and rhodochrosite.

TABLE 26.—*Chemical analyses (in weight percent) of carbonate-pelitic rocks from the Nova Lima Group*

	R–940	C–4	C–5	C–8	2148	2554	2411	2399
SiO_2	33.5	30.6	42.3	58.9	60.60	55.57	42.92	27.48
Al_2O_3	9.9	8.9	11.7	13.7	13.70	13.57	13.30	6.74
Fe_2O_3	1.1	.8	.6	.4	1.71	2.42	1.18	1.95
FeO	4.5	9.7	7.8	6.1	2.91	6.36	6.30	3.55
MgO	10.0	5.6	12.5	7.6	3.50	5.36	5.32	11.62
CaO	17.2	15.8	6.3	2.7	3.67	2.77	9.89	17.55
Na_2O	nil	.09	1.28	1.68	3.76	1.36	2.04	2.16
K_2O	2.9	2.71	.78	1.23	2.94	2.14	1.48	
TiO_2	.14	.23	.21	.46	.40	.80	.58	.32
P_2O_5		.00	.00	.09	.098	.11	.12	.032
MnO	.29	.40	.11	.09	nil	nil	Tr.	Tr.
H_2O	2.2	1.9	5.3	4.3	7.16	2.49	16.72	27.73
CO_2	[1]18	[1]23	[1]10	[1]2		6.68		
Cr_2O_3	.43	.38	.31	.10				.15
S		Tr.	Tr.	Tr.	9.10	.79		.15
Sum	[2]100.2	100.1	99.2	99.9	100.55	[3]100.68	99.86	99.97

[1] By difference.
[2] NiO=Tr., CoO=nil.
[3] 0.45 percent C.

Sample descriptions:
R–940—Chromian sericite schist, Raposas mine, Nova Lima quadrangle. See Tolbert, 1962. Analyst: A. Espinola, DNPM, Rio de Janeiro (rapid methods).
C–4—Chromian sericite-carbonate-quartz schist, Raposas mine, Nova Lima quadrangle. Reference and analyst same as R–940.
C–5—Composite of 6 samples of quartz-carbonate-chlorite schist, Raposas mine, Nova Lima quadrangle. Reference analyst same as R–940.
C–8—Black banded quartz-chlorite schist, Raposas mine, Nova Lima quadrangle. Reference and analyst same as R–940.
2418–Dolomitic schist, Morro Velho mine, Nova Lima quadrangle. See Leinz and others (1937). Analyst: M. L. Fontouro, DNPM, Rio de Janeiro.
2554–Graphitic schist, Juca Vieira, 3 km south of Caeté, Caeté quadrangle. Reference same as 2418.
2411–Dolomitic phyllite. Locality, reference, and analyst same as 2418.
2399–Calc-schist, Morro Velho mine, Nova Lima quadrangle. Reference and analyst same as 2418.

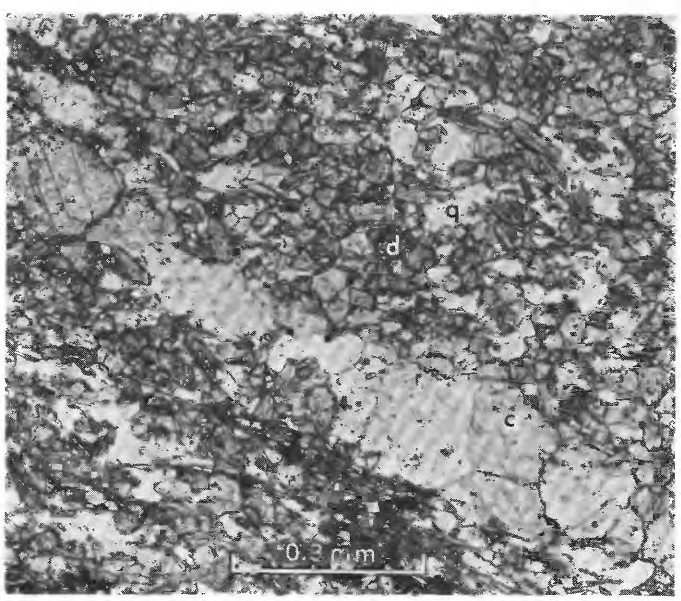


FIGURE 35.—Photomicrograph, quartzose dolomite, lower Piracicaba cut by gash veins of calcite, J–390, Dom Bosco quadrangle, plane light. Calcite (c) in gash veins and dolomite (d) form about 60 percent of rock; quartz (q) about 30 percent; and biotite (b) about 10 percent with colorless to brown pleochroism (indicated composition of 60 percent phlogopite). Magnetite forms about 2 percent of the darker layers.

Some tremolite and clinozoisite formed from the breakdown of dolomite near zones of shearing where CO_2 escaped during reactions such as calcite + chlorite + silica → actinolite + epidote + H_2O + CO_2 (Ramberg, 1952, p. 140) or dolomite + silica + H_2O → tremolite + calcite + CO_2 (Deer and others 1963a, p. 258). Presumably a low-Al tremolite-actinolite formed which was stable in association with clinozoisite-dolomite-quartz (-calcite) throughout the greenschist facies (Turner and Verhoogen, 1960, p. 536). The association here of cummingtonite with tremolite, carbonate, and quartz indicates the almandine-amphibolite facies.

Some amphibolite in the Quadrilátero Ferrífero may have formed from "dirty" carbonate rocks. This is suggested by both the chemical composition of the amphibolite (table 29) and their occurrence in stratigraphic positions which are equivalent to those of carbonate formations in adjoining areas. Such amphibolite, however, is found only in the highest metamorphic zones of the area, as around the Bação Complex and in the Monlevade district. Carbonate minerals are not present in the amphibolite nor have transitional marble-amphibolite rocks been found, so definite field evidence for a carbonate-rock origin for amphibolite is not yet forthcoming.

Because the clinozoisite and amphiboles that developed in the low-pressure shear zones are typical of the greenschist facies, it must be concluded that shearing and concomitant metamorphism took place at relatively low temperature. This may have occurred after both the principal phase of mineral metamorphism in the 1,350 m.y. event and the structural deformation which followed it. Widespread retrograde metamorphism, as well as calc-silicate reactions in carbonate rocks, took place at one or more times (1,350?, 1,000?, 500 m.y.?) during structural deformation and the periods of relaxation of pressure that followed.

QUARTZ-RICH ROCKS

Quartzites and quartz-rich rocks make up the bulk of the Moeda (Wallace, 1958), Cercadinho, and Taboões Formations (Pomerene, 1958) of the Minas Series, a large part of the Maquiné Group (Dorr and others, 1957) and the Itacolomí (Barbosa in Dorr and others, 1959/1961) and occur in the pre-Minas Nova Lima Group and in the Sabará Formation (Gair, 1958b) of the Minas Series.

The Moeda and Taboões quartzites are rather pure; the Palmital Formation of the Maquiné Group and parts of the Moeda are sericitic and micaceous; and the Cercadinho Formation and the Itacolomí and Rio das Velhas Series are ferruginous. Some quartzite in the Palmital Formation contains as much as 30 percent chloritoid (J. E. O'Rourke, written commun., 1954). Generally, more massive quartzites are pure and form bold ridges, whereas mica-rich varieties may be friable and weather relatively rapidly, forming topographic lows.

Many quartzites have an inequigranular fine to coarse texture, as, for example, the Casa Forte Formation of the Maquiné Group, (Gair, 1962, p. 32). A mortar matrix around larger detrital grains suggests cataclasis. Essential chloritoid or kyanite of some quartzites forms small clusters of isolated crystals alined either parallel to or across the foliation (fig. 22). Micaceous minerals and elongated quartz may be abundant along bedding plans.

In ferruginous quartzite, quartz is generally in even rounded grains or mosaic intergrowths elongated parallel to the compositional layering and separated by interstitial platy or granular hematite. Both hematite and quartz are detrital in origin. Very large magnetite crystals in the Cercadinho Formation in the Itabirito quadrangle at N7,150, E400, apparently are postmetamorphic (Wallace, 1965, p. 19). The ferruginous quartzites are generally well layered, quartz-rich layers alternating with hematite-rich ones..

GRAYWACKES AND FELDSPATHIC QUARTZITES

Graywacke, subgraywacke, and arkose (Pettijohn 1957, p. 291) contain detrital feldspar. Arkoses and feldspathic quartzites grade into feldspar-bearing phyllites in the Nova Lima Group west of the Serra do Maquiné and into quartzites in the Maquiné Group of the Serra do Maquiné (J. E. O'Rourke, written commun., 1954) and in the Itacolomí Series of the Ouro Prêto area (Barbosa in Dorr and others, 1959/1961, p. 82). Although arkose and feldspathic quartzite are widespread, they are nowhere well enough developed to have been mapped separately.

Rocks of the graywacke suite in this area are generally dark gray and have a fine-grained granular matrix consisting largely of quartz and varying amounts of sericite, chlorite, and epidote. Some generally medium-grained quartz and albite-oligoclase appear to be detrital. In addition to detrital feldspar, microcline of metasomatic origin is locally abundant near granite contacts. Accessory minerals include carbonate, sphene and leucoxene, magnetite and hematite, apatite, and tourmaline.

Faint to strong planar structure is caused by alined chlorite or sericite. Detrital fragments of quartz and feldspar may be elongated parallel to foliation and augen structure results from micaceous minerals wrapping around larger quartz and feldspar. Porphyroblasts of biotite occur in the Sabará Formation north of the Serra do Curral near the contact with granite.

The chemical analysis of a graywacke from the Quadrilátero Ferrífero (JG241–55, table 27) is remarkably similar to that of average graywacke given by Pettijohn (no. 7, table 27), differing mainly in having higher Al_2O_3, probably because of greater chemical weathering in the source area, and in having lower water, because of metamorphism.

The minor element abundance in sample JG–241–55 (table 28) compares closely with the average abundances of minor elements in pelitic sediments of the

Quadrilátero Ferrífero (table 22) except that strontium is 10–100 times more abundant in the graywacke. Strontium substitutes diadochically for calcium, which is also proportionally more abundant, and both are largely in the abundant plagioclase of the graywacke.

Subgraywacke in the Quadrilátero Ferrífero (A-5053, table 27) is similar to subgraywacke cited by Pettijohn (1957, p. 319; no. 8, table 27), but has less H_2O because of metamorphism and more Na_2O because of a higher contained plagioclase.

TABLE 27.—*Chemical analyses (in weight percent) of quartzo-feldspathic rocks*

[Analysts: P. L. D. Elmore (samples 1–5), S. D. Botts (samples 1–6), M. D. Mack (samples 1, 2), and H. H. Thomas (samples 1, 2), I. Barlow (samples 3, 6), G. Chloe (samples 3, 4), all of U.S. Geological Survey, Washington, D. C. analyses by "rapid" methods]

Reference no.:	1	2	3	4	5	6	7	8
Sample no.:	J–693	JG241–55	A–5053	Ha–23	Ha–37	Ha–39		
SiO_2	82.5	66.6	73.5	76.2	69.6	67.8	64.7	74.43
Al_2O_3	8.2	16.2	11.8	11.1	12.2	14.5	14.8	11.32
Fe_2O_3	3.4	1.1	2.0	.8	1.5	1.1	1.5	.81
FeO	1.0	2.8	2.6	1.4	4.7	4.0	3.9	3.88
MgO	.12	1.6	1.6	1.1	1.3	2.1	2.2	1.30
CaO	.05	3.3	1.5	1.2	3.4	2.8	3.1	1.17
Na_2O	.08	4.4	3.5	1.5	3.1	2.2	3.1	1.63
K_2O	2.7	1.8	1.1	4.5	1.3	2.6	1.9	1.74
TiO_2	.27	.54	.57	.22	.77	.68	.5	.83
P_2O_5	.06	.19	.11	.04	.14	.18	.2	.18
MnO	.02	.06	.09	.06	.08	.14	.1	.04
H_2O	1.2	1.5	1.4	.85	.80	1.3	3.1	2.35
CO_2	$<$ .05	.22	$<$ .05	.84	$<$ .05	.21	1.3	.48
Sum	99.6	100.3	99.8	99.8	99.0	99.6	101.0	100.45

Sample descriptions:

J–693—Ouro Branco feldspathic quartzite. Strained quartz grains, sericite, plagioclase An_{25} slightly sericitized, orthoclase, chlorite, zircon, leucoxene. Ouro Branco quadrangle, 10,750 E, 330 N.

JG241–55—Nova Lima graywacke. Quartz 42 percent (0.6 mm), plagioclase An_{18} 27 percent, epidote 13 percent, chlorite and sericite 14 percent (0.04 mm), carbonate 2 percent (0.1 mm), sphene, leucoxene. Rio Acima quadrangle, 9100 E, 4500 N. Description by Gair.

A–5053—Moeda subgraywacke. Quartz, plagioclase An_8 sericitized, biotite some replaced by chlorite, magnetite, epidote. Nova Lima quadrangle, 3600, E, 955N.

Ha–23—Mylonitized microcline gneiss below Moeda Formation. Quartz 32 percent, microcline 38 percent, muscovite and sericite 16 percent, biotite 5 percent, plagioclase An_{14} 7 percent, calcite 1 percent, epidote, allanite, xenotime. Marinho da Serra quadrangle, 4,000 E, 10,400 N.

Ha–37—Monlevade gneiss, biotite-quartz epidote gneiss. Quartz 59 percent biotite 27 percent, plagioclase An_{32} 7 percent, epidote 6 percent, apatite, zircon. Monlevade quadrangle. 3250 E, 10,250 N.

Ha–39—Piracicaba Group, biotite-quartz gneiss, Quartz, plagioclase An_{27}, biotite, muscovite flakes cross foliation, apatite, magnetite. Rio Piracicaba quadrangle, 4800 E, 7550 N.

7. Average of 23 graywacke analyses. Pettijohn 1957, p. 307.
8. Subgraywacke from Stanley Shale. Pettijohn, 1957, p. 319.

TABLE 28.—*Spectrographic analysis (in ppm) of minor elements in quartzo-feldspathic rocks*

[Detection limits given in table 1; sample descriptions given in table 27 except for Ha–9]

	*J693	*JG241–55	*A5053	†[1] Ha–9	†Ha–23	†Ha–37	†Ha–39
B	10	10	N.d.	--	--	--	--
Ba	1,000	1,000	300	810	360	645	680
Be	1	1	1	--	6.5	2	9
Ce	100	N.d.	100	--	--	--	--
Co	3	3	20	11	1.7	13	19
Cr	30	30	150	N.d.	4	7	100
Cu	10	30	30	32	4	43	14
Ga	10	30	10	22	8.5	14	13
La	30	30	50	102	68	92	64
Mo	3	3	N.d.	--	N.d.	2	N.d.
Nb	N.d.	N.d.	7	35	21	24	26
Ni	30	30	100	9	1	9	68
Pb	3	3	30	N.d.	14	35	5
Sc	3	10	15	61	2	18	15
Sn	N.d.	N.d.	N.d.	17	10	46	59
Sr	30	3,000	500	14	41	76	220
V	100	100	100	54	7	62	75
Y	30	10	30	130	59	140	39
Yb	3	1	3	--	--	--	--
Zr	300	100	150	370	250	340	350

* Semiquantitative analysis by H. W. Worthing, U.S. Geological Survey, Washington, D.C.

† Quantitative analysis by C. V. Dutra, Instituto de Tecnologia Industrial, Belo Horizonte.

[1] Pre-Minas biotite-quartz gneiss. Quartz 44 percent, plagioclase 24 percent, biotite 17 percent, muscovite 10 percent, microcline perthite 3 percent, calcite, epidote, opaques, apatite, garnet. Rio de Peixe quarry, Itabira quadrangle, E5650, N1750.

The analyzed subgraywacke has more biotite and chlorite than the other quartz-rich rocks (table 27) and correspondingly more Cr and Ni, but less than the amounts of Cr and Ni in the pelitic rocks (table 22).

The development of biotite from chlorite, fine-grained muscovite, and quartz is the criterion used for distinguishing the metamorphic graywackes and feldspathic quartzites of low, medium, and high grade. The anorthite content of plagioclase is not reliable as a measure of low to moderate grades of metamorphism because much plagioclase appears to be detrital in origin. Graywackes of the amphibolite and higher metamorphic grades do not exist in the area, and it is assumed that they are represented by biotite gneiss, which is almost identical chemically (compare biotite gneiss Ha–37 to metagraywacke JG241–55, table 27).

Graywacke from the base of the Minas Series about 4 km southwest of Sabará contains large detrital quartz and feldspar in a matrix of fine-grained quartz, biotite, chlorite, sericite, epidote, and magnetite (sample A–5053, table 27). The rock is moderately metamorphosed and contains the outermost biotite in the metamorphic aureole bordering the granite to the north.

Kyanite in quartzite as in the Serra do Caraça (table 13) and east of the Itabira district (Dorr and Barbosa, 1963, p. 40) reflects metamorphism above the chlorite isograd, as does garnet near the Bação Complex (table 20). Kyanite and garnet are generally euhedral porphyroblasts with some muscovite in a granular medium-to coarse-grained matrix. Kyanite-quartz-muscovite veins are associated with kyanite-bearing quartzites and may be largely derived from material already present in the country rock itself (Herz and Dutra, 1964).

METAMORPHISM

During low-grade metamorphism, the clay minerals in the quartzo-feldspathic rocks were converted largely to sericite and muscovite. Porphyroblasts of albite or potassium-feldspar locally adjacent to granite contacts may be related more to metasomatism than progressive metamorphism (fig. 36).

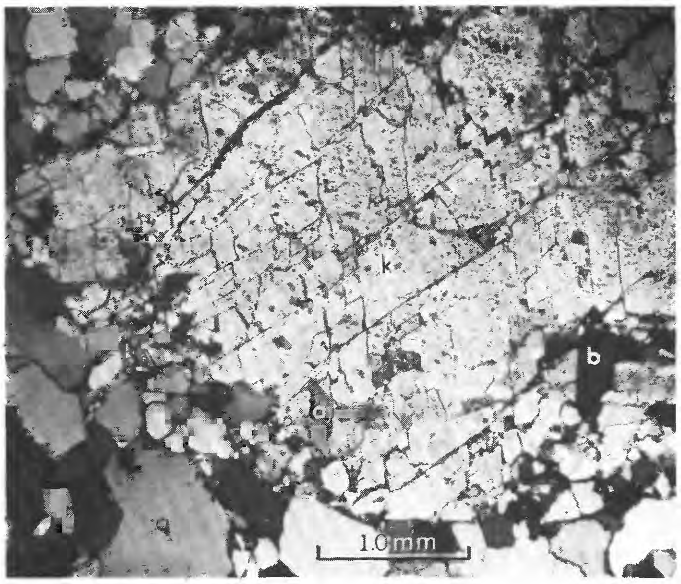


FIGURE 36.—Photomicrograph, microcline gneiss with large porphyroblast of potassium-feldspar, Z–46, Rio de Pedras quadrangle, crossed nicols. Large augen of potassium-feldspar (k) and granular albite (a) and quartz comprise more than half of the gneiss. Large quartz grains (q) are strained. Large microcline crystals replace the granular quartz and appear to be of metasomatic origin. Mafic mineral is mainly biotite (b).

In quartz-rich metasedimentary rocks that had little primary clay, no significant differences in mineralogy are found between the lowest and highest grades of metamorphism. The principal changes are development of sutured textures and the growth of some grains at the expense of others, resulting in two grain sizes, one coarse and irregular in outline and the other fine and rounded.

An extremely fine-grained quartzite that is similar to Arkansas novaculite occurs in the Belo Horizonte and Ibirité quadrangles and may be a large xenolith within granite gneiss (Pomerene, 1964, p. 28).

These quartz-rich rocks are best shown on an ACF diagram (C apex represents CaO) (figs. 37, 38) because they have less K_2O and more CaO than the pelitic rocks. In many relatively unweathered quartzitic rocks, plagioclase is fresh and preserves its original Na_2O content. In quartz-rich rocks containing a high amount of clay minerals in addition to feldspar, metamorphic mineral assemblage are similar to those of phyllite. Sample JG241–55, for instance (table 27), a

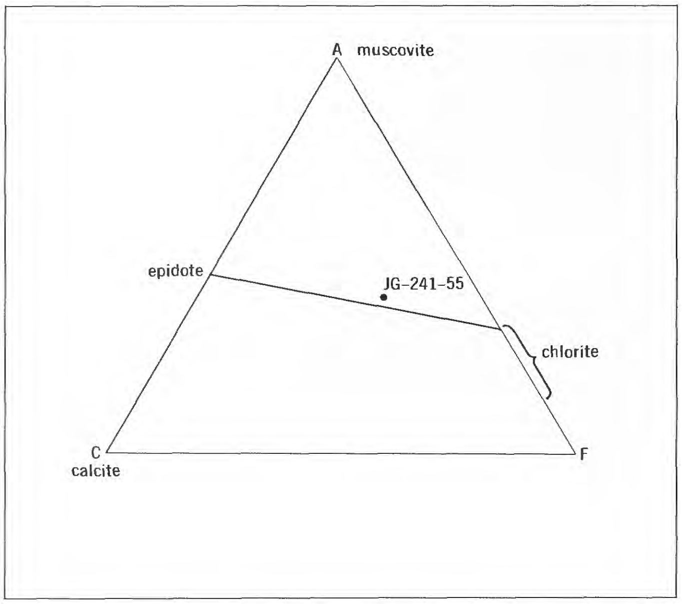


FIGURE 37.—Low-grade ACF diagram. Sample shown is fine-grained quartzite in the Belo Horizonte and Ibirité quadrangles $A=Al_2O_3+Fe_2O_3-(Na_2O+K_2O+CaO)$, $C=CaO$, $F=MgO+FeO+MnO$. Numbers next to points are sample numbers.

graywacke, is composed of plagioclase An_{18}, quartz, epidote, chlorite, sericite, carbonate, and sphene, an assemblage that is stable from the greenschist facies to the staurolite-almandine subfacies of the almandine-amphibolite facies (Turner and Verhoogen, 1960, p. 545). It falls within the epidote-chlorite-muscovite field in the low-grade ACF diagram (fig. 37), which is appropriate for its actual mineralogy.

Although it is possible that the plagioclase An_{18}, is pre-detrital, it is more probable that its composition is a result of the last regional metamorphism because (1) most grains have lost their original boundaries by metamorphic recrystallization, and (2) the plagioclase map (pl. 1) shows that the amount of anorthite molecule in plagioclase increases to the east. The metagraywacke has about the correct amount of anorthite for its position between samples that contain plagioclase, An_{5-10} to the west and An_{22-30} to the east. Although key mafic minerals are missing, the plagioclase suggests the almandine-amphibolite-metamorphic facies. Chlorite is ripidolite (optical determination) which is intermediate Fe-Mg in composition; a high iron chlorite would be unstable under these conditions.

Only quartzo-feldspathic rocks fall within the muscovite-chlorite-microcline field, the K-rich part of the AKF diagram representing the almandine amphibolite metamorphic facies. The high Al compared to alkalis of some pelitic rocks aided the formation of muscovite and kyanite and inhibited that of feldspar and biotite, which was also inhibited by low F. The minerals in the quartz-rich rocks, except for plagioclase, are not diagnostic of any particular metamorphic zone. The almandine-amphibolite facies of regional metamorphism was attained in the Monlevade area as shown by the assemblage biotite, quartz, and plagioclase An_{27-32} in biotite gneiss (Ha-37 and Ha-39, table 27.) Epidote and garnet are also present in Ha-37. Plagioclase An_{25-32} is found in some "impure" sandstones of the almandine-amphibolite facies together with some microcline.

AMPHIBOLITE AND GREENSTONE

Greenstone—metavolcanic rock of mafic to intermediate composition—is found in the Nova Lima Group and in the Sabará Formation (Gair, 1962, p. 13; 1958b, p. 68) and above the Cauê Itabirite in the Congonhas district, the Dom Bosco quadrangle (figs. 10, 11), Monlevade district, and the Catas Altas quadrangle.

The greenstone is massive or schistose and is composed of chlorite and epidote, and, in places, a deep-green amphibole, plus accessory albite or oligoclase, quartz, carbonate, magnetite, biotite, and ilmenite. Original structures generally have been destroyed by metamorphism, but some samples have relict diabasic texture or other textural evidence of igneous origin. Deep-green amphibole or mixed epidote-sericite (saussurite) commonly appear to be pseudomorphic after earlier mafic minerals or calcium-rich feldspar (Herz, 1970, fig. 24). Some quartz is present in stretched amygdules(?), and some in association with carbonate is a metamorphic replacement of primary minerals.

A probable acid flow or tuff from the Congonhas district is gray, fine grained, and contains abundant rounded quartz grains 1 to 2 mm across, very fine grained alined sericite, cryptocrystalline quartz (?), and minor amounts of plagioclase and microcline (Guild 1957, p. 19–20). Some poorly defined fragments suggest that the rock was a welded crystal tuff.

Layers of amphibolite occur in pre-Minas rocks, in the Gandarela and Piracicaba Formations, or less importantly in other formations in the Monlevade (Reeves, 1966), Itabira (Dorr and Barbosa, 1963), and Rio de Pedras quadrangles. Before metamorphism, the amphibolites were mafic igneous rock or impure dolomite or graywacke.

Joseph E. O'Rourke (written commun., 1954) distinguished three types of amphibolites in the Rio de Pedras quadrangle that occur in the zone between the granitic gneisses of the Bação Complex and the metamorphosed sedimentary rocks to the north: (1) A compact, massive, coarsely crystalline rock composed of green hornblende (60–95 percent) and subsidiary amounts of biotite, plagioclase An_{34}, epidote, quartz, magnetite, and garnet. This is the most abundant type and is conformable with the foliation of high-rank metamorphic rocks and is always found within 300 meters of granitic gneiss; (2) A compact, thin-bedded rock comprised of fine laminae of hornblende (40–70 percent), quartz, and accessory epidote, plagioclase, chlorite, and sericite. This rock is interbedded with chloritic phyllite or biotite schist in the low-rank edge of the intermediate zone of metamorphism more than 400 meters from the granite gneiss; (3) A rock composed of thin laminae of hornblende (50–80 percent), quartz (20–30 percent), and magnetite (5–40 percent) and rare plagioclase and biotite; occurs interbedded with type 1 at two localities in the Rio de Pedras quadrangle within 150 meters of granite gneiss.

Amphibolite from the southern contact area of the Bação Complex in the Nova Lima Group from the Dom Bosco quadrangle (J–155 C) and the Cachoeira do Campo quadrangle (J–10, tables 29, 30) has exceptionally low Na_2O and K_2O compared to typical mafic rocks (Turner and Verhoogen, 1960, p. 215) and to amphibolite in other parts of the Quadrilátero Ferrífero.

In the Monlevade area, the Monlevade gneiss contains the Pacas Amphibolite Member and the Itabira Group contains the Sítio Largo Amphibolite (Reeves, 1966). The Sítio Largo is well laminated, dark green, is composed largely of hornblende, quartz, and plagioclase, and is similar to some pre-Minas amphibolite. Amphibolite intimately associated with soapstone in the Itabira district is metamorphosed ultramafic and mafic rock intrusive into pre-Minas rocks (Dorr and Barbosa, 1963, p. 34). Xenoliths of finely laminated amphibolite occur in the granitic rocks north of Belo Horizonte (Ha–16x, table 29). They consist of coarse-grained brown hornblende and plagioclase, as large as 0.5–8 mm in diameter, and accessory quartz, magnetite, apatite, colorless amphibole, and sphene.

J. E. O'Rourke (written comm., 1954) considered that his types (1) and (3) were genetically related to the gneiss of the Bação Complex as a "basic front" and that type (2) represented a metamorphosed carbonate-rich bed within the chlorite phyllites. It is also possible that (2) represents a metamorphosed basic tuff and (1) and (3) are metamorphosed mafic dikes. Other geologists have proposed other modes of origin for amphibolite.

TABLE 29.—*Chemical analyses (in weight percent) and normative minerals of amphibolites*

	J–155C	J–10	[1] Ha–16x	R–10	R–191	R–271	R–413	R–416	R–420	R–421
SiO_2	56.3	61.1	48.8	54.2	45.4	49.3	47.5	49.7	48.1	49.3
Al_2O_3	14.7	13.9	14.5	14.7	16.6	15.7	15.8	15.4	15.2	15.8
Fe_2O_3	4.5	.5	3.2	1.9	4.6	2.0	4.5	1.9	2.2	2.2
FeO	4.7	6.7	10.2	7.9	8.7	9.4	10.3	10.4	11.1	9.7
MgO	3.0	7.2	6.8	6.2	7.0	6.4	5.8	6.4	6.8	7.0
CaO	13.3	5.0	10.0	10.0	8.0	10.0	8.9	11.0	8.3	9.1
Na_2O	.32	.34	3.1	1.9	1.0	2.2	1.2	1.8	1.2	2.1
K_2O	.14	.04	1.0	.20	.29	.51	.16	.14	.21	.26
TiO_2	1.2	.62	1.4	1.0	1.2	1.5	1.2	1.1	1.3	1.7
P_2O_5	.17	.13	.20	.14	.10	.16	.10	.08	.11	.19
MnO	.14	.16	.26	.19	.22	.21	.20	.20	.20	.29
H_2O	1.1	3.1	1.0	1.2	6.4	1.5	3.6	1.6	4.6	1.2
CO_2	<.05	<.05	.34	<.05	.08	<.05	.05	<.05	.06	<.05
Sum	99.6	98.8	100.9	99.5	99.6	98.9	99.3	99.7	99.4	98.8
					Normative minerals					
Quartz	25.7	32.8	--	10.7	6.6	1.6	7.7	2.9	6.2	2.8
Corundum	--	4.5	--	--	.5	--	--	--	--	--
Orthoclase	.8	.2	5.9	11.2	1.7	3.0	.9	.8	1.2	1.5
Albite	2.7	2.9	26.2	16.1	8.5	18.6	10.1	15.2	10.1	17.8
Anorthite	38.3	23.9	22.7	31.0	38.5	31.5	37.3	33.5	35.5	32.9
Wollastonite	11.1	--	9.8	7.4	--	7.1	2.6	8.6	1.9	4.6
Enstatite	7.5	17.9	7.7	15.4	17.4	15.9	14.4	15.9	16.9	17.4
Ferrosilite	3.2	11.2	6.5	11.6	10.6	13.5	13.6	16.1	16.8	13.7
Magnetite	6.5	.73	4.6	2.8	6.7	2.9	6.5	2.8	3.2	3.2
Ilmenite	2.3	1.2	2.7	1.9	2.3	2.8	2.8	2.1	2.5	3.2
Apatite	.4	.3	.5	.3	.2	.4	.2	.2	.3	.5
$CaCO_3$	--	--	.8	--	.2	--	--	--	.1	--
Sum	98.5	95.7	[2]99.8	98.3	93.2	97.4	95.7	98.1	94.8	97.7
DI	29.3	35.9	32.1	27.9	16.8	23.2	18.7	19.0	17.6	22.1
Plagioclase	93.4	89.3	46.4	65.9	82.0	62.8	78.6	68.8	77.8	65.0
An percent										
Discriminant function	−3.53	−2.93	+2.32	−.33	−1.33	+1.96	−1.01	+.51	+.89	+2.90

[1] F=0.10 percent.
[2] Forsterite 6.5 percent; fayalite 6.0 percent.

Sample descriptions:

J–155C. Dom Bosco quadrangle 3,400 E., 12,300 N. Hornblende, actinolite, quartz, epidote some apatite, chlorite. Contact zone with gneiss. Analysts: P. L. D. Elmore, S. D. Botts, M. D. Mack, H. H. Thomas U.S. Geological Survey, Washington, D. C. (rapid methods).

J–10. Cachoeira do Campo quadrangle, 3,400 E., 10,700 N. Hornblende, biotite, quartz actinolite, magnetite, apatite, chlorite. Roof pendant. Analyst: same as J–155C.

Ha–16x. Belo Horizonte quadrangle, 5000 E., 10,400 N. Brown hornblende, andesine, quartz, actinolite(?), apatite, magnetite(?), sphene, xenolith in granite. Anaylst: P. L. D. Elmore, I. H. Barlow, S. D. Botts, G. Chloe, F by S. M. Berthold, U.S. Geological Survey, Washington, D. C. (rapid methods).

R–10. Monlevade quadrangle, 7,900 E., 10,900 N. Hornblende, andesine, quartz, epidote. Sítio Largo amphibolite (Reeves, 1966, p. 19). Analysts: P. L. D. Elmore, S. D. Botts, I. H. Barlow, U.S. Geological Survey, Washington, D. C. (rapid methods).

R–191. Rio Piracicaba quadrangle, 7,900 E., 8,300 N. Hornblende, andesine, quartz, magnetite, apatite, biotite. Amphibolite in Elefante Formation (Reeves, 1966, p. 20). Analyst: same as R–10.

R–271. Monlevade quadrangle, 3250 E., 7500 N. Hornblende, andesine, quartz, biotite; magnetite, apatite. Pacas Amphibolite Member, Monlevade gneiss (Reeves, 1966, p. 13). Analyst: same as R–10.

R–413, R–416, R–420. Rio Piracicaba quadrangle, 12,700 E., 12,000 N.; 12,2000 E., 12,450 N. Hornblende, plagioclase An_{25-30}, quartz; hematite, apatite, garnet. Sítio Largo Amphibolite (Reeves, 1966, p. 19). Analyst: same as R–10.

R–421. Rio Piracicaba quadrangle, 2,000 S., O E. Amphibolite from Monlevade gneiss. (Reeves, 1966, p. 13). Analyst: same as R–10.

TABLE 30.—*Spectrographic analysis of minor elements in amphibolites*

[Analysts: Semiquantitative determinations by H. W. Worthing, U.S.G.S.; quantitative determination (Ha–16x) by C. V. Dutra, Institute de Tecnologia Industrial. See table 1 for detection limits; nd, not detected; dashed lines, not looked for]

	B	Ba	Be	Co	Cr	Cu	Ga	Ge	La	Mo	Nb	Ni	Pb	Sn	Sc	Sr	V	Y	Yb	Zn	Zr
J–155C	30	300	1	10	300	30	30	10	nd	10	nd	30	3	nd	30	300	300	30	3	nd	100
J–10	1,000	300	1	30	1,000	30	10	10	nd	10	nd	300	3	nd	10	300	300	30	3	100	100
Ha–16x	--	125	nd	71	89	80	30	--	17	6.0	nd	79	nd	nd	70	144	109	67	--	--	122

Chemical analysis of amphibolite taken from different parts of the Quadrilátero Ferrífero (table 29) were plotted on an ACF diagram for the amphibolite metamorphic facies (fig. 38). The analyses from the Monlevade district all plot within a very small area of the hornblende-almandine-epidote field, whereas analyses from other areas do not fall within that field. The amphibolites from Monlevade probably occur at different stratigraphic horizons and different modes of origin have been ascribed to them, although they are chemically, as well as mineralogically, quite similar.

The average Monlevade amphibolite was compared to a hypothetical sedimentary antecedent as well as to an igneous one (table 31). The sediment is based on a combination of 20 percent average dolomite from the Dom Bosco quadrangle and 80 percent average pelite from the Quadrilátero Ferrífero; the igneous rock is Johannsen's average for basalt (1937, p. 231).

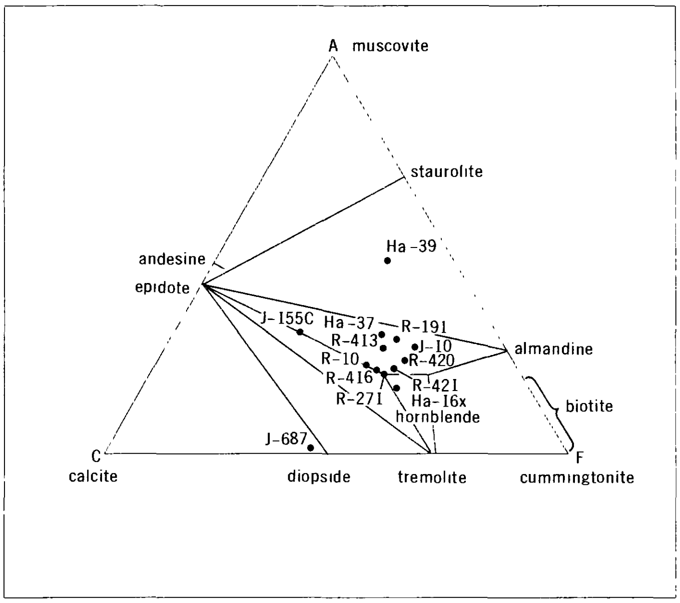


FIGURE 38.—High-grade ACF diagram representing amphibolites in the Quadrilátero Ferrífero. A=Al_2O_3+Fe_2O_3—(Na_2O+K_2O+CaO), C=CaO, F=MgO+FeO+MnO. Numbers next to points are sample numbers.

The average Monlevade amphibolite is chemically similar to average basalt. Amphibolites from elsewhere in the Quadrilátero Ferrífero, on the other hand, are chemically dissimilar to one another and generally to the theoretical or average basalt. These differences indicate that amphibolite originated in more than one way in the Quadrilátero Ferrífero.

Evidence on the origin of amphibolite can be obtained from plots of Niggli numbers (Leake, 1963). Amphibolite derived by igneous differentiation tends to fall on or near the igneous trend curve shown by

TABLE 31.—*Amphibolite analyses compared to hypothetical antecedents*

	(1)	(2)	(3)
SiO_2	53.8	50.9	50.31
Al_2O_3	16.8	16.2	15.54
Fe_2O_3	5.2	2.9	3.09
FeO	2.5	10.0	7.72
MgO	7.4	6.7	6.67
CaO	8.9	9.6	9.50
Na_2O	.29	1.7	2.94
K_2O	3.7	.26	.68
TiO_2	.46	1.3	2.25
P_2O_5	.07	.13	.24
MnO	.89	.23	.21
Sum	100.0	99.9	

Key: (1) 20 percent dolomite, average of 6 dolomites, Dom Bosco Quadrangle (table 25 no. 1) +80 percent pelite, average of pelites from Quadrilátero Ferrífero (table 23).
(2) Average of 7 amphibolites, Monlevade district (table 29, R-samples).
(3) Average of 16 basalts (Johannsen, 1937, p. 261).

analyses of Karroo dolerite in a diagram of Niggli *mg* values plotted against *c* or in the triangular diagram of *mg* vs. *c* vs. *alk*; amphibolite of probable sedimentary origin does not fall near the curve.

All amphibolites from the Quadrilátero Ferrífero, except J–10 and J–155, group into a small area near the igneous trend curve of the $c-mg$ plot (fig. 39*B*). The plots for *alk* – *mg* and *ti–mg* are not as clear, although, again, neither J–10 nor J–155 fall near the clusters made by the other samples, which suggests that they have a different origin.

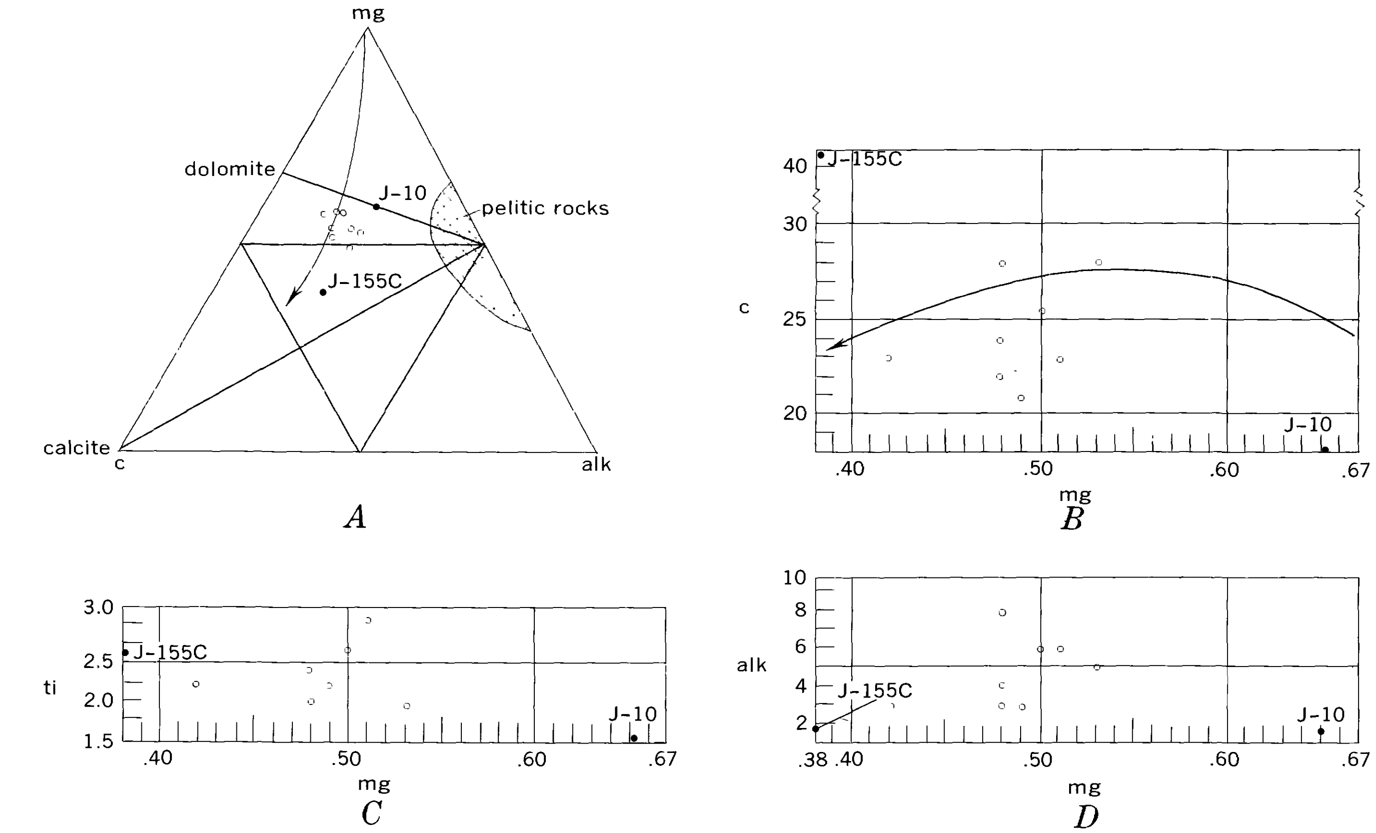
In a triangular diagram of *mg-c-alk*, the analyses again cluster into a small area except for J–155 and J–10, that represents middle-stage differentiates of a mafic magma. J–155 apparently represents a mixture that included pelitic material and calcium carbonate and J–10, pelitic material and dolomite.

Chemical composition can also be used to test for origin by using a multivariate analysis of the major oxide values and calculating discriminant functions (Shaw and Kudo, 1965). In this type of analysis, a positive discriminant-function value suggests orthoamphibolite and a negative value represents para-amphibolite with a probability of incorrect classification of 5.7 percent. Values shown in table 29 show high negative values for J155C (−3.53) and J–10 (−2.93) and high positive values for Ha–16x (+2.32), R–271 (+1.96), and R–421 (+2.90). The discriminant function value thus suggests that the amphibolites in and near the Bação Complex (J–10, J–155C) are metamorphosed sediments; the Pacas Amphibolite Member of the Monlevade gneiss is of igneous origin (R271, R421), as is the xenolith in granite near Belo Horizonte (Ha–16X). Values for the Sítio Largo Amphibolite cluster near zero and indeed average out to about zero, −0.33, −1.01, +0.88, and the value for the Elefante Formation is low and negative, −1.44. These low values are not conclusive evidence for any one mode of origin.

The amphibolites contain equilibrium mineral assemblages typical of rocks having excess SiO_2 in the staurolite-almandine subfacies of the almandine-amphibolite facies (Turner and Verhoogen, 1960, p. 546). Most of them are in the epidote-almandine-hornblende field of the ACF diagram (fig. 38) and also typically contain andesine, quartz, biotite, and actinolite.

IRON-FORMATION

Iron-formation occurs in all the metamorphic environments of the region. The Cauê Itabirite and much of the Gandarela Formation is iron-formation of chemical origin. Iron-rich sediments of largely



	J-155C	J-10	Ha-16x	R-10	R-191	R-271	R-413	R-416	R-420	R-421
si	160	202	110.5	140	111	119	116	117	119	117
al	24.5	27	19.5	22	24	22.5	23	21	22	22
fm	34	54	48.5	45	52	46	51	47	53	49
mg	.38	.65	.48	.53	.49	.50	.42	.48	.48	.51
c	40.5	18	24	28	21	25.5	23	28	22	23
alk	1	1	8	5	3	6	3	4	3	6
ti	2.6	1.6	2.4	1.9	2.2	2.7	2.2	2	2.4	3.1
p	.2	.2	.2	.2	.1	.2	.1	.1	.1	.2

E

Figure 39.—Tabulation and diagrams of Niggli values (1954) for amphibolite in the Quadrilátero Ferrífero. Open circles represent Monlevade amphibolites. *A*, triangular diagram of *mg* vs. *c* vs. *alk* showing the differentiation trend curve of Karoo dolerites (from Leake, 1963); *B*, plot of *c* vs. *mg* showing the differentiation trend curve of Karoo dolerites; *C*, plot of *ti* vs. *mg*; *D*, plot of *alk* vs. *mg*; *E*, breakdown of amphibolite samples into respective components.

detrital origin are found in the Piracicaba Group and the Itacolomi Series. Most post-Rio das Velhas iron-formation belongs to the oxide facies (James, 1954), whereas most iron-formation of the Rio Das Velhas Series probably belong to the carbonate facies (Dorr and others, 1957, p. 18).

Iron-formation is a thinly bedded rock containing alternating layers rich in iron oxide, iron carbonate, or quartz. Beds in the Cauê Itabirite are as much as several hundred meters thick and are continuously mappable from one side of the region to the other. In other formations, iron-formation is generally lenticular and rarely as much as 100 m thick. Hematite and quartz, or magnetite and carbonate, are essential minerals; amphiboles, talc, kaolinite, chlorite, muscovite, and sulfides may be accessory minerals. Quartz tends to be fine and even grained and have a sutured texture. The grain size of iron oxides and quartz appears to vary with degree of metamorphism. In the western part of the area, hematite is generally smaller than 0.05 mm; in the eastern part, in the Monlevade and Itabira quadrangles, some quartz is larger than 1 mm in diameter. Hematite generally occurs as tabular plates or irregular grains and is most abundant in quartz-rich oxide-facies iron-formation. Magnetite occurs as euhedral grains in the carbonate-rich iron-formation (Dorr, 1958, p. 62).

Most oxide-facies iron-formation has no accessory minerals (fig. 17). Isolated flakes or radiating groups of talc or kaolinite less than 0.5 mm in length rarely occur and tremolite-actinolite and other amphiboles are developed in the Brumadinho and Sao Julião quadrangles. A deep-green iron-rich chlorite having a high median index of refraction in carbonate-facies iron-formation of the Nova Lima Group resembles greenalite and is associated with magnetite. Siderite, ankerite, or ferrodolomite are the carbonate minerals (Gair, 1962, p. 17–18). In the Minas Series, the only carbonate in iron formation is dolomite. Late sulfides in rocks of the Nova Lima Group form blebs and veinlets that cut bedding surfaces.

Most available chemical analyses of oxide-facies iron-formation from the Quadrilátero Ferrífero show only total iron, SiO_2, Al_2O_3 P_2O_5, and MnO (table 32). Chemical analyses of dolomitic itabirite, carbonate-facies iron-formation, (table 33) and iron-formation of relatively high metamorphic grade (also table 32) are generally more complete. Minor elements were determined only from iron-formation of relatively high metamorphic grade (table 33).

TABLE 32.—*Chemical analyses (in weight percent) of iron-formation*

	Oxide-facies iron-formation					Dolomitic itabirite and carbonate-facies iron-formation				Higher metamorphic grade iron-formation			
Reference no.:	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	52.9	14.4	35.5	7.6	35.63	38.9	51.2	48.1	47.4	56.1	43.9	43.1	51.1
Al_2O_3	.40	5.2	Tr.		.18	.55	<.05	.02	.0	.2	<.1	.00	.6
Fe_2O_3	41.6		61.3			9.7	4.8		2.0	36.4	36.8	6.8	
} Fe_2O_3 + FeO		78.6		88.8	61.5			28.3					32.2
FeO	3.2		.9			27.6	20.9		20.9	5.9	6.6	17.7	
MgO	.07					.8	.9	4.7	1.6	.00	1.7	2.2	5.4
CaO	<.05					3.1	5.0	7.3	7.1	.10	9.0	14.0	9.3
Na_2O	.09					.22			.04	.04	.06	.04	
K_2O	<.01					<.01			.02	.01	.01	.18	
TiO_2	<.01					<.01			[1]	.07	.02	.32	
P_2O_5	.10	.02	.03	.37	.11	.08			.09	.26	.23	.01	
MnO	<.01		1.2	Tr.	Tr.	<.01	.71	.60	.41	.12	.13	.65	
S	<.005					.53	3.4		Tr.			Tr.	
H_2O	1.1			.12	.10	<.1			.69	.55	.82	+2.42	
CO_2	<.01					17.9			[2].19			−.08	
Ignition										<.05	<.05	[2]12	
loss	--		1.06				13.3	11.0					1.5
Sum	99.5	98.2	100.0	96.9	97.5	99.4	100.2	100.2		99.8	>99.3	[3]99.5	100.1
CaO/Mgo								1.6					1.7

[1] Two have 0.00, one has 0.58 percent.
[2] By difference.
[3] Cr_2O_3=0.00.

Key: 1. Average of 2 analyses, weathered from formation, Nova Lima Group, Rio Acima quadrangle. See Gair, 1962, table 4, samples 2, 3. Analyst: J. I. Dinnin, U.S. Geological Survey, Washington, D. C. (rapid methods).

2. Average of 10 analyses, itabirite, Cauê Peak, Itabira quadrangle. See Dorr and Barbosa, 1963, samples 16–25, table 5. Analyst: A. Penido, Cia. Vale do Rio Doce, Itabira.

3. Average of 4 analyses, soft Cauê Itabirite, Dom Bosco Quadrangle. See Johnson, 1962, table 4, samples 208, 319, 385, 554. Analyst: C. M. Pinto, DNPM Belo Horizonte.

4. Average of 2 analyses, itabirite. Congonhas district. See Guild, 1957, table 12, samples 1, 2. Various analysts.

5. Average of 10 analyses, itabirite. Congonhas district. See Guild, 1957, table 12, samples 3–12.

6. Unweathered carbonate iron-formation, Nova Lima Group, Raposas mine, Nova Lima quadrangle. See Gair, 1962, table 4, sample 1.

7. Average of 4 analyses, unweathered carbonate iron-formation, Nova Lima group, Nova Lima district. See Gair, 1957, table 4, samples 4–7. Analyst: C. M. Pinto, DNPM, Belo Horizonte.

8. Hard dolomitic itabirite, Dom Bosco quadrangle. See Johnson, 1962, table 4, sample 764.

9. Average of 3 analyses, siderite-quartz iron-formation, Raposas mine, Nova Lima quadrangle. See Tolbert, 1964, samples 3, 6, and 7, table 1.

10. Amphibole-bearing iron-formation, R–108–54, Bação quadrangle. Analyst: P. Elmore, I. Barlow, S. Botts, and G. Chloe, U.S. Geological Survey, Washington, D.C. (rapid methods).

11. Pyroxene-bearing iron-formation, H–24n, Santa Luzia quadrangle. Analyst: same as no. 10.

12. Green- and black-banded iron-formation, Raposas mine. Green bands are cummingtonite-grunerite and quartz; black bands are magnetite and carbonate. See Tolbert, 1964, sample 1.

13. Hard diopside actinolite itabirite, Dom Bosco quadrangle, N 3,760, E 12,600. See Johnson, 1962, table 4, sample J–687–1.

TABLE 33.—*Semiquantitative spectrographic analysis of higher metamorphic grade iron-formation*

[Sample numbers are keyed to table 32. Analyst: Helen W. Worthing, U.S. Geological Survey. See table 1 for detection limits]

	10	11
Ag	3	.7
Ba	10	70
Co	0	0
Cr	7	2
Cu	5	1.5
Ga	0	0
La	0	0
Mo	50	30
Nb	0	0
Ni	10	10
Pb	0	5
Sc	0	0
Sn	20	30
Sr	5	50
V	5	0
Y	30	30
Yb	3	3
Zn	0	0
Zr	15	10

Iron-formation with the high-temperature iron silicate minerals, andradite, hedenbergite, and grunerite, is uncommon in the area. Generally, increasing temperature and pressure during metamorphism only caused the itabirite to become coarser grained. Thus the typical oxide-facies assemblage of quartz and hematite, plus magnetite in places (James, 1955, p. 1475), is characteristic of low- to high-grade metamorphic zones (table 34). The scarce iron silicates are interpreted to be products of the metamorphism of dolomitic iron-formation.

Comparitively pure itabirite occurs in the pre-Minas Monlevade gneiss in the staurolite zone and is indistinguishable from Cauê Itabirite (Reeves, 1966 p. 10). Cauê Itabirite in the biotite or staurolite zones in the Itabira district is finely laminated and is composed of specularite, 0.01 to 0.1 mm in size, angular granoblastic quartz grains, 0.04 to 0.4 mm in size, minor magnetite as small euhedra, and traces of talc (Dorr and Barbosa, 1963, p. 19). The itabirite from Monlevade and Itabira is similar to itabirite of the chlorite zone except for having abundant specularite and coarser grain sizes.

High-temperature silicate minerals occur in iron-formation in the Dom Bosco (J-687-1, table 32, ref. no. 13), Itabira, Santa Luzia (H-24n, table 32, ref. no. 11), Piedade, Bação (R-108-54, table 32, ref. no. 10), and Nova Lima quadrangles. Most of the iron-formation belongs to the Itabira Group, but north of the Serra do Curral and in other structurally complicated areas stratigraphic relationships are uncertain and the iron-formation may belong to the Piracicaba or the Nova Lima Groups. Iron-formation of high metamorphic grade, as J-687-1, for example, has alter-

TABLE 34.—*Apparent changes during metamorphism of iron-formation*

[Principal minerals in upper case letters; accessories in lower case letters; generally rare minor accessories in parentheses]

Low grade	Medium grade	High grade
	"Pure" itabirite	
HEMATITE	SPECULAR HEMATITE	SPECULAR HEMATITE.
QUARTZ	QUARTZ	QUARTZ.
(Kaolinite)	(Tremolite-Actinolite)	(Cummingtonite-grunerite).
(Pyrophyllite)		
(Talc)		
(Chlorite)		
	Dolomitic itabirite	
MAGNETITE	MAGNETITE	MAGNETITE.
HEMATITE	SPECULAR HEMATITE	SPECULAR HEMATITE.
QUARTZ	QUARTZ	QUARTZ.
DOLOMITE	Dolomite	(Dolomite).
(Talc)	Diopside	Pyroxene.
(Kaolinite)	Tremolite-actionolite	Andradite.
(Chlorite)		Cummingtonite-grunerite.

nating layers of light-green quartz-magnetite-actinolite and dark-gray diopside-specularite actinolite, 1 to 3 mm thick. Quartz grains are 0.1 to 0.4 mm in size and diopside grains average 0.04 mm. Rare carbonate grains occur in the quartz-rich layers. In iron-formation in the Santa Luzia quadrangle, garnet forms almost pure layers, except for some grunerite, that are 1 to 3 mm thick (fig. 28). Alternating layers are rich in quartz, grains of which are 0.1 to 0.3 mm in diameter, and pyroxene, grunerite, and magnetite.

Mineralogic changes in itabirites during metamorphism are identical to those reported by James (1955) for hematite-banded oxide-facies iron-formation of northern Michigan. At intermediate metamorphic grades, some hematite changes to specular hematite, but the most important change is an increase in grain size of quartz in layers of relatively pure chert. In the chlorite and biotite zones the diameter of typical quartz grains is less than 0.1 mm; in the garnet and staurolite zones, 0.1 to 0.2 mm; and in the sillimanite zone, more than 0.2 mm. Actinolite and cummingtonite are also minor accessory minerals.

In the Quadrilátero Ferrífero, quartz grains in layers of recrystallized chert also increase in grain size during metamorphism (table 9). In the western part of the area, as in the Fecho do Funil, Ibirité, and Belo Horizonte quadrangles, grain sizes range from 0.01 to 0.086 mm and average 0.03 to 0.04 mm. In the Congonhas district, the range is 0.01 to 0.1 mm, and in the Nova Lima and Dom Bosco quadrangles it is 0.05 to 0.4 mm, the average being 0.13 mm in Dom Bosco. In the extreme eastern part, as in the Itabira and Monlevade districts, the common range in size is also 0.04 to 0.4; some quartz grains are as large as 1 mm or more. Although none of these rocks are within the sillimanite zone, many have quartz grains greater than 0.2 mm in diameter, a grain size typical of that zone in northern Michigan (James, 1955).

Carbonate-bearing oxide-facies iron-formation consists of calcite or dolomite, quartz, magnetite, and hematite and in places undergoes important mineralogic changes during metamorphism. Although no single beds can be traced continuously from areas of low to high metamorphic grade, iron-formation of high metamorphic grade originated as carbonate-bearing itabirite and not "pure" itabirite, as suggested by CaO+MgO contents of about 10 to 16 percent (samples 11–13, table 32).

Good evidence that iron-formation of high metamorphic grade is derived from dolomitic itabirite is also seen in the Dom Bosco quadrangle (Johnson, 1962, p. 31). Chemical analyses of a diopside-bearing iron-formation (J–687–1) and of a dolomitic itabirite (J–764) from the same general area are similar (table 35) and indicate that: (1) the diopside-bearing iron-formation is derived from dolomitic itabirite and (2) that metamorphism was essentially isochemical, except for a loss of H_2O and CO_2.

TABLE 35.—*Comparison of dolomitic itabirite and diopside-bearing iron-formation*

[Analyses (taken from Johnson, 1962, p. 31) recalculated to 100 percent. Analyst Cassio Pinto DNPM, Belo Horizonte]

	[1] J–764 Dolomitic itabirite	[2] J–687–1 Diopside iron formation
SiO_2	5.39	51.8
Al_2O_3	.2	.6
Fe_2O_3, FeO, MnO	32.4	32.7
MgO	5.3	5.5
CaO	8.2	9.4
Sum	100.0	100.0
CaO/MgO	1.55	1.71

[1] Dom Bosco quad, N 4720, E 5920
[2] Dom Bosco quad, N 3760, E 12,600

METAMORPHIC TEMPERATURES

There is good geologic evidence that at least three metamorphic events took place (Herz, 1970) and that during each period of metamorphism, temperatures were not uniform throughout the area but depended on thermal gradients away from granitic intrusions. Post-Minas metamorphism may have been progressive early and retrograde late in the same cycle, as evinced in rocks of the Minas Series by chloritization of biotite and garnet, replacement of kyanite by pyrophyllite, and saussuritization of plagioclase. The zonal arrangement of metamorphic minerals bordering on igneous intrusion north of the Serra do Curral (Gair, 1962, p. 52) and around the Bação Complex (Johnson, 1962, p. 25–26) is proof of a temperature gradient due to igneous activity. In both places, staurolite, andesine-oligoclase, and garnet are present near the granitic rocks, whereas chlorite, albite, and other minerals typical of the chlorite zone of metamorphism occur at some distance from the granites.

An approximate idea of metamorphic grade can be obtained from the degree of granularity in recrystallized metamorphic rocks as well as from indicator minerals. The grain size of quartz in quartz-rich bands if iron-formation increases with increasing metamorphic grade in northern Michigan (James 1955, p. 1474–1475) as well as in the Quadrilátero Ferrífero. Grain size can also be used in rocks other than iron-formation, but no quantitative measure has been established. Coarse-grained chlorite in schist formed at higher temperatures than fine-grained mats of chlorite-sericite in phyllite.

In the present study, relative or absolute geologic temperatures have been determined by both the measure of grain sizes and the identification of mineral pairs or solid-solution series in mineral groups whose mutual reactions fix a temperature.

PARAGONITE–MUSCOVITE SOLID SOLUTION

In systems that are saturated with respect to sodium, the amount of the Na-mica, paragonite, to enter muscovite is directly dependent on the temperature of formation (Eugster and Yoder, 1955, p. 125). To be sure of excess sodium, albite and paragonite should both be present in the rock as separate mineral phases.

An X-ray diffractometer study was made of 12 samples suspected of having both paragonite and muscovite (table 6), but only muscovite was found. Sodium is low in nearly all the pelitic (table 21) and quartzitic rocks (table 27) of the area and presumably entered muscovite as paragonite solid solution. Albite is present in some quartzite that contains a few percent Na_2O, but because paragonite is not present as an independent phase, sodium that entered muscovite was controlled by its availability and not by temperature.

DOLOMITE–CALCITE SOLID SOLUTION

In metamorphosed carbonate rocks, the temperature of recrystallization can be determined if calcite and dolomite coexisted at the time of metamorphism. Ideally, the system should be saturated with respect to magnesium, shown by the crystallization of dolomite as an independent phase, so that excess magnesium can be free to enter calcite as a solid solution (Graf and Goldsmith, 1955). The curve relating temperature to mole percentage of $MgCO_3$ in calcite (Graf and Goldsmith, 1958) shows a variation ranging from about 5 percent $MgCO_3$ at 500°C to 18 percent at 800°C. The reaction does not vary with CO_2 pressure.

Fourteen carbonate samples from various parts of the Quadrilátero Ferrífero were analyzed with a Philips X-ray diffractometer running at 1° 2θ per minute using Cu $K\alpha$ radiation between 26° and 34° 2θ. Dolomite has a strong reflection at about 30.9° and calcite at about 29.5°; these reflections increase with increasing dolomite solid solution.

Eleven of the samples have only one carbonate; one has only calcite and the other 10, only dolomite. The three samples that have both carbonates were rerun at 1/8° 2θ per minute (table 36). Because all have low amounts of dolomite in solid solution and so fall near the origin and in the steepest part of the curve of Graf and Goldsmith (1958), the temperature determinations should be considered only an order of magnitude.

The indicated temperatures of about 400°C for the chlorite-bearing rock (J–134) and 550°C for the biotite-bearing rock with the gash veins (J–390) indicate temperature conditions of the middle and uppermost parts of the greenschist facies, respectively (Turner and Verhoogen, 1960, p. 534).

TABLE 36.—*Dolomite content of calcite and indicated temperatures of formation*

Sample No.	d-spacing of calcite	Indicated percent dolomite in calcite	Approximate temperature at formation	Location
J–134 -----	3.0232	3	[1]±400°C	Dom Bosco quad, 13,000 N, 12,500 E.
J–390 -----	3.0118	7	±550°C	Dom Bosco quad, 7,050 N, 6,100 E.
Z–549 -----	3.0199	5	±500°C	Gandarela quad, 6,600 N, 8,250 E.

[1] By extrapolation from curve of Graf and Goldsmith, 1958.
J–134—Schistose green mica-carbonate rock from the Gandarela Formation; carbonate-rich layers are 1 mm thick and alternate with thinner layers made up of muscovite, quartz, chlorite, epidote, and magnetite. The rock is about two-thirds carbonate, 15 percent muscovite, and 10 percent quartz. Chlorite has ultra-brown birefringence, epidote is weakly pleochroic and is approximately clinozoisite$_{75}$.
J–390 (fig. 35)—Sandy dolomite from the Piracicaba Group, about 60 percent carbonate, 30 percent quartz, 10 percent biotite with colorless to brown pleochroism; magnetite is concentrated in thin bands and some apatite(?) is also present. Cut by gash veins of coarsely crystalline calcite averaging about 0.3 mm in diameter; outside of the veins the grain size of carbonate varies from about 0.05 to 0.1 mm.
Z–549—Carbonate iron-formation from the upper part of the lower dolomite member of the Gandarela Formation, differentiated by J. E. O'Rourke (written commun., 1954) in the Gandarela quadrangle. Layered, fissile rock consisting of about 65 percent carbonate, particles of which average 0.02 mm in diameter; 25 percent magnetite, about 0.06 mm in size, and the rest mostly quartz in discrete angular grains, about 0.02 mm in size. Some talc(?) is also present.

DOLOMITE–SIDERITE SOLID SOLUTION

The geothermometric concepts outlined for dolomite-calcite solid solution apply equally well to other carbonate mineral pairs. David R. Wones, U.S. Geological Survey, (written commun., 1966) determined the compositions of siderite and dolomite from vein material of the Morro Velho mine by unit cell and optical data:

	Composition	A_o	C_o	*W*
Dolomite --	$Ca_{.51}Mg_{.44}Fe_{.05}CO_3$	4.814 ± .001	16.048 ± .006	1.692
Siderite ---	$Fe_{.63}Mg_{.37}CO_3$	4.670 ± .001	15.234 ± .005	1.803

Assuming that (1) little or no manganese is present and (2) that the dolomite-ferroan calcite tie lines given by Goldsmith and others (1962) are subparallel, a crude estimate of temperature of 400°C±75° can be made.

PYRRHOTITE–PYRITE SOLID SOLUTION

The mineral pair, pyrrhotite-pyrite, has been used as a geological thermometer, by measuring the atomic percentage of Fe in pyrrhotite (Arnold, 1958). Temperatures can be obtained in the range from 300°C, to about 743°. An approximate temperature of 325°C was determined for pyrite-pyrrhotite from the Morro Velho mine (R. G. Arnold in Gair, 1962, p. 56). This is well within the temperature of the lower greenschist metamorphic facies as also indicated by the chlorite-albite-quartz assemblage in the wall rock.

REACTIONS IN SILICEOUS CARBONATES

Quartz and calcite coexisting below 600°C react under temperature conditions of 600°C to about 800°C and pressure conditions of 5,000 to about 50,000 lbs. p.s.i. to form wollastonite: $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$ (Harker and Tuttle, 1956). At a minimum depth of burial of 5 km, a temperature of about 750°C would have been necessary to produce wollastonite from siliceous carbonates; the lack of wollastonite in the area, shows that temperatures did not exceed 750°C.

Coexisting dolomite and quartz react between about 300°C to 550°C at pressures ranging from 0 to 5,000 atmospheres to form diopside: $CaMg(CO_3)_2 + 2SiO_2 \rightarrow CaMg(SiO_3)_2 + 2CO_2$ (Weeks, 1956). Diopside formed by this reaction in beds of dolomitic itabirite in the Passagem gold mine (fig. 5), in the Dom Bosco quadrangle north of the Serra do Ouro Branco (J–687–1, table 32, no. 13), Itabira, and Santa Luzia quadrangles (fig. 28). Assuming a depth of burial of 8 km, according to the equilibrium pressure/temperature curves of Weeks (1956, p. 259), the temperature necessary for the reaction to proceed is about 490°C; at a depth of burial of 12.5 km, the necessary temperature is about 520°C. From these data, it can be assumed that throughout most of the area, the temperature did not much exceed about 500°C; if it had, diopside would be much more common in dolomitic itabirite. Diopside in the area probably formed at temperatures above 500°C but below 750°, judging by the absence of wollastonite in beds of the proper chemical composition.

ALBITE IN PLAGIOCLASE AND ALKALI FELDSPAR

Barth (1956) suggested that the mole fraction of albite in potassium-feldspar compared to that in plagioclase should vary with temperature and pressure. Feldspars were separated from gneisses and granites and the albite molecule was determined in potassium-feldspar by chemical analysis and in plagioclase by indices of refraction (Herz and Dutra, 1966). Nine samples showed temperatures of crystallization or recrystallization ranging from 380°C to 430°C—temperatures expected in the lower green-schist facies of metamorphism. A sample of granite gneiss from Engenheiro Corrêa indicated 460°C, a granodiorite from Congonhas, 570°C, and a post-tectonic granite from Peti, 610°C.

ORGANIC COMPOUNDS IN PHYLLITES

Samples of "graphitic" phyllite were collected by G. C. Simmons from (1) the Barreiro Formation at its type locality in the northeast part of the Ibirité quadrangle (Pomerene, 1958, p. 67), (2) from the Batatal Formation, (3) from the Nova Lima Group, 300 m underground in the Raposas mine, and (4) from the Cercadinho Formation near Fazenda Alegria.

Irving Breger, U.S. Geological Survey, (written commun., 1966) isolated unsaturated fatty acids from the first three samples. Since these compounds break down at temperatures greater than about 200°C, it must be assumed that in some places in the Quadrilátero Ferrífero, the temperature never rose higher than 300°C, which is lower than the minimum temperature suggested for the greenschist facies (Turner and Verhoogen, 1960, p. 534).

PETROLOGY

Granitic intrusions are directly related to some local rises in the grade of metamorphism. Increases in metamorphic grade are generally shown by an aureole in the country rock that parallels the contact with the intrusive, as is seen north of the Serra do Curral and around the Bação Complex. Towards the eastern and southern parts of the area, however, metamorphic grade increases and metamorphic mineral assemblages are typical of the Barrovian-type of regional dynamothermal metamorphism (Miyashiro, 1961, p. 279) which develops at pressures of about 2 to 5 kilobars.

It is known that at least three events were accompanied by widespread regional metamorphism (Herz and others, 1961). The last, about 500 m.y. ago, was a post-Minas low-grade metamorphic event accompanied by pegmatites (Herz, 1970, p. 7); it effectively masked the effects of earlier metamorphism. Dorr and Barbosa, (1963, p. 10) stated that pre-Minas regional metamorphisms was of high grade but that its assemblages were largely destroyed by retrograde action during low-grade metamorphism of post-Minas age. Gair, (1962, p. 9), on the other hand, said that widespread, pre-Minas deformation(s) was of low metamorphic grade, except for local contact metamorphic effects, and that the most important effect of the post-Minas deformation(s) was to impose deformational textures and structures on these older rocks.

Clearcut evidence for retrograde metamorphism during post-Minas orogeny is seen in contact aureoles, where biotite and garnet have been partly replaced by chlorite and staurolite by chloritoid. Such incipient facies changes may also be related to falling temperatures after intrusion accompanied by increased diffusion of fluids and may not necessarily indicate a later metamorphic event.

The post-Minas orogeny at 1,350-m.y. was accompanied by widespread intense mechanical deformation, which conceivably so comminuted the minerals in pre-Minas rocks that most evidence of high-grade regional metamorphism has been masked. Many pre-Minas quartzitic rocks, for instance, are now cataclasites (Maxwell, 1972). Certainly the deformation at 1,350 m.y. could have opened access to relatively impermeable metamorphic rocks by hydrothermal solutions. Possible evidence of original higher grade mineralogy and coarser grained textures in some pre-Minas rocks is shown in some almandine amphibolite metamorphic-facies contact rocks and xenoliths of post-Rio das Velhas granites.

Chloritoid and kyanite are abundant in aluminum-rich rocks of specific bulk chemical compositions. They may occur in folds or other environments in which shearing or a directed pressure must have been important and in such occurrences correspond to Read's (1957, p. 362) examples of dislocation metamorphism. Shearing is equivalent to the "tectonic overpressure" of Clark (1961), and its probable local effect must have been to raise the effective total pressure and to facilitate the formation of kyanite in rocks containing excess Al and Si. The development of chloritoid, however, appears to be controlled only by bulk chemical composition (see p. 56) and any control exercised by structural environment may be more apparent than real.

Cataclastic metamorphism with or without subsequent silicification is common in the major fault zones of the region. Some beds of the Cambotas Quartzite in the central part of the area were recognized and mapped on the basis of intense cataclastic structure—surfaces of rupturing—lying parallel or subparallel to bedding planes (Moore, 1969, p. 12–13). The cataclastic structure is characterized by a matrix of fine-grained quartz and sericite around larger strained quartz grains, by crushed and partly recrystallized quartz and feldspar, and by small augen built up by mica and chlorite surrounding felsic cores.

The relative importance of metasomatic metamorphism as a cause of widespread "granitization" is not generally agreed upon by the different geologists who worked in the region, although it is agreed that metasomatic metamorphism may have occurred near the contact of some granitic and gneissic rocks. Such metamorphism is illustrated by small porphyroblasts of potassium-feldspar and albite in basal Moeda quartzite near a contact with intrusive granite on the southern slope of the Serra do Curral, in the Ibirité quadrangle (Pomerene, 1964, p. 36). Metasomatism is considered to have formed much of the gneiss in the Itabira district (Dorr and Barbosa, 1963).

"Ultrametamorphism" may have produced the interlayered amphibolite schist and felsic granitic rock around the Bação Complex and other granitic-appearing rocks (Johnson, 1962, p. 22). Winkler and Platen (1961) found, at temperatures of 700°C±40° and 2,000 atmospheres P_{H_2O} pressure, that solutions of granitic composition formed from metamorphic rocks containing quartz and alkali feldspar; at lower temperatures, higher pressures were needed to produce the same results.

Metasomatic transport over short distances is probably responsible for kyanite-quartz veins in the quartzite of the Serra da Moeda syncline and kyanite-pyrophyllite veins in phyllite of the Serra do Itabirito (Herz and Dutra, 1964). These veins are probably similar to the recrystallization pegmatites of Ramberg (1952), in which most of the vein material is derived from the country rock itself (fig. 42).

METAMORPHIC ZONES

Metamorphic transformations can be analyzed from the viewpoint either of metamorphic zones (Turner and Verhoogen, 1960) or metamorphic facies. On the metamorphic map (pl. 1), isograds have been drawn to show the first appearance of minerals indicative of increasing temperature-pressure zones. The chlorite zone underlies the greater part of the region. The presence, however, of high Al-Mg chlorite, which is stable to the highest grades of metamorphism, makes it difficult to define the low-grade chlorite zone in parts of the area.

Throughout most of the region within the biotite isograd typical rocks are chlorite-sericite-quartz schists, but some biotite is found scattered through their area of outcrop. Similarly developed widespread zones have been found in the greenschist terrane of Eastern Otago, New Zealand, on the boundary of the chlorite zone (Turner, 1938) and elsewhere. This would suggest either that (1), although the probable reaction at the biotite isograd is ferromagnesian chlorite + muscovite + silica = aluminous chlorite + biotite (Ramberg, 1952, p. 140), there exists a narrow temperature range in which all minerals are in equilibrium or that (2) the reaction frequently does not go to completion.

Chlorite from within the chlorite zone of the Quadrilátero Ferrífero (table 5) has less aluminum in both 4- and 6-coordinated positions than chlorite from the biotite zone, so that an aluminum-rich chlorite probably accompanies the development of biotite. Where biotite first appears, it is generally interleaved with and appears to replace sericite and chlorite. Where it is abundant, it is commonly porphyroblastic. Both biotite and chlorite are also found within the staurolite zone, which is the highest of the area.

In addition to pressure/temperature conditions and bulk chemical composition, the oxygen activity as determined by the degree of oxidation of the iron component of the rock played a role in the development of biotite. Chinner (1960, p. 187) defined the oxidation ratio (o.r.) as molecular $(2Fe_2O_3 \times 100)/(2Fe_2O_3 + FeO)$ and found that with increasing oxidation ratio, total biotite and garnet decreased whereas muscovite and iron oxides increased. Following Chinner, low o.r. (ilmenite-magnetite suite) = 0–14, moderate o.r. = 15–42, and high o.r. > 43 (magnetite-hematite suite).

Low-grade pelitic rock of the Quadrilátero Ferrífero, including slate and phyllite, has a moderate to high o.r. and biotite (table 37). The only analyzed schist, A–4953, has a high o.r., 44.4, and has biotite that has partly retrograded to chlorite, which suggests that oxidation may have accompanied retrograde metamorphism.

Biotite developed in all high-grade quartzo-feldspathic rocks that have low to moderate o.r.'s. In rocks with o.r. > 35, much biotite has retrograded to chlorite, which suggests again that oxidation accompanied retrograde metamorphism.

The only amphibolite having abundant biotite, J–10, has an extremely low o.r., and that with the highest o.r., J–155c, has no biotite. In short, it appears that biotite developed only in rocks having low to moderate o.r., sufficiently high pressure/temperatures conditions, and correct bulk composition.

In rocks of the biotite zone that have no significant pelitic fraction or are potassium-poor generally, almandine, garnet, and kyanite form instead of biotite. Phyllite at Poço Fundo in the Casa de Pedra quadrangle has both garnet (almandine?) and chloritoid (Guild, 1957, p. 24). Abundant fine crystals of kyanite occur in the thick quartzite of the Serra do Caraça. The formation of almandine and kyanite can be attributed to the metamorphism of a rock high in Al_2O_3 and Fe_2O_3 and low in alkalies. Kyanite phyllite in the Cercadinho formation in the Lagôa Grande quadrangle and elsewhere is exceptionally high in Al_2O_3 and probably represents reworked regolith below the unconformity at the base of the Piracicaba Group (Herz and Dutra, 1964).

Other polymorphs of Al_2SiO_5 did not form in any great abundance, evidently because P_{load}, increased in part by the tectonic overpressure, was too high. Nucleation factors, suggested by the presence of Fe_2O_3 in all kyanite analyzed from low-grade rocks (table 15), may have facilitated the crystallization of kyanite in the lowest pressure/temperature part of its stability field. Chloritoid occurs in or near kyanite-bearing rocks metamorphosed in the biotite zone, but is not associated with kyanite in rocks of higher metamorphic grade.

In kyanite-chlorite pelitic rock just east of the Serra do Caraça, high total aluminum, suggested by the presence of kyanite, probably extended the stability field of the chlorite (Turnock, 1960, p. 99). If mineral transformations and structural deformation occurred simultaneously, tectonic overpressure helped to produce a high total pressure. High pressure tends to expand the stability fields of muscovite, iron-and magnesium-rich chlorite, kyanite, and chloritoid into higher temperature fields (fig. 40).

Kyanite crystallized from low-temperature/high-pressure conditions to the highest conditions of metamorphism in the area, those of the staurolite zone. In the staurolite zone, the amount of chlorite and chloritoid diminished, chlorite became Al-Mg-rich, and biotite and muscovite formed.

TABLE 37.—*Oxidation ratios of rocks*

[Oxidation ratio: $(2\ Fe_2O_3 \times 100)/(2\ Fe_2O_3 + FeO)$ (Chinner, 1960)]

Sample number and rock type	Oxidation ratio	Developed biotite?
Pelitic rocks (from table 21)		
Z–597, slate	92.3	No.
Z–842, slate	32.4	No.
J–211, phyllite	88.1	No.
J–341, phyllite	29.6	No.
J–682b, phyllite	40.0	No.
J–84b, phyllite	33.8	No.
BP–1, phyllite	90.6	No.
A–4953, schist	44.4	Yes, partly retrograded to chlorite.
Quartzo-feldspathic rocks (from table 27)		
J–693, feldspathic quartzite	75.0	No.
JG241–55, graywacke	26.4	No.
Ha–37, gneiss	21.7	Yes.
Ha–39, gneiss	20.0	Yes.
A–5053, subgraywacke	41.9	Yes, largely retrograded to chlorite.
Ha–23, gneiss	34.5	Yes, partly retrograded to chlorite.
Amphibolites (from table 29)		
J–155C	46.3	No.
J–10	6.1	Yes.
Ha–16x	22.0	No.
R–10	17.9	No.
R–191	32.4	Rare.
R–271	16.7	Yes.
R–413	28.1	No.
R–416	14.3	No.
R–420	15.4	No.
R–421	17.2	

Staurolite indicates the highest degree of metamorphism in pelitic schist of the area. It is generally porphyroblastic and may replace chloritoid, but generally forms from an indeterminate metamorphic reaction. Garnet, biotite, and oligoclase-andesine are typically associated with staurolite but are also found in the biotite zone. According to Halferdahl's experimental data (1961, p. 99), staurolite + almandine + hercynite + vapor replaces chloritoid at temperatures above 700°C; the breakdown of chloritoid apparently took place at much lower temperatures in the Quadrilátero Ferrífero.

Higher-temperature minerals than staurolite, such as sillimanite and cordierite in pelitic rocks and pyroxene in dolomitic iron-formation occur in a few isolated places. (See discussions under Mineralogy.) Because these occurences are sporadic it is impractical to map any isograd higher than staurolite.

METASOMATIC METAMORPHISM

It is generally assumed that metamorphism takes place with little change in relative proportions of

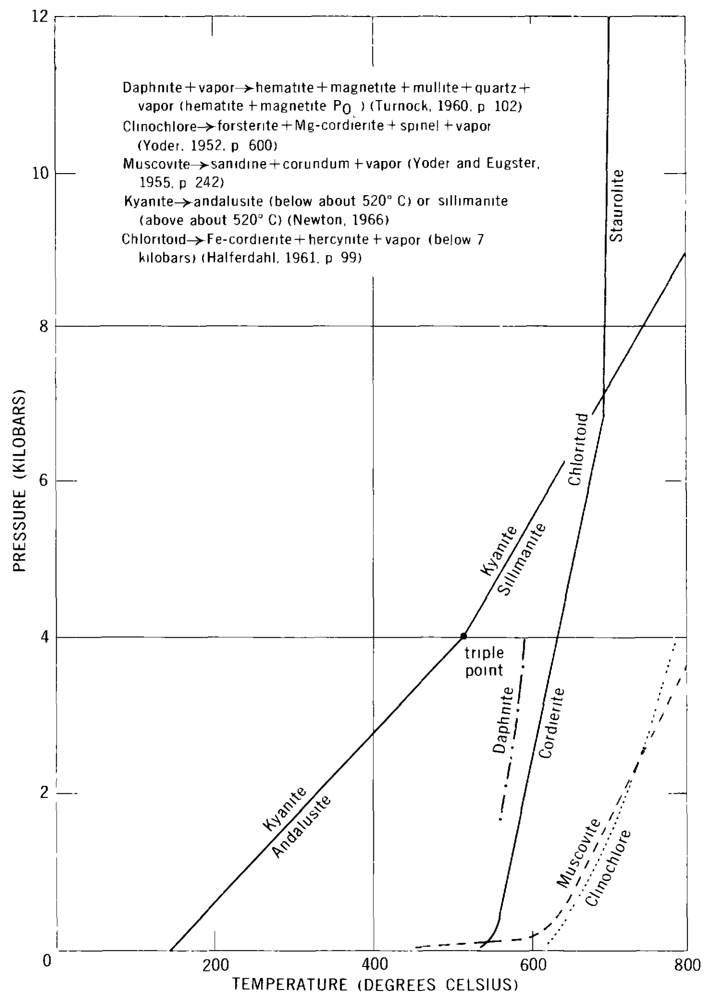


FIGURE 40.—Stability fields of some metamorphic minerals.

cations and with only water and CO_2 lost in progressive metamorphic reactions (Turner and Verhoogen, 1960, p. 561). Near igneous intrusions, however, the metasomatic effects of fluids and gases on the country rock may be significant. The nature and extent of metasomatism related to igneous activity in the Quadrilátero Ferrífero is not generally agreed upon. One or another of the five general types of metasomatism of Eskola (1939, p. 375) representing additions of alkalies, lime, iron-magnesia, nonmetallic elements, and carbon dioxide, occur locally in the Quadrilátero Ferrífero.

ALKALI METASOMATISM

Alkali metals are abundant in salic magmatic fluids and are relatively soluble in water, so they may produce metasomatic effects near granitic contacts. Alkali elements probably become mobile under the lowest metamorphic conditions of the epidote amphibolite facies (Ramberg, 1952, p. 172).

Wallace (1965, p. 24) found a gradational contact between granite and the basal Minas quartzite of the Serra da Moeda, and O'Rourke (written commun., 1954) found one between granite gneiss of the Bação Complex and Rio das Velhas pelitic rocks in the Rio de Pedras quadrangle. Coarse-grained muscovite porphyroblasts lying at an angle to the foliation of chlorite schists in the Itabira district are considered to be evidence of alkali metasomatism (Dorr and Barbosa, 1963, p. 11, fig. 3). Elsewhere in the Quadilátero Ferrífero, coarse-grained muscovite has been taken to represent a consequence of regional metamorphism of K–Al-rich pelitic rocks.

Porphyroblasts of alkali feldspar occur in quartz-rich rocks adjacent to granitic gneiss north and south of the Serra dos Três Irmãos and west of the Serra da Moeda. In the Serra da Jangada, Ibirité quadrangle, porphyroblasts of alkali feldspar occur in quartzite and sericitic quartzite of the basal Moeda Formation (Pomerene, 1964, p. 32–33). The feldspar is untwinned and appears to be the last mineral to have crystallized, replacing quartz, chlorite, and muscovite. In these cases, the porphyroblasts are present in the quartzite within 5 meters of the contact with granitic rocks. North of the Bação Complex, myrmekitic intergrowths of quartz and alkali feldspar occur in metasedimentary rocks near the contact with gneiss (fig. 41). Feldspar myrmekite replaces the quartz and muscovite which is generally taken to result from a deuteric stage of granitic intrusion (Howell, 1957, p. 195).

In the granite gneiss at Itabirito, 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 (Herz, 1970, fig. 19) are further evidence of alkali metasomatism.

The replacement of amphibole by biotite is taken as evidence of potassium metasomatism in places. In the Quadrilátero Ferrífero, biotite having a generally high uniform iron-magnesium ratio partly replaced hornblende in magnetite-bearing amphibolite. The presence of magnetite and the uniform composition of the biotite (table 8) suggests that biotite largely reflects the primary composition of the rock and not metasomatic additions.

CALCIUM METASOMATISM

The most common evidence for calcium metasomatism is the presence of calcium silicates, such as diopside, grossularite, and vesuvianite, between carbonate rocks and silicate rocks or the presence of epidote in

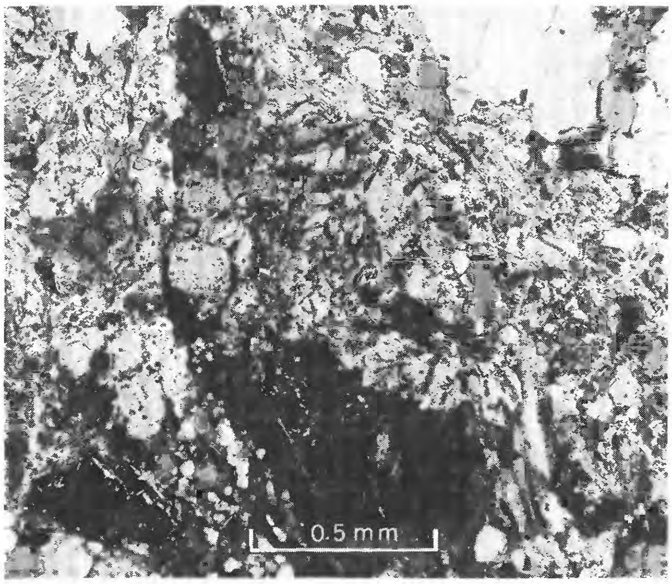


FIGURE 41.—Photomicrograph, muscovite schist, near granite contact, Z–97, Rio de Pedras quadrangle, crossed nicols. Rectangular porphyroblasts of myrmekitic plagioclase, about An_{26} occupy most of photograph. Some grains zoned and some twinned. Large flakes of muscovite interleave with biotite and occur in shreds that wrap around feldspar. Feldspar contains small grains and inclusions of muscovite. Limonite replaces some opaques.

mafic igneous rocks. Both these processes have taken place in the Quadrilátero Ferrífero.

During the metamorphism of some dolomitic itabirites, CO_2 was lost and Ca-Mg reacted with quartz, magnetite, and hematite to produce diopside, cummingtonite-grunerite, tremolite-actinolite, and andradite. Whether the formation of these minerals can be called metasomatism or metamorphism depends on the scale of the system considered; in the rock as a whole, the process is metamorphism, but between the layers of the rock it is metasomatism.

The appearance of vesuvianite instead of grossularite in carbonate-bearing graywackes near granitic contacts of the Belo Horizonte quadrangle (p. 49) is attributed to magmatic fluids. Ca and Al of the vesuvianite may have moved only a few millimeters or so from nearby parts of the rock, but the required OH and F have been added to the rock, probably by hydrothermal solutions.

Epidote veins averaging about 0.3 mm in width occur both in granitic gneiss and biotite-quartz-plagioclase-magnetite schist in their mutal contact zone north of the Serra do Curral. The epidote is not in contact with plagioclase of the biotite schist country rock and can be attributed to calcium-metasomatism from the nearby granitic gneiss. Numerous amphibolite xenoliths in the gneiss (as Ha-16x, table 29) show that mafic rocks picked up by the granitic magma were recrystallized largely to amphibole-biotite-plagioclase assemblages, which may have been the source for the Al- and Ca-rich solutions.

METASOMATISM BY METALLIC ELEMENTS AND SILICA

Metasomatism occurred at least over a scale of millimeters in the Dom Bosco quadrangle, where diopside formed in dolomitic itabirite (table 35) as did andradite garnet in a former dolomitic itabirite (table 20) in the Santa Luzia quadrangle. The metasomatism was between silica- or carbonate-rich layers and the iron oxide-rich layers. There was probably no introduction of metallic elements, and these rocks should be considered as closed systems.

Chromian-bearing chlorite and muscovite is associated with gold-bearing sulfides in the basal Moeda Formation and in the Rio das Velhas Series (table 7). Chromian chlorite has been described by Tolbert (1964, p. 786) from the Raposas and Morro Velho mines, Nova Lima quadrangle, where Cr ranges respectively from 0.072 to 0.580 percent and from 0.022 to 0.31 percent; fuchsite from the Raposas mine averages 0.5 percent Cr. Gair (1962, p. 12) found that fuchsite was generally less than 0.1 mm in diameter and comprised from minor amounts to more than 15 percent of some quartz-rich sericite phyllites. The association or close proximity of fuchsite-bearing rocks and gold mineralization suggests that Cr was mobile and was introduced into these rocks during metasomatism. In late solutions derived by igneous differentiation, Cr is mobile, probably as Cr-complexes (Ringwood, 1955), much more mobile than the sulfides and gold which crystallized only in veins but percolated into the country rock where it was easily fixed by the high-K low-Na sericite and high-Fe chlorite.

Throughout the Quadrilátero Ferrífero, silica metasomatism is common in quartz-rich rocks in and near fault zones. This may be due to migration of Si cations into the fault zones, which became loci of low pressure after movement ceased as in the Alegria district (Maxwell, 1972) (fig. 42).

METASOMATISM BY NONMETALLIC ELEMENTS

Boron, fluorine, and OH tend to be concentrated in solutions derived from differentiated granites and are generally considered to be important agents of metasomatism. Metasomatism involving B and F is generally acknowledged to be of magmatic origin. The common formation of tourmaline near granitic intru-

FIGURE 42.—Quartz vein in quartzite of the Serra do Caraça. Foliation of rock, shown by dark stringers, cuts through vein. Knife is 9 cm long.

sions in this area and tourmaline pods in phyllites are prime examples of B metasomatism (see p. 48). The rarity of the Li-rich tourmaline elbaite suggests that tourmaline formed largely from cations present in the country rock and that the only significant contribution of metasomatic solutions was boron.

Topaz associated with euclase and large quartz crystals is indicative of fluorine metasomatism south of the Bação Complex, in the Ouro Prêto and Dom Bosco quadrangles in an east-west belt in the Cercadinho Formation (Gorceix, 1881). Fluorite occurs in calcareous rocks and is also associated with the sulfide mineralization in the Dom Bosco quadrangle (Johnson, 1962, p. 15). A "greisen" of quartz-muscovite-topaz in the Ouro Prêto quadrangle indicates high-temperature replacement of country rock by F-bearing solutions (A. L. M. Barbosa, written commun., 1965).

Ultramafic rocks in the Quadrilátero Ferrífero commonly have undergone metasomatism by CO_2-rich solutions. In the Itabira, Caeté and Nova Lima quadrangles, magnesite and talc commonly have replaced ultramafic rocks.

SUMMARY METAMORPHIC HISTORY

Isotopic age determinations of samples from the Quadrilátero Ferrífero suggest four events at 2,300 m.y., 1,000 m.y. and 500 m.y. (Herz, 1970, table 2, fig. 4). The Rio das Velhas Series and gneisses from the Bação Complex are older than 2,300 m.y. The Minas Series is younger than that and older than 1,350 m.y., the age of intrusion of the Borrachudos granite. The Itacolomí Series is tentatively considered older than 1,000 m.y. and may also predate the 1,350 m.y. event. The 500 m.y. event is based largely on Ar ages and is responsible for pegmatite formation in the Rio Piracicaba quadrangle. No large granite bodies of that age are known in the Quadrilátero Ferrífero.

EARLY PRECAMBRIAN METAMORPHISM

The earliest Precambrian events apparently resulted in widespread, low-grade, regional metamorphism. Near igneous contacts bordering the Bação Complex, and on the western slope of the Sèrra da Moeda, where the grade of metamorphism reached the almandine-amphibolite facies, quartz-rich roof pendants or large xenoliths were converted to granitic gneisses and mafic volcanic rocks or graywackes were metamorphosed to granite amphibolite (Herz in Dorr and others, 1959/1961).

The original grade of regional metamorphism of the Rio das Velhas sediments is moot. Gair (1962, p. 52) found no evidence of retrograde metamorphism in phyllite and schist of the Nova Lima Group. Other workers in the area think that all bedding in the Rio das Velhas rocks is obliterated by a through-penetrating foliation or cleavage. Eugene Callaghan (oral commun., 1960) found structural evidence of two metamorphisms in the same rocks in the Morro Velho mine, each in the form of flow cleavages. Recrystallization along each cleavage makes it probable that higher grade minerals would have been destroyed during the second cleavage development.

Most rocks of the Rio das Velhas Series are today at the lowest grade of metamorphism, the chlorite and biotite isograds of the greenschist facies. Typical assemblage is quartz-sericite-chlorite. Higher metamorphic facies are found in the Rio das Velhas Series around the Bação Complex. In the Rio de Pedras quadrangle, biotite schist and associated amphibolites grade into granite in three steps (J. E. O'Rourke, written commun., 1954):

1. Conversion of chlorite phyllite to biotite schist; appearance of biotite and plagioclase An_{28-36}.
2. Gradation of biotite quartzites into granitic gneiss;

substitution of feldspar, largely plagioclase, for biotite, and abundant epidote.

3. Development of microcline gneiss.

O'Rourke concludes that the main process involved was metasomatic metamorphism.

LATER PRECAMBRIAN METAMORPHISMS

The Minas Series and the Rio das Velhas Series are separated by an erosional unconformity. The first post-Minas orogeny took place about 1,350 m.y. ago. A thermal event occurred about 1,000 m.y. but its petrographic effects, if any, are impossible to distinguish from those of the 1,350 m.y. event. The regional metamorphism in the greenschist facies during the 1,000 and 1,350 m.y. events appear to be identical to the metamorphism of the earliest event at 2,300 m.y. The grade of metamorphism is higher in the eastern part of the region and also near igneous intrusions (pl. 1).

PALEOZOIC AND YOUNGER EVENTS

The youngest radiometric date in the area is about 500 m.y. which has also been measured at Rio de Janeiro (Goldich and others, 1957), Rio Grande do Sul (Herz and others, 1961), and between Recife and São Luis in northeastern Brazil (Almeida and others, 1968). This age is similar to the Caledonian and Taconic orogenies in Europe and North America respectively. In the Quadrilátero Ferrífero no large-scale intrusion of granite took place at 500 m.y., but a thermal event at that time caused a loss of Ar in some micas.

Younger deformations also affected the area. Diabase dikes intruded northwest trending fractures north of the Serra do Caraça, and multiple basic dikes occupy faults in Maquiné quartzites. Elsewhere in Brazil, diabase dikes have been dated at about 120 m.y. (Amaral and others, 1966).

In all probability then, the orogeny that was manifested elsewhere in Brazil by the widespread extrusion of basaltic flows and intrusion of diabasic and related dikes was also felt in the area of the Quadrilátero Ferrífero. The intrusion of these dikes was accompanied by normal faulting in a north-northwest direction seen throughout the entire region. The mafic dikes apparently follow only this late fault set and are unaffected by older pre-existing structures.

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