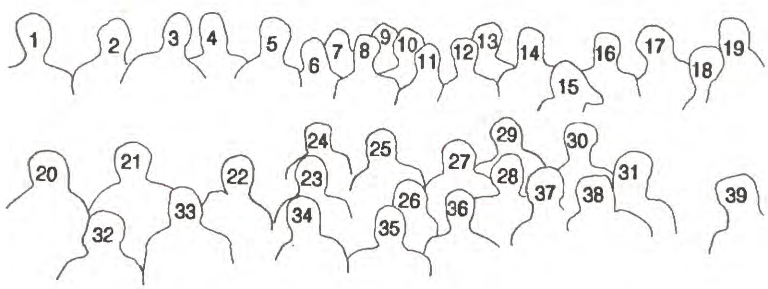
GOLD DEPOSITS RELATED TO GREENSTONE BELTS IN BRAZIL– DEPOSIT MODELING WORKSHOP
Part A–Excursions

U.S. Geological Survey Bulletin 1980-A

A workshop sponsored by the International Union of Geological Sciences and the United Nations Educational, Scientific, and Cultural Organization Deposit Modeling Program. The workshop held December 1-10, 1986, in Belo Horizonte, Brazil, was hosted by the Instituto Brasileiro de Mineração

WORKSHOP PARTICIPANTS

Group photograph at Quintas, Mineração Morro Velho Club, Nova Lima, Brazil
December 4, 1986



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GOLD DEPOSITS RELATED TO GREENSTONE BELTS IN BRAZIL– DEPOSIT MODELING WORKSHOP
Part A–Excursions

Edited by CHARLES H. THORMAN,

EDUARDO A. LADEIRA, and DIANE C. SCHNABEL

Field excursions of the surface geology and to several gold mines in the Quadrilátero Ferrífero, Minas Gerais, Brazil

Workshop:
Belo Horizonte, Brazil, December 1–10, 1986
Sponsors:
International Union of Geological Sciences (IUGS)
United Nations Educational, Scientific, and Cultural Organization– Deposit Modeling Program (UNESCO)
Host:
Instituto Brasileiro de Mineração (IBRAM)

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U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

GOLD DEPOSITS RELATED TO GREENSTONE BELTS IN BRAZIL–
DEPOSIT MODELING WORKSHOP

Part A–Excursions

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Katherine Dorr Abreu
IBRAM coordinator

EXCURSIONS
Above and below ground

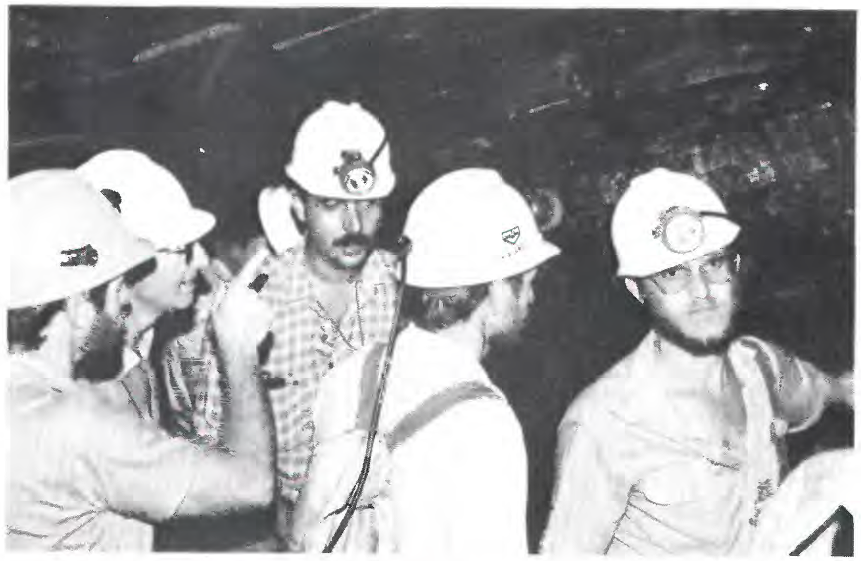
Belo Horizonte to Ouro Preto -- Stop 1 (lower left), Stop 14 (center right)

Morro Velho gold mine-- (left, center left, lower right)

Introduction to a Workshop on Gold Deposits Related to Greenstone Belts in Brazil–Belo Horizonte, Brazil, 1986

By CHARLES H. THORMAN and
EDUARDO A. LADEIRA

U.S. GEOLOGICAL SURVEY BULLETIN 1980-A



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FIELD-TRIP LEADERS
(from left to right):
Skip Cunningham, John Kerswill, Chuck Thorman, Eduardo Ladeira, Stan Caddey, and Carl Anhaeusser

Introduction to a Workshop on Gold Deposits Related to Greenstone Belts in Brazil– Belo Horizonte, Brazil, 1986

By Charles H. Thorman[1] *and* Eduardo A. Ladeira[2]

INTRODUCTION

This volume comprises two parts (Bulletins 1980–A and 1980–B) and presents the results and scientific contributions of a workshop and field trips on "Gold deposits related to greenstone belts in Brazil," held December 1–10, 1986, in Belo Horizonte, Brazil (fig. 1). The workshop was sponsored by the International Union of Geological Sciences (IUGS) and United Nations Educational, Scientific and Cultural Organization (UNESCO) Deposit Modeling Program, a program designed to advance geoscientific knowledge and expertise in mineral-deposit modeling for use in exploration, assessment, and development of resources. The purpose of the Deposit Modeling Program workshops is to facilitate the transfer of knowledge and expertise in these subject areas and to assist in training and educating geoscientists so that they can more effectively explore and assess resources in their home countries. Belo Horizonte was chosen as the workshop site because of its location in the Quadrilátero Ferrífero ("Iron Quadrangle"), famous for its world-class gold deposits (Morro Velho, Raposos, Cuiabá, São Bento) and iron deposits (Itabira, Águas Claras, Itabirito, Alegria). The goals of the workshop were attained through a series of lectures, discussion groups, and several field trips and mine visits, beginning with the general geologic setting of the Quadrilátero Ferrífero and ending with the construction of deposit models for the gold mines visited. This mixture of formats introduced the participants to gold occurrences in a major gold province and resulted in the development of deposit models for greenstone belts that can be applied in South American and other Precambrian shield areas in the exploration for gold and related commodities (silver, lead, zinc, copper). Figure 1 shows the field trip routes for the workshop and figure 2 shows the locations of the major gold mines and occurrences in the Quadrilátero Ferrífero.

The Instituto Brasileiro de Mineração (IBRAM) in Belo Horizonte was the host agency for the workshop. The organizing committee for the workshop consisted of the following people:

- Katherine Dorr Abreu, IBRAM.
- Aristides Eustáquio Machado, IBRAM.
- Paulo Bahia Guimarães, Mineração Marex Ltda.
- Charles G. Cunningham, U.S. Geological Survey.
- Charles H. Thorman, U.S. Geological Survey.
- Eduardo A. Ladeira, Departamento de Geologia, Instituto de Geociências, Universidade Federal de Minas Gerais.
- Ronald Fleischer, Andrade Gutierrez Mineração Ltda.

Workshop leaders and coordinators were as follows:

- Charles H. Thorman, workshop coordinator and leader.
- Charles G. Cunningham, IUGS/UNESCO coordinator and leader.
- Katherine Dorr Abreu, coordinator for all logistical functions and support for the workshop.
- Eduardo A. Ladeira, field trip coordinator, editor of field trip guidebook, and leader.
- Carl R. Anhaeusser, University of Witwatersrand, leader.
- Stanton W. Caddey, Homestake Mining Company, leader.
- John A. Kerswill, Geological Survey of Canada, leader.

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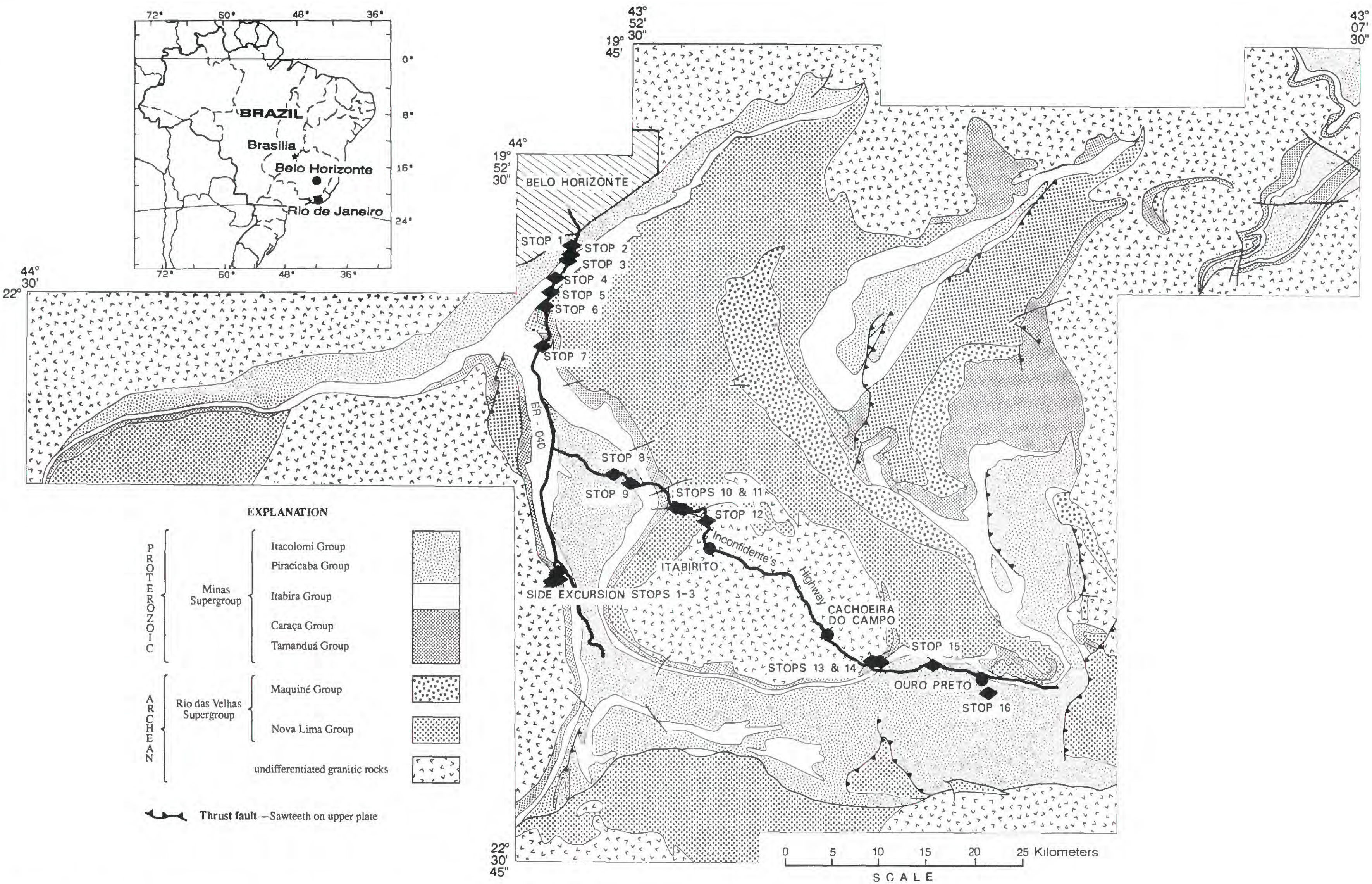

Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the field trip routes for the workshop.

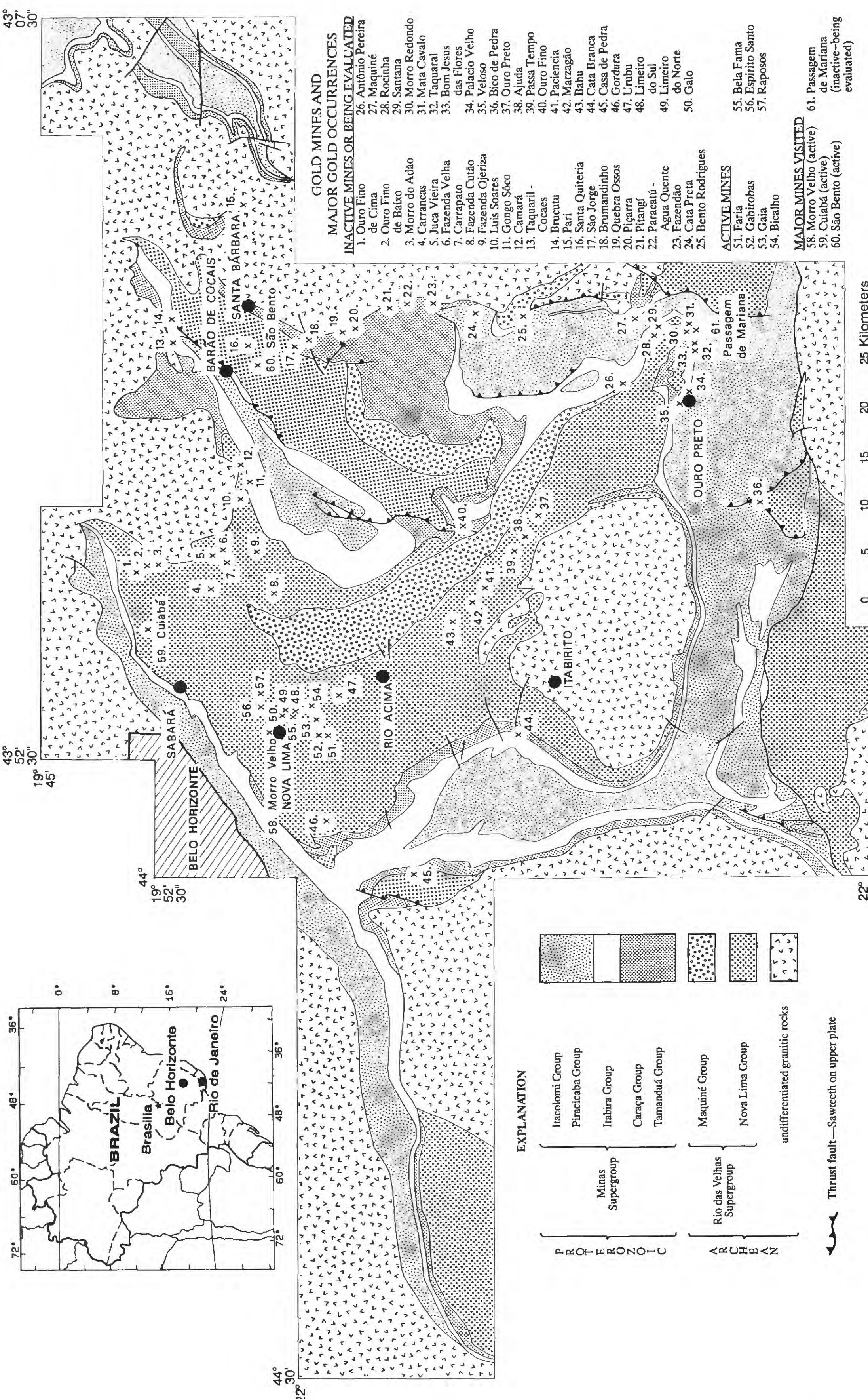

Figure 2. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the location of major gold mines and occurrences in the area.

The two parts of this bulletin are divided as follows: Part A—Excursions (1980–A) includes (1) a field trip from Belo Horizonte to Ouro Preto (fig. 1); (2) a supplementary side field trip; and (3) field-trip logs of visits to the Morro Velho, Passagem de Mariana, and Cuiabá gold mines. Part B—Geology of deposits (1980–B) includes (1) the geology of the Quadrilátero Ferrífero; (2) the geology of the Morro Velho, Passagem de Mariana, São Bento, and Cuiabá gold mines; (3) the Homestake and Lupin gold mines in North America; and (4) deposit models for the Brazilian and North American deposits.

This introductory chapter covers the following topics that relate to the Quadrilátero Ferrífero: the regional geologic setting of the Quadrilátero Ferrífero; a summary of the Precambrian history of the Quadrilátero Ferrífero; structural and stratigraphic interpretations of the Quadrilátero Ferrífero; and a summary of the concepts on the origin of the gold deposits in the Quadrilátero Ferrífero. Some of the alternative regional stratigraphic and structural interpretations presented herein have been discussed for many years and are generally accepted by geologists working in the Quadrilátero Ferrífero, but these interpretations may not be widely recognized outside of Brazil. Other stratigraphic and structural interpretations are the subject of much debate and are far from settled. A byproduct of the workshop was the release of previously unpublished data by mining companies on the geology of several of the ore deposits visited in Brazil and on North American deposits.

This publication differs from most in presenting a mixture of new data in a variety of formats. The papers on the gold mines visited contain new data concerning both the basic geology of the mines as well as production and reserve information. Also, some of these papers describe trips through the mines, as made by the participants in the workshop. We have included these descriptions because they provide important insights into mine geology.

REGIONAL GEOLOGIC SETTING

The Quadrilátero Ferrífero has been an area of mineral exploration and geologic investigation for centuries, dating back to the search for gold and precious stones that began in the 16th century. The discovery in 1699–1701 of black gold—gold contaminated with iron and platinum-group metals—in the southeastern corner of the Quadrilátero Ferrífero gave rise to the name Serra de Ouro Preto (Black Gold Range) and the name of the town Ouro Preto. The Quadrilátero Ferrífero contains world-class gold and iron ore deposits, manganese ore, bauxite, and precious-stone locales. Much data has been generated about the mineral wealth and geology of the area. The best known and most easily available work, which forms the basic geologic framework of the Quadrilátero Ferrífero, resulted from a cooperative study between the Departamento Nacional da Produção Mineral (DNPM) of the Ministério das Minas e Energia (MME) and the United States Geological Survey (USGS) from 1946–1962. This study was primarily a geologic mapping program designed to develop a solid geologic data base that would help in the future utilization of Brazil's natural resources. Many reports and maps on the general geology and economic geology of the Quadrilátero Ferrífero have been published in Brazil and the United States. The summary report by Dorr (1969) includes a geologic map of the Quadrilátero Ferrífero at a scale of 1:150,000, based on the detailed and reconnaissance mapping of forty-seven 7½-minute topographic quadrangles at 1:25,000 by DNPM and USGS geologists.

The following outline of the geologic history of the Quadrilátero Ferrífero was established by the DNPM/USGS program. The distribution of units, their relative positions in time, and the sequence of tectonic events is little changed. Dorr's 1969 summary paper of the geology of the Quadrilátero Ferrífero has truly stood the test of time. This is an impressive statement for the work of such a large group of geologists in a highly complex and, at the time, not easily accessible region. Work by many geologists in the past two and one-half decades has indicated the need for only a few revisions of Dorr's geologic outline. One revision, however, has major implications on the structural evolution of the Quadrilátero Ferrífero and is presented in the following section. Figure 3 shows a generalized stratigraphic section of the Precambrian rocks in the Quadrilátero Ferrífero modified from Dorr (1969).

SUMMARY OF PRECAMBRIAN HISTORY OF THE QUADRILÁTERO FERRÍFERO

This summary is based on Dorr (1969); modifications to it are discussed in the section after this one.

1. The oldest rocks comprise the Rio das Velhas Supergroup, a metasedimentary and metavolcanic succession divided into the Nova Lima and Maquiné Groups (fig. 3). Dorr (1969) considered the Nova Lima Group to be a eugeosynclinal flysch unit and the overlying Maquiné Group to be eugeosynclinal molasse. The Rio das Velhas Supergroup is now recognized as a greenstone belt. The Nova Lima Group hosts most of the large gold deposits in the Quadrilátero Ferrífero.

	PROFOUND OROGENY WITH REGIONAL METAMORPHISM		
		Itacolomi Group	
PROTEROZOIC	PROFOUND ANGULAR UNCONFORMITY		
	Minas Supergroup	Piracicaba Group	Sabará Formation Barreiro Formation Taboões Formation Fêcho do Funil Formation Cercadinho Formation
		Itabira Group	Gandarela Formation Cauê Itabirite
		Caraça Group	Batatal Formation Moeda Formation
		Tamanduá Group	
	MAJOR OROGENY WITH REGIONAL METAMORPHISM		
ARCHEAN	Rio das Velhas Supergroup	Maquiné Group	Casa Forte Formation Palmital Formation
		Nova Lima Group	Upper unit* Middle unit* (includes Lapa Seca Formation) Lower unit*
	CONTACT CONSIDERED INTRUSIVE BY DORR (1969)		
	Granitic-gneissic basement rocks, including granitoids of various ages		

Figure 3. Generalized stratigraphic column of Precambrian rocks of the Quadrilátero Ferrífero (modified from Dorr, 1969). Asterisk (*) indicates units not included in Dorr's paper but discussed in the text of the present paper.

2. The Rio das Velhas Supergroup rocks were deformed and metamorphosed during a major orogenic event at about 2700 Ma (Herz, 1970), before deposition of the overlying Minas Supergroup. This orogenic event may have been accompanied by igneous activity.

3. The Minas Supergroup includes four groups. (1) The basal Tamanduá Group contains a lower paralic prismatic clastic unit (Cambotas Formation) and an upper dolomitic phyllite, dolomitic oxide-facies iron-formation, and a quartzose phyllite unnamed unit. A local unconformity separates the overlying Caraça Group from the Tamanduá Group. (2) The Caraça Group has a lower conglomerate, sandstone, and minor shale unit (Moeda Formation) and an upper phyllite, graphitic phyllite, metachert, and oxide-facies iron-formation unit (Batatal Formation). These rocks are conformably overlain by (3) the Itabira Group, which comprises the lower Cauê Itabirite and upper Gandarela Formation. The Cauê Itabirite is made up of oxide-facies iron-formation (itabirite), dolomitic itabirite, amphibolitic itabirite, and minor phyllite and dolomite. The Gandarela Formation consists primarily of dolomitic marble, but includes dolomitic phyllite, dolomitic iron-formation, and phyllite. The world-class iron deposits in the Quadrilátero Ferrífero occur in the Cauê Itabirite, and manganese is produced from both the Cauê and the Gandarela formations.

(4) The Piracicaba Group unconformably overlies the Itabira Group. A local basal conglomerate (basal Cercadinho Formation) occurs at the base of the group along the unconformity with minor relief. A concordant, continuous sequence of deposition is interpreted from

the Cercadinho Formation through the Fêcho do Funil Formation, Taboões Quartzite, and Barreiro Formation. These units are primarily quartzites to quartzitic phyllites with minor dolomitic lenses. The Cercadinho includes ferruginous strata. The Barreiro, mainly fine-grained rocks, consists primarily of phyllite and graphitic phyllite. The uppermost unit, the Sabará Formation, rests on all the older units in the Piracicaba Group and locally has a basal conglomerate; beds above and below the contact are concordant structurally. The Sabará consists of schist and phyllite, probably derived from tuffaceous and graywacke protoliths, and local tilloid-like conglomerate. A stable shelf or blanket environment was interpreted by Dorr (1969) for the siliciclastic Cercadinho through Barreiro sedimentary cycle and a eugeosynclinal flysch environment for the Sabará.

4. An angular unconformity occurs at the top of the Minas Supergroup; it was interpreted to indicate broad uplift and erosion and to be epeirogenic.

5. The Itacolomi Supergroup, a quartzitic to conglomeratic unit with varied amounts of sericite, was considered by Dorr (1969) to be paralic (molasse?) in origin.

6. A post-Itacolomi orogeny probably formed the basic geologic framework of the Quadrilátero Ferrífero. The age of this event, according to Herz (1970), was about 1000–1350 Ma. This event caused all the complex large-scale folds and other major structures of the Quadrilátero Ferrífero, including the emplacement of the several domal granitic structures (Bação Complex and others), considered intrusive igneous granitic rocks by Dorr (1969).

7. The area was probably covered by carbonate and pelitic rocks of the Late Proterozoic Bambui Group, and the entire region was folded and faulted by the Brasilian Cycle (about 600 Ma). Events post-dating these activities are not considered here.

Modifications to the basic geologic framework of the Quadrilátero Ferrífero just outlined that have been developed since the DNPM/USGS program and are generally accepted are presented next. These modifications include both stratigraphic and structural contributions.

STRUCTURAL MODIFICATIONS

The most fundamental and far-reaching modification to the geologic framework of the Quadrilátero Ferrífero outlined in the summary of Dorr's work (1969) is the concept that the granitic-gneissic basement complex is as old or older than the Rio das Velhas Supergroup, which overlies it, and that the basement complex is cratonic. This modification considers the Archean Rio das Velhas Supergroup as part of a greenstone belt deposited on oceanic crust—somewhere east of the Quadrilátero Ferrífero—and thrust westward onto the craton. In this model, the contact between the Rio das Velhas Supergroup and the basement was a major thrust. The Minas Supergroup is interpreted as a Proterozoic continental margin assemblage that was also thrust over the basement complex and the Rio das Velhas Supergroup. Some members of the DNPM/USGS team considered several major thrusts to be present (Guild, 1957; Barbosa, 1969; Maxwell, 1972) although the concept of the Rio das Velhas and Minas Supergroups as allochthons thrust over the granitic basement was not included in Dorr's geologic framework. These thrusts included one at the contact of the Rio das Velhas-Minas Supergroup with the basement and another between the Rio das Velhas Supergroup and the Minas Supergroup at many localities.

In addition to Dorr's (1969) summary of the region, Herz (1970), Drake and Morgan (1979), Ladeira and Viveiros (1986; this volume, Part B—Geology of deposits) and Morritt (1988) presented summaries that have many common aspects as well as some significant differences. Herz, who was part of the USGS team involved in the DNPM/USGS Quadrilátero Ferrífero mapping project, based his outline of the Quadrilátero Ferrífero geologic history largely on Dorr's work, but Herz's major contribution was to radiometrically date many of the rock units, thus giving substance to the time factor. Drake and Morgan (1979) added a new interpretation based on a plate tectonics model, in which they considered ultramafic rocks at and near the base of the Archean Rio das Velhas Supergroup to represent ophiolite and the Rio das Velhas to be an allochthonous greenstone belt thrust westward onto a cratonic basement complex coeval with or older than the Rio das Velhas. Ladeira and Viveiros (1986; this volume, Part B—Geology of deposits) identified six stages of deformation, but did not correlate them with any regional tectonic or thermal events. In contrast, Morritt (1988), in a more regional study, correlated the individual deformational events identified by the previous workers and placed them in an order with regionally established events. Figures 4 and 5 show these summaries and the correlations of Morritt. Although ideas and interpretations differ among the workers, the basic concepts of Dorr (1969) remain unchanged except for the interpretation that the supracrustal Rio das Velhas greenstone suite is allochthonous.

It is difficult to know who to credit with the concept of the Rio das Velhas being allochthonous. The idea was considered by some of the DNPM/USGS geologists in the 1950's and 1960's (informal discussions by C.H.

EVENT	AGE	DEFORMATION	Dorr (1969)	Herz (1970)	Drake & Morgan (1979)	Ladeira & Viveiros (1984, 1986)	Morritt (1988)
South Atlantian	22-195 Ma	8	-	"D6"-H	-	"D6"-LV	Dn+4
Brazilian	450-700 Ma	7	"D3"-D	"D5"-H	-	"D5"-LV	Dn+3
Espinhaço	1000-1300 Ma	6	-	"D4/3"-H	"D3"-DM	"D4/3/2"-LV	Dn+2
Transamazonian	2000-2100 Ma	5	"D2"-D	"D2"-H	-	-	Dn+1
pre-Transamazonian	2700 Ma	4	"D1"-D	"D1"-H	-	"D1"-LV	Dn
pre-Transamazonian	+2700 Ma	3	-	-	-	-	Dn-1
pre-Transamazonian	??	2	-	-	"D2"-DM	-	Dn-2
??	?	1	-	-	"D1"-DM	-	-

The following outline of Precambrian events includes the depositional history indicated by an asterisk (*) as well as the numbered events (D).

* Accumulation of the Archean Nova Lima Group greenstone sequence in an oceanic setting.
  1,2. Nappe-forming events during which the Nova Lima Group was deformed and thrust northwestward from an oceanic setting onto cratonic crust.
  3. Subsidence of the deformed Nova Lima Group sequence to form depocenter for Minas Supergroup.
  4. Folding of entire Rio das Velhas Supergroup about broad east-west axes. Included emplacement of crystalline bodies, such as the Bação and Moeda complex.

* Deposition of Minas Supergroup on folded Rio das Velhas Supergroup.
  5. Broad warping and uplift of Minas Supergroup. Includes emplacement of granitic bodies.

* Deposition of Itacolomi Group on Minas Supergroup with angular unconformity of as much as 12°.
  6. Post-Itacolomi Group folding and thrusting with north-northwest vergence. Includes emplacement of granitic bodies as well as renewed activity in the Bação and Moeda complexes.
  7. West- to southwest-verging folding and thrust faulting of rocks as young as the Late Proterozoic Bambui Group.
  8. Intrusion of diabase sills and small gabbroic stocks.

Figure 4. Precambrian deformational events in rocks in the Quadrilátero Ferrífero. The correlation of the deformational events is from Morritt (1988), including the letter/numbered events by author(s).

Thorman with several members of the DNPM/USGS team); however, this interpretation is difficult to glean from their reports. Grossi Sad and Ladeira (1968), Ladeira (1976, 1980), and Schobbenhaus and others (1981) all indicated a thrust relationship between the Archean basement complex and the Rio das Velhas and Minas Supergroups over much of the area. The following sequence of events indicates how one of us (Thorman) developed ideas regarding the allochthonous nature of the Rio das Velhas and Minas Supergroups in the Quadrilátero Ferrífero.

1. In February, 1973, Thorman was teaching a photogeology reconnaissance mapping course as part of an MME/USAID (United States Agency for International Development) program for MME geologists. One part of the course entailed constructing a geologic map of part of the Quadrilátero Ferrífero and then field-checking the work. The first area checked was in the Serra da Moeda, on the west side of the Quadrilátero Ferrífero, from the Minas Supergroup down into the granitic basement complex. The first traverse was on the dirt road from Highway BR−040 to Moeda (see Ladeira and Fleischer, this volume, Part A—Excursions). Thorman and several geologists taking the course recognized that the contact of the Rio das Velhas-Minas Supergroups with the basement shown on the geologic map of Wallace (1965) was not intrusive but a major fault dipping gently to the east beneath the Rio das Velhas and Minas Supergroups. The fault is marked by many mylonitic zones within the basement (for more than 100 m (meters) below the contact) that increase upward to the contact and become more closely spaced and more intensely deformed toward the contact. Tectonic breccia occurs locally along the contact. Indications of the deformation disappear a short distance above the contact. A similar relation was noted farther north, where the contact is exposed in several locales. Thorman and the group looked at exposures of this contact in the southern and western parts of the Quadrilátero Ferrífero. At more than a dozen places, the contact was obviously a low-angle fault. In other places, however, the evidence was not as clear. For example, around the margin of the Bação Complex, the deformed rocks have been annealed by subsequent metamorphism. However, both the map pattern, which suggests strongly thinned and pinched units against or near the contact, and the strongly sheared rocks at the contact indicate that the contact is a shear zone that resulted from thrust faulting and was later locally metamorphosed.

The overall map pattern of units at the base of the metasedimentary sequence throughout the Quadrilátero Ferrífero indicates either highly irregular stratigraphic relationships and (or) major structural complications commonly observed at the base of allochthons. From March, 1973 until July, 1974, Thorman examined several other contacts of the basement with the overlying Rio das Velhas and Minas Supergroups in the Quadrilátero Ferrífero and became convinced that this contact is tectonic and locally modified by younger metamorphism or intrusion.

2. Later in the 1973 photogeology course, Oscar Braun (then with Companhia de Pesquisa de Recursos Minerais (CPRM)) took the group to visit several contacts of the Rio das Velhas Supergroup with the basement to show why he also thought the contact was tectonic. He also pointed out that other Brazilian geologists were of the same opinion.

3. Shortly before Thorman returned to the United States in 1974, he took Avery Drake of the USGS on a tour of the Quadrilátero Ferrífero during the planning stages for a field geology course for MME geologists to be run out of Belo Horizonte. During the tour, Thorman showed Drake the exposures on the west side of the Quadrilátero Ferrífero, as well as others, as potential sites for detailed geologic mapping for training in structure and stratigraphy. Thorman pointed out his interpretation of the allochthonous setting of the Rio das Velhas and Minas Supergroups. Subsequently, Drake and Morgan (1979) developed the concept that mafic and ultramafic rocks at and near the base of the Rio das Velhas Supergroup were part of an ophiolite sequence, out of place on cratonic basement, that had been thrust westward from an oceanic setting.

4. Charles Maxwell and Samuel Moore (part of the USGS team that mapped the Quadrilátero Ferrífero), pointed out to C.H. Thorman in the middle 1970's that the concept of the Rio das Velhas and Minas Supergroups being allochthonous was not new and that it had been discussed at great length earlier by many members of the team in the early 1960's. To present the idea in the context of the regional tectonics as understood in the 1960's, however, was difficult; if the concept of plate tectonics had existed at that time, the overall geologic framework established by the DNPM/USGS team would have been quite different. The idea that the Rio das Velhas-Minas/basement contact might not be intrusive was alluded to in indirect terms by several individual workers (including Johnson, 1962; Pomerene, 1964; Wallace, 1965; Simmons, 1968a,b; Moore, 1969), but it was not included in Dorr's (1969) summary of the geology of the Quadrilátero Ferrífero. Dorr believed all the basement rocks intruded, and thus were younger than, the metamorphic rocks.

5. It is now evident that many geologists who have worked or are working in the Quadrilátero Ferrífero believe that the allochthon concept is the only logical

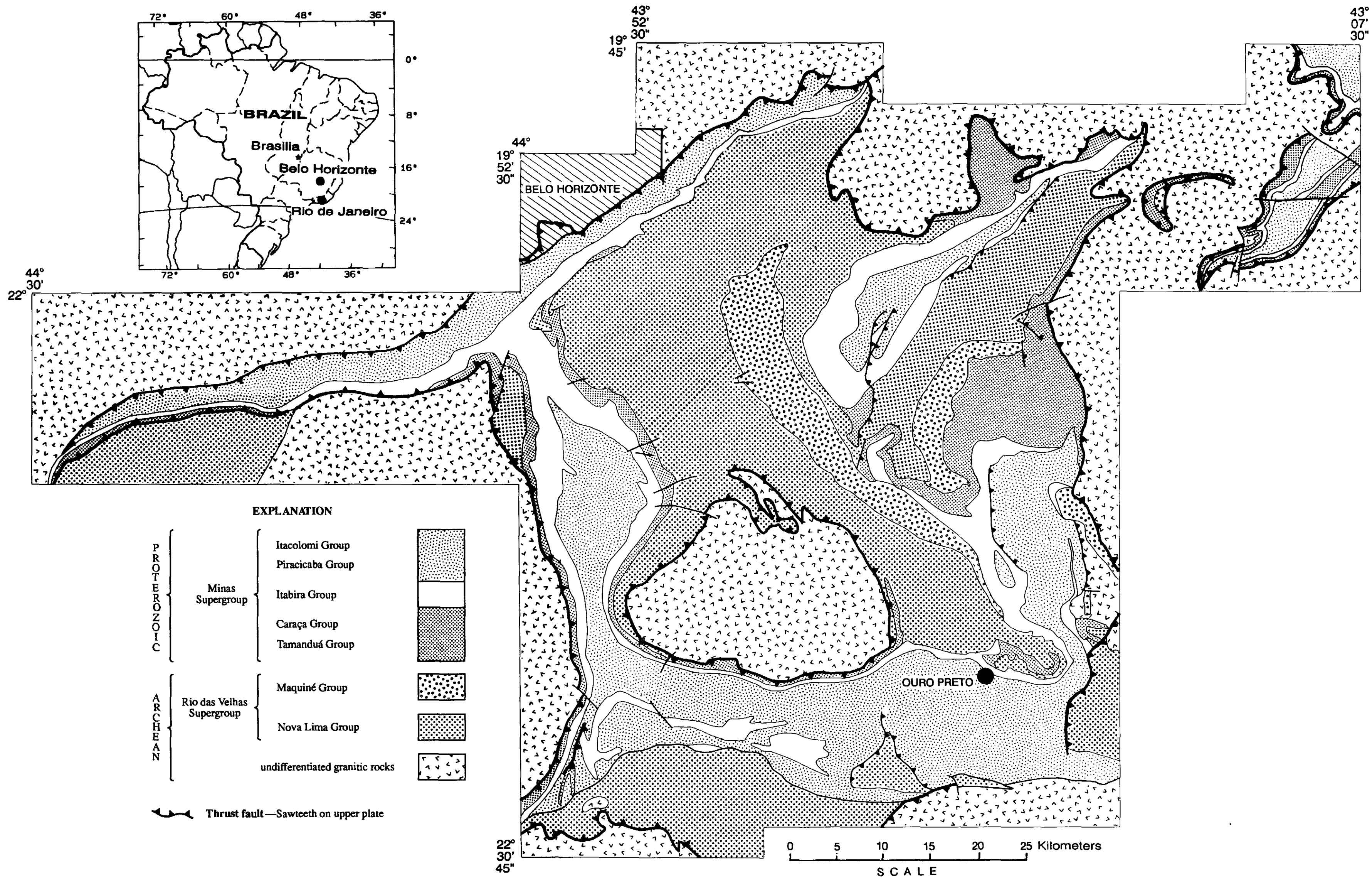

Figure 5. Simplified geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the interpretation of the Rio das Velhas and Minas Supergroups as allochthonous on the basement complex.

way to explain the observed relationships. In the paper by Ladeira and Viveiros (this volume, Part B—Geology of deposits), the allochthon concept is a major part of their geologic reconstruction of the Quadrilátero Ferrífero.

We show the concept of the supracrustal rocks as an allochthon juxtaposed on the basement complex in figure 5. The geology is that of Dorr (1969) with one major change. The contact of the basement with all overlying rocks is shown as a thrust fault; the basement complex is the footwall of the thrust fault. This interpretation does not exclude the possibility that some parts of the thrust fault have been modified by younger structures, by intrusion of igneous or granitoid bodies, or by the remobilization of basement in the form of partial melting or plastic flow as large domal masses or mantled gneiss domes. For example, (1) basement is faulted over the Rio das Velhas Supergroup on the east side of the area near Santa Rita Durão, (2) an igneous body appears to intrude the contact on the east side of the Quadrilátero Ferrífero south of Santa Barbara (C.W. Maxwell, oral commun., 1988), and (3) the Bação Complex, a domal massif or mantled gneiss dome in the southern part of the area, intruded preexisting structures and has a contact aureole.

STRATIGRAPHIC MODIFICATIONS

Modifications of the stratigraphic column subsequent to Dorr's (1969) publication, have been few. Two changes in the Rio das Velhas Supergroup are included on the stratigraphic column of figure 3.

1. A succession of submarine ultramafic to mafic rocks (lower unit) forms the base of the Nova Lima Group; its relationship to the basement complex has been obliterated by shearing and (or) granitization. These submarine rocks were named the Quebra Osso Group by Schorscher (1978) and Inda and others (1984), but inasmuch as their work did not comply with the stratigraphic code of Brazil, we herein assign the rocks to the Nova Lima Group. The existence of these submarine rocks prompted Drake and Morgan (1979) to suggest that an ophiolite complex was at the base of the Rio das Velhas Supergroup greenstone belt and that these rocks had been thrust westward onto cratonic crust from an original oceanic setting.
2. The Nova Lima Group is divided into three informal units by Ladeira (1980) and company geologists working at the Cuiabá mine (Vieira, Corbani, and others, this volume, Part A—Excursions), Morro Velho and Raposos mines (Vieira, Lisboa, and others, this volume, Part A—Excursions), and São Bento mine (Moseley, this volume, Part B—Geology of deposits).

A major nomenclature and correlation problem exists in the use of the term "Espinhaço," a possible correlative either of the Itacolomi or Tamanduá Groups, in the Quadrilátero Ferrífero region. Immediately north of the Quadrilátero Ferrífero is the Serra do Espinhaço, the type area for the Middle Proterozoic Espinhaço Supergroup, a succession of quartzite, phyllite, and lean BIF (low-grade banded iron formation). About 20 km (kilometers) north of the Quadrilátero Ferrífero, similar rocks extend about 1200 km to the north into the state of Bahia from the Serra do Espinhaço, but the physical continuity with the former units of the Quadrilátero Ferrífero is not known at this time. The problem lies in the suggested correlations of the Espinhaço Supergroup with the Tamanduá Group, the basal unit of the Early Proterozoic Minas Supergroup, and with the Itacolomi Group, the Middle Proterozoic unit that overlies the Minas Supergroup. This correlation uncertainty is beyond the scope of this paper but it is mentioned to make the reader aware of what might be interpreted as discrepancies between authors. Ladeira and Viveiros (this volume, Part B—Geology of deposits) discuss this problem and make structural interpretations based on their reinterpretation of Tamanduá and Itacolomi correlations. Schobbenhaus and others (1981) and Inda and others (1984) revised Dorr's (1969) use of these units.

SUMMARY OF THE CONCEPTS ON THE ORIGIN OF THE GOLD DEPOSITS IN THE QUADRILÁTERO FERRÍFERO

The topic most hotly and emotionally debated at the workshop was the origin of the gold deposits—syngenetic *versus* epigenetic and combinations thereof. Individual geological experience strongly influenced a debater's position. After 10 days together in a wide range of working environments, from air-conditioned bars to the sweltering +120 °F heat in the Morro Velho mine 2.45 km below the surface, the pendulum appeared to swing in every direction at one time or another, but no unanimous agreement as to the origin of the gold deposits could be reached. However, from the many hotly contested discussions, agreements were reached, not the least of which were the topics that needed further study.

Before launching into discussions of deposit models for the various gold deposits, we believed a definition of a greenstone belt was essential. This initial exercise in defining the belt was one of the most interesting we embarked upon in the workshop and clearly reflected the background and bias of individuals. The participants readily formed into two camps—those with a restricted definition and those with a looser definition. Fortunately, considerable common ground existed between the two camps and a concensus was not too difficult to arrive at. The following criteria made up the common ground.

- An elongate orogenic belt of supracrustal rocks 20–200 km wide and 100–800 km long.
- Stratigraphic sequence commonly consists of the following rock types from base to top:
  1. A lower suite of metavolcanic rocks with ultramafic rocks at base and calc-alkaline mafic to felsic rocks at top that contains some chemical sedimentary rocks.
  2. An upper suite of clastic argillaceous deep-water rocks that grade upward into shallow-water clastic rocks and chemical precipitates (carbonates, iron formation).
- Supracrustal belt rocks have been moderately to intensely deformed; typically more than one regional metamorphic event; complex structural setting.
- Metamorphic grade ranges from greenschist to granulite facies; typically greenschist over large areas.
- Belt is bounded by and intruded by granitic plutons that form large massifs.
- The supracrustal rocks commonly occur in major synclinoria separated by granitic massifs.
- Marked increase in metamorphic grade adjacent to plutons is common.
- World-class metallic ore deposits related to plutons, volcanic rocks, and iron formation.
- Rocks contain earliest forms of life.

The camp favoring a restricted definition of a greenstone belt required the presence of considerably more ultramafic to mafic volcanic material than did the other camp. The amount of this volcanic material is extremely important, because the restricted view was applied to the Rio das Velhas greenstone belt—our workshop area. Ultramafic to mafic volcanic rocks in the Rio das Velhas Supergroup in the Belo Horizonte area were considered to be minimal by several participants. And, therefore, they questioned referring to the Rio das Velhas sequence as a greenstone belt.

An upper suite of clastic and chemical rocks have long been recognized in the area, but not until recently has anyone emphasized the ultramafic to mafic volcanic rocks (Drake and Morgan, 1979). During our trip to the São Bento mine we saw pillow structures in mafic flow rocks in drill cores from the Rio das Velhas; these structures convinced participants that mafic volcanic rocks were more plentiful than previously realized. More recent work by Ladeira and other workers have documented the presence of komatiites with spinifex texture in the Quadrilátero Ferrífero (Ladeira and others, 1985; Noca and others, 1990).

General consensus was reached that the presence of volcanic rocks is more important than the relative amount of such rocks. In addition, both camps agreed that the amount of ultramafic to mafic rock recognized commonly may be a function of the interpretation of previous workers and that further work will probably reveal more of these rocks. From this common ground, we mutually agreed that the Rio das Velhas sequence does indeed constitute a greenstone belt.

Some of the most productive time was spent developing deposit model forms for each of the mines visited and for most of the deposits discussed by the workshop leaders (the deposit-model form used for this task is explained in the appendix). In the discussion groups assigned to fill out the forms for the various models, a major part of the exercise was to separate fact from interpretation so that the deposits could be compared objectively. The deposit-model form for each of the deposits are presented in a separate chapter (Thorman, this volume, Part B—Geology of deposits). The data for each deposit were compiled in tabular form in order to readily compare similarities and differences among the deposits (tables 1 and 2). A model for the origin of the deposits, based on these observed similarities and differences, is shown in table 3.

Two extremes or ends of the spectrum were taken with regard to the source and transportation of the gold. At one end, the gold was considered to be of strictly syngenetic origin in iron-formation, carbon-rich sedimentary rocks, or mafic-felsic volcanic units. During later remobilization (metamorphism) the gold was moved laterally within the system, for some unknown but probably small distance, to favorable sites determined by host-rock chemistry and structure.

At the other end of the spectrum, the gold was considered to be of strictly epigenetic origin and introduced to the system during deformation at the same time as or just after metamorphism. The final site of deposition was controlled by the rheology and chemistry of the host-rock environment and by favorable structures, such as dilational shear zones (see fig. 6).

Many of the workshop participants believed that some deposits visited could not be readily categorized as either syngenetic or epigenetic. However, other participants argued heatedly that most of the deposits were clearly epigenetic, whereas a few pressed just as strongly for a syngenetic origin. Perhaps a realistic view is that an environment characterized by volcanic activity (greenstone) and chemical sedimentation, including oxide, carbonate, sulfide, and silica-rich iron-formation facies and carbon-rich pelites, was later metamorphosed to produce the contained gold deposits. In such an environment, gold derived from exhalative activity

Table 1. Criteria for gold deposits examined or analyzed during the workshop and shown on figure 6

[D, diagnostic criteria; P, permissive criteria; P/D, not certain if criteria is diagnostic or permissive; X, not present in deposit; ?, sufficient data are not available to determine the role of that particular factor or there is a question as to whether or not that particular item is present at the deposit; asterisk (*) indicates the option of two interpretations; first letter refers to a facies or syngenetic model and the second letter refers to a structural or epigenetic model]

Criteria	Morro Velho	Cuiabá	São Bento	Passagem	Lupin	Homestake
Greenstone belt	D	D	D	P/D?*	D	D
Chemical sediments (Algoma type)	D	D	D	P	D	D
Oxide facies	X	X	D	X	X	X
Iron-rich carbonate	D	D	D	P	X	D
Chert	P	P	D	P	P	D
Sulfur-rich chemical sediment ("sulfide facies")	D	D	X	X	D	P
Graphitic phyllite/rock	P	P	P	P	P	P
Quartz-sericite schist (+/- intermediate/volcanic rocks)	P/D	P/D	P/D	P/D	X	P
Itabirite (Superior type/Proterozoic/well developed)	X	X	X	P	X	X
Mafic volcanics	P?	P/D	P/D	X	X	P
Orebody controlled by structure	?	P	D	P/D*	?	D
Stratabound	D	D	D	P/D*	D	P
Stratiform	D	D	X	X	D	X
Metamorphism in greenschist or lower amphibolite facies	D?	D?	D?	D?	D	D
Age of host rock	Archean	Archean	Archean	Early Proterozoic?	Archean	Early Proterozoic
Host-rock lithology:						
BIF (includes iron-rich chemical sediment; not itabirite)	D	D	D	X	D	D
Graphitic phyllite	X	X	P	P	X	P
Mafic volcanic	X	P	X	X	X	X
Felsic volcanic	X	X	X	P	X	X
Itabirite	X	X	X	P	X	X
Quartz veins in ore body	P	P	D	D	P	D
Quartz-carbonate veins in ore body	?	?	D	D	X	D
Absence of base metals (except in trace amounts)	D	D	D	D	D	D
Iron sulfides	D	D	D	D	D	D
Pyrite	P/D	D	P/D	P/D	P	P
Pyrrhotite	D	P/D	D	P/D	D	D
Arsenopyrite	P/D	P	D	D	P	D
Tourmaline	P	?	X	P	X	P
Scheelite	P/D	?	D?	D?	P	P
Bismuth	X	?	?	D?	X	X
Antimony	P	?	D	?	X	X
Silver (silver:gold about 6:1)	D	D	D(8:1)	D	D	D
Mercury	X	?	D?	?	X	X
Sphalerite	P	P?	X	X	X	P
Galena	P	P?	X	?	X	P
Chalcopyrite	P	X	X	X	D	P
Alteration assemblages	??	P?	D	D	P	D
Sulfides	X	P	D	D	P	D
Carbonates	??	P?	D	D	X	D
Sericite	P?	?	?	?	X	P
Chlorite	?	?	P	?	P	D
Biotite	?	?	?	?	X	D
Hornblende	X	X	X	X	D	P
Complex structure	D	D	D	D	D	D
Shear zones	D	P/D	D	D	D	D

Table 2. Postulated criteria for overall setting of iron-formation-related gold deposits in greenstone belts examined or analyzed during the workshop and shown on figure 6

[Note that the general classification of the deposits to a syngenetic or epigenetic origin is highly controversial. An asterisk (*) indicates those deposits for which there is less agreement on their classification and are therefore listed under more than one heading; see figure 6 and discussion in text]

Criteria	Morro Velho	Cuiabá	São Bento	Passagem	Lupin	Homestake
Relative position to volcanic center: 1, proximal; 2, intermediate; 3, distal	2-3	1-2	2	3?	2-3	3
Tectonic setting of host rock when formed: 1, unstable; 2, intermediate; 3, stable	3	3	3	1-2	3	3
Tectonic setting at time of mineralization: 1, strong def.; 2, intermediate; 3, no def.	2?	2	1	1	2?	1?
Igneous intrusive activity: 1, very active; 2, moderate; 3, no activity	3	3	3	3	3	3
Igneous extrusive activity: 1, very active; 2, moderate; 3, no activity	2	2	2	2	2	2

GENERAL GEOLOGIC SETTING:

Greenstone belt.

Periods of chemical sedimentation with BIF (including carbonate, oxide, sulfide, and minor silicate facies) and carbonaceous rocks (graphitic association important).

Bimodal volcanism *may* be important.

Sulfur is needed in the system. In a syngenetic model, the sulfur would have to be deposited with the sediment, whereas in an epigenetic model the sulfur could be introduced later.

Greenschist-facies metamorphism appears to be important in the Quadrilátero Ferrífero deposits and elsewhere. This level of metamorphism may be the minimum required; the upper limit is probably middle amphibolite facies. In a syngenetic model, regional metamorphism is not needed, whereas in one variant of the epigenetic model the metamorphism would be the heat source for hydrothermal activity.

Moderately complex deformational history is common, typically with several episodic phases of structural development.

Ductile shear zones are important in some models.

MINERALOGICAL AND CHEMICAL SETTING:

Sulfur occurs as abundant iron-sulfides.

Arsenic and tungsten more common in structurally controlled deposits.

Silica is common to the overall system.

Iron carbonate is common to the overall system.

Iron important as catalyst to drop sulfur, both during chemical sedimentation and subsequent sulfide mineralization associated with deformation and metamorphism.

Carbon may be important to the overall system, but its exact relationship is not clear.

GENERAL CLASSIFICATION OF THESE DEPOSITS is considered to be as follows:

Syngenetic--probably has some subsequent movement of gold;
Lupin, Morro Velho*, Homestake*.

Syngenetic--moderate amount of movement of gold due to later events;
Cuiabá, Morro Velho*, São Bento*.

Epigenetic--major control of mineralization due to deformation;
Homestake*, Passagem, São Bento*.

Table 3. Model for the origin of the deposits visited or discussed during the workshop

GENERAL GEOLOGIC SETTING:

- Greenstone belt.
- Periods of chemical sedimentation, with BIF (including carbonate, oxide, sulfide and minor silicate facies) and carbonaceous rocks (graphitic association important).
- Bimodal volcanism *may* be important.
- Sulfur is needed in the system. In a syngenetic model, the sulfur would have to be deposited with the sediment, whereas in an epigenetic model, the sulfur could be introduced later.
- Greenschist-facies metamorphism appears to be important. This metamorphism may be the minimal grade required; the upper limit is probably middle amphibolite facies. In a syngenetic model, regional metamorphism is not needed, whereas in one variant of the epigenetic model, the metamorphism would be the heat source for hydrothermal activity.
- Moderately complex deformational history is common and typically includes several episodes or phases of structural development.
- Ductile shear zones are important in some models.

MINERALOGICAL AND CHEMICAL SETTING:

- Sulfur occurs as abundant iron-sulfides.
- Arsenic and tungsten are more common in structurally controlled orebodies.
- Silica is common to the overall system.
- Iron carbonate is common to the overall system.
- Iron is important as a catalyst to drop sulfur, both during chemical sedimentation and subsequent sulfide mineralization associated with deformation and metamorphism (see earlier comments regarding sulfur).
- Carbon may be important to the overall system, but its exact relationship is not clear.

during sedimentation was deposited as an extremely fine, disseminated stratiform component of the system and formed a gold occurrence, not an economic gold deposit. Whether the gold was originally tied up with the carbon, with sulfide minerals, or with other minerals, is unknown. The gold was probably confined to a particular stratigraphic horizon or interval, rather than disseminated throughout a large vertical section. The transformation of the gold from a disseminated element in trace amounts to a major gold deposit appears to have depended on (1) regional metamorphism to at least the greenschist facies, and (2) on strong deformation that formed moderate- to large-scale folds and faults or shear zones. The metamorphism was the catalyst that provided the heat to drive the fluid system that remobilized gold, arsenic, sulfur, iron, boron, silica, calcium, and other elements. The folding and faulting provided the plumbing system for the fluids, forming porosity and permeability. Dilated shear zones, axial zones of folds (some of which cross shear zones), and fault zones became sites for ore deposition from mineralizing fluids. The fluids probably did not move great distances from original syngenetic source beds, for the gold in all the deposits is restricted to the same type of host rock—oxide-, carbonate-, or sulfide-facies rocks, silica-rich iron-formation, and (or) graphitic rock.

The favored explanation at the workshop for the Quadrilátero Ferrífero gold deposits in the Rio das Velhas Supergroup was a combination of syngenetic and epigenetic processes. Figure 6 shows syngenetic and epigenetic origins as end members of a system and shows two alternatives to the interpretation of the genesis of these deposits. Figure 6*A* represents the general consensus of the participants at the end of the workshop and figure 6*B* that of Thorman in view of recent data (this interpretation is discussed in Thorman, this volume, Part B—Geology of deposits). The intent is to emphasize the generally strong inclination to favor an epigenetic origin for most of the deposits. The Homestake and Lupin deposits are included for comparison with the Brazilian deposits. Positioning a deposit on the scale is highly subjective. It appears to us that any origin must take into consideration a certain element of both ends of the system. Such a consideration becomes especially pertinent in the development of a model for mineral exploration. For instance, continued detailed study of the Homestake deposit led company geologists to switch from a syngenetic to an epigenetic interpretation in 1987, though during the workshop an syngenetic model was

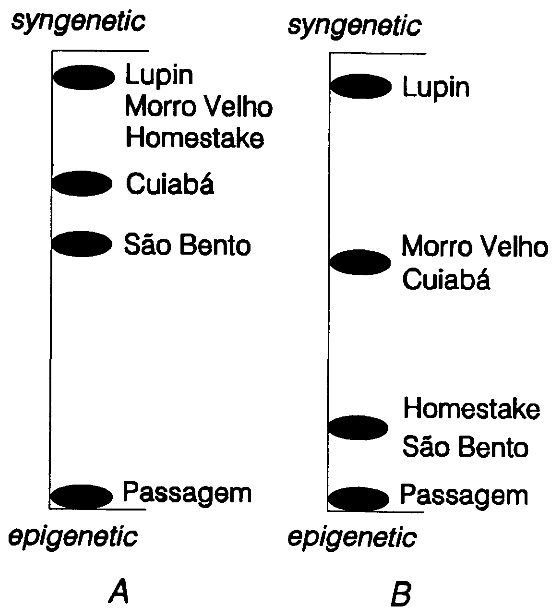

Figure 6. Diagram showing gold deposits (as classified in table 2) relative to syngenetic versus epigenetic origin. The positioning of these deposits on this scale is highly subjective and is not intended to indicate that we are certain of any particular or exact relative position of one deposit versus another. Rather, the intent is to show that both syngenetic and epigenetic factors should be considered in the genesis of these deposits. *A* represents consensus of participants at workshop and *B* that of Thorman (this volume, Part B—Geology of deposits).

presented. An epigenetic model is presented for Homestake in Part B of this bulletin by Caddey and others. S.W. Caddey (Homestake Mining Co., oral commun., 1990) believes that as more detailed studies are done elsewhere, there will be a strong shift to the epigenetic interpretation for many gold deposits throughout the world. Thorman (this volume, Part B—Geology of deposits) describes the deposit models and discusses in more detail the conclusions forged during the workshop.

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APPENDIX

Explanation of the Deposit-Model Form Used to Organize Data

EXPLANATION OF THE DEPOSIT-MODEL FORM USED TO ORGANIZE DATA

Deposit type: (fill in your preferred name for the deposit type and the author of model, if known, and the reference)
Site name: (common name the area, mine, or district is best known by)
Synonyms for site:
Site type: (mine, prospect, mining district)
County, state, province, country:
Latitude and longitude:
Commodities: (include major and minor metals and (or) commodities produced; may include important nonmetallic byproducts)
Production: (include production history of the deposit, if any; include known dates of production, commodities produced, and data on tonnage and (or) grade of ore produced)
Deposit description: (general geologic description of the deposit)
Rock types: (rocks typical of the geologic terrane)
Textures: (special textures of rock units)
Host-rock lithology: (concise lithologic description of rock that forms the principal host for the deposit)
Host-rock name: (formal and (or) informal name of the host-rock unit)
Host-rock age: (give the most specific age possible; include any radiometric dates available)
Mineralization age: (give the most specific age possible; include any radiometric dates available; if no radiometric dates, then give line of reasoning that supports the inferred age)
Lithotectonic setting and (or) depositional setting when host rock formed:
Tectonic setting at time of mineralization: (regional tectonic features important in the genesis of the deposit)
Associated igneous rock: (briefly describe all igneous rocks genetically associated with the mineralization)
Associated igneous rock age: (as above)
Ore minerals: (give complete names of all ore minerals known at the site being described, in decreasing order of importance; list important or guide minerals with + sign; list ore minerals in assemblages; show zonal or temporal relation between assemblages; group trace minerals separately; list byproduct metals (such as Cu, Ag) that may not form minerals)
Mineralogy: (describe completely but briefly alteration, gangue, and other mineral assemblages associated with the mineralization)
Alteration: (minerals produced by reaction of ore-forming fluids with rocks; list in assemblages; show zonal or temporal relation between assemblages)
Texture and (or) structure: (describe appearance of ore)
Ore controls: (describe factors controlling mineralization, including structure, stratigraphy, chemistry, or any other type of control)
Geochemical signature and (or) metal concentrations: (regional geochemical anomalies that might indicate the deposit or related associated deposits; elements expected to be anomalous, either enriched or depleted, in and near the deposit; list element assemblages and show zonal arrangement where possible)
Weathering: (optional; list any special weathering characteristics or secondary minerals that might serve as prospecting guides)
Associated deposits: (other deposit types associated with this deposit)
Comments: (use this space for general comments on the deposit that don't seem to fit any other field; an excellent place to include speculations concerning origin that should be kept separate from the facts included in the other fields; a place to expound)
References: (include important references on the deposit and the general region of the deposit)
Diagrams: (include a well-labeled map and (or) cross section of the deposit and (or) a sketch of an idealized map or cross section showing ore controls, zoning, and approximate dimensions)

Geological Field Excursion from Belo Horizonte to Ouro Preto, Minas Gerais, Brazil

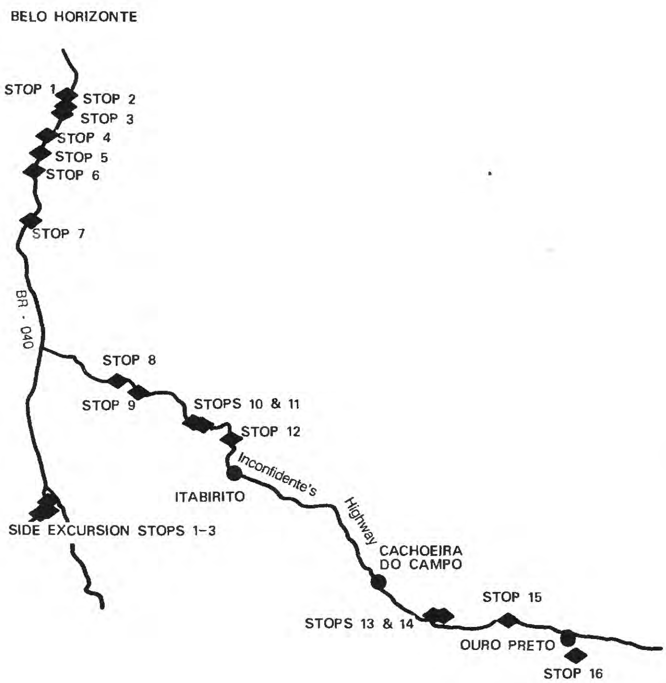
By EDUARDO A. LADEIRA

Regional stratigraphy and tectonics of the
Archean Rio das Velhas greenstone belt and the
Proterozoic Minas Supergroup
as background for gold metallogenesis

U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

Town of Ouro Preto

CONTENTS



FIGURES

TABLE

Folded specular hematite and quartz-muscovite schist of Cauê Itabirite (stop 15)

Geological Field Excursion from Belo Horizonte to Ouro Preto, Minas Gerais, Brazil

By Eduardo A. Ladeira[1]

INTRODUCTION

This geological field excursion should be used in connection with "Brief Introduction to the Geology of the Quadrilátero Ferrífero" by Ladeira and Viveiros (this volume, Part B—Geology of deposits). A companion paper ("Field excursion from Belo Horizonte to Ouro Preto—Side excursion along the road to Moeda"; this volume, Part A—Excursions) by Ladeira and Fleischer begins at kilometer 27 of this trip. The side excursion is an integral part of understanding the tectonics and the basal Minas Supergroup.

SCOPE OF THE EXCURSION

The purpose of this field excursion is to provide insight into the regional stratigraphy and tectonics of the Archean Rio das Velhas greenstone belt and the Proterozoic Minas Supergroup, which will aid in understanding the geological setting and the metallogenesis of the Passagem, Morro Velho, Cuiabá, and São Bento gold deposits. Papers on the geology of the Passagem, Cuiabá, and São Bento gold deposits are included in Part B of this volume.

Figure 1 shows the field trip route on a geologic map of the Quadrilátero Ferrífero (Iron Quadrangle) that has been simplified from Dorr (1969). Figure 2 shows the location of major gold mines and occurrences in the same area. Figure 3 is a generalized stratigraphic column of the area.

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ROAD LOG

For the convenience of the user, the highway (BR–040) kilometer marks (kmM), which are on the right margin of the southbound lane when one travels south, are listed as reference points. Distance in kilometers (km).

Marks (kmM)	Distance (km)	
0	0	Intersection of Contorno Avenue and Federal Highway BR–040, which links Belo Horizonte to Rio de Janeiro. Belo Horizonte was built on a granitic migmatitic terrane, but this part of the city lies along the contact of this terrane and rocks of the Sabará Group.
1.8		To the right and left, the road intersects schists and phyllites (some of volcanic origin) of the Sabará Group. The range to the left is the Serra do Curral, which was carved in an inverted homoclinal structure formed by metasedimentary rocks of the Minas Supergroup in such a way that the ridge is made up of Cauê Itabirite overlying the dolomites, phyllites, and dolomitic itabirites of the Gandarela Formation. The dolomites have been mined at several quarries to be used as flux in metallurgy or for the production of refractory material. The lower hills are formed by strata of the Piracicaba Group.

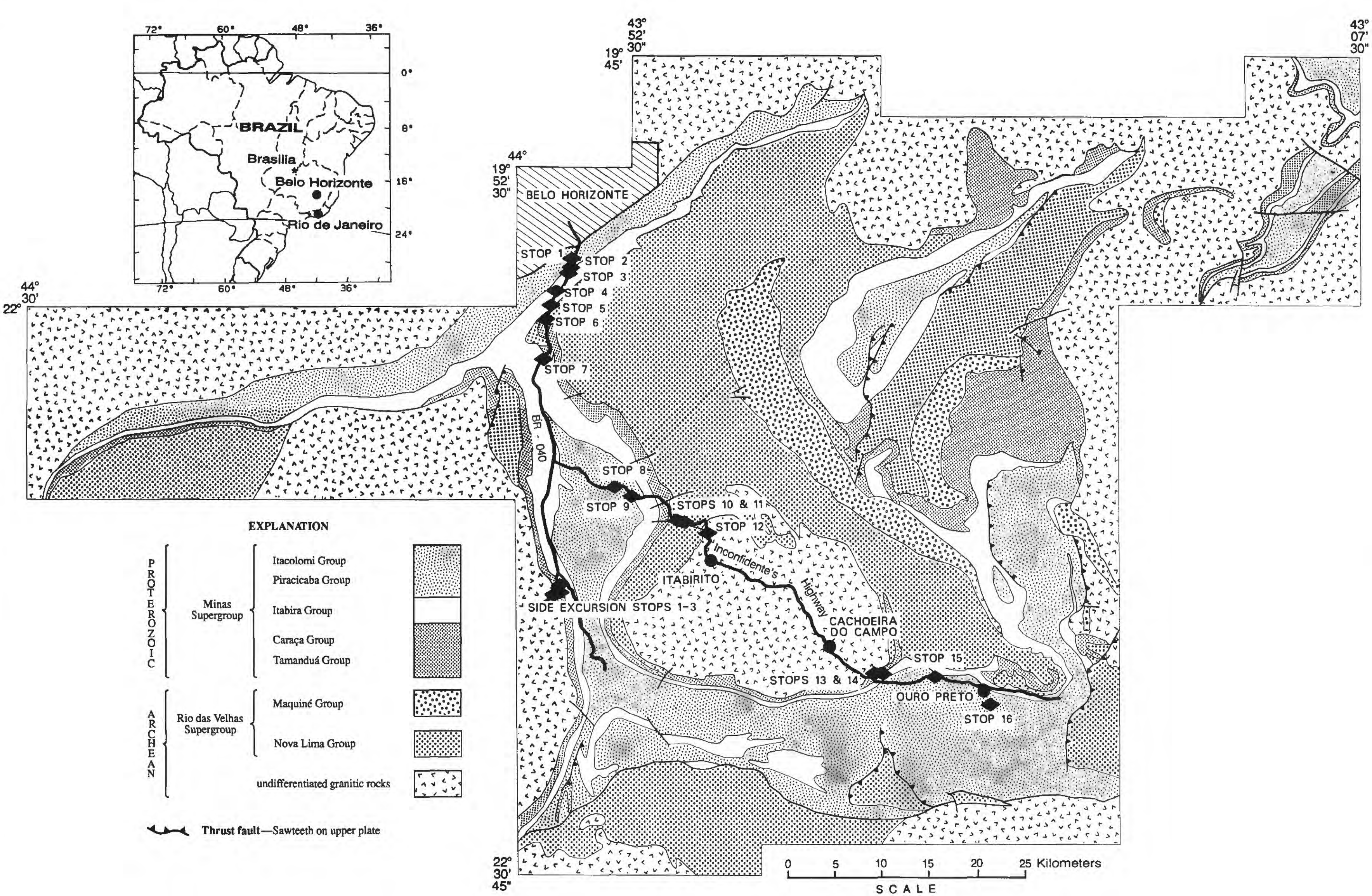

Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the stops for the field excursion. Details of the side excursion, stops 1 to 3, are described in the paper by Ladeira and Fleischer (this volume, Part A-Excursions).

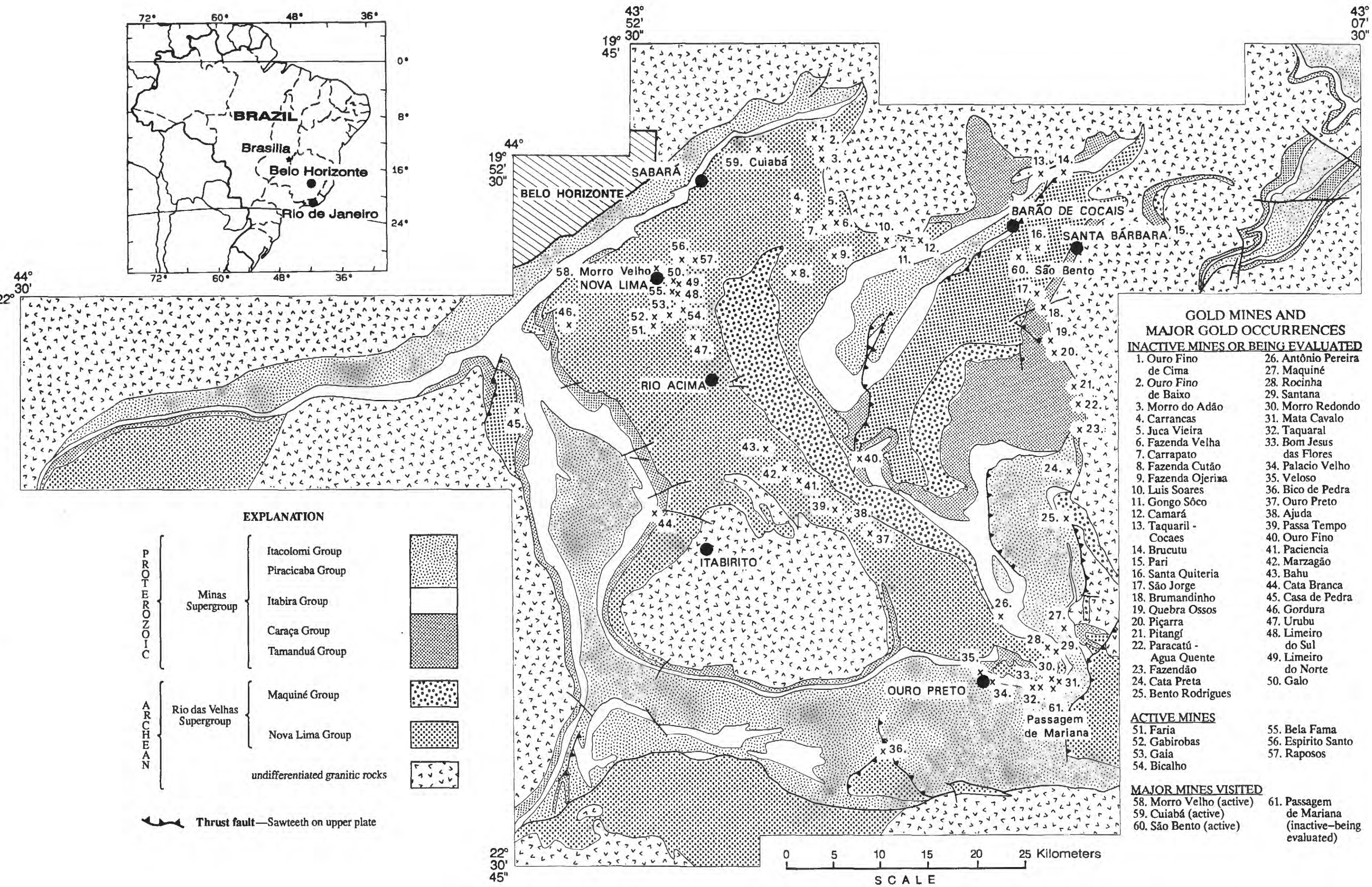

Figure 2. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, (1969) showing the location of major gold mines and occurrences in the area.

PROTEROZOIC

PROFOUND OROGENY WITH REGIONAL METAMORPHISM

Itacolomi Group

PROFOUND ANGULAR UNCONFORMITY

- Minas Supergroup
  - Piracicaba Group
    - Sabará Formation
    - Barreiro Formation
    - Taboões Formation
    - Fêcho do Funil Formation
    - Cercadinho Formation
  - Itabira Group
    - Gandarela Formation
    - Cauê Itabirite
  - Caraça Group
    - Batatal Formation
    - Moeda Formation
  - Tamanduá Group

ARCHEAN

MAJOR OROGENY WITH REGIONAL METAMORPHISM

- Rio das Velhas Supergroup
  - Maquiné Group
    - Casa Forte Formation
    - Palmital Formation
  - Nova Lima Group
    - Upper unit*
    - Middle unit* (includes Lapa Seca Formation)
    - Lower unit*

CONTACT CONSIDERED INTRUSIVE BY DORR (1969)

Granitic-gneissic basement rocks, including granitoids of various ages

Figure 3. Generalized stratigraphic column of Precambrian rocks of the Quadrilátero Ferrífero (modified from Dorr, 1969). Asterisk (*) indicates units not included in Dorr's paper but discussed by Thorman and Ladeira in the introductory chapter of this volume, Part A—Excursions. The granitic-gneissic basement unit includes several informal units, including the Bação Complex or Bação Granitic Complex, which is the oval basement body in the south-central part of figures 1 and 2.

Marks (kmM)	Distance (km)	
		STOP 1
2	2–2.5	Contact of Sabará Group (the author prefers raising the Sabará Formation to Group status). In an inverted sequence along the road to the left, one finds the Sabará Group overlain by the graphitic phyllite of the Barreiro Formation. The Barreiro is overlain by very thin and brecciated Taboões Quartzite, which is overlain by the weathered phyllites and dolomites of the Fêcho do Funil Formation.

Marks (kmM)	Distance (km)	
		STOP 2
3	3–4	The cuts to the left are in the Cercadinho Formation, a sequence of interbedded silvery phyllites and ferruginous quartzites thrown into various asymmetric folds. The quartzites are medium to coarse grained and display cross-bedding and graded bedding that are used to determine the overturned nature of the beds. The roadcuts are now covered with concrete.
		STOP 3
4	4	Gravity fault transecting the Cercadinho Formation shows drag structures and "fault horses" along the fault zone. When the observer faces the structure, the drag structures indicate that the left block has moved up relative to the right block.
5	5	Belo Horizonte Shopping Center to the left, built on a filled-in karst lake that formed in dolomites of the Gandarela Formation. The hills to the right are on the Cercadinho Formation (ferruginous quartzites and phyllites).
6		Weathered dolomites of the Gandarela Formation with ochre as a weathered product, overlain by the Cauê Itabirite, which is covered by a thick lateritic crust ("canga"). At the open pits, iron and iron-manganese ore has been mined.
	6.5	Railway bridge to Águas Claras iron-ore deposits.
		STOP 4
8		Outcrop of fresh dolomite of the Gandarela Formation, weathers to a peculiar soil known as "coffee powder." $S_0 // S_1$: N. 55° E., 60° SE. Gash quartz veins have attitude N. 10° E., 50° NW. S_2: N. 55°–60° W., 55° NE. Crenulations plunge E. 35° or S. 85° E. at 35°.

Marks (kmM)	Distance (km)	
		Highway to the right is the road to São Paulo; it passes through Cidade Industrial de Contagem, seen in the distance.
		STOP 5
9		The highway cuts asymmetrically folded Cauê Itabirite. To the right, iron-ore mine of Mannesmann Company. The primary bedding-layering of the itabirite is strongly transposed by a foliation averaging N. 45° E., 55°-65° SE., which parallels the hinge surface of folds. Crenulations trend N. 75° E., 42° (intersection of S_0 with S_1). Slip striae trend S. 50° E., 60°. To the left, on the mountain top, are the Mutuca iron deposits in Cauê Itabirite of the Minas Supergroup.
10	10	New Viaduto da Mutuca (Mutuca highway bridge). Drive over the old Mutuca bridge.
		STOP 6
		Both road cuts are on fragmental rocks and metaconglomerates of the Nova Lima Group, which contains stretched pebbles and is intersected by various quartz veins that probably formed during movement on the Mutuca thrust fault.
12	12	Quartz-chlorite schists with thin interlayered quartzites and minor graphitic phyllite of the Nova Lima Group are exposed in the road cut to the left.
13	13	Quartz-chlorite schists of the Nova Lima Group, interbedded with metaconglomerate (volcanic agglomerates?).
	13.5	Highway Police station.

Marks (kmM)	Distance (km)	
14	14	Greenschists of the Nova Lima Group, interbedded with unweathered agglomerate, locally pyritiferous.
	14.3	Turnpike to Rio Verde Mining Company.

STOP 7

Marks (kmM)	Distance (km)	
	15.5	Drive about 0.5 km to the right on a gravel road to a bauxite deposit. The ore probably is derived from aluminous sediments that accumulated on the argillaceous bottom of a Tertiary lake. Later upgrading was caused by supergene enrichment. Two mines can be visited. The first, and nearest one, belongs to Magnesita S.A., a producer of refractory tiles from the local clay. The other is held by Alcan, which owns an aluminum plant near Ouro Preto and extracts bauxite at several sites in the Quadrilátero Ferrífero, including this one.
	16.5	Gas station.
	17.5	Jardim Canadá, dry karst lake to the right.
	20.2	Skol Brewery to the left.
	22.1	Thick canga crust with pebbles, cobbles, and fragments of hematite and itabirite. This crust covers both the Gandarela Formation (which doesn't crop out) and part of the Cauê Itabirite.
	22.7	About 40° to the left, if the sky is not cloudy, one can see the Pico do Itabirito (Itabirito Peak), carved in hard hematite ore, which will be seen again a couple of times during our trip; it is part of the range with the same name that constitutes the inverted limb of the Moeda synform, whose normal limb is to the right and is evidenced by the dip slopes to the right of the road and farther on. The inverted limb will be seen shortly.
27	27	Rodovia dos Inconfidentes (BR/MG−356, Inconfidente's Highway). Drive to the left to Ouro Preto, former capital of Minas Gerais State.
	27.3	Highway Police station.
29	29	Exposure of ferruginous grayish quartzites and silvery phyllites of the Cercadinho Formation overlain by weathered dolomites (which produce a brownish to black saprolite) and silvery phyllites of the Fêcho do Funil Formation. Tight asymmetric folds have enveloping surfaces whose attitude is N. 15° E., 58° NW. $S_0//S_1$ is N 10°E., 45°-50° NW.
31	29.5–31	Cercadinho and Fêcho do Funil, as above.

STOP 8

Marks (kmM)	Distance (km)	
34	34	Folded and faulted metaconglomerates mapped by Wallace (1965) as the Itacolomi Group, with distorted pebbles and cobbles of quartz and quartzite. $S_0//S_1$: N. 15° W., 58° W., 65° NE. The current author, Ladeira, believes this may be a fragmental volcanic rock.
	34.5	This area was a former Horto Florestal (forest station).
	34.5	To the left, Codornas Lake. Three hundred meters before the bridge to the right, varicolored phyllite interlayered with graphitic phyllite, both of Barreiro Formation, overlain by the younger, thin, saccharoidal Taboões Quartzite. Dip of beds is vertical to near vertical. Strike is northeast.
	35.8	Bridge over the Codornas Creek. Roadcuts are on the varicolored argillaceous phyllite and interlayered dolomites of the Fêcho do Funil Formation.
36	36–36.5	Varicolored argillaceous phyllites of the Fêcho do Funil Formation interlayered

Marks (kmM) Distance (km)

with "splash rock" (Guild, 1957), a name given to the saprolite of dolomite—here the saprolite of Fêcho do Funil Formation. Reduction or bleached spots with ellipsoidal shape and light color are oriented parallel to fold hinges. S_0: N. 30° W., vertical; N. 16° W., 30° NE.

STOP 9

37 37 Alluvial deposit of a Tertiary lake, with quartz pebbles and cobbles in an arenaceous, argillaceous matrix, covers "splash rock" and phyllites of the Fêcho do Funil Formation.

38 38 Cercadinho Formation (ferruginous quartzites and phyllites) overlain by the Fêcho do Funil Formation. $S_0 // S_1$: N. 60°–70° E., 60° SE. Contact with laterite and canga.

39 38.5–39.5 Roadcuts are cut successively deeper into the Cercadinho Formation due to folding with the underlying weathered dolomites of the Gandarela Formation. The weathered product of the Gandarela Formation is commonly referred to as "splash rock."

39.8 Highway Police station and truck balance.

40 40 As one approaches the police station, the hidden contact between the Gandarela Formation and the Cauê Itabirite will be crossed. The section is the inverted limb of the Moeda synform in which the younger Gandarela Formation is overlain by the Cauê Itabirite. To the right is Itabirite Peak.

40.1 Folded Cauê Itabirite with kink folds. Canga crust derived from the itabirite caps the roadcut. To the left, ITAMINAS Mining Co. iron-ore deposit, hosted in Cauê Itabirite.

40.8 The road cuts the inverted sequence consisting of Cauê Itabirite overlain by Batatal Formation, which in turn is overlain by the older Moeda Formation. Beds have a general trend of N. 15°–25° W. and are overturned 60°–70° NE. More incompetent Batatal Phyllite is crumpled between the Cauê and Moeda Formations. Note thick canga crust on top of mountain to the right, carved in Cauê Itabirite.

41 41 Bonga strike-slip fault with attitude N. 70° E., 60°–70° NW. The northern block moved northeast relative to the southern block; total strike-slip is about 250 m (meter). This movement caused repetition of the inverted sequence: Cauê Itabirite, Batatal, and Moeda Formations, having steeper dips of 80° SE.

41.5 Quartzite quarry to the left, from which quartz sand is extracted, cleaned, and stockpiled (to the right).

42 42–43.5 From 42.0 to 43.5 km, the road swings through quartzites and minor interlayered phyllites of the Moeda Formation, which crop out to the right, forming cuneiform controlled by a strong lineation ("pencil structure"). To the left is the Rio das Velhas Valley carved in the Nova Lima Group (Rio das Velhas Supergroup) of the Rio das Velhas Greenstone Belt (Ladeira, 1980).

STOP 10 "Santa" at the Serra do Itabirito.

43.5 Angular and erosional unconformity between the variegated schists of the Nova Lima Group and the Moeda Formation. The contact zone trends about N. 10° E. Immediately to the west of the rest area, the Nova Lima schists have two schistosities. The older, S_1 (N. 40° W., 65° NE.), locally parallels bedding S_0 of the schists; the younger, S_2 (N. 10°-35° E., 70° SE.), parallels the contact. Fracture cleavages are S_3 (N. 70° W., 30° NE.) and S_4 (N. 70° E., 65° SE.). The Moeda Formation begins with a basal polymictic metaconglomerate

Marks (kmM) | Distance (km)

with pebbles of quartz, quartzite and greenschist (the latter similar to Nova Lima Group greenschists). S_0 in the Moeda quartzite trends N. 15° E., 80° SE, forming an angle of about 70° with S_0 of Nova Lima Group schists. The S_2 schistosity in Nova Lima schists is also common to the Moeda Formation quartzites. Fracture cleavages parallel to S_3 and S_4 of the Nova Lima Group also intersect the Moeda quartzite. The angular pattern of S_0 in both the Nova Lima Group and Moeda quartzite indicates the unconformable relation, which is proven by the presence of a basal conglomerate that contains clasts of schist from the Rio das Velhas Supergroup. However, the unconformity was disrupted during the deformation of the Minas Supergroup and is now a fault surface.

STOP 11

44 44 Cata Branca strike-slip fault. This structure follows the valley to the right. Nova Lima schists crop out along the highway. The fault trends northwest-southeast and dips 80° NE. and the hanging wall (northern block) has a total slip of 500 m towards the west. Gold associated with stibnite in the Moeda quartzite and related to this fault was mined nearby. The Cata Branca fault shifts the Bação Complex-Nova Lima Group contact near the Esperança Co. steel plant to the east of this plant. The Bação Complex is the oval body in the southern part of the Quadrilátero Ferrífero (figs. 1 and 2).

44–49 The highway swings through weathered Nova Lima variegated schists derived from interlayered metavolcanic and metasedimentary rocks.

STOP 12

49 49 Near the head of highway bridge over RFN (Rede Ferroviara National) railway. To the right, Esperança Co. blast furnace. Contact of the Nova Lima Group metavolcanic and metasedimentary rocks with the Bação Granitic Complex, which thermally metamorphosed the rocks and resulted in a garnet-staurolite metamorphic aureole. These rocks are cut by numerous tourmaline-quartz veins, which elsewhere contain little gold. Metamafic rock and lean (low-grade) Archean type banded iron formation (BIF), not reported earlier by the DNPM–USGS (Departamento Nacional da Produção Mineral-United States Geological Survey) team and similar to BIF strata in the Nova Lima District, are interlayered in the local succession. See side-road roadcut (dirt road to the left to Rio Acima).

50 After the highway bridge, weathered metamafic dike cuts weathered Bação granite. To the right, a view of Esperança Co. iron blast furnace.

51 51–52.5 Fresh exposure of Bação Complex. Itabirito Country Club to the left; city of Itabirito to the right. From here to Cachoeira do Campo (20 km ahead) and back to STOP 12, the highway runs through and exposes the granitic-migmatitic rocks of the Bação Complex.

52 52 Bação Complex rocks.

54 54 Bação Complex rocks.

54.5 Southeastern Itabirito turnoff.

57 CEMIG plant turnoff.

59 To the left, road to Acurui village (15 km) and Camping Club do Brasil (22 km).

60 Alluvial flat.

62.5 Road to Minas Serra Geral (iron ore). Capanema mine.

Marks Distance
(kmM) (km)

72 Town of Cachoeira do Campo, built on Bação Complex.

74 Alluvial flat.

78 Outcrop of migmatites of the Bação Complex showing subvertical shear zones transecting earlier folded foliation.

STOP 13

78.5 Intersection of Inconfidente's Highway and CVRD (Companhia Vale do Rio Doce) Railway. Funil railway bridge. At the exposures to the right of the highway, the Moeda quartzite is tectonically concordant with the underlying Nova Lima schists (mostly staurolite-chlorite-garnet schists) derived from volcanic and sedimentary rocks. These rocks are intruded by the Bação Complex in an intricate contact zone in which Nova Lima schists are penetrated or invaded by numerous pegmatitic and aplitic bodies. The Bação Complex is interpreted to be a mantled gneiss dome derived from a reworked basement (Ladeira, 1980). The Moeda quartzite is tectonically thinned, boudinaged, and cut by minor faults. Fresh Cauê Itabirite crops out at the bottom of the valley, and, in addition to the normal itabirite, it also includes carbonate-amphibole (grunerite-cummingtonite) itabirite. The discordant relations can be observed only in the railway cuts above you, through which we will be driving.

STOP 14

78.5 Drive back 500 m, turn right on the dirt road, and drive up hill for 2 km to the CVRD railway station. Walk 500 m to the south along the railway tracks.

Faulted, originally discordant unconformable contact between the Moeda quartzites and fresh Nova Lima chlorite-garnet staurolite schist (greenschists). No conglomerate has been found at the base of Moeda quartzite at this site, but the unconformable relation (established at many localities in the region) can be deduced because the Nova Lima schists have two penetrative schistosities that are truncated at the contact, whereas the Moeda has just one schistosity; two sets of fracture cleavage intersect both units. In addition, the schists and Moeda quartzite have distinct structural styles that cannot be explained solely by the difference of competency. The schists are asymmetrically folded and refolded, and their axial surfaces trend differently from those in the quartzite. The present contact is clearly a tectonic one (thrust), which has been healed by metamorphism. The structural data indicate that the units were deformed under different conditions, lending support to the statement that the two are stratigraphically distinct units.

Attitude of S surfaces:
S_0 (schist, folded): N. 60° E., 35° SE.
S_1 (schist): N. 60° E., 35°–40° SE.
S_2 (schist): N. 15°–25° E., 45° SE.
S_3 (common to schist and quartzite): N. 15°–25° E., 55° SE. refracts through the quartzite and changes to N. 25° E., 60°–70° SE.

Thrust faults with related minor structures such as "mullions," slip striae, and sheath folds that have been dismembered and now appear as tectonic inclusions can be observed along the section. The Nova Lima schists locally have interlayers of Archean-type BIF (200 m north of this contact) that were not described at this locality by the DNPM–USGS team nor by other previous workers. Along this section, the author recently found intrafolial tight recumbent folds in the Moeda quartzite, which are also associated with shear zone and sigmoidal folds. Apparently these are the first reported recumbent folds in this formation at this site. Drive back to Inconfidente's Highway and head towards Ouro Preto.

Marks (kmM)	Distance (km)	
	78.7	Folded dolomites of Gandarela Formation; 800 m ahead along the road the dolomites contain an intraformational metabreccia.
	79	BEMIL crushing and milling plant for production of dolomite "dust," for soil correction, and broken stone.
80	80	Conformable contact between the Gandarela and Cercadinho Formations.
81	81	Contact of Cercadinho and Fêcho do Funil Formations.
	81.3	Roadcut of Fêcho do Funil dolomites and silvery phyllites; recumbent fold associated with thrust fault.
82	82	Fine-grained, banded ferruginous quartzites interbedded with silvery phyllites of the Cercadinho and Fêcho do Funil Formations.
83	83	Farther to the right, at the mountain top, asymmetric synform in Cercadinho and Fêcho do Funil Formations.
	83.6	Cercadinho Formation, normal and ferruginous quartzite with cross-bedding and flaser structures; on right are asymmetric folds, that have thin laminae of silvery phyllite.
84	84	Fine-grained, fine-banded ferruginous quartzite of the Cercadinho Formation.

Marks (kmM)	Distance (km)	
		STOP 15
86	86	"Black and White." This section has been mapped by Miranda Barbosa (in Dorr, 1969) as Cauê Itabirite. The "black" material is a tightly folded and laminated specular hematite rock. The "white" rock is a quartz-muscovite schist.
		S_1 (schistosity): N. 70° E., 55° SE. Crenulations: S. 30° E., 50°; S. 20° W., 50°.
	87–88	The road intersects a thrust fault that juxtaposes the Sabará Formation on top of Cauê Itabirite and then cuts down through the Cauê Itabirite; farther ahead, another fault juxtaposes ferruginous quartzite of the Cercadinho Formation in thrust contact on the Sabará Formation, near the intersection of the roads to Ouro Preto and Saramenha.
		Drive to Ouro Preto to the left.
		View of Pico do Itacolomi (Itacolomi Peak) at 15° to the right.
	89–90	This section of the road is mainly Cercadinho Formation ferruginous quartzite and silvery phyllites.
	92.8	Cercadinho Formation underlying Fêcho do Funil Formation.

Table 1. Analyses of samples taken from bauxite prospect pit (altitude 1,223 m) at Morro do Cruzeiro, Ouro Preto, Minas Gerais, Brazil

[Table prepared by Professor Messias Gilmar Menzes from Guimarães and Coelho (1945). All values shown in percent; L.O.I., loss on ignition; leaders (---) indicate interval not analyzed; n.d., not determined]

Depth, in meters	Al_2O_3	FeO_3	SiO_2	TiO_2	P_2O_5	MgO	CaO	Na_2/K_2O	L.O.I.	TOTAL	Material
0.0–0.3	---	---	---	---	---	---	---	---	---	---	Lateritic crust
0.3–0.9	---	---	---	---	---	---	---	---	---	---	Bauxite laterite
0.9–2.1	36.79	9.65	32.80	2.21	0.116	traces	0.45	0.06	17.80	99.88	Ferruginous clay
2.1–3.6	38.70	3.46	40.14	1.74	0.075	traces	0.67	nil	14.96	99.74	Light-yellow clay
3.6–5.1	40.61	1.73	40.30	1.95	0.043	traces	0.50	0.09	14.76	99.98	Yellow clay
5.1–6.5	42.30	1.70	43.78	0.50	---	0.87	0.70	n.d.	9.77	99.62	White clay

Marks (kmM)	Distance (km)	
93	93–94	Road follows the strike of Cauê Itabirite, which overlies the Moeda quartzites (not seen).
	95.0	Ouro Preto, Praça Tiradentes.
		From here drive to Morro do Cruzeiro.

STOP 16

Bauxite deposit of Morro do Cruzeiro. This deposit is next to and partly underlies the campus of Universidade Federal de Ouro Preto. The Morro do Cruzeiro (Hill of the Cross) is a small plateau 1,230 m above sea level and is superficially covered by a lateritic crust ("canga") and lateritic soil. The "canga" maintains the leveled surface and ranges in thickness from 1 to 1.5 m. The bauxite layer, which has been almost entirely mined out, overlies phyllite and dolomites of Fêcho do Funil Formation. Before mining, the layer covered about 130,000 square meters and had an average thickness of 1.5 m. The bauxite is light pink to intense red, which is a function of variable proportions of Fe_2O_3. It is compact, has a specific gravity of 2.6, and occurs as disseminated concretions in laterite. Analyses of the bauxite ore in table 1 (facing page) indicate vertical migration of iron and alumina. Exploration and mining work demonstrated the presence of a large clay deposit underlying the bauxite layer.

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Bação Complex along CVRD railroad (stop 14)

Field Excursion from Belo Horizonte to Ouro Preto–Side Excursion Along the Road to Moeda, Minas Gerais, Brazil

By EDUARDO A. LADEIRA and RONALD FLEISCHER

U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

Sheared basement rock below Moeda Complex-Moeda Formation contact (stop 1)

CONTENTS

FIGURES

Sheared basement rock of Moeda Complex (stop 1)

Field Excursion from Belo Horizonte to Ouro Preto—Side Excursion Along the Road to Moeda, Minas Gerais, Brazil

By Eduardo A. Ladeira[1] *and* Ronald Fleischer[2]

INTRODUCTION

This side excursion is an appendage to the "Geological field excursion from Belo Horizonte to Ouro Preto..." by Eduardo Ladeira (this volume, Part A—Excursions) and is to be used in conjunction with it. The zero kilometer mark for this side excursion begins at the junction of Highway BR–040 and the Rodovia dos Inconfidentes (Inconfidente's Highway) (kilometer 27 in the Belo Horizonte excursion). Figure 1 shows the location of the side excursion in relation to the main excursion and figure 2 shows the location of the three stops and the geology of the area for the side excursion (Wallace, 1965).

SCOPE OF THE EXCURSION

The purpose of this side excursion is twofold—structural and stratigraphic. The geology to be seen is extremely critical to the overall geologic setting of the Quadrilátero Ferrífero. This locale was chosen because relationships are more clearly displayed here than at almost any other place in the region and the access is excellent.

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Structural Setting

The first purpose of the excursion is to examine and discuss the nature of the contact between the metasedimentary Moeda Formation of the Minas Supergroup and the Moeda Complex, a granitic-gneissic unit. For a discussion of the Moeda Complex and the interpretations applied to the contact between it and the overlying rocks, see Ladeira and Viveiros (this volume, Part B—Geology of deposits) on the general geology of the region. Briefly, the problem is whether the contact between the Moeda Formation, at the base of the section observed in this immediate area, and the underlying granitic rocks of the Moeda Complex is depositional or tectonic. The presence of mylonitic rocks along the contact and for more than 100 m (meter) downsection into the complex, plus the presence of this same relationship all along the western side of the Quadrilátero Ferrífero, strongly suggest that the contact is faulted. Further discussion on this topic and its regional significance is presented in the introduction to Part A of this volume by Thorman and Ladeira.

Stratigraphic Setting

The second purpose of the excursion is to gain an insight into the stratigraphy of the Caraça and Itabira Groups and to examine the type section of the Moeda Formation, which is made up of three members (Wallace, 1965):

1. The lowermost member—Moeda 1—starts at the base with local metaconglomerates and coarse quartzites that contain clasts of bluish quartz grains, and grades

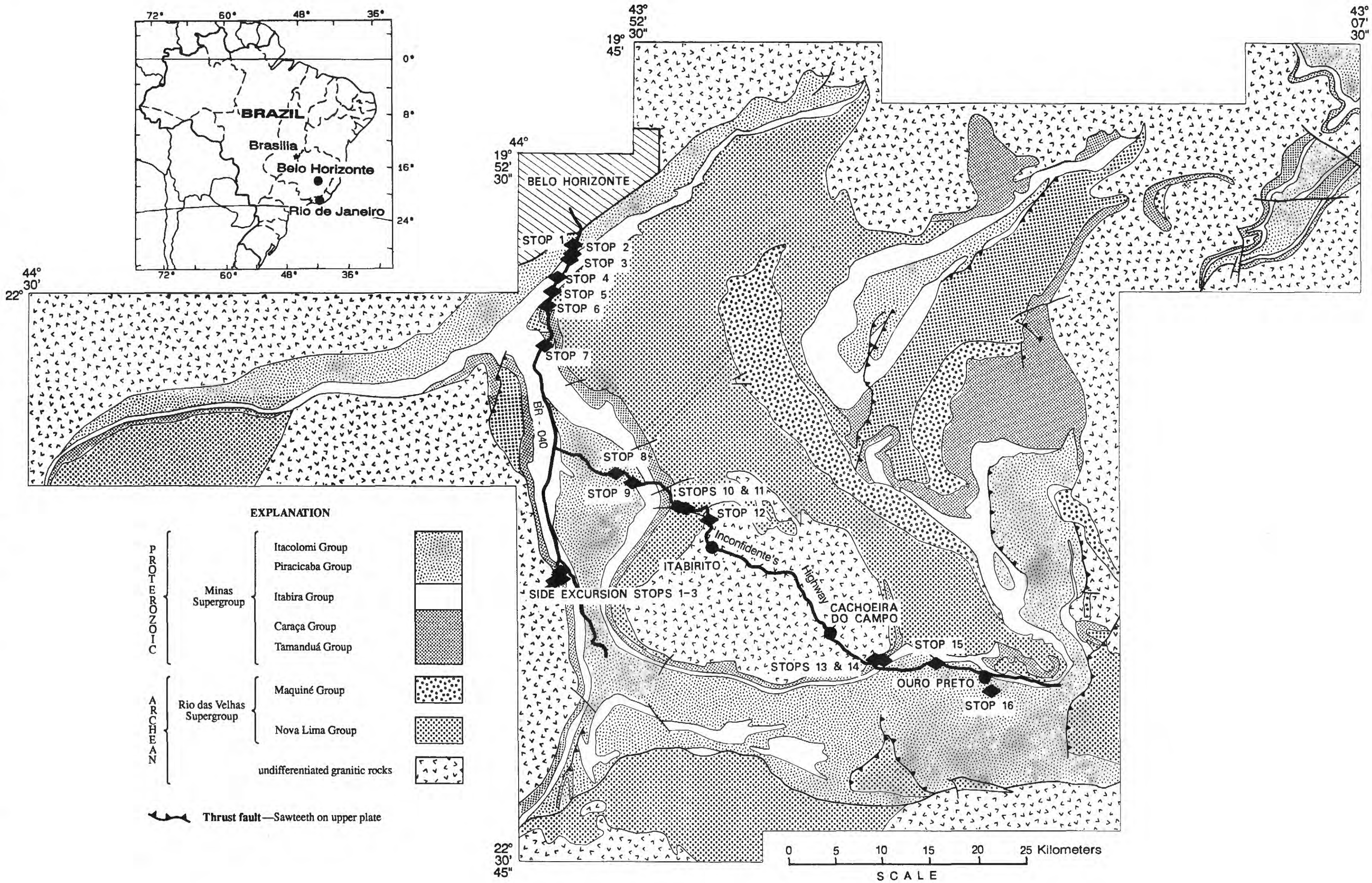

Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the stops for the side excursion. Details of the main excursion are described in the paper by Ladeira (this volume, Part A-Excursions).

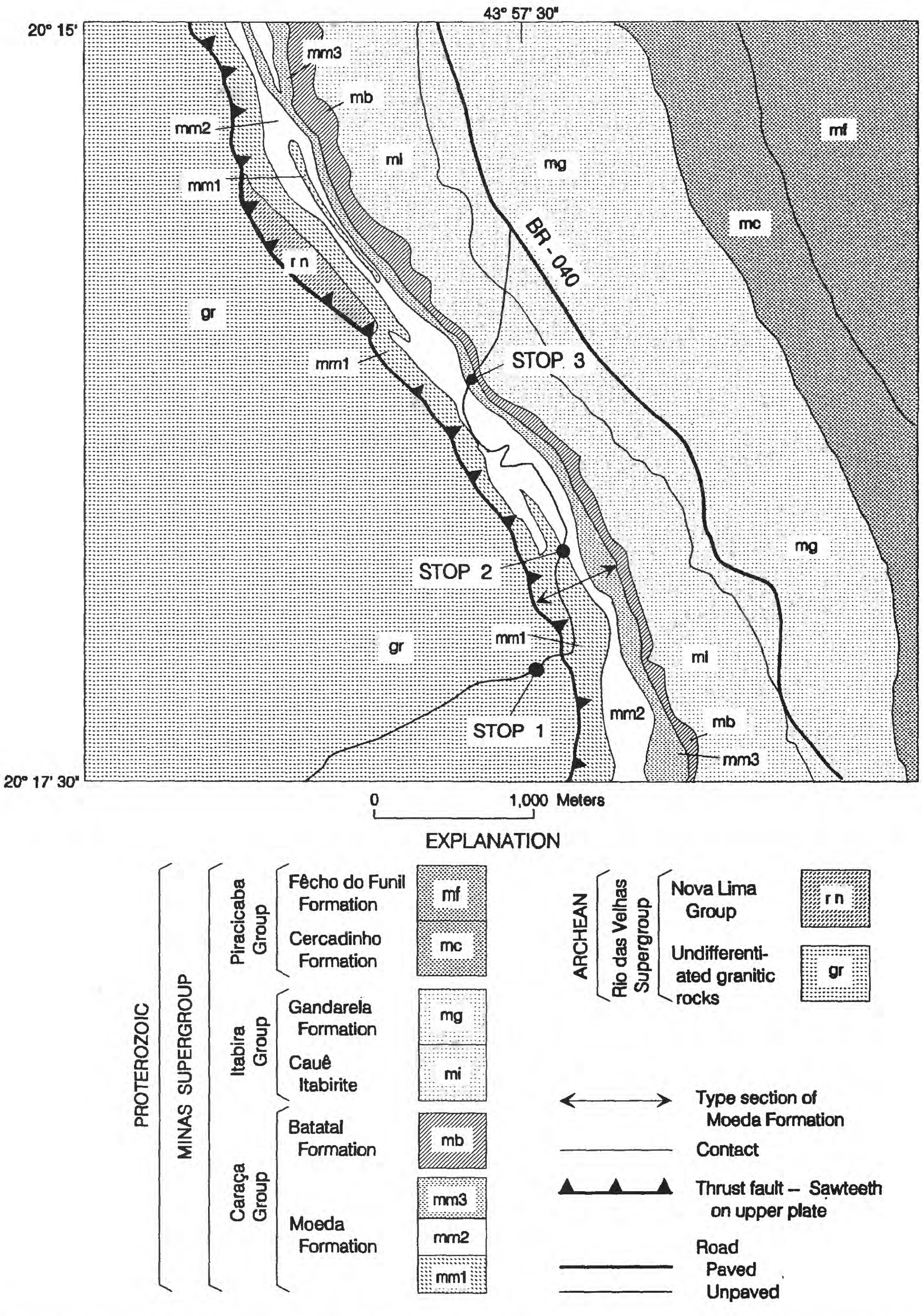

Figure 2. Geologic map (from Wallace, 1965) of the field excursion area showing the location of stops 1–3.

upward to light-gray to light-reddish-brown, medium to fine cross-bedded and parallel-bedded quartzites.

2. The middle member—Moeda 2—consists mainly of varicolored sandy phyllites that grade upward to thin intercalations of fine-grained quartzites.

3. The upper member—Moeda 3—consists of light-gray to light-reddish-brown medium-grained to very coarse grained cross-bedded quartzites.

ROAD LOG

As noted in the "Introduction," the zero kilometer mark for this side excursion begins at the junction of Highway BR-040 and the Rodovia dos Inconfidentes (Inconfidente's Highway).

Kilometer

0 BR–040 and Inconfidente's Highway junction. Continue south on BR–040, under the highway overpass.

1.8 To the right, gravel road to Piedade do Paraopeba. Continue along BR–040.

4.9 To the right, road to Retiro do Chalé. From here, if the sky is not cloudy, one can see Itabirito Peak at 40°–50° to the left on the overturned limb of the Moeda synform; to the right, one can see the normal limb, which will be crossed in a few minutes. At about zero degrees (straight ahead), one can observe the narrowing of the synform.

11.3 Highway Police and truck-weighing station.

12.5 Drive to right on the gravel road that leads to the town of Moeda. For practical reasons, drive directly to the base of the Minas Supergroup, down the foothills of the Moeda Plateau, because most of the route is winding and steep. Begin stop 1 at the base of the foothills.

STOP 1

16.1 Leave the vehicle, and walk about 100 m (meter) east to an exposure of the granitic rocks of the Moeda Complex. Many types of granitic rocks can be seen here in the foothills. At this stop, our objective is to examine a series of east-dipping shear zones in the granitic rocks and the relationship of the zones to the overlying

Kilometer

metasedimentary sequence. Along the shear zones, some of the granitic rocks have been transformed, through cataclasis and accompanying recrystallization, into tremolite-actinolite-tourmaline schist. Up the hill towards the northeast (upwards structurally and stratigraphically, also), the sheared rock changes somewhat abruptly into a mylonitic augen gneiss; at least one of its foliations trends N. 60 ° E to N. 80° E., discordant to the contact of the overlying quartzitic sequence. The cataclasites, mylonites, and phyllonites here have bluish quartz crystals, 0.3–10 millimeters in size, which led Ferrari (in Loczy and Ladeira, 1976) to consider them as quartz of volcanic origin. Cataclastic foliation is N. 10° E., 80° SE. S_0/S_1 of overlying quartzite is N. 10° W. to N. 15° W., 55° NE. Fracture cleavage is N. 30° E., 70° SE.

The quartzite sequence begins with a fragmental rock whose fragments are made up of the same bluish quartz, but here grains are rounded and angular in a sericitic quartzose matrix; this rock was termed "metaconglomerate" by Wallace (1965). This "metaconglomerate" changes to medium- to fine-grained quartzites and, farther upsection, grades into cross-bedded quartzites. Both the foliation-bedding relation and the cross-bedding indicate a normal, rightside-up sequence.

Walk down the hill to a small waterfall on the granitic-gneissic complex. Note that the complex has several small shear zones in which the gneiss is transformed either to a mylonitic augen gneiss, cataclasite, or, in some places, a phyllonite. These zones are a few centimeters to a few meters thick. Older foliation in the augen gneiss is N. 60° E., 65° SE. Lineation crenulation is S. 60° E., 55°. Return to vehicle and drive back upsection.

STOP 2

17.8 Outcrop of Moeda 2. This member is made up of fine-grained schists and phyllites; facies changes are normal to bedding. It is mostly a quartz-mica schist with subordinate intercalation of rhythmic phyllites that weather green. Here and there are thin intercalations (10–50 centimeters) of sericite quartzites, which locally have highly micaceous laminae. Continue up section.

Kilometer

STOP 3

18.8 Contact between the Moeda 3 (medium-grained to very coarse grained quartzites) and the overlying, locally graphitic phyllites of the Batatal Formation (about 20 m thick). The Batatal is conformably overlain by itabirites of the Cauê Formation. Return to the BR–040 Inconfidente's Highway junction where the excursion will continue on a traverse through the Moeda synform.

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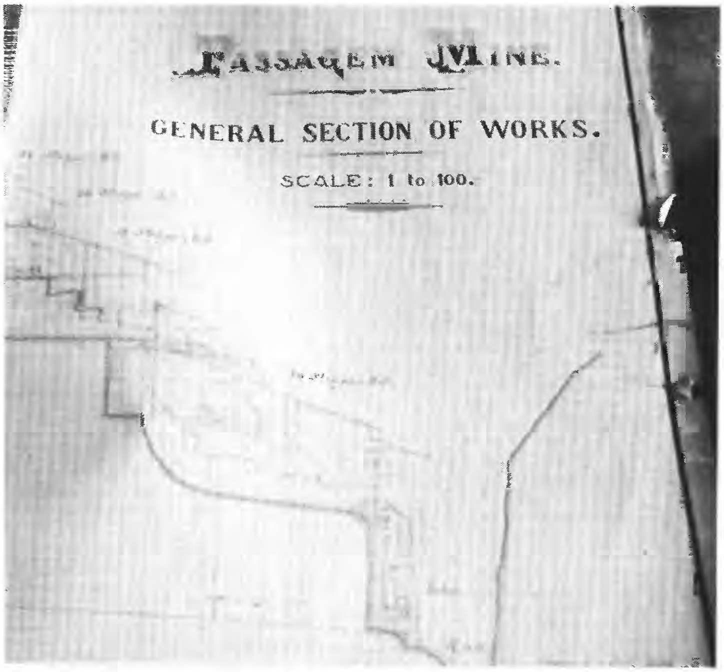

July 1894 drawing of Passagem de Mariana stamp mill and 1986 photograph of stamp mill buildings

Surface and Underground Geological Excursion Around and in the Passagem de Mariana Gold Mine, Minas Gerais, Brazil

By RONALD FLEISCHER and DIÔGENES SCIPIONI VIAL

U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

Quartz veins--Passagem de Mariana gold mine

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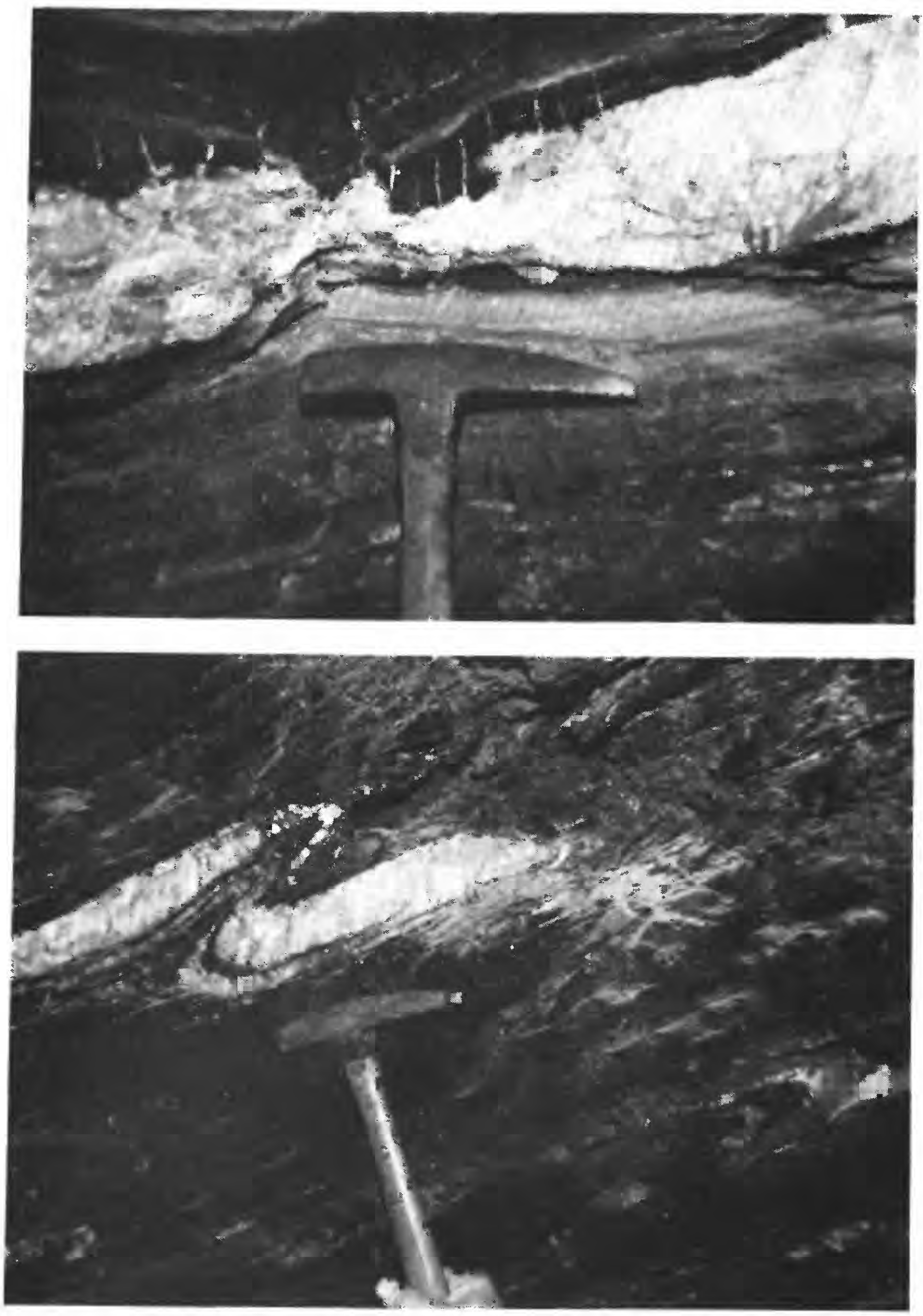

Boudinaged and folded rocks with quartz fillings in Passagem de Mariana gold mine

Surface and Underground Geological Excursion Around and in the Passagem de Mariana Gold Mine, Minas Gerais, Brazil

By Ronald Fleischer[1] *and* Diôgenes Scipioni Vial[2]

INTRODUCTION

The object of this field excursion is to see the stratigraphic and structural setting around and in the Passagem de Mariana gold mine in the southeastern part of the Quadrilátero Ferrífero (fig. 1). The deposit has been exploited discontinuously since the end of the 17th century and has produced at least 60 tons of gold. Figure 2 shows the location of the Passagem mine and other gold mines in the region. Figure 3 is a generalized stratigraphic column that includes nomenclature used in this paper.

The Passagem gold deposit has been described and interpreted by several geologists (Hussak, 1898; Derby, 1911; Legraye, 1937; and Guimarães, 1965). Classical metallogenetic textbooks have summarized these data and considered this deposit to be an example of epigenetic mineralization, foreign to its geological framework (de Launay, 1913; Lindgren, 1933; Emmons, 1937) .

The emplacement of the ore was considered to be due to percolation of high temperature mineralizing solutions (pegmatitic-pneumatolytic or deuteric type) along inferred shear zones by the authors just listed. Geological maps on a 1:25,000 scale by Miranda Barbosa (in Dorr, 1969) show a thrust fault running exactly through the site of the Passagem mine (fig. 2), which had been assumed by the early authors to be the channelway for the mineralization. However, the mineralized interval along the thrust fault was not critically examined. The mineralized interval is composed mostly of vein quartz, carbonates, tourmaline, arsenopyrite, and gold and has a maximum thickness of 5 m (meter). It extends for more than 15 km (kilometer) in a definite stratigraphic position below the Cauê Itabirite, concordant with the enclosing rocks.

Fleischer (1971, 1973) concentrated his study along this mineralized interval, the thrust fault of Barbosa, and emphasized the relations of the ore horizon with the structural, metamorphic, and paleogeographic features of the surrounding rocks of the Passagem district. The thrust-fault hypothesis, which assumed the fault zone to be a conduit for mineralizing fluids, was discarded in favor of an syngenetic concept in which lateral facies-change explains why different lithologic units within the same narrow stratigraphic position are mineralized. This coexistence of different lithologic units, which are known elsewhere in the pre-Minas succession as well as in the Minas Supergroup, is the main reason for the debate concerning the genesis of the mineralization.

In view of these different interpretations, three hypotheses or models are presented for the genesis of the gold mineralization: the first two are epigenetic and depend on structural controls, and the third is syngenetic.

1. The deposit is Archean in age, because the thrusting juxtaposes the Cauê Itabirite on top of different lithologic units interpreted to be part of the Rio das Velhas Supergroup, a volcanic-sedimentary sequence. The mine sequence would be of a more distal facies than that present at the Morro Velho mine. This hypothesis accepts the general structural picture of Barbosa (in Dorr, 1969), who showed a regional thrust at the base of the Minas Supergroup. This hypothesis differs from Barbosa's, however, in that Barbosa showed

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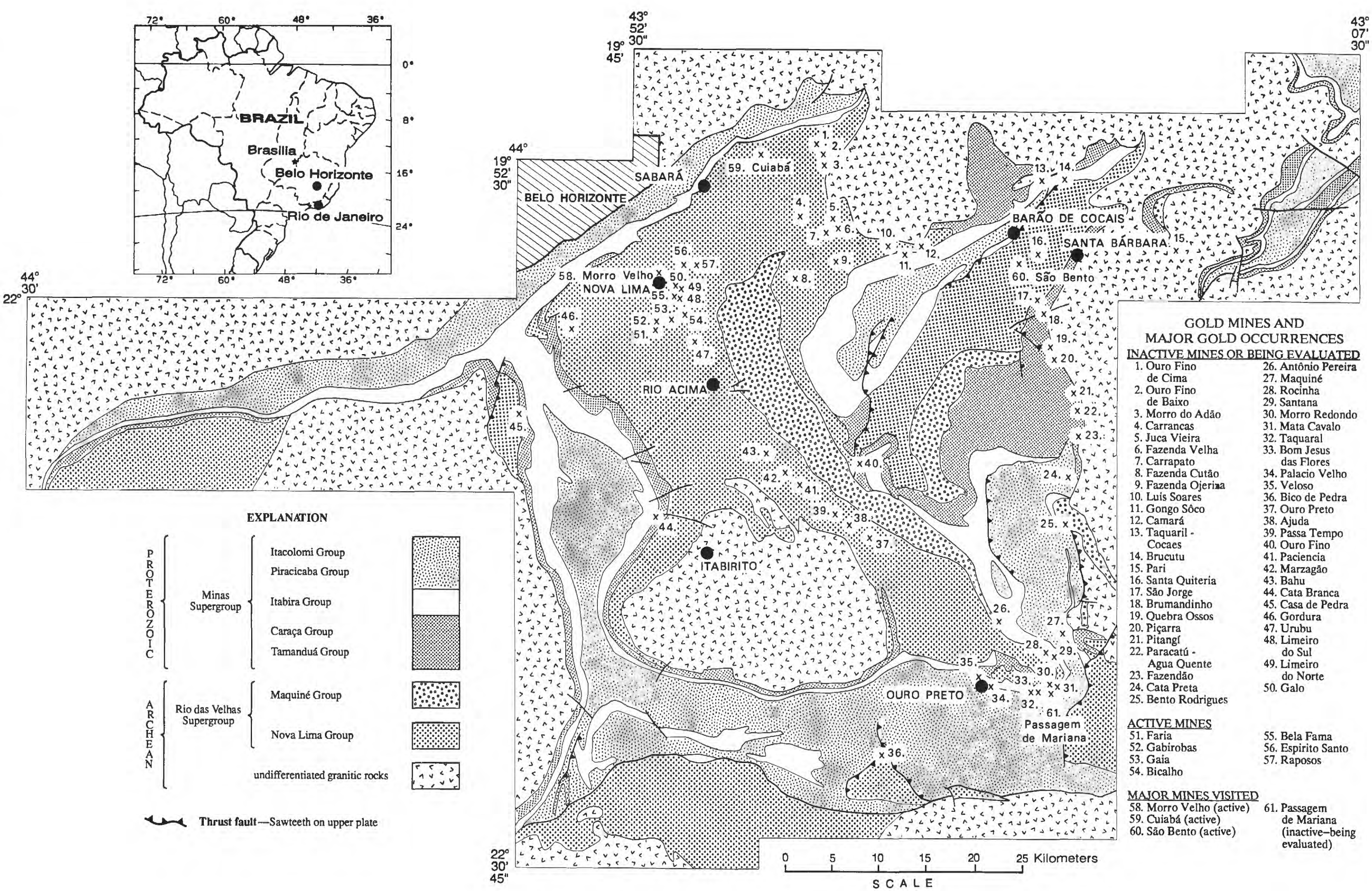

Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the location of the Passagem de Mariana gold mine, other major gold mines visited, and other gold mines and occurrences in the area.

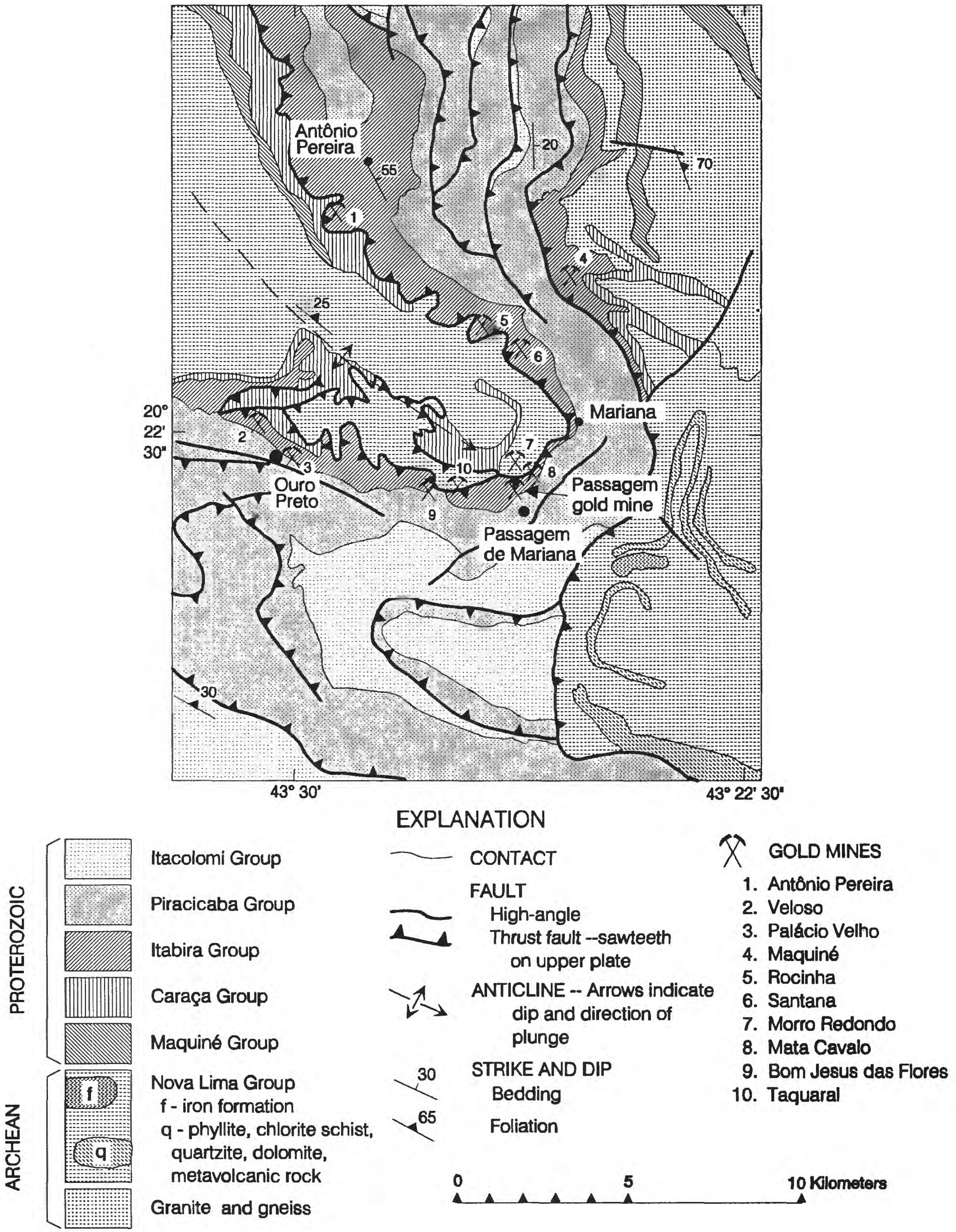

Figure 2. Generalized geologic map of the Ouro Preto-Mariana region in the southeastern part of the Quadrilátero Ferrífero (modified from Barbosa in Dorr, 1969).

PROFOUND OROGENY WITH REGIONAL METAMORPHISM

Itacolomi Group

PROFOUND ANGULAR UNCONFORMITY

PROTEROZOIC

- Minas Supergroup
  - Piracicaba Group
    - Sabará Formation
    - Barreiro Formation
    - Taboões Formation
    - Fêcho do Funil Formation
    - Cercadinho Formation
  - Itabira Group
    - Gandarela Formation
    - Cauê Itabirite
  - Caraça Group
    - Batatal Formation
    - Moeda Formation
  - Tamanduá Group

MAJOR OROGENY WITH REGIONAL METAMORPHISM

ARCHEAN

- Rio das Velhas Supergroup
  - Maquiné Group
    - Casa Forte Formation
    - Palmital Formation
  - Nova Lima Group
    - Upper unit*
    - Middle unit* (includes Lapa Seca Formation)
    - Lower unit*

CONTACT CONSIDERED INTRUSIVE BY DORR (1969)

Granitic-gneissic basement rocks, including granitoids of various ages

Figure 3. Generalized stratigraphic column of Precambrian rocks of the Quadrilátero Ferrífero (modified from Dorr, 1969). Asterisk (*) indicates units not included in Dorr's paper but discussed by Thorman and Ladeira in the introductory chapter of the volume, Part A—Excursions. The granitic-gneissic basement unit includes several informal units, including the Bação Complex or Bação Granitic Complex, which is the oval basement body in the south-central part of figures 1 and 2.

the rocks at the Passagem mine to belong to the lower part of the Minas Supergroup rather than as part of the Nova Lima Group.

2. The deposit is Middle to Late Proterozoic in age, of a typical epigenetic origin; the source of the mineralizing fluids is not specified. The low-angle to bedding-parallel thrusting would have provided the channelways for the mineralizing fluids. This hypothesis is the basic concept proposed by earlier workers (de Launay, 1913; Lindgren, 1933; Emmons, 1937) and reemphasized by Barbosa (in Dorr, 1969) in his regional work.

3. In the syngenetic lateral facies-change concept, the mineralization took place during Early Proterozoic in a sedimentary (distal volcano-sedimentary?) environment. The rocks were deformed and the gold was remobilized and redeposited during at least three periods of folding related to an undetermined number of tectonic events.

SCOPE OF EXCURSION

On this excursion, we present features that support each of the three interpretations or models. Fleischer favors a syngenetic origin for the deposits, whereas Vial prefers an epigenetic origin.

The location of stop 1 at the abandoned Bom Jesus das Flores mine and the Passagem de Mariana mine are shown on figure 2, and stops 2.1-2.22 in the mine are shown on figure 4. For an overview of the geology of the Quadrilátero Ferrífero and the geology of the Passagem mine, the reader is referred to the papers in Part B (Geology of deposits) of this volume by Ladeira and Viveiros and by Vial, respectively.

ROAD LOG

STOP 1

3.4 km Beginning at the Praça Tiradentes, in Ouro Preto, just in front of the Ouro Preto School of Mines, take the road to Passagem de Mariana; at 3.4 km take a dirt road to the left toward the Bom Jesus das Flores do Taquaral chapel and drive 200 m to a small bridge over the Taquaral Creek. This stop is intended to show a profile through the basal part of the Minas Supergroup around the São Bartolomeu anticline (fig. 2). The Passagem gold mine and the Morro de Santana gold-mine workings (fig. 2) are on the nose of the anticline.

The profile from north to south begins with a chlorite-biotite-calc schist, which grades into a ridge-forming itabirite. In a drift of the abandoned Bom Jesus das Flores mine (mine 9, fig. 2), which follows this contact, one can observe, in the footwall, the sericite-quartz schist locally overlain by sericite quartzite, which is separated from the overlying itabirite by a gray graphitic phyllite a few centimeters thick.

Two interpretations or models are considered for this profile: the thrust-fault and the facies-change interpretations. The thrust-fault interpretation was first proposed by Miranda Barbosa and considers the chlorite-biotite calc schists as well as the sericite-quartz schist to belong to the Archean basement that has been overthrust by the Early Proterozoic Minas Supergroup, here represented by the itabirites and locally by slices of quartzite (Moeda Formation) and gray graphitic schist (Batatal Formation). In this interpretation, the gold mineralization occupies a thrust fault that cuts the Proterozoic sequence either at the basal quartzite level, at the gray graphitic horizon, or at the middle of the itabirite strata.

The facies-change interpretation (Fleischer, 1971, 1973) considers the sericite-quartz schist to be the lateral equivalent to the Moeda fine-grained sericite quartzite at Ouro Preto. That this lithology is common to the Moeda Formation has been shown at the type locality at Serra da Moeda. The sericite quartzite is distinct from the underlying chlorite-calc schists, from which it can be distinguished by detailed mapping. It is important to note that in this southeastern part of the Quadrilátero Ferrífero, both the Moeda and Batatal Formations, as well as the overlying itabirites, are much thinner than in more northerly sectors. Some movement along the thin, gray, graphitic horizon surely took place during the two folding events during which rocks in the area were deformed, as will be seen in the Passagem Mine, but the movement was not strong enough to tectonically thin the Moeda and Batatal Formations over such a large area.

STOP 2

7.3 km Return to the main road and continue to Passagem de Mariana, and, after 3.9 km, turn left to the mine parking lot. In the mine, the tour will go down the PIA Nova inclined shaft. After visiting some exposures in this part of the mine, known as Fundão orebody, the tour will follow the 265 level to the east, passing by the PIA 1 inclined shaft and back to the surface in the PIA 2 shaft. Stops in the mine are shown in figure 4; stops are numbered in text from 2.1 to 2.22 and in figure 4 from 1 to 22.

STOP 2.1: PIA NOVA–175 level.

A typical sequence of a large section (Fundão orebody) of the mine: at the bottom, a fine-grained sericitic quartzite in a slightly calcareous matrix; above it, a dolomitic horizon that has common boudinage structures and that grades toward the top into gray graphitic phyllites interbedded with centimeter-thick light-colored laminated cherts containing pyrrhotite. At the roof, the phyllites grade over a short interval into itabirites.

Two important aspects of the dolomitic horizon are seen here. First, the presence of a centimeter- to decimeter-thick discontinuous intercalation of dark tourmalinite, which some workers have referred to as an important guide to the mineralization. All the steps of

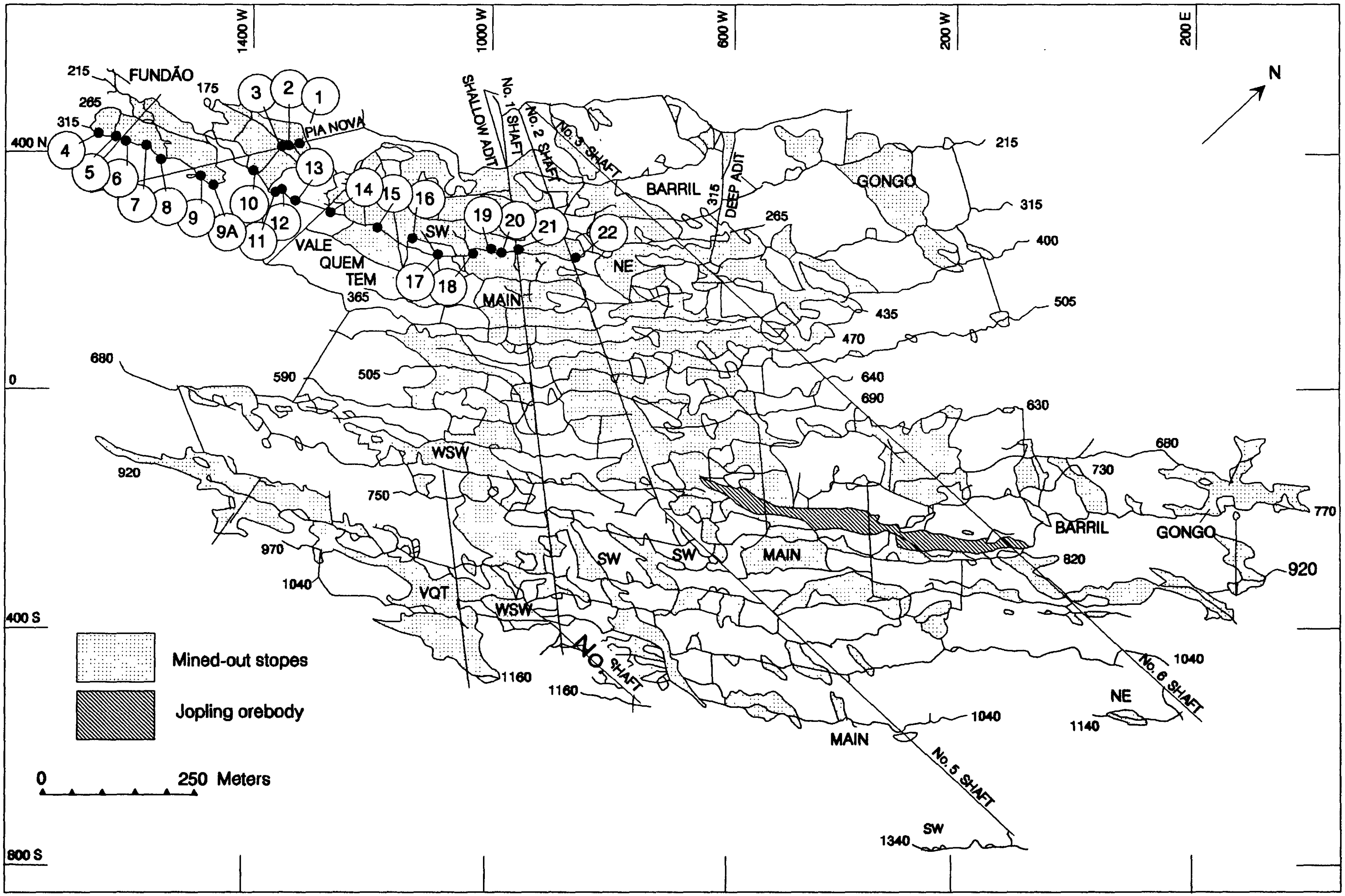

Figure 4. Mine plan of the Passagem de Mariana gold mine showing the location of stops (2.1 to 2.22 in text) and major orebodies in the mine.

disruption of the tourmalinite bands can be seen, beginning with simple vertical fractures filled with white quartz, to total separation resulting in angular blocks drowned in a recrystallized quartz and dolomite vein-like mass. That this structure is due to tectonic thinning and plastic deformation resulting in boudinage structures and not to tectonic brecciation within a fault becomes obvious when one observes that the metamorphic banding of these blocks has a definite orientation, continuous with the banding of neighboring blocks and parallel to the enclosing rocks. Dolomitic recrystallization characterizes the upper part of the ore zone; milky quartz dominates the lower part. This distribution reflects the stratigraphy and shows an intimate relationship between the host rocks and the minerals of recrystallization. The recrystallized material was derived from nearby host rocks and was not transported more than a few meters.

Points to debate:

1. Sericitic quartzites in a slightly calcareous matrix grade into pure sericite quartzites. Is the pure sericite quartzite a product of silicification of the calcareous rock or is it a primary feature?

2. Why is the intense dolomite and quartz recrystallization restricted to the ore zone and why is it stratabound?

STOP 2.2: PIA NOVA between levels 175 and 265.

A crosscutting east-west oriented quartz vein.

STOP 2.3: PIA NOVA between levels 175 and 265, about 20 m beyond Stop 2.2.

At this stop note the milky quartz mass. It is a concordant veinlike mass, which crosscuts both the tourmalinite-bearing dolomites at the top and the quartzites at the bottom. At one corner of the drift, the crosscutting relations become ambiguous. Although it clearly crosscuts the dolomites and tourmalinites, it seems to grade into the quartzite. Around the corner, at the beginning of the raise, both crosscutting and transition features occur simultaneously, which raises two questions:

1. Is the grading of the milky quartz into the quartzite an argument for silicification of the quartzite or is it evidence that the quartzite is the source of the recrystallized quartz in the form of concordant veins?

2. The solution to this question is crucial to the further discussion about the significance of widespread quartz impregnation of the Passagem ore zone. Can this milky quartz impregnation be attributed to the percolation of fluids from an unknown source through a low-angle thrust fault, or is it the result of silica remobilization during the tectonic event during which boudinage and other disruptive structures were produced?

STOP 2.4: Level 315 to the west of PIA NOVA, where the drift becomes narrower, at the 12–14 channel sample.

The regularly bedded rock, on the hanging wall, is an actinolite-rich amphibolite. It contains interbeds of a quartz-biotite schist and 2-decimeter-thick beds of finely laminated chert. One of these chert beds is pinched out by boudinage, whereas the other one is in a tight synschistose fold. At the footwall, the same sericitic quartzite with a slightly calcareous matrix. The mineralized interval between is marked by the milky quartz concordant mass permeating dolomites with tourmalinite.

Recent gold assays on channel samples by DOCEGEO (Rio Doce Geologia e Mineração) show that mineralized rock is more concentrated in the 20- to 50-cm-thick concordant quartz veins; grades range anywhere between 0 and 18 g/t (gram per ton) and show no special affinity with the tourmalinite or where arsenopyrite is concentrated. These results tend to refute old mine descriptions by various authors, including those who were in charge of the workings. If confirmed in other sections of the mine, this observation can be explained by the higher mobility of gold relative to boron and arsenic during the boudinage-related deformation.

STOP 2.5: Level 315, west of PIA NOVA, at the 40–46 channel sample.

This channel sample illustrates the observation referred to at Stop 2.4. From footwall to hanging wall, the following lithologic units yielded the following gold contents (in grams per ton):

DOCEGEO channel sample No.	Dominant lithology	Gold (g/t)
40	Quartz-biotite-calc schist ----------	0.27
41	Milky quartz -------------------	0.43
42	Quartz-biotite-calc schist ----------	23.00
43	Milky quartz plus tourmalinite ------	4.20
44	Milky quartz without tourmalinite ---	35.00
45	Amphibolite -------------------	9.00
46	Amphibolite ------------------	4.40

STOP 2.6: Level 315, west of PIA NOVA.

Flooding level of the mine.

STOP 2.7: Level 315, west of PIA NOVA, at channel sample 102-105.

In this profile, no concordant milky quartz vein is present and only part of the ore zone has been cut. Channel sampling gave the following gold content (in grams per ton):

DOCEGEO channel sample No.	Dominant lithology	Gold (g/t)
102	Sericitic quartzite ---------------	0.0
103	Quartz-biotite-calc schist ----------	0.13
104	Quartz-biotite-calc schist plus banded calcareous gray rock -----------	0.14
105	Amphibolite ------------------	0.10

The hanging wall at this locality is amphibolitic dolomitic itabirite and the footwall is carbonate-biotite schist.

STOP 2.8: Level 315, west of PIA NOVA, near channel sample 102-103.

Biotite-calc schist of the hanging wall has late-stage isoclinal folds with axes oriented N. 35° W. and dipping to the SE. A "b" lineation parallel to the fold axis can also be seen and corresponds to the intersection between bedding planes and the main schistosity. These intrafolial folds illustrate the intensity of the second folding phase and show that associated transposition must be taken into account when small-scale observations on detailed stratigraphy are made.

STOP 2.9: Level 315, east side of PIA NOVA.

From top to bottom, one can observe amphibole-bearing (mainly cummingtonite) itabirites that overlie biotite-garnet schists and contain centimeter-thick layers of carbonates and cherts. The cherts contain pyrrhotite. Note several vertical fractures that tend to be larger within the schists than within the carbonate and chert layers. The fractures are filled with quartz in the center and tourmaline plus arsenopyrite on the borders. They are a local feature and have no continuity with the itabirites at the top nor with the carbonates at the bottom.

These observations bring up the discussion of whether the filling material of the vertical veins originated from lateral secretion or by introduction of epigenetic fluids.

STOP 2.9a: 20 m to the east along the same drift.

Again the biotite-calc schists have late-stage isoclinal folds whose axes are oriented N. 5° E. and dip to the south. The fold asymmetry indicates an upright position for the sequence if tectonic movement from south to north is accepted.

STOP 2.10: Back to the 265 level and then to the east.

Dolomites have isoclinal folding, genetically associated with intersection lineation and crenulation, both oriented N. 10°–20° W. and plunging south. These folds are second-phase folds because they crenulate micaceous minerals. The folds show that the second phase was as strong as the first one in this area. On the roof, one can observe a boudinage axis oriented east-west.

Tight folding is observed in metachert bands within biotite-quartz schists. The geometry of the folds indicate they are upright, and thus movement was from southeast to northwest.

STOP 2.11: 265 level, near channel sample 284-285.

Note the discordant relationship between the overlying itabirites and the interbedded graphitic calc-schists and metachert. From this stop to the east, the ore zone becomes less and less dolomitic and more graphitic.

In the thrust-fault interpretation, the itabirites were thrust over two distinct lithologic units that dip gently to the east; the dolomites dip west, and the graphitic phyllites dip east.

In the lateral-facies change hypothesis, dolomites and graphitic phyllites interfinger and are lateral equivalents. Both are normally overlain by itabirites; local movement has occurred along the contact due to boudinage development.

STOP 2.12: Level 265 near sample channel 289–291.

Calc-schists have second-phase folding that caused intense transposition of earlier features.

STOP 2.13: Level 265 near channel sample 303–307.

The vertical succession from the hanging wall to the footwall of the gold ore zone shows the following sequence: tourmalinite + arsenopyrite in dolomites as well as recrystallization of carbonates; a 30-cm-thick horizon of metachert with thin pyrrhotite-rich layers; a 60-cm-thick horizon of pyrrhotite-bearing graphitic calc-schists; a 20-cm-thick horizon of metachert with thin interbeds of pyrrhotite-rich layers and graphitic calc-schist. This succession illustrates the interfingering relationship between the dolomites at one extreme and the gray graphitic schists (or phyllites) at the other extreme. This section has no gold values.

STOP 2.14: Level 265 near channel sample 342–345.

Short drift toward the base of the sequence. The drift begins in graphitic calc-schists, just above the quartzites, which mark the base of the sequence, and cuts dolomites containing a zone of fractured tourmalinite associated with recrystallized quartz. Between the tourmalinite zone and the quartzites is a 10-to 20-cm-thick graphitic phyllite.

A quartz shoot, within the quartzite, contains recrystallized tourmaline that differs from the tourmalinite above the quartzite, in the sense that the quartzite has a fractured and disrupted layer geometry.

STOP 2.15: Level 265 near channel sample 380–381.

From this point on, dolomite becomes scarce and the gray graphitic phyllite common.

STOP 2.16: Level 265 near channel sample 424–427.

A cross section near the base of the sequence is seen here. From the top to the base of the mine face, the succession is as follows: (1) itabirite; (2) garnet-bearing black graphitic schists with a 0.5-m-thick layer of pure quartzite near the contact with the itabirite; and (3) ore zone with tourmalinite and recrystallized quartz within the black graphitic schist and not far from the contact with the underlying sericitic quartzite.

STOP 2.17: Level 265 near channel sample 463–468.

Repetition of itabirite and black graphitic schist. Is this repetition due to a transitional contact or to slicing by overthrusting?

STOP 2.18: Level 265 near channel sample 1189–1190.

Quartzite at the base and mineralized rock in the overlying black graphitic schist.

STOP 2.19: Level 265 near channel sample 505–507.

Here, the black graphitic schist of the Batatal Formation has thinned to 1.5 m.

STOP 2.20: Level 265 near channel sample 508–512.

Short raise exposing a good example of the discordant relationship between the quartzite below and the black graphitic schists and tightly folded calc-schist with tourmalinite above. Near this feature is a quartz vein that trends N. 20° W., 70° E. Is the discordant relationship an evidence of thrust-faulting or is it a simple tectonic thinning and plastic deformation resulting in boudinage-appearing features?

STOP 2.21: Ore pass connecting 265 level with PIA 1 inclined shaft.

The ore pass crosses the footwall quartzite; below the quartzite a repetition of vein quartz + tourmalinite + arsenopyrite can be observed within the quartz-biotite-calc schist.

STOP 2.22: Level 265 at its junction with the PIA 2 inclined shaft.

From the last stop to this point, the 265 level drift was cut in the footwall quartzite, which has become thicker.

Take a maze-like path that cuts through the footwall quartzite and once again check a vein quartz-tourmalinite-arsenopyrite assemblage within the footwall biotite-calc schists.

RETURN TO SURFACE.

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Excursion to the Morro Velho Gold Mine, Minas Gerais, Brazil

By FREDERICO WALLACE REIS VIEIRA,
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PASCHOAL LUIZ CAIAFA CLEMENTE, and
RAFAEL LIMA DE OLIVEIRA

U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

Underground—Morro Velho mine

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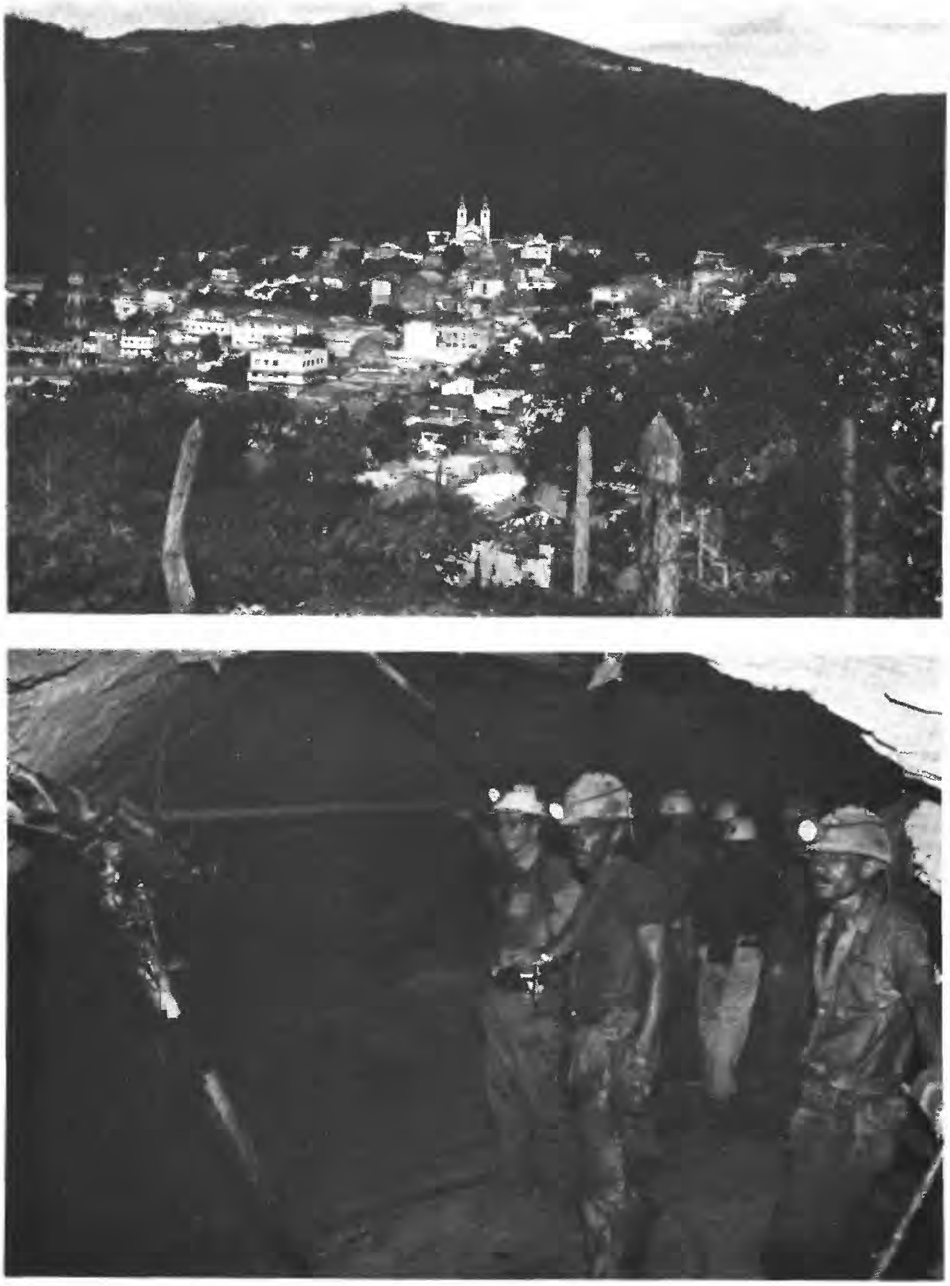

Morro Velho gold mine is in town of Nova Lima (top); mining operations are shown at level 25 (bottom)

Excursion to the Morro Velho Gold Mine, Minas Gerais, Brazil

By Frederico Wallace Reis Vieira, Luiz Henrique do Amaral Lisboa, Jose Lamas Chaves, Geraldo Antônio Ibrahim de Oliveira, Paschoal Luiz Caiafa Clemente, *and* Rafael Lima de Oliveira[1]

ABSTRACT

The Morro Velho gold mine, located in the northern part of the Quadrilátero Ferrífero, is a gold deposit related to banded iron formation (BIF) in the Archean Nova Lima Group. The orebodies are stratiform sulfide lenses in association with metarhyolitic and quartz-carbonate units in a complexly folded metavolcaniclastic-metavolcanic greenschist terrane. Gold occurs in sulfides or along sulfide-silicate grain boundaries.

INTRODUCTION

The Morro Velho mine is in the town of Nova Lima in the northern sector of the Quadrilátero Ferrífero (fig. 1). Nova Lima is about 10 km (kilometer) southeast of Belo Horizonte and is accessed by highway MG–030.

Gold was first recovered at Morro Velho by Padre Freitas in 1810, although industrial mining did not begin until 1834, when the mineral rights were acquired by St. John del Rey Mining Co., Ltd.; the mine was active from 1834 to 1960. The Moreira Sales Group bought the mining rights from St. John del Rey Mining Co., Ltd. in 1960 and formed Companhia Mineração Morro Velho S.A. (MMV). In 1975, AngloAmerican Corporation joined MMV, and, in 1978, the Bozzano Simonsen Group acquired the Moreira Sales Group holdings in MMV.

The Morro Velho mine is exploited from two workings because of operational problems; both workings are in the same orebody. The upper workings, Mina Velha, reach a depth of 156 m (meter) above sea level, and the lower workings, Mina Grande, go to 1,610 m below sea level, a total depth of 2,453 m at level 27. The excursion was made to level 25 of Mina Grande, situated at 1,314 m below sea level, and there were eight stops in the mine (fig. 3).

REGIONAL GEOLOGY

The Quadrilátero Ferrífero is underlain by a sequence of Archean rocks of the Rio das Velhas Supergroup, which is in turn overlain by the Proterozoic Tamanduá or Espinhaço Group, Minas Supergroup, and Itacolomi Group. This entire sequence rests on and is bounded by a gneissic and migmatitic Archean complex that was widely remobilized during the Brazilian cycle (550–600 Ga). The Morro Velho mine is in the Nova Lima district, which was mapped and described by Gair (1962). The geology of the Quadrilátero Ferrífero was compiled and synthesized by Dorr (1969). Figure 2 shows a generalized stratigraphic column for the Quadrilátero Ferrífero modified from Dorr (1969). For an overview of the geology of the Quadrilátero Ferrífero, the reader is referred to Ladeira and Viveiros (this volume, Part B—Geology of deposits). The Rio das Velhas Supergroup comprises a typical greenstone belt sequence that Schorscher (in Schobbenhaus and others, 1984) divided into three groups, from bottom to top:

1. Quebra Osso Group—Ultramafic and mafic volcanic rocks of komatiitic character with intercalations of BIF. Thorman and Ladeira (this volume, Part–A, Excursions, p. A14) assign these rocks to the Nova Lima Group, as shown in figure 2.
2. Nova Lima Group—Metapelites, metavolcanics, and BIF.

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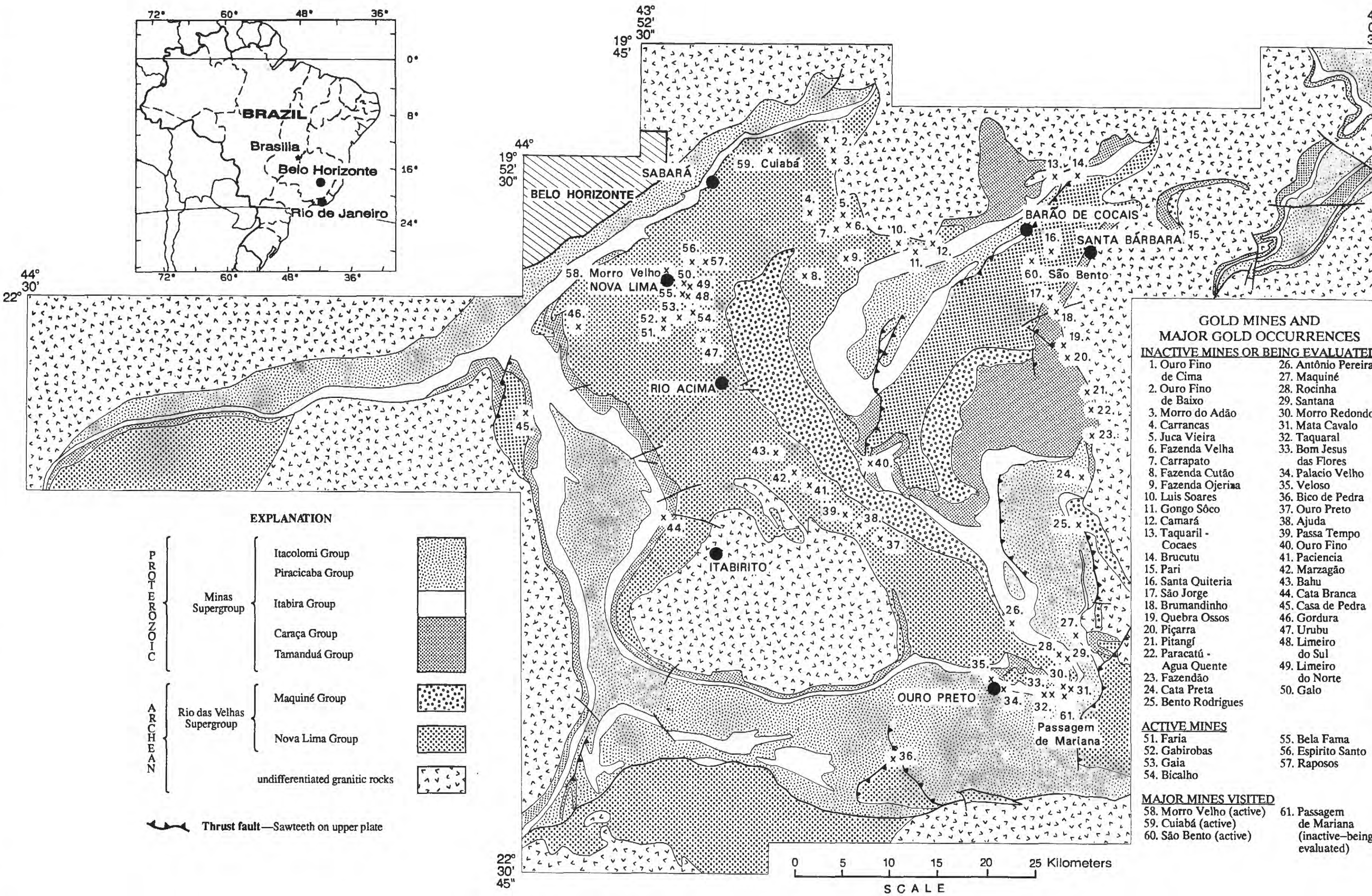


Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the location of the Morro Velho gold mine, other major gold mines visited, and other gold mines and occurrences in the area.

PROFOUND OROGENY WITH REGIONAL METAMORPHISM

Itacolomi Group

PROFOUND ANGULAR UNCONFORMITY

PROTEROZOIC

- Minas Supergroup
  - Piracicaba Group
    - Sabará Formation
    - Barreiro Formation
    - Taboões Formation
    - Fêcho do Funil Formation
    - Cercadinho Formation
  - Itabira Group
    - Gandarela Formation
    - Cauê Itabirite
  - Caraça Group
    - Batatal Formation
    - Moeda Formation
  - Tamanduá Group

MAJOR OROGENY WITH REGIONAL METAMORPHISM

ARCHEAN

- Rio das Velhas Supergroup
  - Maquiné Group
    - Casa Forte Formation
    - Palmital Formation
  - Nova Lima Group
    - Upper unit*
    - Middle unit* (includes Lapa Seca Formation)
    - Lower unit*

CONTACT CONSIDERED INTRUSIVE BY DORR (1969)

Granitic-gneissic basement rocks, including granitoids of various ages

Figure 2. Generalized stratigraphic column of Precambrian rocks of the Quadrilátero Ferrífero (modified from Dorr, 1969). Asterisk (*) indicates units not included in Dorr's paper but discussed by Thorman and Ladeira in the introductory chapter of this volume, Part A—Excursions. In this paper on Morro Velho, the authors assign the Lapa Seca Formation to the Upper unit of the Nova Lima Group (see text below). The granitic-gneissic basement unit includes several informal units, including the Bação Complex or Bação Granitic Complex, which is the oval basement body in the south-central part of figure 1.

3. Maquiné Group—Quartzites, conglomerates, and phyllites (divided into two formations: Palmital and Casa Forte).

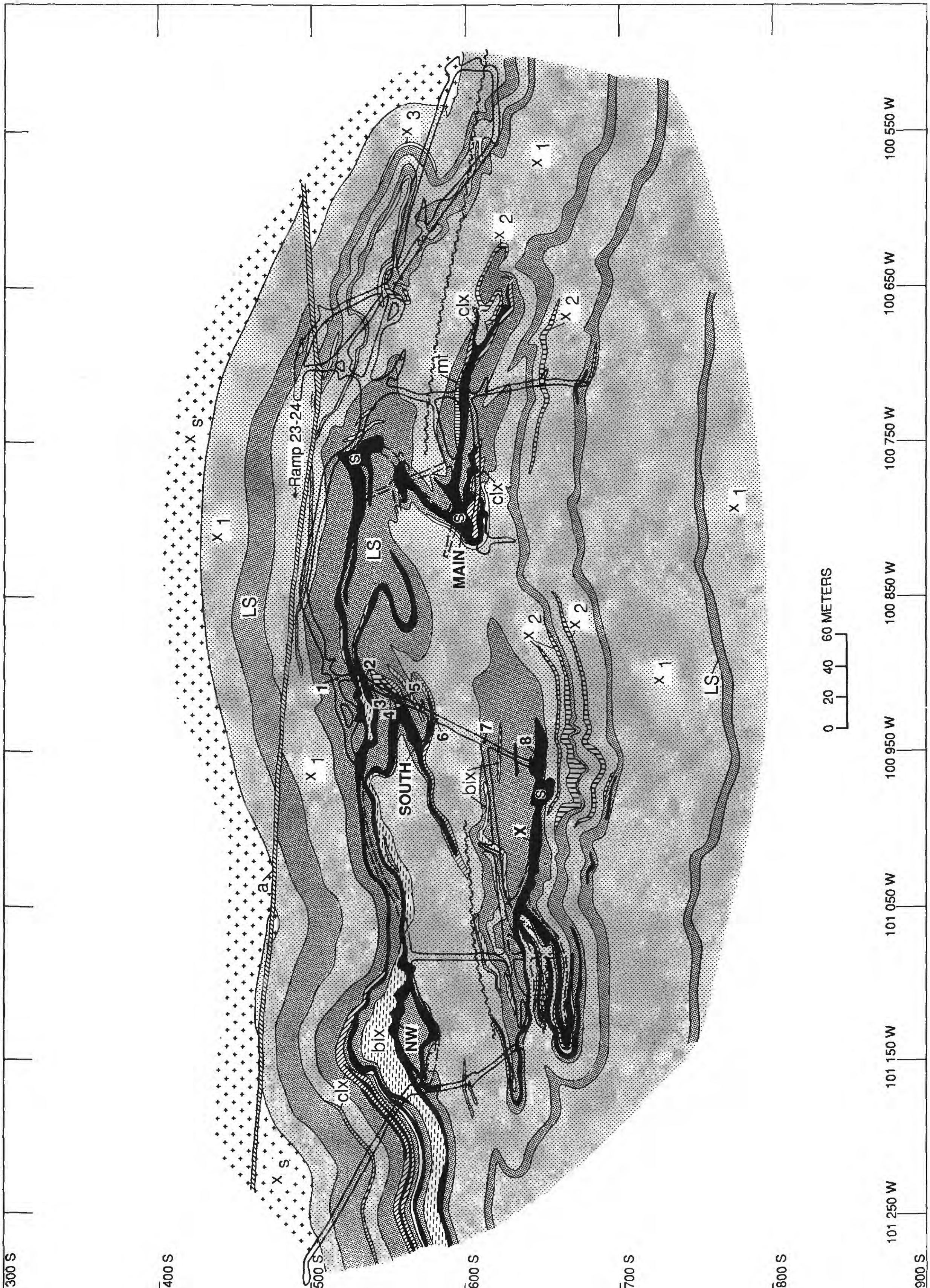
The Nova Lima Group was divided by Mineração Morro Velho geologists into three units: the Morro Velho gold deposit is in the Upper Unit.

Upper Unit—Metapelites interlayered with acidic metavolcanoclastics, a quartz-carbonate (dolomite and ankerite) rock (a lithologic unit called the Lapa Seca Formation), sandy metasiltites, and metaconglomerates.

Middle Unit—Acid metavolcanoclastics interlayered with metapelites. The top is marked by meta-andesite and a layer of BIF.

Lower Unit—Meta-andesites, locally contain pillow lavas, and interlayered with ultramafic komatiites, metapelites, acid metavolcanoclastics, and BIF.

Rocks of the Nova Lima Group in this area have been deformed during four deformational events; the first two events were accompanied by greenschist facies dynamo-thermal metamorphism. The first event was related to the Rio das Velhas orogeny (2.8 Ga) and the other three to the Minas orogeny (2.0 Ga). Diabase dikes intruded during the close of the second deformational event, thermally metamorphosing the wall rocks. The dikes generally occupy shear zones that parallel the axial-planes of D_2 folds.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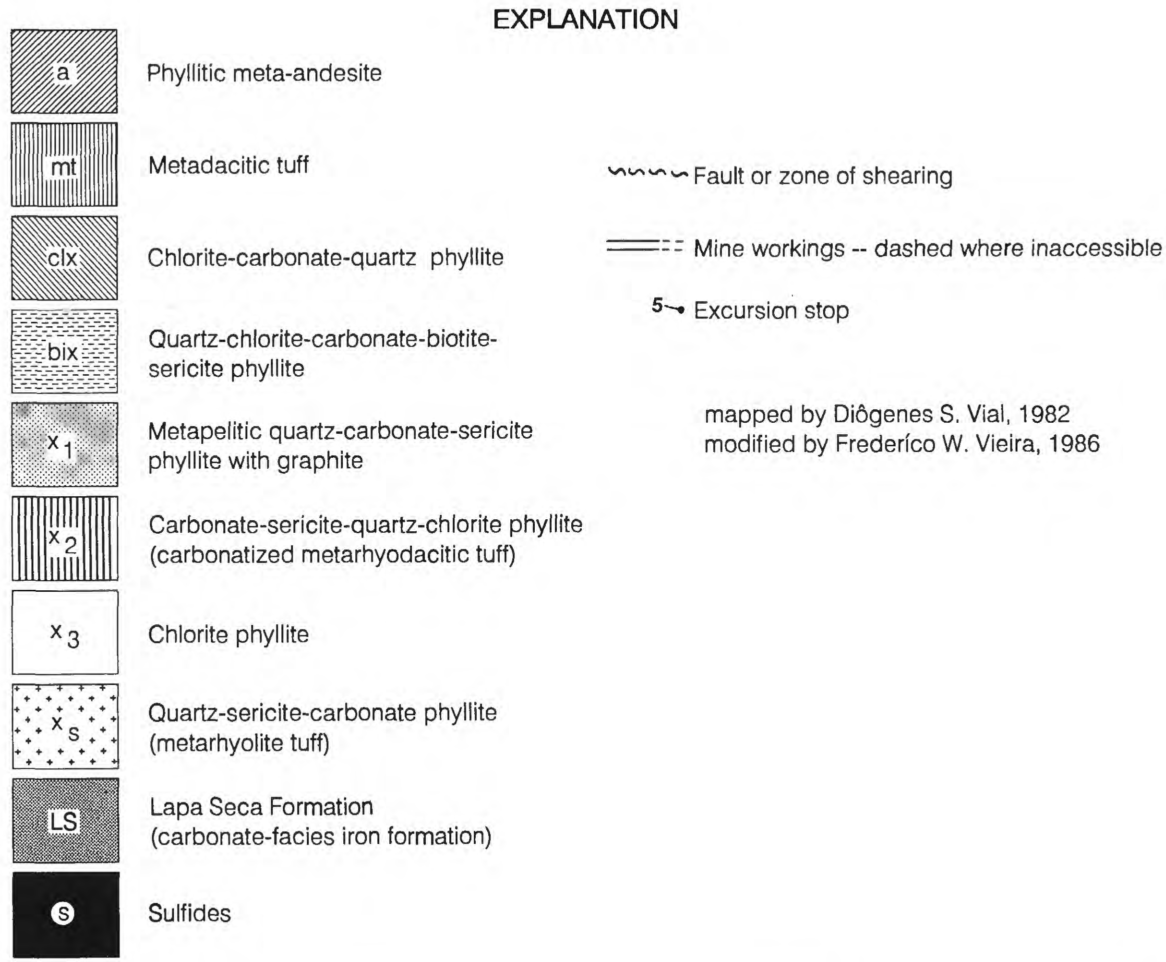

Figure 3. Geologic map of level 25 of the Morro Velho gold mine showing the location of stops 1-8 for the mine excursion and the Main, X, South, and NW orebodies.

GEOLOGY OF THE MORRO VELHO MINE

Stratigraphy

The Morro Velho mine is in the basal part of the Upper Unit of the Nova Lima Group, which is a sequence of metapelites (x_1) and two units of Lapa Seca (LS). This sequence is complexly folded and intruded by a phyllitized diabase dike (a). Here and in the following sections, letters in parentheses refer to map-unit notations used on figure 3.

Sulfide orebodies are restricted to the lower unit of the Lapa Seca, which is usually intercalated with submarine rhyolite and rhyodacite tuffs. The upper unit of the Lapa Seca is barren and has no intercalated volcanic rocks. Above the Lapa Seca is a bed of metarhyolitic tuff (x_S), which is also intercalated in the metapelites (x_1).

Lithologic Units

The rocks mapped on level 25 of Mina Grande (fig. 3) have been metamorphosed dynamothermally to the greenschist facies (biotite subzone). The following is a generalized description of the major lithologic units observed on level 25:

(a) Dark-green phyllitic "meta-andesite" dike rocks composed of chlorite, plagioclase, quartz, and post-tectonic poikiloblastic carbonate. Originally called "meta-andesite" (Oliveira and others, 1983), but is now recognized as metadiabase dikes with locally assimilated wall-rock material.

(mt) Brownish-grey massive metadacitic tuff composed of quartz, sericite, chlorite, and carbonate, as well as relict phenocrysts of andesine and minor quartz.

(clx) Dark-green phyllite composed of chlorite, carbonate, and quartz with subordinate sericite, biotite, tourmaline, and andesine. Metavolcanic rock of basaltic composition.

(bix) Brown phyllite composed of quartz, chlorite, carbonate, biotite, and sericite with relict andesine phenocrysts. According to Vial (1982), the bix is a meta-andesitic tuff.

(x_1) Dark-grey phyllite composed of quartz, carbonate, and sericite with minor chlorite, biotite, and graphite. A thinly laminated metapelite.

(x_2) Greenish to greenish-beige phyllite composed of carbonate, sericite, quartz, and chlorite with relict andesine phenocrysts. A carbonate-altered metarhyodacitic to metadacitic tuff.

(x_S) Grayish phyllite composed of quartz, sericite, and carbonate with minor chlorite and relict quartz phenocrysts. A metarhyolitic tuff.

(x_3) Phyllite composed of chlorite, sericite, and carbonate; unit occurs locally (Vial, 1982).

(LS) Lapa Seca Formation. Gray, banded to massive quartz-carbonate rock with subordinate graphite, sericite, feldspar, and chlorite. Carbonate is primarily ankerite, but locally contains calcite and dolomite. Laminations vary in thickness from a few millimeters to more than a centimeter. Some aspects of the mineralogy (such as sericite, feldspar, chlorite) suggest that some of the Lapa Seca is altered volcanic or volcaniclastic material.

Structural Geology

The rocks in the region were deformed during four events; during the first two events, isoclinal folds were formed whose axes are parallel (fig. 3). The first event is readily identified by a schistosity parallel to the well-preserved bedding in the hinges of D_2 folds. Deformation in the second event produced transposed isoclinal folds associated with the most prominent lineation and foliations, which, according to Vial (1982), have average attitudes of S. 85° E., 16°, and N. 35° E., 26° SE., respectively. Vial (1982) defined a lineation at N. 60°–64° E.,16°–22° and a cleavage resulting from a fracture at N. 77° E., 77° SE, which are correlated here with the third event. Deformation during the fourth event produced open and monoclinal folds responsible for the reduction of the plunge (L_2) at depth within the mine. The fourth event is characterized by fracture cleavage and crenulations, which, according to Vial (1982), have attitudes of N. 15° E., 74° SE. and S. 4° E., 20°, S. 8° W., 10° and N. 12° E., 3°.

Economic Geology

At level 25, nearly all gold is in the sulfidic orebodies; free gold is rare in metachert, a minor constituent in the stratigraphic succession. According to Vial (1982), the sulfidic orebodies are of three types: massive, 75 percent of ore; banded, 20 percent of ore; and orebodies associated with phyllite (clx), 5 percent of ore. All sulfidic orebodies are stratiform. The massive and banded types are associated with the Lapa Seca. These types appear to be products of volcano-exhalative processes. The sulfidic orebodies associated with phyllite (clx) contain sulfides that occur as spheres disseminated throughout the micaceous material (Vial, 1982).

The principal sulfides are pyrrhotite (35 percent), arsenopyrite (8.5 percent), pyrite (3 percent), and chalcopyrite (0.5 percent). Cubanite, sphalerite, galena, tetrahedrite, and ullmannite are locally abundant. Gold varies in size from 1 to 110 microns and is included in sulfides or along sulfide-silicate grain boundaries. The principal host minerals are pyrite (40 percent), pyrrhotite (35 percent), arsenopyrite (10 percent), and cubanite and chalcopyrite (5 percent) (Ladeira, 1980, 1985).

Pyrite and pyrrhotite were remobilized and concentrated in the hinge zones of folds during the second deformational event. Gold occurs with silver in a Au:Ag ratio of 5:1 (Ladeira, 1980, 1985). The ore has a fairly constant grade throughout the plunge of the orebody.

LOG OF THE EXCURSION UNDERGROUND

The excursion consisted of a visit to level 25 of Mina Grande. Access to this level is by six separate shafts.

STOP 1

Lapa Seca Formation with interbedded metapelite (x_1) and isoclinal folds of the second event.

STOP 2

Massive sulfide (NW orebody) in contact with bix.

STOP 3

Finely laminated Lapa Seca.

STOP 4

x_2 --Carbonate-sericite-quartz-chlorite phyllite, brownish-grey, with some biotite.

STOP 5

clx--Chlorite-carbonate-quartz phyllite with some sulfides.

STOP 6

x_1 --Quartz-carbonate-sericite phyllite (metapelite); massive sulfide (South orebody) is associated with clx.

STOP 7

bix--Intercalations of brown quartz-chlorite-carbonate-biotite-sericite phyllite in beige-gray Lapa Seca.

STOP 8

Area of mining of X orebody
Massive sulfide
Plunge S. 85° E.,18°
Mining Method: Cut and fill
Area of Mining: 1,151.1 square meters
Grade: 11.86 grams per ton (in situ).

REFERENCES CITED

[* indicates references cited in this paper that are not available outside of Brazil or are unpublished dissertations. These references are used in the interest of crediting workers, even though their work is not published, and letting the reader know where to find these references]

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Excursion to the Cuiabá Gold Mine, Minas Gerais, Brazil

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U.S. GEOLOGICAL SURVEY BULLETIN 1980-A

Entrance to Cuiabá gold mine property

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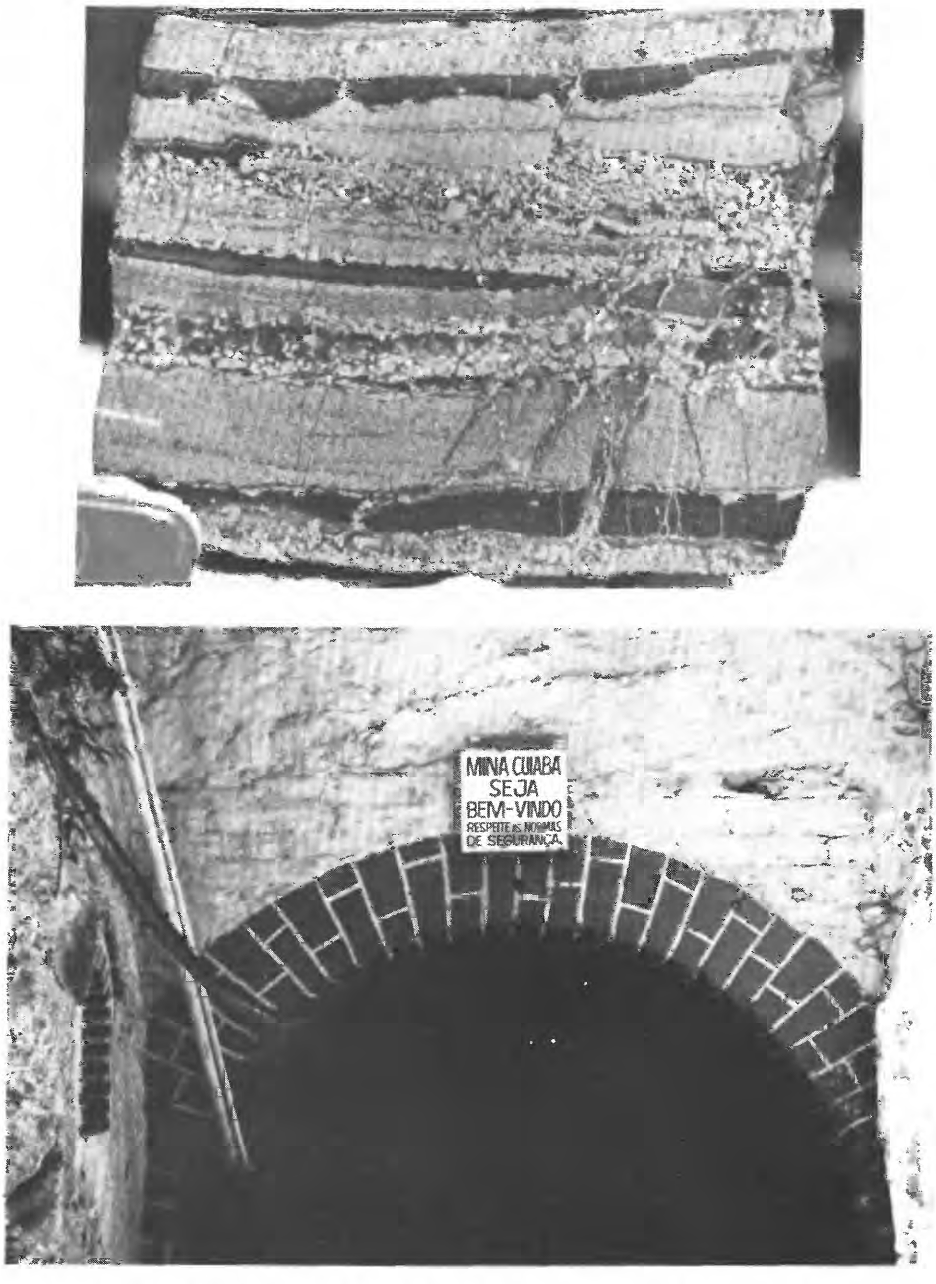
FIGURES



Bedded, pyrite-rich ore from the Cuiabá gold mine (top) and the mine portal (bottom)

Excursion to the Cuiabá Gold Mine, Minas Gerais, Brazil

By Frederico Wallace Reis Vieira, Mário Corbani Filho, Jose Teotonio de Faria Fonseca, Aguinaldo Pereira, Geraldo Antônio Ibrahim de Oliveira, *and* Paschoal Luiz Caiafa Clemente[1]

ABSTRACT

The Cuiabá gold mine, in the northeast part of the Quadrilátero Ferrífero, is a banded iron-formation deposit in the Archean Nova Lima Group. Most of the gold occurs in pyritic orebodies that are stratiform and stratabound in banded iron-formation sulfide-facies rocks. The main structure at the Cuiabá mine is an east-west-trending anticline produced during the second of four deformational events recorded in the Archean rocks.

INTRODUCTION

The Cuiabá Mine is 5.5 km (kilometer) east of Sabará, beneath the town of Cuiabá, which is southeast of the Serra da Piedade in the northeast part of the Quadrilátero Ferrífero (fig. 1). Access is from Belo Horizonte on Highway MG–05, which connects Belo Horizonte to Caeté; the mine is situated between Sabará and Caeté and is finally reached by a private unpaved road.

The first work in the area was undertaken in 1740 by garimpeiros (prospectors). The mine was acquired by the St. John Del Rey Mining Co. Ltd. in 1877 and was operated intermittently for the next 100 years; Mineração Morro Velho resumed development in 1977 and began mining in 1985. As of 1986, Cuiabá had the largest reserves of all the gold mines owned by Mineração Morro Velho.

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REGIONAL GEOLOGY

The Quadrilátero Ferrífero is underlain by a sequence of Archean metasedimentary and metavolcanic rocks of the Rio das Velhas Supergroup, which is in turn overlain by the Proterozoic Minas Supergroup and the Itacolomi Group of Dorr (1969). This upper Archean and Proterozoic sequence rests on and is bounded by a gneissic and migmatitic Archean complex, widely remobilized during the Brazilian cycle (550–600 Ga). The mine is within the Serra de Piedade quadrangle, the geology of which was mapped by Benedito P. Alves (in Dorr, 1969). The geology of the Quadrilátero Ferrífero was compiled and synthesized by Dorr (1969). Figure 2 shows a generalized stratigraphic column for the Quadrilátero Ferrífero. For an overview of the geology of the Quadrilátero Ferrífero, the reader is referred to Ladeira and Viveiros (this volume, Part B—Geology of deposits). The Rio das Velhas Supergroup comprises a typical greenstone belt sequence that Schorscher (in Schobbenhaus and others, 1984) has divided into three groups, from bottom to top:

1. Quebra Osso Group—Ultramafic and mafic volcanic rocks of komatiitic character with intercalations of BIF (banded iron formation). Thorman and Ladeira (Part–A, Excursions, this volume, p. A14) assign these rocks to the Nova Lima Group, as shown in figure 2.
2. Nova Lima Group—Metapelites, metavolcanics and BIF.
3. Maquiné Group—Quartzites, conglomerates and phyllites (divided into two formations: Palmital and Casa Forte).

The Nova Lima Group, which is the major host for the BIF-related gold deposits in the region, has been divided by Mineração Morro Velho geologists into three units. Most of the Cuiabá ore is near the top of the lower unit of the Nova Lima Group.

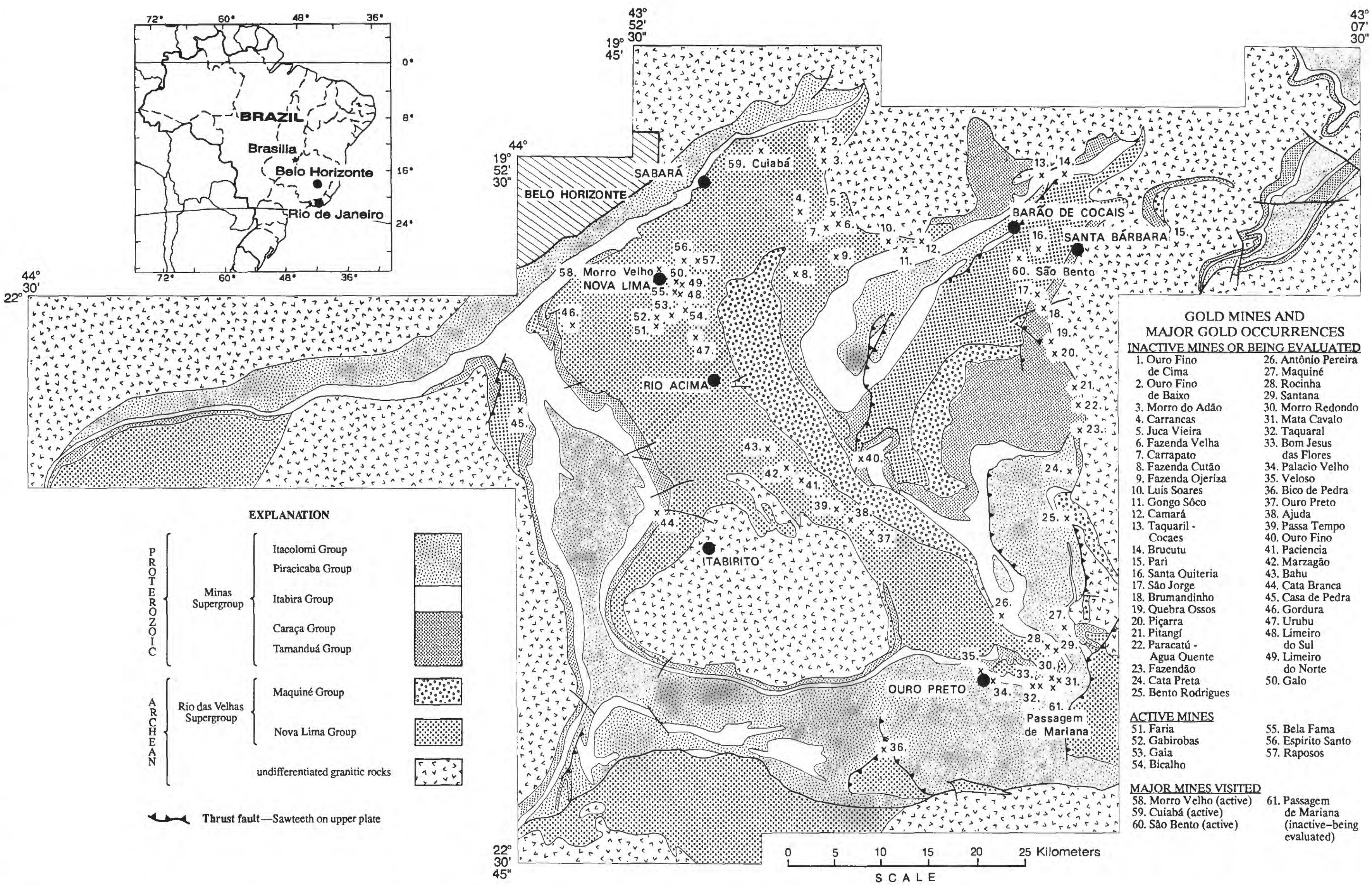


Figure 1. Geologic map of the Quadrilátero Ferrífero (modified from Dorr, 1969) showing the location of the Cuiabá gold mine, other major gold mines visited, and other gold mines and occurrences in the area.

Era	Supergroup	Group	Formation
	PROFOUND OROGENY WITH REGIONAL METAMORPHISM		
		Itacolomi Group	
PROTEROZOIC	PROFOUND ANGULAR UNCONFORMITY		
	Minas Supergroup	Piracicaba Group	Sabará Formation Barreiro Formation Taboões Formation Fêcho do Funil Formation Cercadinho Formation
		Itabira Group	Gandarela Formation Cauê Itabirite
		Caraça Group	Batatal Formation Moeda Formation
		Tamanduá Group	
	MAJOR OROGENY WITH REGIONAL METAMORPHISM		
ARCHEAN	Rio das Velhas Supergroup	Maquiné Group	Casa Forte Formation Palmital Formation
		Nova Lima Group	Upper unit* Middle unit* (includes Lapa Seca Formation) Lower unit*
	CONTACT CONSIDERED INTRUSIVE BY DORR (1969)		
	Granitic-gneissic basement rocks, including granitoids of various ages		

Figure 2. Generalized stratigraphic column of Precambrian rocks of the Quadrilátero Ferrífero (modified from Dorr, 1969). Asterisk (*) indicates units not included in Dorr's paper but discussed by Thorman and Ladeira in the introductory chapter of the volume, Part A—Excursions. The granitic-gneissic basement unit includes several informal units, including the Bação Complex or Bação Granitic Complex, which is the oval basement body in the south-central part of figure 1.

CUIABÁ MINE GEOLOGY

Stratigraphy

The mine workings intersect the Lower, Middle, and Upper Units of the Nova Lima Group; the orebodies are near the top of the Lower Unit. The Lower Unit in the mine includes meta-andesites (man and manx) with intercalations of metapelites (x_1 and fg). (See following paragraphs for explanation of symbols.) Overlapping the andesite sequence are metapelites (x_1) with interlayers of metarhyodacitic tuffs (x_2). A BIF bed, 5–15 m (meter) thick, is at the top of this unit. The overlying Middle Unit includes metarhyodacitic tuff (x_2) with intercalations of metapelite (fg); a metabasalt (mba) flow is close to the top. The Upper Unit is characterized by intercalated metapelites (x_1) and metarhyolitic tuffs (x_5).

Lithologic Units

The Nova Lima Group rocks in the Cuiabá mine area show evidence of having been metamorphosed during at least two episodes of chlorite-zone greenschist-facies metamorphism. Nine major lithologies are recognized in the mine and are described here. The letters in parentheses at the beginning of each description correspond to units on the geologic map of level 3 (fig. 3)

(mba) Moderately schistose, dark green metabasalt(?) with pillow structures, composed of actinolite, epidote, chlorite, carbonate, titanite, and laths of plagioclase with fine diabasic texture. Probably a metabasalt; possibly a meta-andesite.

(clx) Phyllitic bottle-green metabasalt(?) composed of chlorite, carbonate, and quartz with sericite and tourmaline; has lenticular shape; associated with BIF.

(man) Light green massive meta-andesite, locally with pillow structures and amygdules, composed of epidote, quartz, chlorite, tremolite, actinolite, and carbonate, with randomly oriented laths and phenocrysts of andesine.

(manx) Schistose to phyllitic dark green and gray meta-andesite composed of chlorite, quartz, and carbonate with some epidote; contains randomly oriented laths and phenocrysts of andesine. The protolith was andesite that was erupted into, and subsequently interacted with, sea water and was later modified by hydrothermal solutions.

(x_2) Beige phyllitic metarhyodacitic tuff composed of carbonate, sericite, and quartz with laths of andesine. The rock appears to have been carbonatized by hydrothermal solutions during or before metamorphism.

(x_S) Light grey phyllitic metarhyolite tuff composed of quartz, sericite, chlorite, and carbonate with relict volcanic quartz and plagioclase; contains minor amounts of graphite; typically has a rough and wrinkled parting plane and is locally distinctly layered.

(x_1) Dark grey phyllite composed of quartz, carbonate, and sericite with chlorite and graphite; thinly layered metapelite with acidic volcanic contribution.

(fg) Black graphitic phyllite with sericite, quartz and carbonate; thin layers of quartz, carbonate and sulfides; interpreted to be a metapelite.

(BIF) Carbonate and sulfide facies banded iron formation in equal proportion; carbonate and sulfide facies rocks are distinctly laminated on a millimeter to centimeter scale; quartz (chert) and carbonate beds dominate in carbonate facies; rocks are generally light colored in carbonate facies, but become dark gray where graphite is present.

Structural Geology

Rocks at the Cuiabá gold mine were deformed during four events. The first event is indicated by a relict schistosity (S_1) parallel to the bedding; this schistosity may include transposed isoclinal folds, but such folds have not been identified in the mine area. The second event is represented by anisotropic isoclinal folds with a prominent foliation (S_2) and lineation (L_2). Intense transposition along the schistosity caused segmentation and thrusting of fold structures. Shear zones along the foliation are characterized by swarms of quartz boudins. S_2 trends N. 55°–70° E. and dips 40° SE., and L_2 trends S. 60°–70° E. and plunges 32°–34°. The third event is identified by lineation (L_3) subparallel to L_1 and L_2 and is poorly represented in the area. The fourth event is represented by gentle folds whose axes trend S. 12° E. and plunge 17°. Fracture cleavage or transposition cleavage has an attitude of about N–S/65° E. The shear zones are parallel to cleavage and are characterized by sigmoidal structures.

The main structure at the Cuiabá mine is an east-west-trending anticline (fig. 3) produced during the second deformational event. The inverted north flank of the anticline was strangled and broken during folding. The strangled area (Galinheiro Extensão) is characterized by tight folds associated with thrusts and shearing along S_2.

All the structures can be projected at depth along L_2, with minor deflections caused by interference effects from the subparallel fold axes of events 1, 2, and 3. The L_2 plunge tends to flatten at depth due to refolding during the fourth deformational event.

Economic Geology

Most of the gold in the Cuiabá mine occurs in pyritic orebodies in the BIF sulfide facies. Thirteen orebodies are recognized and include Balanção Leste, Centro, and Oeste; Galinheiro, Galinheiro Sul, and Galinheiro Extensão; Surucucu Leste and Oeste; Serrotinho; Fonte Grande and Fonte Grande Sul; Viana; and Canta Galo. The area of these orebodies totals 5,067 m^2 (square meter) in level 3. The rocks in the sulfide orebodies are banded or homogeneous, are distinctly laminated and strongly deformed, and are locally separated by faults. The sulfide orebodies are stratiform and stratabound in BIF near the top of the Lower Unit. They are interpreted to have emanated from volcanoes, and they were reconcentrated and recrystallized in the D_2 hinge zones during regional metamorphism. Some gold is stratigraphically higher in basalt-hosted quartz veins and in the alteration zones associated with the veins, such as in the Viana orebody. Many fractures commonly crosscut the Serrotinho orebody.

Pyrite is the principal sulfide, followed by arsenopyrite and pyrrhotite. The pyrite is idioblastic to xenoblastic and ranges in size from 0.02 to 15 mm (millimeter). Arsenopyrite is idioblastic and ranges in size from 0.009 to 3.55 mm. White pyrrhotite ranges in size from 0.02 to 2.8 mm. Accessory minerals include sphalerite, chalcopyrite, magnetite, marcasite, and rutile. The fine-grained sulfide minerals are finely banded and appear to be syngenetic, but the coarser ones are clearly later and most likely formed during subsequent events.

Gold is less than 60 microns in size and on average the Au:Ag ratio is 6:1. The gold is both within sulfide grains and along grain boundaries and is most commonly associated with pyrite, arsenopyrite, and pyrrhotite. Some free gold is associated with milky or smoky quartz orebodies (Viana orebody) along S_2 and surrounded by a recrystallized, carbonatized, and chloritized zone.

LOG OF THE EXCURSION

The excursion was to level 3 of the mine, where the lithotypes and structural features were emphasized, as well as the different aspects of mineralization. See figure 3 for location of the stops in the mine.

STOP 1.

(x_s) Quartz-sericite-chlorite-carbonate phyllite with phenocrysts of volcanic quartz (metarhyolitic tuff). (x_1) Well-bedded quartz-carbonated sericite phyllite with chlorite (metapelite).

STOP 2.

(man) Light-green massive meta-andesite.

(manx) Dark-green schistose meta-andesite.

STOP 3.

(mba) Moderately schistose dark-green metabasalt.

STOP 4.

(mba) Metabasalt with pillow structures that have dark-green coarse-grained nuclei and light-green fine-grained borders (chilled contact). The material between the pillows is chlorite-rich.

STOP 5.

Viana orebody sub-level. Milky or smoky quartz with free gold, enclosed by a zone of sericitization, chloritization, and carbonatization.

Mining area: 90.2 m^2; ore grade 4.70 g/t (gram per ton)(in situ)
Plunge S. 50° E./34°

STOP 6.

Mining area: Serrotinho orebody
Banded sulfide
Plunges S. 58° E/30°
Mining method: Cut and fill
Mining area: 1,117 m^2
Grade: 5.18 g/t (in situ)

STOP 7.

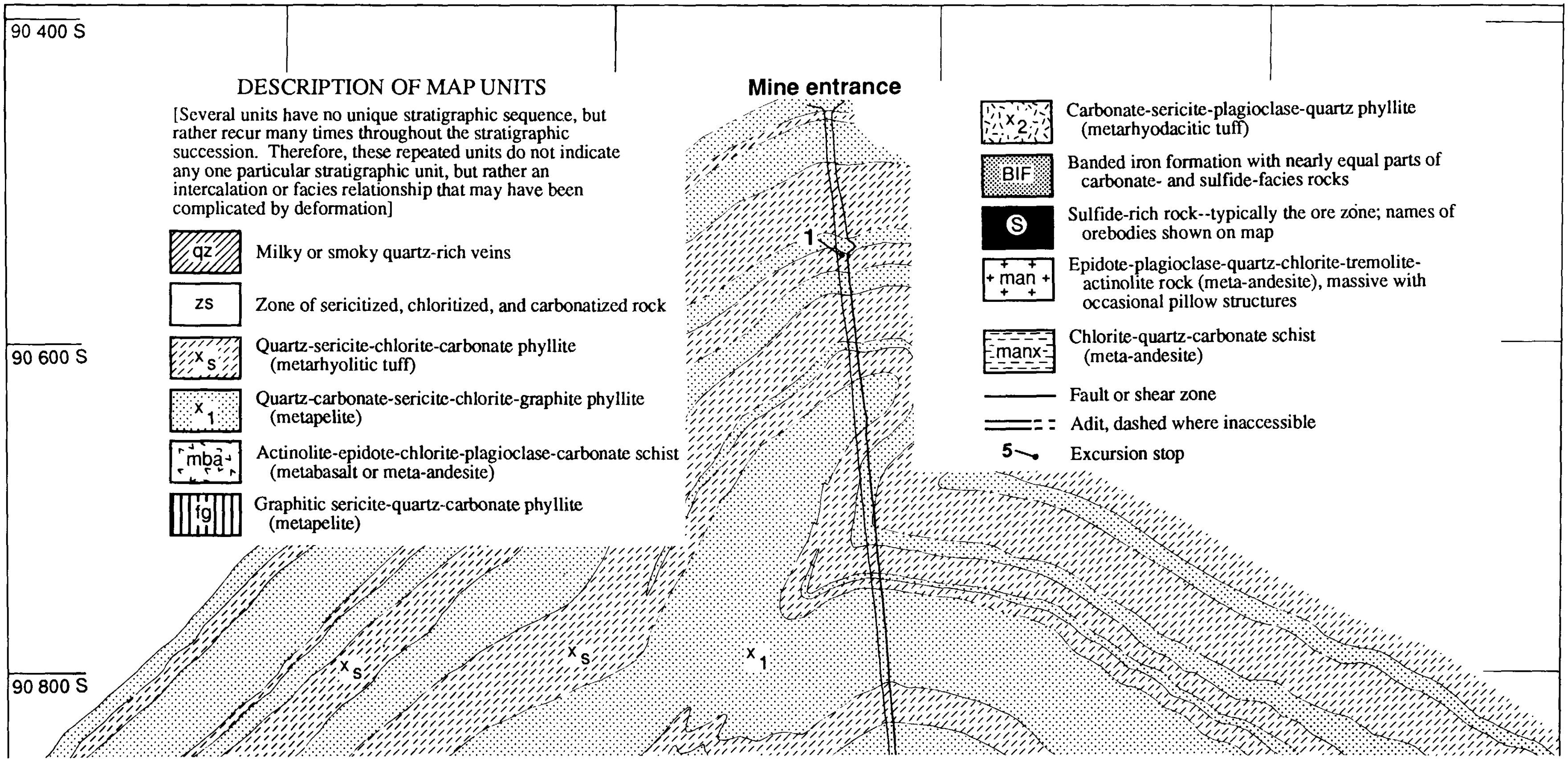
Folds of the fourth deformational event with transposition cleavage or fracture cleavage in schistose meta-andesite.

STOP 8.

Brecciated BIF in fault zone of the second deformational event.

STOP 9.

Shear zone of the second event with quartz boudins in graphitic phyllite (fg).


90 400 S
90 600 S
90 800 S
Mine entrance
1
xs
xs
x1
DESCRIPTION OF MAP UNITS
[Several units have no unique stratigraphic sequence, but rather recur many times throughout the stratigraphic succession. Therefore, these repeated units do not indicate any one particular stratigraphic unit, but rather an intercalation or facies relationship that may have been complicated by deformation]
qz Milky or smoky quartz-rich veins
zs Zone of sericitized, chloritized, and carbonatized rock
xs Quartz-sericite-chlorite-carbonate phyllite (metarhyolitic tuff)
x1 Quartz-carbonate-sericite-chlorite-graphite phyllite (metapelite)
mba Actinolite-epidote-chlorite-plagioclase-carbonate schist (metabasalt or meta-andesite)
fg Graphitic sericite-quartz-carbonate phyllite (metapelite)
x2 Carbonate-sericite-plagioclase-quartz phyllite (metarhyodacitic tuff)
BIF Banded iron formation with nearly equal parts of carbonate- and sulfide-facies rocks
S Sulfide-rich rock--typically the ore zone; names of orebodies shown on map
man Epidote-plagioclase-quartz-chlorite-tremolite-actinolite rock (meta-andesite), massive with occasional pillow structures
manx Chlorite-quartz-carbonate schist (meta-andesite)
Fault or shear zone
Adit, dashed where inaccessible
5 Excursion stop

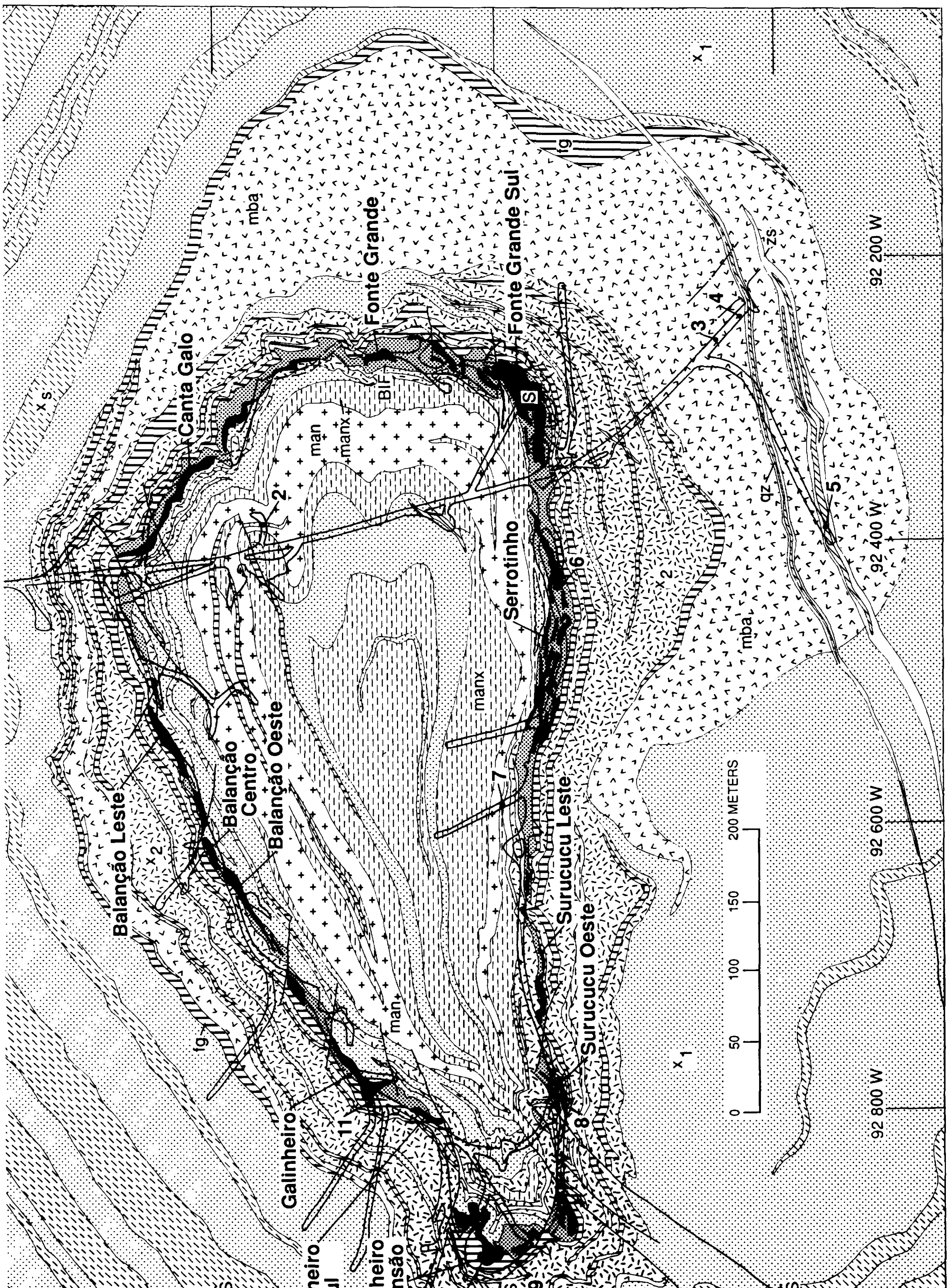


Figure 3. Geologic map of level 3 in the Cuiabá gold mine showing the excursion stops and main orebodies.

STOP 10.

Mining area: Galinheiro Extensão orebody
Massive sulfide
Plunge S. 56° E./33°
Mining method: Cut and fill
Mining area: 538.2 m^2
Grade: 13.50 g/t (in situ)

STOP 11.

Shear zone of the fourth deformational event with sigmoidal structure in graphitic phyllite (fg). x_2 – carbonate-sericite-quartz phyllite, beige; carbonatized metarhyodacitic tuff.

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