Revista Brasileira de Geociências 28(3):339-354, setembro de 1998

# STYLES OF HYDROTHERMAL ALTERATION AND GOLD MINERALIZATIONS ASSOCIATED WITH THE NOVA LIMA GROUP OF THE QUADRILÁTERO FERRÍFERO: PART I, DESCRIPTION OF SELECTED GOLD DEPOSITS

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**RESUMO** *ESTILOS DE ALTERAÇÃO HIDROTERMAL E MINERALIZAÇÕES A URÍFERAS ASSOCIADAS AO GRUPO NOVA LIMA DO QUADRILÁTERO FERRÍFERO: PARTE I, DESCRIÇÃO DE DEPÓSITOS SELECIONADOS* Três principais estilos de mineralização são reconhecidos em depósitos mesotermais filoneanos de ouro associados a rochas do Grupo Nova Lima, *Greenstone Belt* arqueano Rio das Velhas, no Quadrilátero Ferrífero, Minas Gerais, Brasil. Constituem 1) zonas sulfetadas, e estruturalmente controladas, de substituição em formação ferrífera bandada fácies oxido e carbonato; 2) sulfetos disseminados em zonas de alteração hidrotermal em encaixantes cisalhadas, sejam essas rochas vulcânicas metamáficas ou metassedimentares; e 3) veios de quartzo com carbonates e sulfetos. Esses estilos refletem variações na interação fluido-rocha e, assim, composições mineralógicas distintas no minério. Associações mineralógicas distintas também caracterizam padrões zonais da alteração hidrotermal nos envelopes dos corpos de minério. Estudos de det alhe nas minas de Cuiabá, Jucá Vieira, Raposos, Santana e São Bento indicam que, assim como em muitos outros depósitos similares no mundo, os processos responsáveis pela deposição do minério são os mesmos que dão lugar à geração de associações de alteração hidrotermal. A alteração hidrotermal superpõe-se às paragêneses metamórficas e é, de forma geral, dominada por zonas de desenvolvimento de clorita, carbonato e mica branca nas proximidades do minério. Sulfetação e silicificação são abundantes nas duas últimas zonas mais internas e de composição mineralógica tipicamente simples. Essas características sugerem que, com o aumento da alteração hidrotermal, houve variações na razão $H_2O:CO_2$, de fluido mineralizante aquo-carbônico, rico em enxofre, e razões variadas na interação fluido-rocha.

*Palavras-chave:* ouro, Quadrilátero Ferrífero, alteração hidrotermal

**ABSTRACT** Three main mineralization styles are recognized in a number of mesothermal, lode-gold deposits associated with rocks of the Nova Lima Group, Rio das Velhas Archean Greenstone Belt, Quadrilátero Ferrífero, Minas Gerais, Brazil. They comprise 1) structurally controlled, sulfide-replacement zones in metamorphosed oxide- and carbonate-facies BIF; 2) shear-related, disseminated sulfides in nydrothermal alteration zones within metamorphosed mafic volcanic- or sedimentary rocks; and 3) Auríferous quartz-carbonate-sulfide veins and veinlet systems. These styles reflect variations in fluid to rock interaction, and thereby a distinctive ore mineral compoSítion. In addition, distinctive mineral associations characterize hydrothermal alteration zonal patterns around orebodies. Det alled investigations in Cuiabá, Juca Vieira, Raposos, Santana and São Bento mines indicate that, as is the case with other similar deposits worldwide, the processes of ore depoSítion are the same processes that give rise to the alteration assemblages. Hydrothermal alteration overprints metamorphic assemblages, and is overall dominated by zones of chlorite, carbonate and white mica development in proximity to ore. Sulfidation and silicification abound in the latter two, minerallogically simple, inner alteration zones. These characteristics suggest variations in the $H_2O$ to $CO_2$-ratio of the sulfur-bearing, aqueous-carbonic ore fluid and interaction at varying fluid to rock ratios with the progression of hydrothermal alteration.

*Keywords:* gold, Quadril&ero Ferrífero, hydrothermal alteration

**INTRODUCTION** Hydrothermal ore deposits form when a hot, aqueous solution - a hydrothermal solution - flows through a defined channel in the crust (an ore trap), or over a restricted portion of the surface of the crust, and precipitates a localized mass of minerals from its dissolved load (Skinner 1997).

Hydrothermal alteration is a chemical replacement of the original minerals in a rock by new minerals via interaction with a hydrothermal fluid. The fluid delivers chemical reactants to the rock and removes aqueous reaction products. It is a function of variations in temperature (T), pressure (P) and, most importantly, fluid compoSítion (Reed 1997, Rose and Burt 1979). Hydrothermal alteration is a major factor in the precipitation of many ores, and provides insights into the chemical attributes and origins of ore fluids and the physical conditions of ore formation (Reed 1997).

The processes of ore depoSítion are generally the same processes that give rise to alteration assemblages (Susak 1994). Hydrothermal alteration zones surrounding hydrothermal ore systems (e. g., veins) are very common. Common zonal patterns reflect changes in the compoSítion of the fluid with time or extent of reaction with rock (Meyer and Hemley 1967). They are therefore manifestations of the extent to which the original wallrocks were out of chemical equilibrium with the fluids that were traversing them (Lindgren 1895 and Knopf 1929, *in* William-Jones *et al.* 1994).

Important questions concerning the study of hydrothermal ore deposits are the investigation about the physical and chemical characteristics of the ore-forming fluid, the mechanisms for dissolving and transporting ore-forming components, and the causes of precipitation from the fluid (Skinner 1997).

Just how hydrothermal solutions form, flow and react are the most commonly addressed topics. This paper is concerned with the mineral transformations and chemical changes taking place between a moving solution and rocks lining channel-ways, and their implication for the precipitation of gold. To meet this purpose the alteration and mineralization styles of a number of mesothermal gold deposits in the Quadrilátero Ferrífero (QF) region (Figure 1) of the State of Minas Gerais, Brazil, are described. These are used to review this much-debated topic worldwide (de Ronde *et al.* 1997, Herrington *et al.* 1997, Lobato and Vieira, 1998, the present volume).

Vieira (1987a, b) was one of the pioneers in det alling mineral assemblages associated with the hydrothermal alteration affecting rocks of the Archean Rio das Velhas Greenstone Belt, hosting mesothermal, lode-gold deposits in the QF. Other thorough contributions are Vieira (1988,199la) and Vieira and Simões (1992). Textural, mineralogical and chemical relationships are also addressed by e.g. Ladeira (1980), Souza Filho (1991), Duarte (1991), Godoy (1994), Godoy (1995), Martins Pereira (1995), Pereira (1996), Junqueira (1997), Toledo (1997), Borba (1998), Menezes (1998), Ribeiro-Rodrigues (1998). These contributions served as the motivation for the present attempt to review and integrate the dispersed data into a single, coherent unit.

**GEOLOGICAL SETTING OF THE QUADRILÁTERO FERRIFERO** The QuadriWtero Ferrífero (QF) is located in the southernmost São Francisco Cráton (Almeida 1967, Almeida and Hasui 1984) in southeastern Brazil (Figure 1). The São Francisco Cráton is limited by Brasíliano-age (700-450 Ma) mobile belts, and is constituted by a basement consolidated during the Archean and Eoproterozoic. The geological units of the QF embody 1) granite-gneissic terranes of Archean age; 2) Archean greenstone belts of the Rio das Velhas Supergroup and other related successions; and 3) Eo- and Mesoproterozoic, metasedimentary units of the Minas Supergroup, the Itacolomi Group and the Espinhafo Supergroup (Dorr 1969, Noce 1995 and Noce *et al.* 1996, and references therein). The latter is exposed in the northeastern portion of the QF, and is composed of metaconglomerates, metarenites and metamafic rocks. Toledo (1997) and Zucchetti (1998) provide more recent, excellent reviews of the present knowl-

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**Rio das Velhas Supergroup** Dorr *et al.* (1957) subdivided the Rio das Velhas Supergroup in the Nova Lima and Maquine Groups. There is no widely accepted stratigraphy for the Nova Lima Group as a whole, because of intense deformation, hydrothermal alteration and weathering, notwithstanding the lack of det alled, published geological cartography in various parts (Dorr 1969, Ladeira 1980, Oliveira *et al.* 1983, Belo de Oliveira 1986, Vieira and Oliveira 1988, Pinto *et al.* 1996).

Schrank and Silva (1993) have recently revised the geology of the basal metavolcanosedimentary Nova Lima Group. It hosts a large number of gold deposits (see Ladeira 1991) and comprises volcanic, chemical and clastic sedimentary rocks. The metamorphosed mafic-ultramafic volcanic rocks embody komatiite and tholeiitic basalt (e.g. Schorscher 1978, Schorscher *et al.* 1982, and Noce *et al.* 1990). Volcaniclastic rocks and minor felsic volcanic rocks are also present (e.g. Ladeira 1980, 1981, Oliveira *et al.* 1983, Vial *et al.* 1987, and Noce *et al.* 1992). Chlorite phyllite, banded iron formation (BIF), greywacke, quartzite and conglomerate comprise the clastic and chemical metasedimentary rocks in the region (Dorr 1969, Ladeira 1980). Turbidites of mafic to felsic compoSítions are also important (Schrank and Silva 1993).

The sequence displays mineral associations typical of the greenschist metamorphic facies. Herz (1978) indicates that the regional metamorphic grade increases eastward from lower greenschist to lower amphibolite facies. Contact metamorphic aureoles are present around mafic dikes that crosscut the lithological package. The metamorphic associations are modified by hydrothermalism in proximity to gold deposits, with the development of concentric, locally symmetric, sericite, carbonate, chlorite alteration zones away from the ore.

The Maquine Group overlies the Nova Lima rocks. It occurs in the central-eastern portion of the QF, and is subdivided into the Palmital and Casa Forte Formations. It comprises quartzite, conglomerate and lesser phyllite and greywacke (Dorr 1969).

The stratigraphic reconstitution of the Rio das Velhas Greenstone Belt indicates a 3:2 ratio of sedimentary to igneous rocks, and a 1:5 ratio of intrusive to volcanic rocks. Komatiite represents less than 15% of the volcanic succession, which is dominated in aerial extent by rocks of mafic and ultramafic compoSítions (Baars 1997).

**Minas Supergroup** The Minas Supergroup is an Eoproterozoic, complexly infolded, continental-margin sequence, long-known for its economic, Lake-Superior-type banded ironstone formations (BIFs), the original itabirites.

The Supergroup is divided by Dorr (1969) into the basal, clastic Caraga Group, the intermediate, chemical metasedimentary Itabira Group, the upper, clastic Piracicaba Group metapelites and metatuffs of the Sabar3 Group.. The basal unit is composed of quartzite, intercalated with phyllite and metaconglomerate, and separated by an erosional unconformity over which the chemical and biochemical Itabira Group metasedimentary rocks occur. These are predominantly quartz or dolomite, and rarely amphibole BIF, with ferruginous phyllite and metadolostone. The Piracicaba Group has quartzite, phyllite and metadolostone lenses. Chlorite schist, phyllite, metagreywacke, metatuff, metaconglomerate, quartzite and rare itabirite occur at the top (Noce 1995).

**Tectonic Evolution and Geochronology** The QF lies in the tranSítion between the São Francisco Cráton, to the west, and the Aracuai and Alto Rio Grande Mobile Belts to the east and southeast (see Alkmim *et al.* 1993). This tranSítional boundary transects the eastern portion of the QF along N-S, east-dipping thrust faults that affect the Rio das Velhas and Minas Supergroups. These faults are part of the Cambotas-Fundao System described by Chemale *et al.* (1994). The main structures in the QF, its great structural complexity and polycyclic tectonic evolution are discussed in the works by Dorr (1969), Ladeira (1980), Ladeira and Viveiros (1984), Belo de Oliveira (1986), Belo de Oliveira and Vieira(1987), Vieira and Oliveira (1988), Marshak and Alkmim (1989), Belo de Oliveira and Teixeira (1990), Chauvet *et al.* (1994), Chemale Jr. *et al.* (1994), and Correa Neto and Baltazar (1995), Endo (1997), Marshak and Alkmim (1998), among others.

In general terms, the QF is characterized by large-scale fold structures interpreted by Dorr (1969) as polyphase overturned folds and by Ladeira and Viveiros (1984) as overturned synclines. Endo (1997) and Toledo (1997) offers an excellent review of the structural geology of the QF.

The Rio das Velhas and Minas Supergroups are thrust-stacked to the west. Vieira and Oliveira (1988) describe four deformation phases $D_1$, $D_2$, $D_3$ and $D_4$, adopted in the present paper. Marshak and Alkmim (1989) also indicate four phases of deformation. Other studies in the region have variously proposed one (Belo de Oliveira and Vieira 1987), two (Guimaraes 1931), three (Dorr 1969) and six (Ladeira and Viveiros 1984) deformation phases. More recent works (Marshak *et al.* 1992, Chauvet *et al.* 1994, Chemale *et al.* 1994, Correa-Neto and Baltazar 1995) re-evaluate this ever-controversial topic.

$D_1$ is characterized by the schistosity $S_t$ that is parallel to bedding. Large-scale, ductile shear zones are parallel to $S_1$ and are well preserved in BIF. $D_2$ is characterized by an axial planar foliation ($S_2$) that obliterates S, and is associated with W-vergent thrusts. Fold axes for both $D_1$ and $D_2$ are parallel to the stretching lineation. In zones of gold mineralization, $D_1$ and $D_2$ lineations are parallel and dip to the east.

$D_3$ is localized, and is characterized by an NS-striking, E-dipping, spaced cleavage, a crenulation lineation and fold axes nearly orthogonal to $L_2$. Vieira and Simões (1992) interpret $D_3$ as resulting from $D_2$ progressive evolution. $D_4$ displays fractures that may represent another deformation phase.

Taking into consideration new and published geochronological data, Noce (1995), Noce *et al.* (1996) and Baars (1997) review the geological evolution of the QF.

A continental nucleus dates at least as far back as 3380 Ma (Machado and Carneiro 1992), although 3500-2857 Ga detrital zircons suggest even older continental precursors (Schrank and Machado 1996). The main period of crustal accretion seems to have occurred around 3000-2900 Ma. Baars (1997) reports Sm-Nd and Rb-Sr errochron alignments of rocks possibly of the same greenstone association, including comagmatically differentiated metakomatiites (Seixas 1988), at 3.19 and 3.22 Ga. Detrital zircons with ages between 3.0 and 3.54 Ga have been detected in various QF metasedimentary rocks *(Machado et al.* 1993,1996).

The Rio das Velhas Event as proposed by Carneiro (1992) had an initial phase *ca.* 2780-2770 Ma, with the formation of the Nova Lima Group and emplacement of associated granitoids; a final phase of younger granite generation occurred between 2720-2700 Ma and at *ca.* 2600 Ma.

The original Archean architecture of the Rio das Velhas greenstone belt has been largely obliterated by subsequent tectonic histories. These encompass the platformal sedimentation of the 2.6 to 2.1 Ga (Babinski *et al.* 1991, Machado and Noce 1993, Renger *et al.* 1994) Minas Supergroup.

Between 2.15 and 1.8 Ga, the region was involved in the Transamazonian Event. The Brasíliano, Crátonward, thin-skinned tectonism is devoid of firm geochronological evidence, although lower concordia intercepts of U-Pb zircon analyses corroborate Teixeira's (1985) suggestion of partial rehomogenization around 600 Ma, based on Rb-Sr and K-Ar data.

## THE NOVA LIMA GROUP ROCKS HOSTING GOLD DEPOSITS

Brief descriptions of metavolcanic and metasedimentary rocks are taken from the publications by Vieira (1987a) and (Vieira and Oliveira 1988). They cover rock types commonly hosting gold deposits associated with the Nova Lima Group.

Host rock descriptions can also be found in various other works on gold mineralizations in the QF. We citet albert (1964; Raposos Mine) Ladeira (1980; Morro Velho Mine); Duarte (1991; Passagem de Mariana Mine), Souza Filho (1991; Carrapato Mines); Godoy (1994) and Junqueira (1997; Raposos Mine); Abreu (1995; Pari Mine); Pereira (1996; Juca Vieira Mine); Martins Pereira (1996) and Godoy (1995; São Bento Mine); Ribeiro-Rodrigues (1998) and Toledo (1997; Cuiabá Mine); Borba (1998; Bico de Pedra Mine); Ribeiro 1998; Antônio Pereira deposits); Cavalcanti (1999; Lages-Antônio Dias); Galbiatti (1999; Caue Mine); Passos (1999; Brumal Mine), amongst others that have also published on the subject. Most also present studies of whole-rock, major and trace element variations. Vieira (1991 a) published rock geochemical investigation for the Morro Velho, Faria, Cuiabá, Raposos (also Vieira 1987a), Bela Fama, Morro da Glória, Paciência and Juca Vieira mines.

**Metavolcanic Rocks** Ultramafic rocks at the base of the Nova Lima sequence are intercalated with more abundant, mafic rocks. Tholeiitic metabasalt occurs, in places, as pillowed flows, and displays varioles with preserved subophitic textures. Komatiitic basalt can exhibit original pyroxene spinifex texture imposed by actinolite laths in a fine matrix. The mafic rocks are composed of actinolite, albite, epidote and/or clinozoisite, chlorite, titanite and quartz. The precursor plagioclase is completely albitized but preserves some textural char-

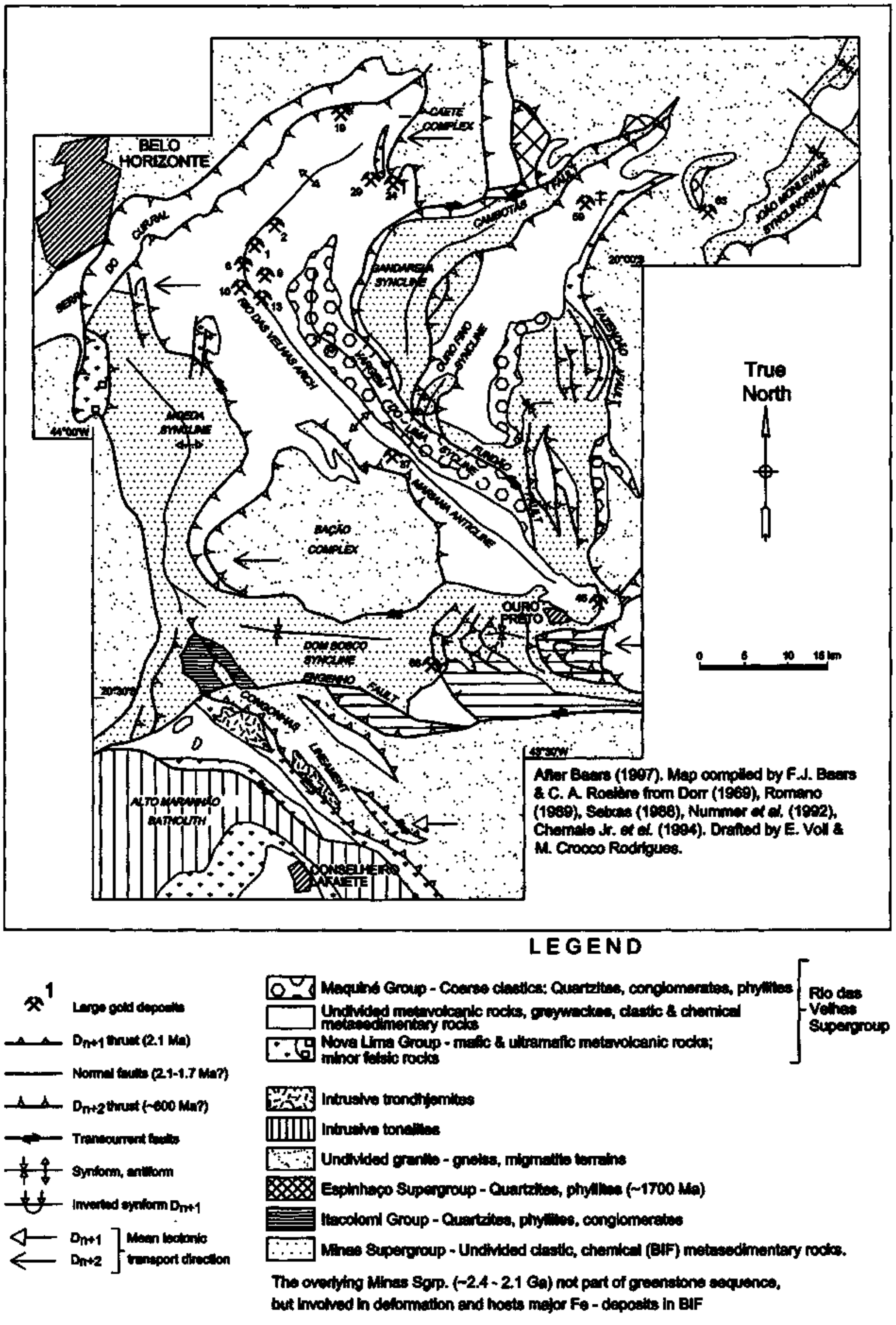


*Figure 1 - Simplified geological map of the Quadrilátero Ferrífero region showing selected gold deposits: 6 - Bela Fama, 9 - Bicalho, 66 - Bico de Pedra, 19 - Cuiabá, 10 - Faria, 24 - Juca Vieira, 13 - Morro da Glória, 1 - Mono Velho, 37 - Paciência, 63 - Pari, 2 - Raposos, 46 - Santana, 59 - São Bento, 29 - Tinguá. Numbering according to Ladeira (1991, Fig. 1).*

acteristics. Mafic intrusive rocks, comprising diabase and locally gabbro, form NE-striking dikes parallel to $S_2$.

Highly modified peridotite exhibits pseudomorphed olivine (antigorite), at places with talc and magnetite along fractures. Pseudomorphs of pyroxene in pyroxenite are made of tremolite, antigorite, some Mg-chlorite and magnetite, in a fine-grained, Mg-chlorite matrix.

Vieira (1991b), Pereira (1996) and Junqueira (1997) conclude that the metamafic rocks have tholeiitic basalt compoSítion; a Kamatiitic component is also indicated by Vieira (1991b). Since they show close similarities to Condie's (1981) Archean tholeiitic basalt TH2 and subordinately to TH1, they have been correlated with modern, calc-alkaline, island arc, tholeiitic basalt and to mid-ocean ridge basalt (MORE). Ladeira (1988) also recognizes a MORB-type signature.

Zucchetti (1998) undertook a det alled petrographic and whole-rock, major and trace-element variations study of metabasaltic rocks, devoid of alteration, away from gold mineralization sites and collected in various locations in the QF. The author identifies two main families, one that is Mg-rich, plume-MORB tholeiitic basalt, and another composed of mostly differentiated terms evolved from compoSítions like those of the Mg-rich tholeiitic basalt.

As pointed out by de Wit and Ashwal (1995), individual greenstone belts may be dominated by one type of mafic clan *(i.e.* calc-alkaline- or MORB-affinity) or, as is being increasingly recognized, several volcano-tectonic fields can be distinguished within the same greenstone belt. This now appears to be the case in the QF, where carefully controlled cartography is required to display the distribution of these fields in the Nova Lima Group.

Breccia and lapilli tuffs of andesitic compoSítion occur above the mafic sequence. They form 10 m-thick, volcanic cycles that begin with centimetric, angular, coarse fragments with a low-matrix percentage, characterizing a volcanic breccia. To the top of the volcanic cycles the fragments are smaller, the matrix is more abundant and the breccia grades into lapilli-tuff to tuff. They are essentially composed of plagioclase suggesting an andesitic compoSítion.

Felsic tuff occurs in thin, continuous horizons alternating with metapelitic rocks. Their contact with the latter is gradational, indicating a significant sedimentary contribution. The tuff is composed of quartz, sericite and carbonate. Cycles that display gradational bedding are, on average, one meter thick. Fragments are mainly millimeter-sized phenocrysts of quartz, plagioclase, and in places of rock fragments ranging from dacitic to rhyodacitic compoSítion. Quartz phenocrysts either are rounded or exhibit bipyramidal shapes. Plagioclase fragments are rare; they are angular and occur with bipyramidal quartz.

**Metasedimentary Rocks** Gradational bedding indicates the sedimentary origin of carbonate-metapelitic rocks, with quartz-carbonate bands at the base grading to sericite-carbonate bands at the top. Quartz-carbonate bands have quartz and plagioclase clasts at the base, together with abundant carbonate.

Although generically referred to as graphite schist, this dark rock is better classified as carbonaceous phyllite. It contains sericite and quartz, and occurs at the top of BIF layers or between basaltic flows.

Continuous, centimetric to metric BIF marks the top of basaltic flows. It displays a millimeter- to centimeter-thick banding with alternating polygonal quartz grains and Fe-bearing minerals, like magnetite or carbonate (siderite) and locally pyrite.

*Lapa seca* is a generic term applied to grey-beige, massive, carbonate (ferrodolomite, ankerite, siderite, and calcite) rocks. It constitutes typical ore at the Morro Velho, Bicalho and Bela Fama mines, and contains subordinate quartz, albite, sericite, carbonaceous matter and locally pyrite. It is generally granoblastic, though finely banded *lapa seca* can also occur.

**GOLD DEPOSITS ASSOCIATED WITH ROCKS OF THE NOVA LIMA GROUP** The QF was the most productive gold region in Brazil in the 18th century. The most important gold deposits are located in the northern portion of the QF, including Cuiabá, Morro Velho (Grande and Velha), Raposos, São Bento, Faria, Bicalho and Bela Fama mines, hosted by rocks of the Nova Lima Group (e. g. Ladeira 1991, Vieira 199la, Ribeiro-Rodrigues *et al* 1996a). Lode-gold mineralization at the Santana Mine is located along the sheared contact between rocks of the Minas Supergroup (Itabira Group) and schists of the Nova Lima Group (see Ladeira 1991, Menezes 1996).

**Structures** The gold deposits within rocks of the Nova Lima Group are associated with regional lineaments, typifying NW/NE-NE/SE-directed, thrust-related, oblique ramps or EW-directed, transcurrent faults, the latter being the most favored loci for gold depoSítion (e. g. Vieira 1991b, Ribeiro-Rodrigues *et al.* 1997). This is typical of the Morro Velho and Raposos mines, because their largest and highest-grade orebodies are EW-directed. Besides, within a single orebody changes in met al grade are related to shifts in structural direction.

Cigar-shaped orebodies (length *versus* width ratio 15:1) are controlled by a stretching lineation that coincides with fold axis ("a"). Along the fold plunge, orebodies are twisted, disrupted, ramified and the shape of folds is modified. Folds are commonly tight alongside mineralized zones and control ore distribution. This is particularly clear in the Morro Velho Mine X Body, where a package of the carbonate-rich *lapa seca* has a slightly arcuate surface expression with small, sub-economic quartz veins. The progressive folding of the *lapa seca* is accompanied at depth by the systematic increase in gold grade and in mineralized aerial distribution. At 2450-m depth, this 12 g Au/t orebody is a D, phase, isoclinal fold occupying an area of 2100 $m^2$.

The orebodies fill the central portion of kilometric, ductile shear zones with widths that rarely exceed 300 m, and that are parallel to bedding. This parallelism led to the misinterpretation that the shear structures are of sedimentary origin (Ladeira 1980).

**Generic Mineralization Styles** Mesothermal, lode-gold mineralizations can be classified according to the scheme proposed by Hodgson (1993). Regardless of age, the author divides the deposits into those in belts dominated by metavolcanic or metasedimentary rocks.

Within belts dominated by metavolcanic rocks, further subdivision of each deposit is based on the dominant form of mineralization and on the host rock, determining three styles of gold mineralization. In the specific case of deposits in belts dominated by metasedimentary rocks, they are further divided into those hosted by BIF and those hosted by clastic sedimentary rocks.

In the metavolcanic-dominated belts, the styles of mineralization are: (1) breccia, stockwork and bedding-replacement (stratabound and/or stratiform) sulfide-rich zones in oxide-facies BIF; (2) shear-related, mafic volcanic- or sediment-hosted, disseminated sulfide-rich, quartz-albite and (or) potassium feldspar-carbonate replacement zones; (3) Auriferous quartz veins and veinlet systems truncating all rock systems.

BIF-hosted gold deposits are divided by Kerswill (1993) into stratiform and non-strati form types on the basis of empirical (non-genetic) characteristics. In the former, gold is uniformly disseminated in laterally continuous units of cherty, well-laminated sulfide BIF that are conformably interlayered with gold-poor silicate and/or carbonate BIF. In non-stratiform deposits, gold is restricted to late structures (veins and shear zones) and/or sulfide BIF immediately adjacent to such structures.

These mineralization styles may describe either entire gold deposits, individual orebodies or particular portions of orebodies. This classification system is understood to be useful because each mineralization style 1) is associated with distinct grade-tonnage relationships; 2) reflects a particular host rock structural preparation; and 3) reflects the compoSítional evolution of fluid to rock interaction and, thereby, a distinctive ore mineralogical compoSítion.

**Nova Lima Group Gold Mineralization Styles** Gold mineralizations associated with rocks of the Nova Lima Group are sulfide bearing.

Orebodies hosted in BIF result from the replacement of magnetite and siderite, characterizing zones of varying sulfide compoSítion. This led Vieira (1987b) to discriminate different styles of gold mineralization, based mainly on observations at the Raposos Mine. That author's mineralization styles are denominated as Types 1, 2 and 3, and they display a close though not precise correlation with the scheme offered by Hodgson (1993).

Ductile-brittle or ductile $D_1$ shear zones in BIF and *lapa seca* are loci for pyrrhotite-dominant, Type-1 mineralization style. Pyrrhotite occurs with subordinate pyrite and arsenopyrite; magnetite, chalcopyrite, ilmenite and hematite occur as accessory minerals. Shear zones are parallel or sub-parallel to bedding, and associated with folded or *en echelon,* boudinaged quartz veins. They alternate with BIF or non-sheared *lapa seca,* displaying ramifications and disruption of the stratigraphic poSítioning. Shear zones crosscut shear zones indicating multiple pulses of mineralization.

Pyrrhotite in $D_2$ shear zones is less common, at varying angles with bedding. Hypidioblastic pyrite and arsenopyrite may occupy the nuclei of pressure fringes. Aggregates of polygonal or elongated, deformed pyrrhotite crystals are aligned along the foliation or form laths in pressure fringes.

Gold-bearing, pyrrhotite-rich shear zones constitute the gross of the ore in the QF, dominating in Morro Velho, São Bento, Raposos, Faria, Morro da Gldria and Bicalho mines, and is subordinate in Cuiabá, Lamego and Juca Vieira mines (Table 1). It is equivalent to style 1 of Hodgson (1993).

Pyrite and arsenopyrite fill fractures and replace siderite or magnetite in BIF and *lapa seca,* constituting Type-2 mineralization style. This substitution forms discontinuous bands in BIF and is homogeneously distributed in *lapa seca.* It is symmetrical or asymmetrical in relation to $D_2$ fractures, foliations, shears and quartz veins that cut the host rocks at a high angle. In BIF, it is clear that fractures parallel to $S_2$ and subordinately to $S_3$ functioned as conduits to fluids. The fractures vary from centimeter to meter in width, and can be filled by sulfides, quartz and chlorite. Subhedral to anhedral pyrite and arsenopyrite are coarser and less deformed than sulfide grains in Type-1 mineralization style. The two sulfides are intimately intergrown and display inclusions of carbonate (siderite) and quartz; rare pyrrhotite, chlorite and calcite also occur.

Pyrite and arsenopyrite dominate ore mineral compoSítion in Cuiaba and Lamego mines, and are more restricted in Morro Velho, São Bento, Raposos, Faria, Morro da Glória and Bicalho mines (Table 1). These replacement bands are equivalent to Hodgson's (1993) style 1.

A third (Type-3) mineralization style is suggested by Vieira (1991a). Pyrite, arsenopyrite and at places pyrrhotite occur disseminated in schists of the sericite and subordinately of the carbonate alteration zones, with which quartz veins are intimately associated. The veins vary from millimeter- to meter-thick, are generally boudinaged and exhibit sulfides along the walls with host alteration envelopes. Gold is associated with veins, mainly along their sulfide-rich borders, and with sulfide-rich schists. Schists are predominantly sulfide-enriched next to quartz veins.

This mineralization style is commonly identified in Juca Vieira, Santana, Corrego do Sítio and Bela Fama, and has a more restricted occurrence in Morro Velho, Cuiabá and Bicalho mines. It is equivalent to styles (2) and (3) of Hodgson (1993).

Ribeiro-Rodrigues *et al.* (1997) proposed an alternative. Three main styles of gold mineralization are depicted in Table 2, and these are (1) stratabound, replacement-dominated deposits; (2) shear-zone-hosted, replacement-dominated deposits; and (3) shear-related, quartz vein hosted deposits. While the stratabound, replacement-dominated style is associated with BIF, the shear-zone-hosted, replacement dominated style is represented by disseminated sulfides occurring in shear zones, mainly within Fe-rich, metavolcanic and metasedimentary rocks. Shear-related, quartz-vein-type deposits are associated with quartz remobilization within metavolcanic and metasedimentary rocks.

**Common Ore Characteristics** In gold deposits associated with the Nova Lima Group, sulfide-bearing orebodies are composed of massive sulfide, either banded or disseminated, associated with BIF and *lapa seca.* Orebodies can also exhibit disseminated sulfides in zones of sericite and/or carbonate alteration associated with and enveloping quartz veins and veinlets, hosted by metavolcanic and metasedimentary rocks. In plan view, they have from 0.5 to 20 m of thickness, and are 10 to 300 m-wide. They are from 800 to at least 5,000 m long down plunge. The true length of several of the orebodies is not known and therefore future ore potential is not yet fully accounted for.

The gold to silver ratio varies from 6:1 to 5:1. Gold forms anhedral grains or thin films along fractures in sulfides. In association with pyrrhotite, gold is the coarsest in the 50 to 120 um range, usually along grain boundaries. As inclusions in pyrite, gold grains vary from 10 to 50 um. Where included in arsenopyrite and associated with gangue minerals, gold is in general finer (below 10 um). It occurs as inclusions and along grain boundaries in gangue minerals. Table 3 shows a strong positive correlation between gold and pyrite. The pyrite to pyrrhotite transformation results in an increase in the amount of free gold.

The positive correlation of gold with Ag, As and S is good in all mines. The correlation with Cu, Pb and Zn is not marked, although these elements are enriched in the ore zones. Chalcopyrite, galena and sphalerite add to less than 0.5 volume (vol.) % of sulfides.

**Hydrothermal Alteration Styles** Pervasive, shear-related hydrothermal alteration in gold mineralizations associated with rocks of the Nova Lima Group is characteristic. With the exception of deposits hosted by both Archean and Eoproterozoic rocks of the Mariana Anticline, hydrothermal reactions essentially predominate during $D_1$, despite the different deformation peaks recognized.

*METAVOLCANIC ROCKS* Ductile shearing and hydrothermalism largely modify igneous textures and structures of metabasalt, including pillows and varioles. The resulting rock type is a mylonitic schist with boudinaged, sigmoidal and folded quartz veins, with varying mineral compoSítion according to hydrothermal zonation. Such textural features reflect the importance of hydrothermal fluids. As pointed out by Rubie (1990), fluids play a significant role in strain softening thus facilitating reaction-enhanced deformation.

Metavolcanic rocks modified by mylonitic deformation are marked by an anastomosing foliation, S-C structure, mica fish, and rotated and recrystallized porphyroblasts in pressure shadows. The minerals are aligned and stretched along the main lineation. Quartz, carbonate and albite display grain size reduction and dynamic recrystallization, with the growth of larger quartz and carbonate crystals (e.g. Vieira and Simões 1992, Godoy 1994, Pereira 1996). BIF and *lapa seca* are characterized by a generally ductile-brittle to ductile deformation, also displaying tension gashes, micro-fractures and rotated blocks and breccia.

Tremolite and/or actinolite, epidote, and less chlorite, quartz, plagioclase and rare pyroxene dominate the metamorphic paragenesis of mafic rocks. Meta-ultramafic rocks embody serpentinite with Mg-chlorite and tremolite-actinolite. Metamorphic temperatures in the range of 350 to 430°C are indicated by Vieira (1991b), based on mineral associations.

The hydrothermal alteration zones are well established for metamafic and meta-ultramafic rocks(e.g. pereira 1996, Junqueira 1997). Vieira (1991a) and Vieira and Simões (1992) describe a progressive deformation from the outer (chlorite), furthermost zone towards the ore-bounding, sericite zone where calcite poikiloblasts are rotated and recrystallized. In the intermediate carbonate alteration zone, poikiloblasts are elongated and somewhat recrystallized. In the sericite zone, they are completely recrystallized.

The chlorite alteration zone is marked by abundance of chlorite after metamorphic tremolite-actinolite (Table 4) and recrystallization of original plagioclase. Relics of plagioclase sub-grains and minor carbonate alteration, indicated by calcite substitution of the former, are also present. Calcite either displays the lath-like habit of plagioclase or forms post-kinematic poikiloblasts.

The zone of strong carbonate development is characterized by Fe-rich carbonates, either ankerite or Fe-dolomite (Table 4), with carbonate substituting mainly plagioclase. The formation of sericite after chlorite, plus tourmaline and sulfides is discrete.

In the innermost, sericite alteration zone, white mica is abundant as well as carbonates. It is also characterized by some degree of albitization, tourmalinization, sulfidation and silicification.

Hence, hydrothermal alteration is dominated by the development of hydrated silicate phases in the incipient alteration stage, indicating a $H_2O$-predominant fluid, and carbonates in the more advanced stages, suggesting a fluid with varying $CO_2$-$H_2O$ concentration (Vieira 1988, 1991c).

*METASEDIMENTARY ROCKS* In zones of BIF with limited hydrothermal alteration, carbonate haloes surround quartz veins and sulfide-rich zones, suggesting magnetite substitution. Advanced hydrothermal alteration of BIF is associated with gold ore, and comprehends enrichment in pyrite, pyrrhotite and arsenopyrite, ankerite, ferrodolomite, magnetite.

*Table 1 - Relative percentage of opaque minerals in selected gold mines described in the text, according to Vieira´s (1987b) Types-1 and -2 mineralization styles.*

| Minerals | Type 1 | | | Type 2 | |
|---|---|---|---|---|---|
| | Morro Velho | | Raposos | Raposos | Cuiabá |
| | Above Level 22 (1,850 m) | Below Level 22 (1,850 m) | | | |
| Pyrrhotite | 47 | 69 | 47 | - | 6 |
| Pyrite | 22 | 1 | 19 | 67 | 91 |
| Arsenopyrite | 29 | 28 | 20 | 32 | 2 |
| Magnetite | - | - | 12 | - | - |
| Others | 2 | 2 | 2 | 1 | 1 |

**Others: Chalcopyrite, limonite, magnetite, ilmenite, galena, sphalerite, covelite, gold**

*Table 2 - Classification scheme for mesothermal, lode-gold mineralization styles in the Quadrilátero Ferrífero proposed by Ribeiro-Rodrigues et al. (1997).*

| Structural Style | Important Deposits |
|---|---|
| Stratabound, replacement dominated | Morro Velho, Cuiabá, São Bento, Raposos, Lamego, Faria, Esperança III, Tinguá. |
| Shear-zone-hosted, replacement-dominated | Bicalho, Bela Fama, Paciência, Juca Vieira, Pari, (Tinguá, Cuiabá). |
| Shear-related-quartz veins | Bela Fama, Juca Vieira, Paciência, (Morro Velho, Cuiabá, Bicalho). |

Data: MineracSo Morro Velho S. A., Vieira (199la), Ribeiro-Rodrigues, 1998.

*Table 3 - Percentage of gold associated with sulfides and gangue.*

| | Type 1 | | Type 2 |
|---|---|---|---|
| Minerals | Morro Velho Above Level 22 Raposos | Morro Velho Below Level 22 | Raposos Cuiabá |
| Pyrrhotite | 22 | 47 | - |
| Pyrite | 42 | - | 95 |
| Arsenopyrite | 28 | 19 | 1 |
| Chalcopyrite | 2 | 3 | - |
| Gangue | 6 | 31 | 4 |

Outstanding textural features are sulfide grains enveloping magnetite or siderite, surrounded by recrystallized carbonate, and sulfides developing along cleavage lines of both siderite and biotite. This corresponds to a loss of Fe in both carbonate and biotite. Biotite substitution by sulfides is observed in the Turmalina, Faina and Pontal mines (Vieira 1986), at the western outskirts of the QF, close to the town of Pitangui. The presence of biotite in these Áreas is related to locally higher metamorphic conditions compared to other parts of the QF. Carbonate replaces magnetite that may form relics at places. Portions with magnetite relics either form long streaks bounded by veins or fractures, or deformation pods within shear zones. The constant association of carbonate with hydrothermal alteration haloes, together with other textural features suggest that most of the carbonate in Auríferous BIF is of hydrothermal origin.

Metapelitic rocks exhibit discrete alteration zoning due to limited reactivity of quartz, carbonate and sericite relative to the inferred $H_2O$-$CO_2$ compoSition. Hydrothermal haloes are millimeter- to centimeter-thick composed of chlorite, sericite, quartz and carbonate without defining a proper zonation (Córrego do Sítio, São Bento and the NW orebody at Juca Vieira).

THE CUIABÁ GOLD MINE The BIF-hosted Cuiabá Gold Mine, property of Mineração Morro Velho Ltda., is situated some 40 km east of Belo Horizonte (Figure 1). At present, the deposit is the major gold producer in the region and one of the most important gold operations in Brazil. Proven gold reserves of this world-class gold deposit, in 1996, exceeded 1801 Au. Gold production amounts to over 600 0001 of ore per year in underground operations, with average grades of 8-11 g Au/t (e. g. Ribeiro-Rodrigues *et al.* 1996b).

The locally gold-bearing Cuiabá Banded Iron-Formation (BIF) Unit varies in thickness from 6 to 15 m. It is sandwiched between lower (footwall) and upper (hanging wall) mafic metavolcanic rocks. The former is intercalated with metasedimentary rocks, and the latter embodies metavolcaniclastic and metasedimentary rocks. The metamorphism reached greenschist facies (e. g. Vial 1988, Vieira 1992, Ribeiro-Rodrigues *et al.* 1994).

According to Ribeiro-Rodrigues (1998), the inventory of structural elements in the Cuiabá Mine area can be grouped into three deformation phases, namely $D_1$ $D_2$ and $D_3$. However, for this co-author the structures termed D, elsewhere in this paper are not present in the Mine. Hence, Ribeiro-Rodrigues (1998) denomination $D_1$ refers to structures equivalent to those recognized as $D_2$, elsewhere in the QF (Vieira and Oliveira 1998). Ribeiro-Rodrigues' denomination is maintained only in this subsection.

$D_1$, $D_2$ and $D_3$ are considered by one of the authors, L.C.R.-R., to be of a single, progressive, compressional tectonic event, named $E_n$ (Ribeiro-Rodrigues *et al.* 1996b). This event is to have occurred after the depoSítion of the Minas Supergroup. It was responsible for the formation and development of folds, axial plane surfaces, mylonitic foliations, lineations, faults, shear zones and shear fractures. Deformation progresses from the ductile to brittle regime and the structures were reactivated or reoriented during the three phases.

Three phases of deformation are also indicated by Vieira (1992) and Toledo (1997), though their interpretation differs form that of Ribeiro-Rodrigues (1998). Vieira (1992) originally interpreted $D_2$ and $D_3$ as progressive deformation. Toledo (1997) indicates that these three phases reflect a compressive, NW- to W-vergent tectonism developed in distinct crustal levels.

The structure of the deposit is dominated by a large-scale, southeast-plunging (30-40°), cylindrical sheath fold. All lithological units are affected by a pervasive axial planar foliation, locally mylonitic ($S_1$ = 135/45). They show a prominent mineral stretching lineation (LS = 126/22-35), which is expressed by the preferred orientation of elongated sericite, carbonates and sulfides. This lineation is parallel to mesoscopic ($D_2$) fold axes and to the intersection between bedding ($S_0$) and the foliation ($S_1$). Late, north-west-verging, sigmoidal thrust faults reactivated pre-existing structures and caused folding, boudinage and rotation of the Cuiabá-BIF.

**Styles of Gold Mineralization** Three styles of gold mineralization can be identified in the Cuiabá Mine (Ribeiro-Rodrigues 1998). The main mineralization is Stratabound, BIF-hosted and associated with sulfide-rich BIF layers (see Table 2), which can be correlated with Vieira's (1987b) Type-2 and subordinately Type-1 mineralization styles.

Shear-related, metamorphosed mafic volcanic- or sediment-hosted mineralization is less important and represented by disseminated sulfides occurring in bedding-sub-parallel, oblique-slip thrust faults and/or shear zones within metavolcanic or metasedimentary rocks (e. g. Galinheiro Footwall orebody). The third style comprehends gold-bearing quartz veins (e. g. Galinheiro Footwall and Viana orebodies). Both can be correlated with Vieira's (1987b) Type-3 mineralization style.

Economic-grade gold mineralization is related mainly to seven main ore shoots, ranging in thickness between 1 and 6 m. Six are contained within the Cuiabá BIF horizon (Ribeiro-Rodrigues *et. al.* 1994, Ribeiro-Rodrigues 1998) and one is hosted by hydrothermally-altered, metamafic rocks (Viana orebody).

BIF-hosted orebodies consist of alternating sulfide layers, light-colored quartz-carbonate layers, dark quartz-carbonate and chert layers varying in thickness from a few millimeters up to one meter. The layers are crosscut by quartz veins and calcite veinlets (Ribeiro-Rodrigues *et al* 1994) (Figure 2). The bulk of the gold mineralization is associated with sulfide layers. Gold is fine-grained (3-60 µm) and is generally associated with pyrite, occurring as inclusions in fractures or along grain boundaries.

Chemically, gold is characterized by an Au:Ag ratio of 6. The deposit is the type "gold-only" and shows a characteristic association of Au with Ag, As, and low base-met al contents. In plan view, the irregularly shaped orebodies show consistent down-plunge continuity parallel to the linear fabric of the $E_D$ event, e. g., parallel to the DI-phase stretching and intersection lineations (126/24-35). Furthermore, the most intensive development of pyrite-rich zones and associated gold mineralization corresponds to fold hinges and zones of intense D] and $D_2$-phase shearing (Ribeiro-Rodrigues *et al.* 1996b). This clearly suggests that the orebodies are structurally controlled, similar to other mines in the QF (e. g. Scarpelli 1991, Vieira 1991b).

Disseminated sulfides and/or quartz veins occurring in DI and $D_2$ thrusts and/or shear zones within metavolcanic, or subordinately in metasedimentary rocks, represent shear-related gold mineralization.

**Hydrothermal Alteration** Wallrock alteration is an important feature associated with mineralization everywhere. The alteration involves the formation of characteristic mineral assemblages and overprinting of earlier associations. Whereas the carbonaceous metasediments are only locally altered to sulfide-quartz-carbonate veinlets and the Cuiabá-BIF horizon is sulfidized, the mafic metavolcanic rocks show a characteristic pervasive alteration zonation (Ribeiro-Rodrigues

*Table 4 - Mineralogical compoSítion (in vol %) of each zone of hydrothermal alteration of mafic and ultramafic rocks. Averages calculated for various mesothermal, lode-gold mineralizations in the QF. Abbreviations: Chl = chlorite, carb = carbonate, Ser - sericite.*

| Minerals | Host Mafic | Chl. Zone | Carb. Zone | Ser. Zone | Host Ultramafic | Chl. Zone | Carb. Zone | Ser. Zone |
|---|---|---|---|---|---|---|---|---|
| Amphibole | 28 | - | - | - | 22 | - | - | - |
| Carbonate | 3 | 10 | 30 | 41 | 4 | 16 | 28 | 45 |
| Chlorite | 17 | 39 | 22 | 3 | 4 | 38 | 42 | 2 |
| Epidote | 27 | 2 | - | - | - | - | - | - |
| White/Green Mica | - | 4 | 13 | 26 | - | - | 2 | 20 |
| Plagioclase | 13 | 13 | 3 | 3 | - | - | - | 5 |
| Quartz | 5 | 26 | 28 | 20 | - | 6 | 25 | 25 |
| Serpentine | - | - | - | - | 61 | - | - | - |
| Talc | - | - | - | - | 4 | 37 | - | - |
| Others | 7 | 6 | 4 | 7 | 5 | 3 | 3 | 3 |

Others: Titanite, rutile, teucoxene, tourmaline, opaque minerals.
White mica in mafic and green nrica in ultramafic rocks.

1998). Outward from the shear zones, the alteration consists of zones dominated by associations characteristic of sulfidation and/or serialization, carbonatization, chloritization and regional metamorphism (Figure 2).

Sulfidation is a conspicuous wallrock alteration feature and is generally restricted to mineralized Áreas. Gold is an integral part of wallrock alteration and directly related to sulfidation processes in all three styles of gold mineralization.

The mineral assemblage in the unaltered Cuiabá-BIF consists of siderite, ankerite, quartz in the quartz-carbonate layers, ankerite, calcite, quartz in the light quartz-carbonate layers and quartz and Fe-carbonate in chert layers. Toledo (1997) indicates that some of the Fe-carbonate layers result from the oxidation of original carbonaceous matter associated with siderite and Mn-ankerite.

A characteristic feature commonly associated with the BIF-hosted mineralization is the pervasive, selective replacement of quartz-carbonate layers (normally the more Fe-rich, dark layers) by iron sulfides, which is observed both at the hand-specimen scale (Figure 3a), as well as at the mine scale (Ribeiro-Rodrigues *et al.* 1995). Extensive sulfidation has imparted a stratiform, pseudo, syn-sedimentary pattern to the mineralized portions of the BIF. This character gives the impression of laterally continuous, alternating sulfide, quartz-carbonate and chert layers.

Sulfide layers consist of 50-90 vol. % sulfides, the most important alteration minerals, with major amounts of quartz and carbonates (siderite and ankerite). Pyrite is the predominant sulfide (90-95 vol. %) and occurs in at least two generations, described in det all by Toledo (1997) and Ribeiro-Rodrigues (1998). Other sulfides are pyrrhotite, arsenopyrite, chalcopyrite, sphalerite and galena, which are mostly included in recrystallized pyrite.

Chemical changes during sulfidation, determined for constant volume during alteration, involve addition of S and Au, increases of Ca, P, As, Cu, La and Ce, and removal of organic carbon. Considering analytical uncertainties, other elements are relatively immobile. Added elements were consumed in forming sulfides (S, As, base met als), native gold (Au, Ag), carbonates (Ca) and monazite (P, La, and Ce). $CO_2$ was not added during sulfidation (Figure 3b). Arsenopyrite thermometry indicates that the temperature of alteration was from < 250°C to 520°C and gold depoSítion occurred between 270-300°C Ribeiro-Rodrigues (1998).

In the mafic metavolcanic rocks, the sulfidation processes occur associated with $D_1$ and $D_2$ shearing.

Ribeiro-Rodrigues (1998) concludes that ore textures and structures at the Cuiabá Mine indicate and epigenetic, structurally controlled, replacement-dominated mineralization during the D, phase of the $E_n$ event. The oreshoots show a consistent, down-plunge continuity that is parallel to the $L_{m1}$ stretching and $L_1$ intersection lineations. Local remobilization of syn-$D_1$ mineralization occurred during the $D_2$ and $D_3$ deformation phases.

**THE JUCA VIEIRA GOLD MINE** The Juca Vieira Gold Mine, property of the Mineração Morro Velho Ltda., is located at the central-northern boundary of QF, about 6 km south of Caeté (Figure 1). The mine lithological units comprise predominantly mafic metavolcanic and less meta-ultramafic rocks, and intercalated graphite schists and BIF. Ore reserves of 484 600 t have an average grade of 5.64 g Au/t. The Mine is currently inoperative.

According to Vieira (1988), Duchini Jr. *et al.* (1990), and Silva *et al.* (1990, 1991), the orebodies comprise sulfide-bearing, quartz-carbonate vein systems and at places breccias, hosted mainly by metavolcanic rocks of mafic and intermediate compoSítions. The veins vary in thickness from 2 to 40 m. Arsenopyrite is the main sulfide, followed by pyrrhotite and pyrite, lesser galena and sphalerite, and minor chalcopyrite, stibnite and scheelite. The sulfides are concentrated in sericitized envelopes in contact with the quartz-carbonate veins.

A NNW-striking, ductile shear zone is the main structure controlling the Auríferous mineralization. It extends for about 10 km with an approximate width of 2.5 km. A 114/10 mineral-stretching lineation is developed on the 195/43 mylonitic foliation. According to Vieira (1991c) it belongs to the first deformation event which affected the Nova Lima Group rocks and in the Juca Vieira Mine it is related to a transcurrent fault.

**Hydrothermal Alteration** Pereira *et al.* (1995), Pereira (1996) and Pereira *et al.* (1994) undertook geological, petrographic and whole-rock, major- and trace-element compoSítion studies of the hydrothermal alteration at Juca Vieira. From the various orebodies described underground (Duchini Jr. *et al.* 1990), the SE-2 orebody was selected by Pereira (1996). It is hosted by mafic metavolcanic rocks and located in the southeastern portion of the Mine. Previous studies regarding the alteration in the Mine were carried out by Vieira (1987c; Figure 4).

Commonly schistose, subophitic metabasalt (MB) exhibits an assemblage with actinolite, clinozoisite, albite and chlorite (clinochlore), lesser quartz, titanite, calcite and leucoxene, and accessory paragonite. Pyrite, pyrrhotite, chalcopyrite, rutile (± leucoxene) and apatite add to < 1 vol %.

The shear-related, hydrothermal alteration of MB results in the development of mylonitic schists. Petrographic studies determined specific mineral assemblages characterizing chlorite, carbonate and sericite alteration zones enveloping veins (Figures 4 and 5). An albite-quartz-clinochlore schist (CLS) dominates the former, with lesser calcite and/or ankerite, paragonite, rutile (5 vol. % each), and accessory (< 1 vol. %) leucoxene, apatite, pyrrhotite ± pyrite ± chalcopyrite, and tetrahedrite-tennantite. Clinozoisite may occur at places in the absence of plagioclase.

The carbonate alteration zone is defined by a carbonate-sericite-quartz-chlorite assemblage, including chlorite-quartz-sericite-carbonate schist (CLCBS) and quartz-sericite-carbonate schist (CBS).

The CLCBS has a great aerial distribution and is composed of ankerite, muscovite and/or paragonite, quartz and chamosite, lesser (5 vol. %) albite, rutile and leucoxene, and accessory tourmaline (schorl, < 1 vol. %), apatite, chalcopyrite ± pyrrhotite ± pyrite (at places up to 5 vol. %) ± arsenopyrite, bournonite and gold.

In CBS, carbonate (ankerite ± calcite) is more abundant and the mica is paragonite. Chlorite (clinochlore ± chamosite) and rutile occur in 5 vol. % each and sulfides are more abundant than in CLCBS, including arsenopyrite (locally up to 10 vol. %), pyrite (1 vol. %), pyrrhotite (1 vol. %) and chalcopyrite (1 vol. %). The accessories (< 1 vol. %) are albite, schorl, leucoxene, tetrahedrite-tennantite and gold.

Quartz-carbonate-sericite schist (SX) is more restricted and typifies the sericite alteration zone alongside the ore. Paragonite, ankerite ± calcite and quartz predominate, whereas clinochlore ± chamosite, schorl, rutile, arsenopyrite and pyrite occur in less than 5 vol. % each. Leucoxene, albite, apatite, pyrrhotite ± chalcopyrite and tetrahedrite-tennantite plus gold add to less than 1 vol. %.

Silicification, in the form of concordant quartz veins, and sulfidation are important features of the two latter zones, with sulfide trails marking the boundary between SX and the veins. Original pyrite is substituted by arsenopyrite, a second generation of pyrite forms at the expense of chalcopyrite and pyrrhotite, and sulfosalts (tetrahedrite-tennantite and bournonite) replace pyrite and arsenopyrite (see Figure 5).

The mineralogical changes observed in MB involve the partial destruction of actinolite and albite to form clinochlore, paragonite, clinozoisite ± calcite and/or ankerite, probably by way of reactions with a $CO_2$ + $H_2O$-rich fluid. In the chlorite alteration zone, this mineral is partially replaced by ankerite + paragonite and new albite crystals nucleate; original MB phases no longer coexist. CLCBS and CBS are marked by more extensive replacement of chlorite to form carbonate + paragonite + sulfides, and in SX of carbonate to form sulfides. In these alteration stages, unbuffered conditions are suggested by the disappearance of the original minerals.

Gold is observed microscopically from the carbonate zone onwards. It may form minute crystals in arsenopyrite and pyrite. It can also be present as inclusions in ankerite and paragonite and is at places

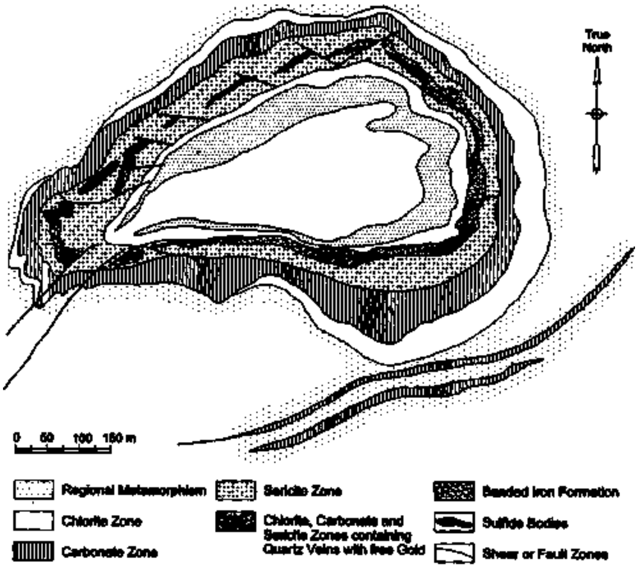


*Figure 2 - Schematic, hydrothermal-alteration, zonal pattern for metamafic rocks at the Cuiabá Mine (after Vieira 1991a).*

intergrown with pyrrhotite, chalcopyrite and tetrahedrite and/or tennantite. Free gold occurs in quartz veins, or in veins together with bournonite. Gold contains 12.5 vol. % of Ag.

Pereira's (1996) whole-rock, chemical compoSítion study focuses mainly on samples of altered MB. Nevertheless, in an attempt to reconstruct the nature of the protholith, the author indicates two distinct geochemical groups based on the Cr, Ni and Cu values, suggesting two original metavolcanic precursors.

Chondrite-normalized, rare-earth-element (REE; Evensen *et al.* 1978) patterns are similar for all rock types (20 samples), with leaching of the heavy rare earth elements (HREE). $CO_2$-rich fluids are capable of leaching REE, especially HREE (Mineyev 1963). There is strong enrichment in light REE (LREE), when compared to patterns of Mg-rich unaltered metabasalts obtained by Zucchetti (1998). Enrichment in LREE in other samples analyzed by this latter author is interpreted as indicative of degree of differentiation.

Chemical mass-balance studies (Pereira 1996) have been performed to evaluate gains and losses during metasomatism, using Gresen's (1967) approach. The intensity of hydrothermal alteration is monitored by the use of the relation $CO_2/(Ca+Fe^{2+}+Mg+Mn)$ that reflects the degree of carbonate development and cation saturation in carbonate.

Under practically isovolumetric conditions, there was leaching of $SiO_2$ and general increment in the amounts of hydrated phases, translated in an increase of $H_2O$. Quartz precipitation is restricted to veins and veinlets that are not included in the sampling, hence explaining apparent silica loss. Muscovite-paragonite nucleation accounts for the slight variations in $Na_2O$ and general increase in $K_2O$ in the intermediate and advanced stages of alteration. There is an overall increase in CaO, $CO_2$, S and As in the hydrothermally altered ore zone. While MgO is enriched in the incipient stage due to chlorite formation, it decreases in the more advanced. Slight enrichment in Sb is related to the formation of sulfosalts in the incipient and intermediate stages.

Pereira (1996) concludes that gold mineralization is related to wallrock alteration and simultaneously enriched in zones of carbonate, sericite alteration, together with quartz and sulfides. The shift from the least-altered, chlorite-bearing assemblage to largely carbonate-dominated in the advanced stages indicates variations in $CO_2$:$H_2O$ ratios of an $H_2O$-$CO_2$ fluid. Gold is assumed to have been transported by reduced sulfur complexes. Cation-consuming reactions (paragonite to albite) might have released a near-acid fluid, hence influencing gold precipitation.

**THE RAPOSOS GOLD MINE** The Raposos Gold Mine, property of Mineração Morro Velho Ltda., is located at the NNW portion of the QF at about 35 km southeast of Belo Horizonte (Figure 1). With a daily production of 650 tons of ore, at an average grade of 6.07 g Au/t, ore extraction was last being carried out at Levels 31 and 32, and mine development at Levels 34 and 36, 1040 m and 1150 m, respectively. In 1997, the ore reserves at Raposos stood at 2.3 Mt (Junqueira 1997). The mine was closed soon after the preparation of this manuscript (June 1998).

Gold mineralization is associated with sheared, hydrothermally altered carbonate- and oxide-facies BIF of the Lower Unit of the Nova Lima Group, commonly limited by envelopes of sericite alteration belonging to footwall and hanging wall schists (Vieira and Oliveira 1988). $D_t$-related shear zones are sub-parallel to Sj and $S_0$ of BIF, and destroy the bedding that is preserved only in fragmented relics elongated according to shearing.

Sulfide-bearing shear zones constitute roughly stratiform orebodies, with abundant quartz veins. The exception is the Ouro Preto quartz-sulfide-vein type orebody. Pyrrhotite is the main sulfide, followed by smaller amounts of pyrite and arsenopyrite; gold grades correlate well with the amount of the former sulfide. Pyrrhotite orebodies can be correlated to Vieira's (1987b) Type-1 mineralization style.

Of restricted importance are low-grade, gold-bearing, pyrite- and quartz-/arsenopyrite-rich fractures that locally crosscut BIF. Originating from such fractures, sulfides extend for a few meters into the rock's bedding. According to Vieira (1987b), these are correlated with Type-2 mineralization style.

The hanging wall to BIF is a meta-ultramafic (MU) schist and the footwall a metamafic (metabasalt - MB) schist. Carbonaceous metapelitic rocks also occur. The deposit is structured as a major $D_t$, inclined fold. At Level 28, the average plunge of both folds and orebodies is 095/22 (Junqueira 1997 and references therein).

**Hydrothermal Alteration** The investigation of the hydrothermal alteration of the host metamorphosed mafic and ultramafic rocks enveloping BIF has been undertaken by Junqueira (1997) at Level 28. The geological mapping, and the petrographic and whole-rock, chemical compoSítion studies indicate that most lithological units contain superimposed hydrothermal mineral associations on earlier metamorphic minerals. This mineralogical distribution designs a zonal pattern surrounding ore (Figure 6a).

Pre-hydrothermal associations in MB comprise albite, epidote, actinolite and lesser Mg/Fe-chlorite, calcite and quartz; pyrite and chalcopyrite are accessory minerals. The MU rocks rarely preserve their metamorphic minerals and the least-altered type displays Mg-chlorite, actinolite, with subordinate talc and calcite. Vieira (199la) describes, for other parts of the Nova Lima Group, rocks with olivine, serpentine and magnetite.

Junqueira (1997) distinguishes incipient (buffered) and advanced (unbuffered) stages of alteration, each encompassing two alteration zones (Figure 7), hence det alling the scheme previously suggested by Vieira (1988; see Table 4). The incipient stage is particular of each lithological type. Both carbonate-albite and carbonate-sericite alteration zones are characteristic and attributed to the advanced stage of hydrothermal alteration.

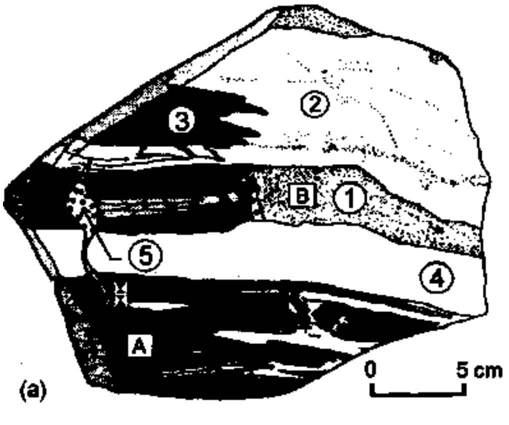
In MB, the incipient stage is marked by the disappearance of both epidote and actinolite, and is subdivided into chlorite-albite and chlorite-sericite zones. The first reactions involve the development of chlorite and calcite from epidote + actinolite, to form a chlorite-albite-carbonate-quartz schist. Carbonates are mainly ankerite, followed by calcite.

The chlorite-sericite zone is marked by the replacement of the albite + chlorite + calcite assemblage to form a sericite-chlorite-carbonate (ankerite)-quartz schist, by way of interaction with a $CO_2$ + K+-rich fluid that may evolve to a $H_2O + Na^+$ fluid.

The advanced stage comprises the carbonate-albite and the carbonate-sericite zones. This stage is characterized by the nucleation of hydrothermal albite associated with Fe-ankerite at the expense of chlorite + calcite + quartz, possibly reflecting the reaction with a $CO_2 + Na^+$ fluid (carbonate-albite zone). In the carbonate-sericite zone, chlorite + calcite can also be replaced by an assemblage containing sericite + Mg-siderite + quartz; this could have been attained through interaction with a $CO_2 + K^+$-rich fluid, with H+ release.

There is pronounced iron enrichment in the carbonates, ranging from calcite in MB to ankerite and Fe-ankerite with the advancement of the alteration. The Fe:Mg ratio of chlorites also increases in the same direction.

In the alteration of MU actinolite is not present at all. There is significant increase in the amount of talc, and Fe-dolomite occurs in the place of calcite. These changes compose talc-chlorite and chlorite-



| Major elements | | | | |
|---|---|---|---|---|
| Sample<br>G | A<br>3.56 | B<br>3.34 | Mass change | |
| | (wt. %) | (wt. %) | (%) | (g/100g) |
| $SiO_2$ | 15.24 | 15.26 | -6.1 | -0.9 |
| $Al_2O_3$ | 0.22 | 0.1 | -59.9 | -0.1 |
| FeO | 45.69 | 40.45 | -16.9 | -7.7 |
| CaO | 0.66 | 4.91 | 603 | 4.0 |
| $P_2O_5$ | 0.02 | 0.07 | 208 | 0.1 |
| $CO_2$ | 33.57 | 26.06 | -27.2 | -9.1 |
| C | 0.38 | 0.09 | -78.1 | -0.3 |
| S | 0.01 | 8.83 | 80 600 | 8.3 |

| Trace elements | | | | |
|---|---|---|---|---|
| Sample<br>G | A<br>3.56 | B<br>3.34 | Mass change | |
| | (ppm) | (ppm) | (%) | ($g/10^6$ g) |
| Au | 11 | 5580 | 47 500 | 5224 |
| Ni | 16 | 23 | 34.9 | 5.6 |
| Co | 53 | 41 | -27.4 | -14.5 |
| Cu | < 20 | 42 | 97 | 19.4 |
| Pb | 15 | 26 | 62.6 | 9.4 |
| Zn | 68 | 74 | 2.1 | 1.4 |
| As | 2 | 14 | 557 | 11.1 |
| Sb | 1 | 3.2 | 1401 | 2.8 |
| Zr | 22 | 16 | -31.8 | -7.0 |
| La | 0.9 | 3 | 213 | 1.9 |
| Ce | 4 | 8 | 87.6 | 3.5 |

(b)

*Figure 3 - Ore textures and det alled alteration pattern at Cuiabá* ***(a)*** *Sketch of typical mineralized BIF (Canta Galo orebody, Level 5) consisting of alternating sulfide layers (1, stippled); clear-quartz-carbonate layers (2, stained clear); smoky-quartz-carbonate layers (3, dark grey); and chert layers (4, clear). Late, local remobilized quartz (5) cross-cuts layers. Sulfidation (1) replaces smoky-quartz-carbonate layers (3).* ***(b)*** *Chemical variations of selected major and trace elements during sulfidation (Ribeiro-Rodrigues 1998). Sulfide layer* ***(a)****-B is compared to the least altered 3-type layer* ***(a)****-A. Notice large gold and sulfur variations. Calculations for constant volume (modified after Gresens 1967); G = specific gravity.*

carbonate zones, which characterize chlorite-carbonate-quartz schists with or without varying amounts of talc. Proposed mineral reactions involve the substitution of serpentine + actinolite + anorthite by Fe-talc + Mg (Fe)-chlorite + Fe-dolomite + quartz, via interaction with $CO_2$. Further carbonate (ankerite) + quartz develop at the expense of earlier talc + calcite.

A carbonate-albite-quartz schist, with or without varying amounts of albite, chlorite and fuchsite , is typical of the advanced stage. The formation of this assemblage can be envisaged through the replacement of calcite + quartz by ankerite + albite, with further development of the Mg (Fe)-chlorite; the reaction might have involved a $CO_2 + Na^+$ fluid and $H^+$ release. Finally, a carbonate-fuchsite schist represents the replacement of chlorite + albite + calcite to form fuchsite + ferroan ankerite + quartz; the reaction must have involved consumption of a $CO_2$ + K+-rich fluid and release of $H_2O$ + Na+.

Lobato *et al.* (1998) undertook the investigation of the mineralogical changes experienced by BIF during shearing and associated hydrothermal alteration and/or mineralization (Figure 6b). Undeformed and unaltered BIF displays layers alternating between fine-grained, granoblastic siderite and/or magnetite, and quartz. Rare pyrrhotite can be present at places. Various authors (Ladeira 1980, Vieira 1987a, Junqueira 1997) interpret this layering as sedimentary bedding ($S_0$).

With the onset of shear-related hydrothermal alteration, there is general recrystallization with grain size increase, suggesting that high fluid pressure (P*f*) conditions prevailed. Deformed, xenoblastic, fine- to medium-sized pyrrhotite crystals develop at the expense of carbonate and magnetite. Textural relationships indicate that poikiloblastic pyrrhotite replaces original siderite and is itself replaced by a new ankeritic carbonate. Though less abundant euhedral to anhedral arsenopyrite and pyrite (± chalcopyrite) develop at the expense of pyrrhotite. Pyrite is also partly replaced by arsenopyrite. Narrow bands of muscovite, euhedral albite crystals and rarer chlorite flakes are associated with gold-rich, pyrrhotite ore. All phases in the ore display textural features indicative of varying degrees of shearing.

Subhedral pyrite and arsenopyrite constitute trails within BIF layers. They also display textural evidence indicative of sulfidation and later carbonate (ankerite) alteration of the original minerals.

The study of whole-rock, major- and trace-element variations by Junqueira (1997) addresses the progression of the hydrothermal alteration by the use of $CO_2/(CaO+FeO+MgO)$. It varies from 0.24 to 0.82 in the MB and from 0.14 to 0.77 in the MU.

The hydrothermal alteration of MB involves progressive loss of $Na_2O$, $Fe_2O_3$ and overall REE contents. There is addition of $K_2O$, and subordinately of $CO_2$. $H_2O$ is mainly enriched in the incipient stage of alteration, but is depleted in the advanced stage. There is a discrete increase in the $Fe^{2+}:Fe^{3+}$ ratio, and a pronounced increase in As and Ba. $Na_2O$ is leached in the chlorite-sericite zone, related to albite consumption in favor of sericite formation. $SiO_2$, $Al_2O_3$, $TiO_2$, V, Co and Zr have a stable behavior.

The main chemical changes in MU are the pronounced enrichment in $Na_2O$ and/or $K_2O$, $TiO_2$ enrichment in the talc-chlorite zone, and discrete loss of $Fe_2O_3$, FeO, CaO or MgO. There is increase in Ba, Sr, Zr and slight decrease in As and S in the carbonate-sericite zone. As and S are somewhat richer in the carbonate-albite zone. Ni and Zn are impoverished in the talc-chlorite and carbonate-albite zones. The REE display a behavior similar to that described in MB. $SiO_2$, $Al_2O_3$, $TiO_2$ and V show a stable behavior.

An earlier investigation by Vieira (1991c) shows that sericitization, carbonatization, sulfidation and tourmalinization of MB are in agreement with K, S, $CO_2$, Au, As, B and Ba gains. In MU, there is enrichment of Ca, Mn, Sr, Sc and loss of Mg, Cr, Ni and Co. Zr, Y, Ga, Ti and Al show low mobility. The normalization of REE values of BIF to sedimentary rocks shows that the regular, though depleted, pattern of sulfide-poor BIF is modified by sulfide enrichment (see Ladeira *et al.* 1991).

**THE SANTANA GOLD MINE** The Santana Gold Mine is located in the northwestern limb of the Mariana Anticline, 6 km to the north of the eponymous town (Figure 1). It is part of the same met allogenetic context of the Passagem de Mariana Gold District (Duarte 1991, Chauvet and Menezes 1992, Chauvet *et al.* 1994), located in the E-W limb and at the closure of the anticline (Fleischer and Routhier 1973). The Dom Pedro North d'el Rey Mining Co. Ltd. exploited the mine from 1863 to 1866, known for its gold since the 18th century. The mine is presently closed.

In the Mariana District, lode-gold mineralization is associated with veins at the contact between the Paleoproterozoic Itabira Group, of the Minas Supergruap, and the archean Rio das Velhas Supergroup. The former is represented by mylonitic amphibole itabirite and the latter by mylonitic biotite-quartz schist. The NW-SE-trending mineralized contact in the Antônio Pereira Range coincides with the tectonic contact, which overlaps itabirite and Archean schists. Gold mineralization is located along this contact, mainly at the SW corner of the anticline. A 090°-120°-dipping, mineral stretching lineation associated with a W- and NW-directed movement marks the main deformation. The west-vergent thrust post-dates the large-scale folds of the Mariana anticline (Chauvet and Menezes 1992).

Hydrothermal activity associated with gold mineralization is believed to have happened during the relaxation that followed thrusting, concomitant with the development of hydraulic fractures. Along the same NW lineament, Menezes and Leonardos (1992) describe gold mineralization in the Maquine Group related to post-tectonic decompression in the region.

**Hydrothermal Alteration** In the lode-gold, shear-related Santana Mine the metamorphic paragenesis of both host rocks and mineralized veins is superimposed by hydrothermal minerals, a subject discussed by Menezes (1996). Discrete hydrothermal alteration is associated with the late stages of the thrust-related, ductile deformation, in response to fluid percolation in structurally-controlled openings developed immediately after (late) thrusting (Chauvet *et al.* 1992 and Chauvet *et al.* 1994). Overall, the alteration of biotite-quartz schist is characterized by the formation of the least-altered, chlarite-sericite (after biotite) assemblage, with carbonates, tourmaline and sulfides forming in the more advanced stages. Arsenopyrite is the dominant alteration sulfide in the biotite-quartz schist and pyrrhotite in the

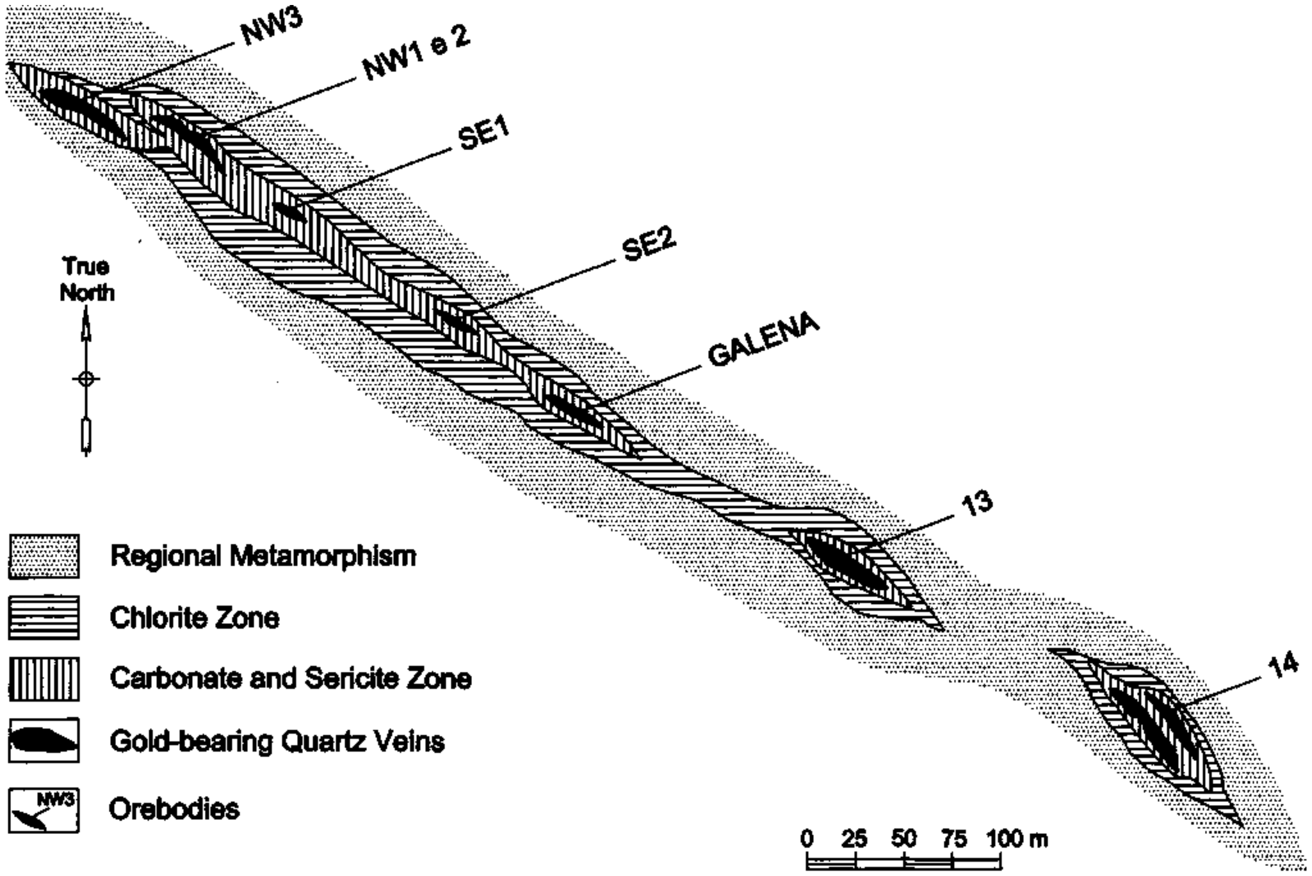


*Figure 4- Schematic, hydrothermal-alteration zonal pattern for metamafic rocks at the Juca Vieira Mine (after Vieira 1987c).*

magnetite itabirite, a variation that may reflect the original availability of iron.

The hydrothermal alteration minerals are concentrated along envelopes of vein contacts, attesting to the late (post-metamorphic) nature of the mineralization. The footwall to the mineralized veins is the mylonitic Nova Lima biotite-quartz schist, and a kyanite-bearing, sericite schist. The Itabira Group itabirite is the hanging wall.

Alteration in the Santana Mine is best imprinted on the footwall biotite-quartz schist (Table 5). In proximity to the mineralized contact, quartz porphyroclasts and biotite-rich domains diminish and a biotite-quartz phyllonite with arsenopyrite develops.

The incipient stage of alteration is limited to the footwall, in the form of chloritization (± sericitization) of biotite, accompanied by titanite and tourmaline nucleation. A more advanced, sericite alteration stage is characterized by chlorite and biotite substitution. The iron released by such reactions is fixed by the formation of ferrodolomite, and arsenopyrite (± pyrrhotite), constituting the carbonate and sulfide alterations, respectively. The result is a carbonate- and sulfide-bearing, quartz-sericite (± chlorite) schist next to mineralized veins.

The above-mentioned transformations can be envisaged by the following, simplified reactions (unbalanced): $\{\text{biotite} + H^+ = \text{chlorite} + K^+ + (Mg, Fe)_2^{2+} + SiO_2\}$ and $\{\text{biotite} + H^+ = \text{muscovite} + Fe^{2+} + H_2O + K^+ + SiO_2\}$ (hydrolysis); $\{\text{chlorite} + K^+ = \text{muscovite} + (Mg, Fe)_2^{2+} + H_2O + H^+ + SiO_2\}$ (with H+ release).

In the Nova Lima Group schists the nucleation of both sericite and tourmaline are the most outstanding alteration phases, ranging from the incipient to the advanced stages, with tourmaline abundant near the veins. This indicates that the aluminum was involved in the formation of both minerals, but is consumed to form only tourmaline in the advanced stage of alteration. Hydrothermal tourmalinite (Menezes 1998) a develops along the borders of the sericite-rich vein contacts; tourmaline appears as fine, euhedral grains as a result mainly of biotite substitution. In adjacent quartz veins, coarser-grained tourmaline develops apparently resulting from direct fluid precipitation. Both are relatively rich in Mg, the former exhibiting Fe/(Fe+Mg) of 0.395 to 0.489, whereas the latter has a Fe/(Fe+Mg) of 0.496 to 0.660. This suggests slight variations in the activity of Fe/Mg in the fluid, from the incipient (chlorite) to the advanced (vein) stage of alteration, and that iron was readily available to participate in the silicate to sulfide reactions.

A kyanite-bearing, sericite quartzite occurs at the base of the mineralization. Although not modified by the least-altered assemblage, it exhibits pyrophyllite after kyanite and rare tourmaline.

The hanging wall, mylonitic itabirite is manganese-rich and originally composed of cummingtonite and Mn-rich magnetite (Table 5). Close to mineralized veins, the itabirite displays carbonate (dolomite) and sulfide alteration, marked by abundant rhodocrosite and pyrrhotite. Post-tectonic sperssatine porphyroblasts develop at the top of the veins, whereas at the base, staurolite and biotite develop, suggesting amphibolite facies conditions of a possibly much younger, perhaps Brasíliano-age, metamorphism (Menezes 1999).

Advanced-stage silicification is attested to by the development of gold-bearing quartz veins, whose emplacement can locally brecciate host lithological units. Quartz veins contain ankerite, sulfides (arsenopyrite, pyrrhotite), tourmaline, and may contain biotite and albite. Gold forms inclusions in pyrrhotite, a characteristic that differs from the free nature of gold in the Passagem de Mariana Mine, where it occupies fractures in arsenopyrite (Fleischer and Routhier 1973).

The development of a quartz-sericite-(± chlorite) ferrodolomite schist with variable amounts of sulfides, gold and tourmaline suggests significant B, $CO_2$ and S addition. These combined with iron, magnesium, potassium and aluminum involved in the break-up of biotite, chlorite and white mica at the various stages of hydrothermal alteration.

**THE SÃO BENTO MINE** The São Bento Mine, property of Eldorado Gold Corporation, is situated 10 km from the town of Santa Barbara. Ore reserves presently stand at 3 Mt at 9 g Au/t.

The geology of the São Bento Mine is dominated from top to bottom by the Lower Iron Formation, the Basal Graphitic Formation, the São Bento Iron Formation and the Carrapato Formation. They belong to the Nova Lima Group (Martins Pereira 1995).

Two types of structurally controlled ore have been identified (Fletcher 1989). The first composes sulfide-bearing quartz veins. A second type constitutes finely laminated and banded sulfides in BIF, resulting from sulfidation of the latter, and is better developed close to veins. These correlated with Vieira's (1987b) Types-1 and -3 mineralization styles, with predominance of the former. BIF is made up of

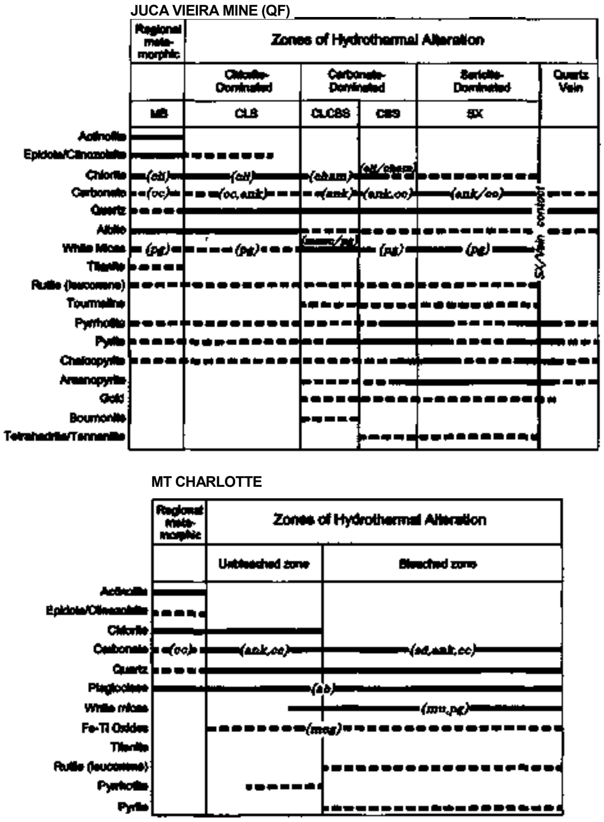


*Figure 5 - Minemlogical compoSítion of hydrothermal alteration zones surrounding metamafic rocks. Alteration at Mt. Charlotte Mine (Australia; in McCuaig and Kerrich 1994) is shown for comparison with the Juca Vieira Mine (data in Pereira 1996). Least-altered, metamorphic assemblages are at left of diagrams and quartz vein assemblage at the right. Abbreviations: MB: metabasalt, CLS: chlorite schist, CLCBS: chlorite-quartz-sericite-carbonate schist, CBS: quartz-sericite-carbonate schist, SX: quartz-carbonate-sericite schist. (Fe)-ank = (Fe)-ankerite; cc = calcite; cham = chamosite; cli = clinochlore; pg = paragonite; mag = magnetite; muse = muscovite; sd = siderite.*

cream-pink, carbonate-quartz (± sericite) bands which alternate with grey, magnetite-rich bands.

Gold-sulfide zones can be parallel to or transect the banding of BIF, which is conferred by the alternating bands of magnetite and quartz-carbonate. The stretching lineation that controls the mineralization is parallel to the constant plunge of 130/55. A sinistral, *en echelon* array of veins implies a system of dextral, strike-slip, lateral shearing (Spencer 1989). Strike-slip dislocation at São Bento is easily identified and visualized in longitudinal plans of the mineralized bodies. According to Martins Pereira (1992, 1995), gold mineralization took place during the strike-slip movement associated with the shear-zone ductile-brittle tranSítion. Under such conditions, permeability of the chemically reactive iron formation would have been enhanced.

Martins Pereira (1995) and Godoy (1995) describe the mineralogical compoSítion of gold-bearing zones. Petrographic characteristics suggest that gold depoSítion is accompanied by varying enrichment of sulfides, carbonate, chlorite, quartz and sericite. This mineralogical variation imposes a zonal pattern that ranges from 1) a central mineralized zone containing quartz + carbonate (ankerite) + sericite + sulfides (pyrrhotite, arsenopyrite, pyrite); through 2) an intermediate zone with quartz + sericite ± carbonate ± sulfides ± chlorite ± magnetite; to 3) an outer zone with quartz + chlorite + sericite + magnetite + carbonate ± pyrite (Martins Pereira 1995).

Pyrrhotite, arsenopyrite and pyrite, in that order, are the most common sulfides. Arsenopyrite is relatively constant, and forms at the expense of pyrrhotite that substitutes pyrite. Both pyrrhotite and arsenopyrite form at the expense of magnetite. Pyrrhotite and pyrite have a conspicuous behavior, because the increased quantity of the former is associated with the diminution of the latter, and vice versa. Pyrrhotite amounts increase at depths below Level 21, a characteristic interpreted by Marchetto (1997) as resulting from a relative increase in the metamorphic grade. Accessory minerals are rutile, magnetite, plagioclase, scheelite, titanite, chalcopyrite, sphalerite, covelite, galena and bornite.

**THE CONTROVERSY REGARDING MINERALIZATION AGE** With the exception of the Santana Gold Mine, all other deposits described are hosted solely by rocks of Archaean age.

The age of the mesothermal gold mineralizations in the QF is controversial. Although the subject is simply beyond the scope of this paper, considering that hydrothermal minerals are interpreted to have developed within structures linked to different deformation phases, a brief comment is in order.

Despite the uncertainties, it suffices to say that the little information available indicates an Archean age of mineralization, based on geochronological data. These consist in a Pb-Pb age in galenas up to 2.71 Ga (Thorpe *et al.* 1984); a Pb-Pb minimum age in arsenopyrite and pyrite from the São Bento Mine of 2.65 Ga (single stage growth curve; DeWitt *et al.* 1994); very discordant U-Pb minimum ages using rutile of hydrothermal origin reported by Noce (1995) and Machado *et al.* (1992) at 2580 and 2309 Ma, respectively. The younger U-Pb (2309 Ma) age is interpreted to relate to Pb loss in Transamazonian *(ca.* 2.0 Ga) times.

A minimum U-Pb age of 2278 Ma was obtained by Schrank and Machado (1996), who analyzed detrital zircon and monazite grains in the host to gold at the Morro Velho Mine. They suggest this to be the maximum age for gold mineralization. A Rb-Sr age of 2130 ±101 Ma (Belo-de-Oliveira and Teixeira 1990) was obtained for white mica associated with hydrothermal alteration near Caet6.

As pointed out above, the tectonic evolution of the QF is complex and much debated in the literature. Lack of precise geochronological data hampers the establishment of the age for the evolution of each deformation stage ($D_1$ $D_2$, $D_3$, $D_4$), notwithstanding the fact that not all students of the QF's structures believe in all four phases (see above). Nevertheless, regional field, geological relationships and structural analyses have led to the characterization of deformation episodes ranging from the Archean to the Upper Proterozoic, Brasíliano times. Within this framework, gold mineralizations have been tied to any one of these geotectonic events, with no consensus yet.

Recently for example, Schrank *et al.* (1996) suggested that the mineralizations at the Cuiabá and the Passagem de Mariana mines are contemporaneous and related to the Transamazonian Event. One of the present authors (Ribeiro-Rodrigues 1998) relates the Cuiabá mineralization to the $D_1$ phase of an $E_n$ event described above, which he concludes to have occurred after the Minas Supergroup depoSítion (younger than 2.1 Ga). Hence, the En event would either correspond to the Paleoproterozoic, Transamazonian Event, or to Negsroterozoic Brasíliano Orogeny.

**SUMMARY AND CONCLUSIONS** This paper describes styles of mineralization and hydrothermal alteration in a number of mesothermal gold deposits in the Quadrilátero Ferrífero region of Minas Gerais.

The alteration associated with different lithological units imposes varying mineralogical associations in zonal patterns enveloping gold ore. Such associations reflect original fluid compoSítion, and the fluid's compoSítional evolution due to fluid to rock interaction in structurally controlled pathways. The zonal pattern reflects varying fluid to rock ratios under roughly isothermal conditions. In the case of mesothermal, lode-gold ore deposits worldwide, the amount of evidence points to a single, dominant fluid source of $CO_2$-$H_2O$ composition (Groves and Foster 1993).

In all deposits described, gold mineralization is sited within or at the boundaries of metamorphosed volcanic and/or sedimentary rocks. The mineralizations are epigenetic, structurally controlled and related to sulfide enrichment of host rocks. It is beyond the scope of the present paper to discuss the epigenetic *versus* syngenetic origin for the QF gold deposits. The subject has been the object of heated debate for at least the past two decades (Fleischer and Routhier 1973, Vial 1988, Duarte, 1991, Ladeira 1991, among others).

The deposits are either replacement-dominated (BIF-hosted mineralizations at the Cuiabá, Raposos and São Bento) or disseminated in zones of hydrothermal alteration (carbonate-sericite) associated with quartz veins (e.g. Juca Vieira and Santana mines). Similarities between both replacement, stratabound and shear-related mineralizations are evidenced by common and/or similar features such as: 1) Fe-rich host lithological units; 2) stratabound characteristics (confinement to a

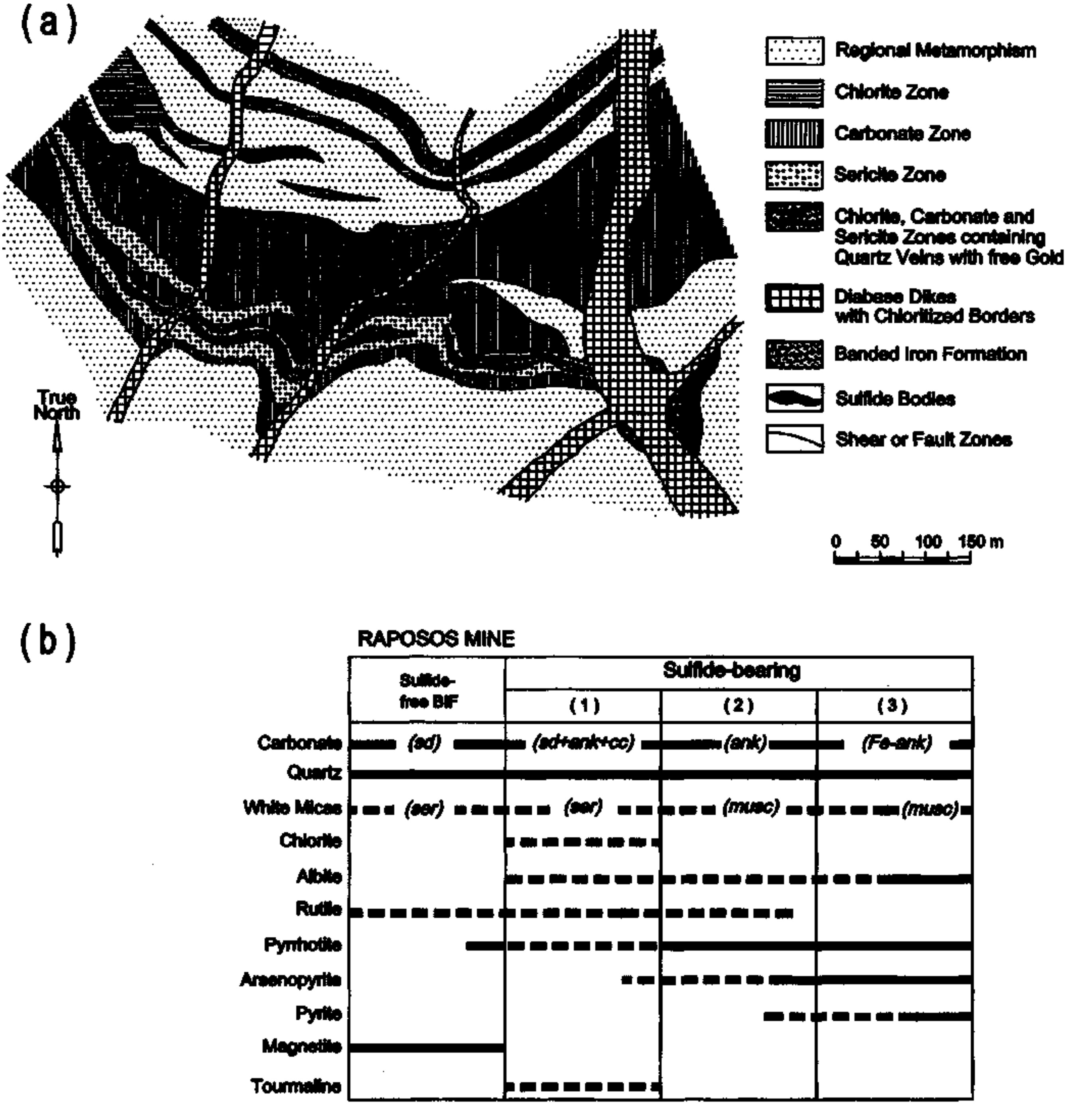


*Figure 6 - **(a)** Schematic, hydrothermal-alteration zonal pattern for metamafic and metaultramafic rocks at the Raposos Mine (after Vieira 1991a). **(b)** Mineralogical compoSítion of sulfide-free BIF and of zones of progressive, hydrothermal-sulfide enrichment and shearing. Percentage ofsulfide increases from (1) to (3). Gold grade increases from left to right (see text). Abbreviations: ser=sericite, and as in FigureS.*

single host lithological type); 3) ore mineralogical compoSítion; 4) ore chemical compoSítion; 5) replacement phenomena; 6) alteration patterns; and 7) structural control.

These mineralization styles may describe entire gold deposits, individual orebodies or particular portions of orebodies. Each style reflects a particular host rock structural preparation and the compositional evolution of the fluid. It is also associated with distinct grade-tonnage relationships.

Precipitation of gold and sulfides is associated with shearing of host Fe-rich rocks, which acted as a chemically favorable trap. This suggests focused fluid flow along structurally induced permeabilities.

Regardless of rock type, alteration assemblages within haloes of varying mineralogical compoSítion mark the hydrothermal alteration styles in all deposits. The main general characteristics are summarized as follows:

(1) Alteration assemblages replace pre-alteration (metamorphic) associations, pointing to their syn- to post-peak metamorphic development age;

(2) Alteration assemblages are dominated by some combination of quartz, carbonate, K/Na-mica, feldspar (albite), Fe/Mg-chlorite, pyrite, pyrrhotite, arsenopyrite, with tourmaline as a common accessory or even a major phase;

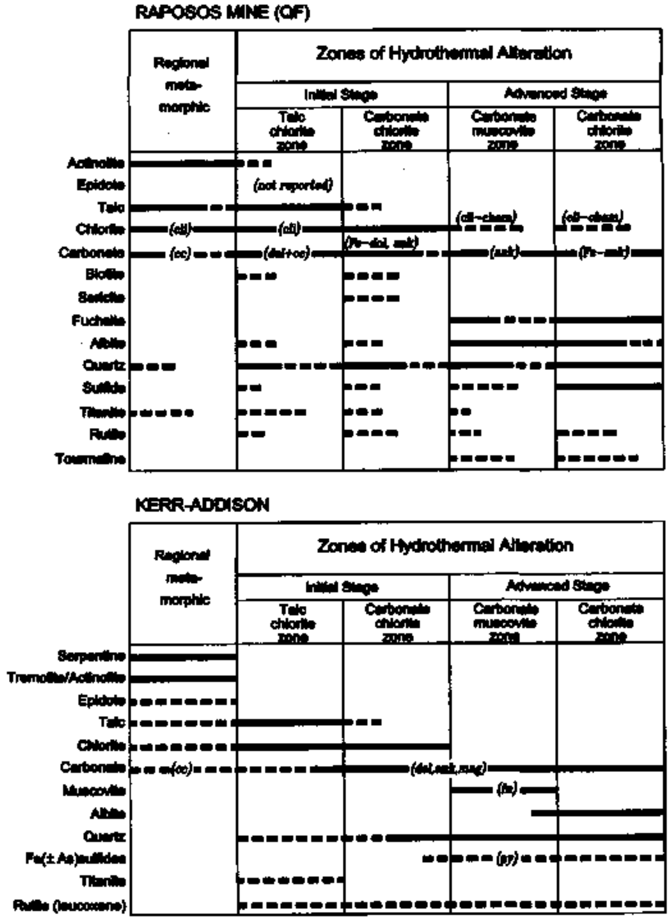


*Figure 7. Minemlogical compoSítion of hydrothermal alteration zones surrounding metaultramafic rocks. Alteration at the Kerr-Addison Mine (Canada; in McCuiag and Kerrich 1994) is shown for comparison with the Raposos Mine (data of Junqueira 1997). Least-altered metamorphic assemblages are at left of diagrams. Sulfide is gersdorffite (NiAsS). Abbreviations: (Fe)-dol = (Fe)-dolomite; fu =fuchsite; py = pyrite, and as in Figure 5.*

(3) K/Na-sericite (and less commonly Cr-bearing mica) alteration usually envelops strongly mineralized zones, mainly around quartz veins in metamafic rocks. Sericite schists containing quartz, carbonate and some sulfides commonly mark the hanging and footwall contacts of BIF-associated orebodies. Quartz veining and silicification are variably developed;

(4) Pervasive carbonate alteration has a central core of Fe-ankerite/ankerite, intermediate ferrodolomite or dolomite grading out into fringes rich in calcite (metavolcanic rocks) and/or siderite (BIF), commonly with associated chlorite;

(5) In Al-poor rocks such as BIF, carbonate alteration (mostly ankerite) is particularly prominent;

(6) Sulfide layers associated with ore do not represent a primary sedimentary depoSítion, but are the result of sulfidation (pyrrhotite, pyrite, arsenopyrite) of quartz-carbonate (mostly siderite)-magnetite layers of BIF;

(7) All incipient-stage mineralogical reactions suggest an initial reducing fluid (magnetite to pyrrhotite, epidote to chlorite);

(8) The predominance of unbuffered assemblages in the proximity to ore indicates infiltration of large volumes of fluid from an external source. The zonation of alteration types reflects evolution in the compoSítion of the fluid through interaction with wallrocks;

*Table 5 - Mineralogical variations associated with the hydrothermal alteration at the Santana Mine in the fallowing order: least-altered, metamorphic assemblage (at left); initial (incipient) and advanced alteration stages.*

| | Regional Metamorphic | Initial Stage of Alteration | Advanced Stage of Alteration |
|---|---|---|---|
| Biotite-quartz schist | biotite | chlorite<br>titanite<br>tourmaline | white mica<br>ferro-dolomite<br>tourmaline<br>arsenopyrite |
| Sericite quartzite | kyanite | | pyrophyllite<br>tourmaline |
| Cummingtonite itabirite (BIF) | magnetite<br>cummingtonite | | pyrrhotite<br>rhodocrosite |

(9) Large fluid volumes under conditions of high Py favored the large-scale recrystallization and precipitation along shear-induced permeability;

(10) The evolution from chlorite-rich to carbonate-rich assemblages, well recorded in metamafic rocks, indicates that a $H_2O$-dominated fluid in the incipient stage af alteration evolved from an original, higher $CO_2$:$H_2O$ ratio fluid typical of the advanced stages of alteration;

(11) Whereas S, $CO_2$, As, Au are added during the alteration, $SiO_2$ is either stable or lost, suggesting that contemporaneous quartz veining is derived from direct silica precipitation;

(12) $CO_2$ addition is constant. It is conspicuous in the advanced stages of alteration. Since $CO_2$ combines with Fe, Ca, Mg and Mn released from reactions in progressive stages of alteration, the saturation index $CO_2/(Ca+Fe^{2+}+Mg+Mn)$ is useful as a measure of alteration degree. During sulfidation $CO_2$ addition may not be registered;

(13) Gold is closely related to wallrock alteration because it is simultaneously enriched in zones of carbonate, sericite, and tourmaline (mainly Santana) alteration, together with quartz and sulfides;

(14) Microtextural studies indicate that gold depoSítion occurred simultaneously with sulfide precipitation. This close association suggests that reduced sulfur complexes were the predominant transport mechanism;

(15) In the case of BIF-hosted mineralizations, gold depoSítion must have occurred due to fluid-wallrock sulfidation reactions;

(16) In the case of gold bearing carbonate and sericite alteration zones, and associated quartz veins, involving cation and or $H^+$ consuming reactions (Juca Vieira and Santana mines), pH variations may have been in part responsible for gold precipitation.

***Acknowledgments*** This review paper results from the senior author's many years of research, teaching and supervising students in the field of hydrothermal alteration, especially in the case of gold. We wish to thank Mineração Morro Velho Ltda. and Eldorado Corporation for their support, for granting permission to collect samples and for sharing data with us. CPRM-Servico Geológico do Brasil, COMIG and colleagues at CPMTC-IGC-UFMG are acknowledged for their valuable co-operation. Discussions with Eduardo Simões and Eduardo A. Ladeira, and many other geologists and geology students, who have worked on gold deposits in the QF, provided a wealth of stimulating ideas over the years. The senior author is indebted to Franciscus J. Baars for his patient discussions and enlightening comments, which enormously improved the earlier draft manuscript. Di6genes L. de Souza Bernardino dispensed great help in putting together the reference list. Silvana R. da Silva helped in the study of thin sections of the Raposos Mine. Joao H. Laurenti drafted most of the figures. Much of the results of our research have benefited from continuing financial support from CAPES, FINEP, FAPEMIG, CNPq and DAAD in the form of bursaries and project resources.

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**Manuscrito A-974**
**Recebido em 14 de abril de 1998**
**ReviSão dos autores em 30 de setembro de 1998**
**ReviSão aceita em 05 de outubro de 1998**