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

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RESUMO ESTILOS DE ALTERAÇÃO HIDROTÉRMICA E MINERALIZAÇÕES A URFÍFERAS ASSOCIADAS AO GRUPO NOVA LIMA DO QUADRILÁTERO FERRIFERO: PARTE I, DESCRIÇÃO DE DEPÓSITOS SELEÇÕES


Geochemical units of the QF embody hydrothermal alteration zones within metamorphosed mafic volcanic- and sedimentary rocks; and 3) Au-bearing quartz-carbonate-sulfide veins and veinlet systems. These styles reflect variations in fluid-rock interaction, and thereby a distinctive ore mineral composition. In addition, distinctive mineral associations characterize hydrothermal alteration in conventional hydrothermal alteration zones surrounding hydrothermal ore systems (e.g., veins). The processes of ore deposition 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 composition 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 Williams-Jones et al. 1994).

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 Ferrifero (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 1997, Herrington et al. 1997, Lobato and Vieira, 1998, the present volume).

Vieira (1987a, b) was one of the pioneers in the study of hydrothermal alteration associated with the hydrothermal alteration of the Archean Rio das Velhas Greenstone Belt, hosting mesothermal, lode-gold deposits in the QF. Other thorough contributions are Vieira (1988, 1999a) 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). 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 QUADRILÂTERO FERRIFERO The Quadrilátero Ferrifero (QF) is located in the southwesternmost São Francisco Craton (Almeida 1967, Almeida and Hasui 1984) in southeastern Brazil (Figure 1). The São Francisco Craton is limited by Brasiliano-age (700-450 Ma) mobile belts, and is constituted by a basement consolidated during the Archean and Eoeproterozoic. The geological units of the QF embody granite-gneissic terranes of Archean age; 2) Archean greenstone belts of the Rio das Velhas Supergroup and other related successions; and 3) Neoproterozoic, metasedimentary units of the Minas Supergroup, the Itu- glam Group and the Espinhaço Supergroup (Dorr 1969, Noce et al. 1997, Herrington et al. 1997), Bibe (1998), Menezes (1998). These contributions served as the motivation for the present attempt to review and integrate the dispersed data into a single, coherent unit.

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Schrank and Silva (1993) have recently revised the geology of the basin 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. Schorsch 1978, Schorsch et al. 1982, and Noce et al. 1990). Volcanoclastic rocks and minor felsic volcanic rocks are also present (e.g. Ladeira 1980, Oliveira et al. 1983, Vial et al. 1987, and Noce et al. 1992). Chlorite phylite, banded iron formation (BIF), greywacke, quartzite and conglomerate comprise the clastic and metaconglomeratic rocks in the region (Dorr 1969, Ladeira 1980). Turbidites of mafic to felsic composition are also important (Schrank and Silva 1993).

The sequence displays mineral associations typical of the green-schist metamorphic facies. Herz (1978) indicates that the regional metamorphism increases eastwards from lower greenschist to upper 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 symmetrical, spaced cleavage, a crenulation lineation and fold axes nearly orthogonal to S2. Vieira and Simões (1992) interpret D2 as resulting from D2 progressive evolution. D2 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 2003). The main period of deformation is recorded by 3400-3000 Ma. Baars (1997) reports Sm-Nd and Rb-Sr isochron ages that differ significantly from the main gold mineralizations. Members of the Nova Lima Group and emplacement of associated granitoids; a final phase of younger granite generation occurred between 2720-2700 Ma and at 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 2.6-2.1 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 Brasiliano, Cratonward, thin-skinned tectonism is devoid of firm geochronological evidence, although lower concordia intercepts of U-Pb zircons 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 cite Albert (1964; Raposos Mine); Ladeira (1980; Morro Velho Mine); Duarte (1991; Passagem de Mariana Mine); Souza Filho (1991; Carrapato Mines); Godoy (1994) and Jungueira (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 (1991a) published rock geochemical investigation for the Morro Velho, Faria, Cuiabá, Raposos (also Vieira 1987a), Bela Fama, Morro da Glória, Paciência and Juca Vieira mines.

Ultramafic Rocks Ultramafic rocks at the base of the Nova Lima sequence are intercalated with more abundant, mafic rocks. Tholeiitic basalt occurs, in places, as pillowed flows, and displays varieties with preserved subophitic textures. Komatiitic basalt can exhibit original pyroxene spinifex texture imposed by actinolite laths and plagioclase 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).
acertistics. Mafic intrusive rocks, comprising diabase and locally gabbro, form NE-striking dikes parallel to S$_1$.

Highly modified peridotite exhibits pseudomorphed olivine (an
tigorite), at places with talc and magnelite along fractures. Pseudo-
morphs of pyroxene in pyroxenite are made of tremolite, and ankerite, some Mg-chlorite and magnelite, in a fine-grained, Mg-chlorite matrix.

Vieira (1991b), Pereira (1996) and Junqueira (1997) conclude that the metamafic rocks have tholeiitic basalt compositio$\text{S}$; A Kamatiitici component is also indicated by Vieira (1991b). Since they show close similarities to Condie’s (1981) Archean tholeiitic basalt TTH and subordinately to TTH, they have been correlated with modern, calc-
akaline, island arc, tholeiitic basalt and to mid-ocean ridge basalt (MORE). Ladeira (1988) also recognizes a MORB-type signature.

Zucchetti (1998) undertook a det al alledd petrographic and whole-
rock major and trace-element analyses to 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 evolved from compositio$\text{S}$ of those of the Mg-rich tholeiitic basals.

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 green-
stone belt. This 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 andesite compositio$\text{S}$ 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 pla-
pioclase suggesting an andesite compositio$\text{S}$$\text{.}$ Fragment sizes in thin, centimetric horizons alternating with meta
tectonic 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, 0.3 to 1 m thick. Fragments are mainly millimeter-sized phe-
nocrysts of quartz, plagioclase, and in places of rock fragments ranging
from dactitic to rhyodacitic compositio$\text{S}$. 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 generally referred to as graphite schist, this dark rock is better classified as carbonaceous phyllite. It contains sericite and carbonate, and occurs at the top of BIF layers or between basaltic flows. The tuff is composed of quartz, sericite and carbonate. Cycles that display gradational bedding are, on
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Lapa seca is a generic term applied to grey-beige, massive, carbon
ate (ferrodolomite, ankerite, siderite, and calcite) rocks. It constitutes
particular 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, Morro Velho do Vale, Tapira, Raposos, São Bento, Faria, Bicalho and Bela Fama mines, hosted by rocks of the Nova Lima Group (e. g. Ladeira 1991, Vieira 1991a, Ribeiro-Rodrigues et al 1996a). Lode

gold mineralization at the Santana Mine is located along the shear
contact between rocks of the Minas Supergrupo (Iabara 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 not restricted to regional fractures, typifying NW/NW, NE/SE-directed, thrust-related, oblique ramps or EW-directed, transcurrent faults, the latter being the most favored loci for gold
depositio$\text{S}$ (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 con-
trolled by a stretching lineation that coincides with fold axes ("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 min-
eralizations 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.

In mafic belts dominated by metavolcanic rocks, further subdivision of each deposit is based on the dominant form of mineralization and on the host rock. Establishing 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 elastic sedimentary rocks.

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

BIF-hosted gold deposits are divided by Kerswill (1993) into
stratiform and non-stratiform 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 or individual orebodies or particular portions of orebodies. This
classification system is understood to be useful because each miner-
alization style 1) is associated with distinct grade-tonnage relationships; 2) reflects a particular host rock structural preparation; and 3) reflects the compositional evolution of fluid to rock interaction and, thereby, a distinctive ore mineralogical compositio$\text{S}$.

Novo Lima Group Gold Mineralization Styles Gold min-
eralizations 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 compositio$\text{S}$.

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, shear zones in BIF and lapa seca are loci for pyrrhotite-dominated, Type-1 mineralization style. Pyrrhotite
occurs with subordinate pyrite and arsenopyrite; magnetite, chalcopy-
rite,珑ite and hematite as accessory minerals. These reefs are
parallel or sub-parallel to bedding, and associated with folded or en echelon, boudined quartz veins. They alternate with BIF or non
sheared lapa seca, displaying ramifications and disruption of the stratigraphic po$\text{S}$itioning. Shear zones crosscut shear zones indicating multiple pulses of mineralization.

Pyrrhotite in D, shear zones is less common, at varying angles with bedding. Hydridioblastic 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 do Góis, and Bicalho mines and subordinate in Cuabi, 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 Style-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 D2 fractures, foliations, shears and quartz veins that cut the host rocks at a high angle. In BIF, it is clear that fractures parallel to S2 and subordinately to S3 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 compoSitioS in Cuabi and Lamego mines, and are more restricted in Morro Velho, São Bento, Raposos, Faria, Morro do Góis 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, Cuabi modified 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 of 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 D1, despite the different deformation peaks recognized.

**METAVOLCANIC ROCKS** Ductile shearing and hydrothermalism largely modify igneous textures and structures of metavolcanic rocks, including pillows and xenoliths. The resulting rock type is a mylonitic schist with boudinaged, sigmoidal and folded quartz veins, with varying mineral composition 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 albition, tourmalinization, sulfidation and silicification.

Hence, hydrothermal alteration is dominated by the development of hydrated silicate phases in the incipient alteration stage, indicating a H2O-predominant fluid, and carbonates in the more advanced stages, suggesting a fluid with varying CO2–H2O 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 comprends 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.**
Table 2 - Classification scheme for mesothermal, lode-gold mineralization styles in the Quadrilátero Ferrífero proposed by Ribeiro-Rodrigues et al. (1997).

<table>
<thead>
<tr>
<th>Structural Style</th>
<th>Important Deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suturabound, replacement dominated</td>
<td>Morro Velho, Cuiabá, Sítio Bom, Repásio, Lavagem, Pimenta, Repásio III, Tingui</td>
</tr>
<tr>
<td>Shear-zone-hosted, replacement-dominated</td>
<td>Bela Fina, Bela Fina, Pimenta, Nova Viúna, Pimenta, Tingui, Cuiabá</td>
</tr>
<tr>
<td>Shear-related-quartz vein</td>
<td>Bela Fina, Nova Viúna, Pimenta, Morro Velho, Cuiabá</td>
</tr>
</tbody>
</table>


Outstanding textural features are sulfide grains enveloping magnetite or siderite, surrounded by recrystallized carbonate, and sulfides developing along cleavage lines of magnetite or 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 Areas 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 Auriferous BIF is of hydrothermal origin.

Metapelitic rocks exhibit discrete alteration zoning due to limited reactivity of quartz, carbonate and sericite relative to the inferred H2O-CO2 compostition. Hydrothermal haloes are millimeter- to centimeter-thick composed of chlorite, sericite, quartz and carbonate without defining a proper zonation (Corrego do Sítio, Sáo 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 600 000 oz 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 thrusts and/or shear zones within metavolcanic or metasedimentary rocks (e.g. Corrego do Sítio, Sáo Bento and the NW orebody at Juca Vieira).

According to Ribeiro-Rodrigues (1998), the inventory of structural elements in the Cuiabá Mine area can be grouped into three deformation phases, namely D1, D2 and D3. However, for this co-author the structures termed D1 elsewhere in this paper are not present in the Mine. Hence, Ribeiro-Rodrigues (1998) denomination D1 refers to structures equivalent to those recognized as D3 elsewhere in the QF (Vieira and Oliveira 1998). Ribeiro-Rodrigues’ denomination is maintained only in this subsection.

D1, D2 and D3 are considered by one of the authors, L.C.R.-R., to be of a single, progressive, compressional tectonic event, named E1 (Ribeiro-Rodrigues et al. 1996b). This event is to have occurred after the depoSition 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 D2 and D3 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 (S1 = 135-245). They show a prominent minor 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 (D1) fold axes and to the intersection between bedding (S0) and the foliation (S1). Late, north-west-verging, sigmoidal thrust faults reactivated pre-existing structures and caused folding, boudinage and rotation of the Cuiabá-BIF.

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

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morro Velho</td>
<td>Repaso</td>
<td>Cuiabá</td>
</tr>
<tr>
<td>Pyrite</td>
<td>22</td>
<td>-</td>
</tr>
<tr>
<td>Fyrite</td>
<td>42</td>
<td>47</td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>28</td>
<td>95</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Gangue</td>
<td>6</td>
<td>31</td>
</tr>
</tbody>
</table>


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, metamorphic rocks (Viana orebody).

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.

Steady, related, metamorphosed mafic volcanics- 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. Galinho Footwall orebody). The third style comprehends gold-bearing quartz veins (e.g. Galinho Footwall and Viana orebodies). Both can be correlated with Vieira’s (1987b) Type-3 mineralization style.

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-metal contents. In plan view, the irregularly shaped orebodies show consistent down-plunge continuity parallel to the linear fabric of the E1 event, e.g. parallel to the D1-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 D1 and D2-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 D1 and D2 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 carbonate-metasediments are only locally altered to sulfide-quartz-carbonate veins and the Cuiabá-BIF horizon is sulfidized, the mafic metavolcanic rocks show a characteristic pervasive alteration zonation (Ribeiro-Rodrigues et al. 1994).
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 areas. 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, calcite, quartz carbonate layers and quartz and Fe-carbonate in chert layers. Toledo (1997) indicates that some of these Fe-carbonate layers result from the oxidation of original carbonaceous matter associated with siderite and Mn-ankerite.

Other sulfides are pyrrhotite, 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, Na, Sr, and less meta-ultramafic rocks, and intercalated graphite schists and quartz-sericite schist (CLCBS). The CLCBS and quartz-sericite-carbonate schist (CBS).

In CBS, carbonate (ankerite ± calcite) is more abundant and the matrix is paragonite. Chlorite (clinochlore ± chamosite) and calcite occur in 5 vol. % each and sulfides are more abundant than in CLCBS, including arsenopyrite (locally up to 10 vol. %), pyrite (1 vol. %), pyrhotite (1 vol. %) and calcite (1 vol. %). The accessories (< 1 vol. %) are albite, leucoxene, paragonite, rutile and tetrahedrite-tennantite. Clinozoisite may occur at places in the absence of plagioclase.

Gold is observed microscopically from the carbonate zone onwards. Quartz-carbonate-sericite schist (SX) is more restricted and typically the sericite alteration zone alongside the ore. Paragonite, ankerite ± calcite and quartz predominate, whereas clinochlore ± chamosite, schoorl, tetrahedrite-tennantite and gold. Chlorite (clinozoisite ± chlorite) 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 boumone) replace pyrite and arsenopyrite (see Figure 5). 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 appearance, pseudo-sedimentary sedimentary processes in the mineralized portions of the BIF. This character gives the impression of laterally continuous, alternating sulfide, quartz-carbonate and chert layers.

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

According to Vieira (1988), Duchini Jr. et al. (1990), and Silva et al. (1990, 1991), the orebodies comprise sulfide-bearing, carbonate veins and at places brecias, hosted mainly by metavulcanic rocks of mafic and intermediate compositions. The deposits 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 saccularized envelopes in contact with the quartz-carbonate veins.

**Hydrothermal Alteration** Pereira et al. (1995), Pereira (1996) and Pereira et al. (1994) undertook geological, petrographic and whole-rock, major- and trace-element compositional 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 northeastern 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, pyrite (± 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-quantum chlorite schist (QCS) 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 JUCA VIEIRA GOLD MINE The Juca Vieira Gold Mine, property of the Mineração Morro Velho Ltda., is located at the central-northern boundary of QR, 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 inactive.
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). CO2-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 Zuccheri (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 metamatism, using Greisen’s (1967) approach. The intensity of hydrothermal alteration is monitored by the use of the relation CO2/(Ca+Fe2++Mg+Mn) that reflects the degree of carbonate development and cation saturation in carbonate.

Under practically isovolumetric conditions, there was leaching of SiO2 and general increment in the amounts of hydrated phases, transposed in an increase of H2O. 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 Na2O and general increase in K2O in the intermediate and advanced stages of alteration. There is an overall increase in CaO, CO2, 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 apparent silica loss. Muscovite-paragonite nucleation accounts for the scheme previously suggested by 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-related shear zones are sub-parallel to Sj and Sg of BIF, and destroy the bedding that is preserved only in fragmented relics elongated according to shearing.

Gold-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. Pyrite-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 D0, inclined fold. At Level 28, the average plunge of both folds and orebodies is 95°/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 lithochemical 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 (1991a) 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 detalling 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 chloride-albite and chloride-sericite zones. The first reactions involve the development of chloride and calcite from epidote + actinolite, to form a chloride-albite-carbonate-quartz schist. Carbonates are mainly ankerite, followed by calcite.

The chloride-sericite zone is marked by the replacement of the albite + chloride + calcite assemblage to form a sericite-chlorite-carbonate (ankerite)-quartz schist, by way of interaction with a CO2 + K+rich fluid that may evolve to a H2O + 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 chloride + calcite + quartz, possibly reflecting the reaction with a CO2 + Na+ fluid (carbonate-albite zone). In the carbonate-sericite zone, chloride + calcite can also be replaced by an assemblage containing Mg-siderite + quartz; this could have been attained through interaction with a CO2 + 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-
Further carbonate (ankerite) + quartz develop at the expense of earlier Mg (Fe)-chlorite + Fe-dolomite + quartz, via interaction with CO2 with or without varying amounts of talc. Proposed mineral reactions carbonate zones, which characterize chlorite-carbonate-quartz schists and unaltered BIF displays layers alternating between fine-grained, drothermal alteration and/or mineralization (Figure 6b). Undeformed, xenoblastic cross-cuts layers. Sulphidation (1) replaces smoky-quartz-carbonate layers (3, dark grey); and chert layers (4, clear). Late, local remobilized quartz (5) cross-cuts layers. Sulphidation (1) replaces smoky-quartz-carbonate layers (3). Chemical variations of selected major and trace elements during sulphidation (Ribet-Rodrigues 1998). Sulphide layer (a)-B is compared to the least altered 3-type layer (a)-A. Notice large gold and sulphur variations. Calculations for constant volume (modified after Gresens 1967); G = specific gravity.

A carbonate-albite-quartz schist, with or without varying amounts of albite, chlorite and fuchsite, is typical of the advanced stage. The west-vergent thrust post-dates the large-scale folds of the Mariana anticline. A 090°-120°-dipping, mineral stretching lineation associated with the contact in the Antônio Pereira Range coincides with the tectonic zone 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 (Flesicher and Routher 1973). The Dom Pedro North del 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 Supergrup, 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 Leonards (1992) describe gold mineralization in the Maquine Group related to post-tectonic decompression in the region. The Santana Gold Mine is located in the northwestern limb of the Mariana Antcline, 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 (Flesicher and Routher 1973). The Dom Pedro North del Rey Mining Co. Ltd. exploited the mine from 1863 to 1866, known for its gold since the 18th century. The mine is presently closed.
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 Ibatira 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): \( \text{biotite} + H^+ = \text{chlorite} + K^+ + (Mg, Fe)_{2}^{2+} + \text{SiO}_2 \) and \( \text{biotite} + H^+ = \text{muscovite} + Fe^{2+} + H_2O + K^+ + \text{SiO}_2 \) (hydrolysis); \( \text{chlorite} + K^+ = \text{muscovite} + (Mg, Fe)_{2}^{2+} + H_2O + K^+ + \text{SiO}_2 \) (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) 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 sperrsmatite porphyroblasts develop at the top of the veins, whereas at the base, stauroilite and biotite develop, suggesting amphibolite facies conditions of a possibly much younger, perhaps Brasiliano-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, CO2 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 comprises 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...
creamy-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 = muscovite; to 3) an outer zone with quartz + carbonate (ankerite) + sericite + chlorite + magnetite ± 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, chloropyrite, sphalerite, covellite, 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 Archean 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 geochemical 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 an epithermal 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 McCuaig (1996), who analyzed detrital zircon and monazite grains in the host to gold at the Morro Velho Mine. They suggest this to be the minimum 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 Caeté.

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 (D1, D2, D3, D4), 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, Brasiliano 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 Cuibá 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 D4 phase of an E, event described above, which he concludes to have occurred after the Minas Supergroup depoSition (younger than 2.1 Ga). Hence, the E, event would either correspond to the Paleoproterozoic, Transamazonian Event, or to Negroterozoic Brasiliano 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 compoSition, and the fluid’s compoSitional 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 CO2-H2O composition (Grovos 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 Roultier 1973, Vial 1988, Duarte, 1991; Teixeira 1991, among others).

The deposits are either replacement-dominated (BF,-hosted mineralizations at the Cuibá, 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 composition of sulfide-free BIF and of zones of progressive, hydrothermal-sulfide enrichment and shearing. Percentage of sulfide increases from (1) to (3). Gold grade increases from left to right (see text). Abbreviations: ser=sericite, and as in Figure 5.

Regardless of rock type, alteration assemblages within haloes of varying mineralogical composition 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;
3. 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.

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.

single host lithological type; 3) ore mineralogical composition; 4) ore chemical composition; 5) replacement phenomena; 6) alteration patterns; and 7) structural control.
Table 5 - Mineralogical variations associated with the hydrothermal alteration at the Santana Mine in the following order: least-altered, metamorphic assemblage (at left); initial (incipient) and advanced alteration stages.

<table>
<thead>
<tr>
<th>Alteration Type</th>
<th>Regional Metamorphic</th>
<th>Initial Stage</th>
<th>Advanced Stage</th>
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<tbody>
<tr>
<td></td>
<td>Regional Metamorphic</td>
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<td></td>
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<tr>
<td>Biotite-quartz schist</td>
<td>biotite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td>chlorite</td>
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<tr>
<td>Sulfides</td>
<td>sulfides</td>
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<tr>
<td>Carbonate</td>
<td>carbonate</td>
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<tr>
<td>Metamorphic Carbonates</td>
<td>metamorphic</td>
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<tr>
<td>Quartz</td>
<td>quartz</td>
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<td>Pyrite</td>
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</table>

(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 metamorphic rocks, indicates that a H₂O-dominated fluid in the incipient stage of alteration evolved from an original, higher CO₂:H₂O ratio fluid typical of the advanced stages of alteration;
(11) Whereas S, CO₂, As, Au are added during the alteration, SiO₂ is either stable or lost, suggesting that contemporaneous quartz veining is derived from direct silica precipitation;
(12) CO₂ addition is constant. It is conspicuous in the advanced stages of alteration. Since CO₂ combines with Fe, Ca, Mg and Mn released from reactions in progressive stages of alteration, the saturation index CO₂/(Ca+Fe₂++Mg+Mn) is useful as a measure of alteration degree. During sulfidation CO₂ 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 deposition 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 deposition 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 H⁺ consuming reactions (Jaca Vieira and Santana mines), pH variations may have been in part responsible for gold precipitation.

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