GENERAL FEATURES OF THE GOLD DEPOSITS IN THE RIO ITAPICURU GREENSTONE BELT (RIGB, NE BRAZIL), DISCUSSION OF THE ORIGIN, TIMING AND TECTONIC MODEL

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INTRODUCTION
A great part of the gold production in Brazil came from the São Francisco craton. Gold mainly occurs within volcano-sedimentary sequences such as those of the Quadrilátero Ferrífero, Jacobina and Itapicuru, in the southern and north-eastern parts of the craton respectively (Fig. 1). The usually high potential of the gold occurrences in hosting gold mineralization has led many mining companies to invest in exploration for precious metal deposits in these terrains. During the last decade, the discovery and exploitation of some mines and the delimitation of several targets have placed the Rio Itapicuru Greenstone Belt (RIGB) as an important locus for gold mining. However, geologists still believe that the "great deposit" remains to be found.

The genesis of mesothermal Au-deposits has been the most controversial subject among any type of gold deposits and many aspects remain enigmatic. Several hypothesis have been proposed to account for gold origin, namely: metamorphic dehydration reactions (Boyle 1961), granulatization during the cratonization of mobile belts (Colvine 1989; Fyson et al. 1989), fractional crystallization of felsic magma (e.g. Burrows and Spooner 1989) and circulation of meteoric water (Nesbitt 1961), granulitization during the cratonization of mobile belts (Colvine 1989; Hodgson and Hamilton 1989). In recent years, the preferred structural setting of gold deposits has been generally a second-order (ductile)-brittle subsidiary structures (e.g. Eisenhlohr et al. 1989). Such a fact is sometimes inconsistent with the existence of a surprising parallelism between the long axes of ore-bodies and stretching lineations. This paradox still remains to be understood.

The purpose of this paper is to present a review of the RIGB auriferous districts, from the exploration phase (geochemical, geological and geophysical mapping) and mine development to the microstructural analysis. The results are essentially based on petrological, structural and metallogenic studies of gold-bearing quartz veins. As long axes of ore shoots frequently parallel the stretching lineation and quartz microfabrics, they indicate diffusion-recrystallization as the main deformation mechanism acting in the Au-bearing quartz veins. This scenario explains the metamorphic and magnetic evidences for the origin of the mineralization as well as the ambiguous "control" of the orebodies (sulphides overprint the mylonitic foliation) by the stretching lineation.

Keywords: Rio Itapicuru greenstone belt, Shear zones, gold mines, Qz C-axis

RESUMO
FEIÇÕES GERAIS DOS DEPÓSITOS DE OURO DO GREENSTONE BELT RIO ITAPICURU (RIGB, NE DO BRASIL), DISCUSSÃO DA ORIGEM, IDADE E MODELO TECTÔNICO

ABSTRACT
Anomalous concentration of gold is associated with relatively narrow shear zones in the supracrustal sequence of the Rio Itapicuru Greenstone Belt (RIGB). Both geological mapping and geochemical / geophysical surveys led to the discovery of several gold mines. Among them, the Fazenda Brasiliero mine (1401 Au) is the largest one. This paper draws the general features of the RIGB gold deposits and puts constraints on the relationship between mineralization and the structural evolution of the belt. Mineralization is essentially associated (directly or indirectly) with carbonaceous lithologies and is represented by quartz veins/veinlets that define the main orebodies. In the main mines, Au is almost always related to the occurrence of arsenopyrite, appearing as inclusions, within microfractures or attached to the crystal faces. Hydrothermal effects have been recognized within the host-rocks. Recent structural and geochronological data show that gold precipitated late (2.083-2.031 Ga) with respect to the regional tectonic events (Ca - 2.100-2.080 Ga). A coupling between thrusting and late stage of granitic magmatism to account for the generation of the mineralizing fluids is suggested. By leaching Au from the volcanic pile, the metamorphic and pluto-related fluids were driven along early planar and linear anisotropies. Hence this pathway within the shear zones led to a geometric disposition of the orebodies in which their long axes are parallel to the stretching lineation and C-axis preferred orientation.

Palavras-chave: Minas de ouro, eixo C do quartzo, greenstone belt do Rio Itapicuru.

INTRODUCTION
The mylonitic foliation) by the stretching lineation.

Regional tectonic evolution of this region is linked with the closure of the "Greenstone basin", leading to the development of SE-directed thrusts (DI) coeval with earliest granite emplacement (Barrocas com...
Inda and Barbosa 1978; Bernasconi 1983). and Early Proterozoic domains and the main gold mines. The study Figure 1 - Simplified map of the São Francisco Craton with Archean

lateral strike-slip tectonics. This D2 event accounts for the overturning of early-formed foliation planes and induced the development of left style of the deformation. The rising of the plutons led to the steeping of Alta, Efícias and Nordestina, Fig. 2), is associated with a change of deposits known collectively as Fazenda Brasileiro mines. The 50 km named the Weber Belt, Fig. 3). This structure hosts several gold zones herein named the Weber belt and Barrocas complex in the south-eastern area of the exploration phase for each mine. Au particle counting in soil was also developed along N-S trending topographic crests due to silicification. These procedures allowed the determination of the anomalous zones to be defined, which include the three main targets Antas I, Antas II and Antas III. The exploration history and discovery of Antas I is representative of the development of the exploration phase for each mine. Au particle counting in soil was first carried out on a 100 x 25 m sampling grid, rapidly restricted to a 25 x 25 m area close to the main anomaly region. Later, multi-element soil geochemistry showed As to be a good pathfinder of gold and then confirmed the existence of the anomaly. During the following stages, these anomalies were evaluated by trench opening and chemical analysis of the bed-rocks. Complementary drilling defined the 3D shape and allowed their economic evaluation. Four years after the beginning of this exploration phase, a minimum geological reserve (to 100 m depth) of about 12,5 t Au justified an initial investment for mining, whilst continuous research aimed to localize and evaluate new anomalies.

**Correlation between Mineralization and Geophysics**

The geophysical methods, first applied to the discovery of the Fazenda Brasileiro gold deposits, were applied to the Antas area, after the recognition of the orebodies, in order to evaluate any relationships between geophysics and mineralization, radiometric and electromagnetic methods were used (Sena 1987, DOCEGEO internal report). The radiometric method measures the gamma-radiation (related to K-emissions) and the natural emission of U + Th + K. The application of this method must take into account that mineralization occurs in hydrothermally altered rocks that, theoretically, could be enriched or depleted in these elements. The electromagnetic method defines zones of maximum conductivity. In the southern part of the RIBG, this method has demonstrated that the greatest anomalies are related to graphic layers, but the relations with gold mineralization were never clearly established.

The radiometric and electromagnetic methods produce coherent results for Antas I (NMZ), illustrated by excellent correlations between anomalies, conductive zones and localization of the orebodies. For Antas III, there exists a weak difference between these anomalies and the known orebodies. Similarly, the Antas III mineralization does not occur inside, but between two conductive zones. The Antas II deposit does not present a good correlation with the geophysical data. Orebodies do not correspond to the higher radiometric values. Such a fact suggests the existence of a more complex pattern for the Antas II deposit compared to Antas I and III. This is confirmed by this study.

As result of this comparison between geophysical data and orebody localization, we can suggest the existence of a more or less valid connection between conductive rocks, radiometric anomalies and mineralization. However, it would be necessary to proceed to further work.
to north, and from bottom to top, can be distinguished four units
(Santos et al. 1988; Vitorasso et al. 1991, mine terminology will be
given in parentheses):

(1) The Incó unit, which is mainly composed of carbonate-chlorite
schist (CCX) with minor intercalations of carbonaceous schist lenses.
The protolith of this rock is assumed to be basaltic lava.

(2) The Fazenda Brasileiro unit, which is dominated by felsic and
mafic schists. Containing the most important gold concentrations, this
unit needs to be described in more detail (Fig. 3b). Three internal
sequences are identified, i) The Graphite schist (GRX), which is the
hanging wall of the main ore zone. Due to its lateral persistence
and distinctive character, it is considered as a guide horizon, ii) The
Iron-rich quartz-chlorite schist (CLX), which corresponds to two
major layers of 20 and 3 m average thickness (Fig. 3b). Part of this unit
situated at the contact with the main granite hosts the main ore shoot.
A detailed discussion about its origin will be presented below, iii) The
"Intermediate Sequence", which is composed of sericite-chlorite-carbonate
schist (CAX) and plagioclase-actinolite schist (PAX). The latter
are weakly altered gabbroic bodies which show opthic to subophitic
textures and which occur disseminated within the CAX and sometimes
within the CLX (Fig. 3b). The CAX rocks represent less mafic sur-
rounding basalts.

According to Teixeira (1985) and Teixeira et al. (1990), the Fazenda
Brasileiro unit as a whole would represent a mafic silt, emplaced
between metabasalts and turbidites; the intrusion being differentiated
into metabasalt (PAX and CAX), grading to metaferrogranobro (CLX),
even into metaanorthosite (quartz-feldspathic breccia) at the top.
Such a pattern appears inconsistent with the reverse dip of the unit. An
alternative interpretation suggests that the gabbro (sensu stricto) is
restricted to the PAX lithologies (Alves da Silva and Matos 1990,
CVRD company internal report) and that the CLX consisted of differ-
etiated tholeiitic basalts (see discussion below).

(3) The Canto unit, which consists of fine-grained carbonaceous
sediments (pelites and rhythmically banded pelites and psammites),
volcanic layers and an agglomeratic pyroclastic sequence. The pyro-
clastic sequence is the main host rock for the mineralization (Alves da
Silva 1990).

(4) The Abóbora unit, which is located in the northernmost part of
the Weber Belt (not represented on Fig. 3b). It comprises a thick sequence of basalt flows with local and narrow sedimentary intercalations.
The Abóbora gold occurrence (not represented in Fig. 3a) is the
only one hosted in this unit (Kishida et al. 1991).

Because of their lithological similarities, both the Incó and Abóbora
units are weakly altered gabbroic bodies which show opthic to subophitic
textures and which occur disseminated within the basal mafic unit. A controversy still exists about the stratigraphic position of the Canto unit. If we consider
that the Canto unit is a part of the upper sedimentary sequence, its
position within the core of the basal unit remains difficult to explain.
Indeed, it appears satisfying to suggest that the Canto unit is a particular
fades of the intermediate or even basal unit.

**DISCUSSION OF THE ORIGIN OF THE CLX LAYER**
The origin of the CLX layer, the part of the Fazenda Brasileiro unit that contains the main gold concentration, needs to be discussed for a better un-
tstanding of the Au mineralization. Based on field, petrological and geochemical arguments, the CLX layer has been successively inter-
preted as Banded Iron Formation (Monte Lopes 1982), quartz-por-
phyry (Vial 1986, CVRD Company, internal report), meta-ferrogranobro
(Teixeira 1985; Teixeira et al. 1990) or meta-graywacke (Melo Jr.
1990). The first and fourth interpretations involve a sedimentary origin,
whereas the others argue for igneous sources.

The CLX has also been interpreted as a differentiated tholeiitic
basalt (Alves da Silva and Matos 1990, CVRD company internal
report). When they are in contact, relationships between the CLX and
CCX layers (part of the Incó unit) support the interpretation that the
first (CLX) results from theoleiitic differentiation of the latter (CCX).
Moreover, the increase of the Fe content, the decrease of the Cr O2 and
TiO2 content and the increase in free quartz are very common features
of differentiated tholeiitic magmas (Teixeira, 1985). The CLX will be
herein considered as a differentiated product, formed at the end of the
tholeiitic basalt volcanism, with two distinct stages of crystallization:
(i) in the magma chamber, where porphyries of quartz, plagioclase and
magnetite are formed; and (ii) during the extrusion stage. Where the
aphanitic matrix is formed. This seems to be in agreements with
Teixeira et al. (1990) statements which suggests that Petrological
evolution of the intrusion shows a trend of iron enrichment.

**Gold mines of the Fazenda Brasileiro unit**

**MINE STRUCTURE**

In mine areas, a bedding parallel foliation is the earliest
Quartz Veins

In order to obtain some constraints about the conditions of deformation during gold mineralization, we have focused our microstructural analysis on the gold-bearing quartz veins of the Fazenda Brasileiro mine.

a) Geometry: Three types of quartz veins have been recognized in the Fazenda Brasileiro mine sensu stricto (Reinhardt and Davison 1990, and this study, Figs. 5,6). Namely they are: i) concordant veins, parallel to S, deformed by boudinage or folding (VI); ii) thin sigmoidal "en-échelon" veins, discordant to the foliation, with either E-W strike and S dip, or W-NW strike and N-NE dip and interpreted as tension gashes (V2) and iii) discordant E-W striking tabular veins (V3) characterized by a greater thickness (several cm) and variable dip (from subhorizontal to 60°S). The V2 and V3 types of vein, that contain gold, are weakly deformed and show an incipient hydrothermal alteration. Reinhardt and Davison (1990) interpreted these veins as coeval with the northward thrusting of the Barrocas pluton, which occurs later in the structural evolution of the RIGB (Alves da Silva 1994). It is worth noting also the occurrence of irregular "masses" (centimeter to meter thick) consisting of dense networks of small diffuse veins, corresponding to zones of intense hydrothermal replacement (Fig. 5). The mineralized veins essentially contain quartz or quartz-albite assemblages. The associated sulphides, when present, are systematically localized along their margins.

Microfabrics: Vein filling is usually massive, although banded structures, witness of multi-stage fracture-infill can be found. The texture of the quartz grains indicates that brittle-ductile deformation occurred, controlled by two distinct mechanisms: "crystal plasticity", marked by the occurrence of a grain boundary migration mechanism (Fig. 7a), and "crystal plasticity", marked by the occurrence of a grain boundary migration mechanism (Fig. 7b). The phenoclasts are affected by the development of elongate phenoclasts (2 mm in size on average) just showing undulatory extinction, deformation bands, lamellae and sub-grain development (Figs. 7a, b). The phenoclasts are affected by the development of elongate subgrains. The occurrence of serrated boundaries characterizes the occurrence of a grain boundary migration mechanism (Fig. 7b). The initiation of new grain formation is shown by the scarce presence of very small size quartz grains along the margins of relict quartz grains. As new grains and subgrains present different crystallographic orientations with respect to the relic host (Fig. 7a), we suggest that a continuous sub-grain rotation recrystallization process operated (White 1977, Drury and Urai 1990).

Quartz C-Axis Preferred Orientation: Quartz C-axes were measured in different points of the Weber belt mines (Fig. 8). Westward, the analyzed samples have been collected in the Pau-a-Pique (location A, FB-04) and Incó (location B, FB-02) mines, within

recognized deformation structure (Teixeira 1985; Reinhardt and Davison 1990). The foliation, representative of the main shearing planes (Kishida et al. 1991), is assumed to have developed in a horizontal position during a top-to-the SE DI thrusting event (Alves da Silva et al. 1993). Elongated minerals and quartz rods define a subhorizontal stretching lineation that can present higher dipping values in the western Weber Belt (see the stereonets, Fig. 3a). Kinematic analysis within the mine areas and their vicinity, points to a general ductile dextral shearing, which in fact corresponds to the overturned top-to-the-SE DI shear criteria. Numerous vertical NE-SW faults that define the "duplex" geometry (Fig. 3a) and affect the imbrication of the main gold-bearing rocks, are also attributed to the DI event. These faults, which are favorable sites for fluid flow, were latter re-used during the more brittle event and ore concentration.

Ore Description: The orebodies consist of sets of centimeter to meter scale quartz veins with variable amounts of sulphides (pyrite, arsenopyrite, pyrrhotite). Gold appears freely with an erratic distribution, as common in quartz-lore gold mines. The main gold occurrence is associated with massive sulphides overprinting the foliation. Gold occurs attached to the sulphide walls (Vasconcelos 1987) and also along microfractures or as inclusions. Arsenopyrite is considered to be the main sulphide because its presence is always associated with Au concentrations. However, recent mining has shown a strong predominance of a gold-pyrrhotite assemblage within the "E-body" in Fazenda Riacho do Incó mine.

In the Fazenda Brasileiro mines, a cut-off of 3 g Au/t and an average of 7 g Au/t is used for the determination of underground orebodies processed by the carbon-in-pulp method. Within open-pit mines, in which weathered ore is extracted by heap-leaching, a cut-off of only 0.7 g Au/t is used. At the mine-scale, few kinds of mapping (e.g. isopach width, grade vs. width) are used to constrain the ore geometry. Because the results are coherent between all the maps, we present in this paper only the isopach representation which satisfactorily defines the orebodies (Fig. 4). The orebodies can reach 500 m in length and up 40 m in width as in the "C-orebody" of the Fazenda Brasileiro mine (sensu stricto, Santos et al. 1988). By comparison with the geological features of the area, we can observe a perfect parallelism between the long axes of the orebodies and the above defined ductile stretching lineation (Fig. 4). See conclusion further bellow for discussion.

Figure 3 - a. Detailed geological map of the South Mineralized Zone with gold mines referred in the text (modified from Kishida et al. 1991). Lower hemisphere, Schmidt stereonets represent the varying attitude of the foliation and stretching lineation across the Weber Belt. b. North-south cross-section of the Fazenda Brasileiro deposit (modified from CVRD company internal report). Note that mineralization (in black) is concentrated within the CLX level. Au-content and orebody thickness are marked for each bore-hole. The level number expresses the height with respect to the sea level.
ten centimeters width foliation parallel quartz veins. Within the Fazenda Brasileiro mine (sensu stricto), a quartz vein (GI-78) and its host rocks (FBA and FBB), coming from the highly mineralized CLX level, where most of the measurements were made using a standard universal stage and in all samples the measurements were done in the XZ plane of the strain ellipsoid.

Sample FB-04 shows a diagram characterized by $<c>$ axes concentrated along the XY plane, with a point maximum close to the Y axis (Fig. 8a). Sample FB-02 shows a type of crossed girdle with the development of maxima between the X and Z axes (Fig. 8b). For sample GL-78, the $<c>$ axis maximum lies in the ZY plane at an intermediate position between both axes (Fig. 8c). The CLX sample is characterized by the presence of blue quartz-eyes. Measurements were made in both porphyroclasts (Fig. 8d) and recrystallized grains (Fig. 8e). The porphyroclasts show a less oriented pattern with the development of three maxima, two of them close to Z while the weaker maximum is near the X axis. $<c>$ axis distribution of the recrystallized grains is marked by the presence of a submaximum near Y axis and a slight obliquity defined by point maximum position.

INTERPRETATION As a whole, the quartz C-axis preferred orientation does not show well defined asymmetry and no clear kinematic informations can be inferred. Moreover, quartz diagrams do not show evidences for high temperature deformation (Fig. 8). This fact is consistent with temperatures obtained by fluid inclusion analysis developed on the Fazenda Brasileiro gold-bearing quartz veins (Xavier 1993). Concerning the texture, the large variation observed along the Weber belt suggests that recrystallized grains were the result of dynamic recrystallization rather than annealing. Combining the fact that there is no evidence for high temperature and no clear preferred orientation of $<c>$ axes, it is likely that dynamic recrystallization was promoted by the presence of a diffusion-enhancing fluid film along the grain-boundary (Druy and Urai 1990). Moreover, the coexistence between recrystallized quartz grains and intergranular / transgranular microfractures, sealed by carbonates and phyllolites, indicates the transition from crystal-plasticity to fracturing that is dominated by diffusion and fluid mechanisms (solution precipitation creep and grain-scale dilatation, Cox and Etheridge 1989). Indeed, quartz $<c>$ axis orientation is interpreted not to result exclusively from intracrystalline slip deformation but to be strongly influenced by fluid-assisted recovery processes (Gleason et al. 1993; Jessell 1988; Jessell and Lister 1990). Such process dominates at low temperature because diffusion rate is too slow for dislocation climb to be efficient (regime 1 of Hirth 1990). Such process dominates at low temperature because diffusion rate is too slow for dislocation climb to be efficient (regime 1 of Hirth 1990). Such process dominates at low temperature because diffusion rate is too slow for dislocation climb to be efficient (regime 1 of Hirth 1990).

HYDRO THERMAL ALTERATION Hydrothermal alteration, developed around the mineralized quartz veins, is traduced by gray leached aspect and general coarser texture, contrasting with the dark-green colour and finer grain size of the host rock. The size, width and extent of these veins is controlled by phyllolite chemistry and orientation. When veins are parallel to the foliation, the halo is regular and symmetric. When veins are, even slightly, oblique to the foliation, the halo is flattened. Moreover, quartz veins extending for few centimeters are the dominant orebody hosted in the mafic Fazenda Brasileiro sequence (Alves da Silva 1990), obtained by the R$^2$(g)-method (Ramsay 1967) applied on the agglomerate pebbles reveal values of strain ratio (Rs) varying from 16 to 25 (see also Alves da Silva 1991a). Stretching along the major principal axis (X axis) attained 163% whereas shortening reached 60% following Z axis. The strain ellipsoid changed from apparent flattening shape in the outer part of the shear zone to apparent contraction in the inner part. Kinematic indicators (e.g., foliation sigmoidal patterns, drag folds and pressure shadows around porphyroclasts) indicate everywhere a dextral shearing (Fig. 7d) herein correlated to the DI tectonics (Alves da Silva 1994).

MINERALIZATION If gold appears systematically associated with Fe-rich lithologies within the Fazenda Brasileiro mines, its occurrence is often different at Canto where quartz veins parallel or sub-parallel to the mylonitic foliation contain the main mineralization (Fig. 7d). They are interpreted as shear veins (Hodgson 1989) and can measure ten meters long and a few meters wide. Oblique and normal veins with respect to the foliation are small and subordinated. Orebodies are also defined by host rocks injected by a great number of quartz veins. The orebody contours, using a cut-off of 0.7 g Au/t, demonstrates that they are elongated E-W, roughly parallel to the ductile lineation (Fig. 9).

Gold-bearing schists are less important than the amphibolites. The emplacement of mineralized quartz veins induced hydrothermalism within the host rocks that is characterized by growth of albite, sericite, carbonate, sphene, chlorite and scarce sulphides (pyrite and arsenopyrite). In fact, it appears that the gold concentration in the upper part of mineralized veins is dominated by quartz-rich fluid during the late stages of the ductile deformation without a strong control by the Fe-rich lithologies like for the Fazenda Brasileiro mines. In this place, the role played by iron-rich layer in gold mineralization seems then less important whereas the rate of deformation looks more crucial.

THE NORTH MINERALIZED ZONE (NMZ) AND ITS GOLD MINES The NMZ rocks show a monotonous geometry characterized by a N-S trending and westward high-angle dipping intrusion of andesitic rocks (see the stereonets, Fig. 9). The NMZ shows a well-developed foliation and lineation. The minerals most important to gold mineralization are quartz, chlorite, and pyrite. The foliation is characterized by a subhorizontal to gently dipping foliation defined by micaceous minerals, and a subvertical to gently dipping lineation. The foliation and lineation are well-developed in the upper supracrustal units beneath the NMZ. Three main volcanic-sedimentary units above described (the basal tholeiite, intermediate felsic and upper sediment) are also represented in this area (Fig. 10). Four main gold mines (C I, Antas I, Antas II and Antas III mines) occur in this area (Fig. 10). C I, Antas I and HI are located along the lithological boundary between the upper supracrustal units beneath Antas II occurs within the intermediate sequence, frequently associated to the presence of minor lenses of upper sedimentary unit (Figs. 10,11).

Lithological description The three main sequences are described in the following section. More details are given for lithologies that contain gold mineralization. Local name is given in parentheses.

e) The basal mafic sequence (the Rebole Unit) occurs western of the studied area and comprises massive to schistose tholeiitic basalts sometimes showing pillow structure. The occurrence of interlayered mafic tuffs, flow breccias, chemical sediments and phyllites can be observed.

b) The intermediate felsic sequence (the Maria Preta Unit) is represented by andesitic lavas with intercalations of pyroclastic lenses and metasediments. The andesite constitutes the footwall rocks of Antas I, Antas HI and CI mines and is the dominant host-lithology of the Antas II mine (Figs. 10, 11). The fresh rock is compact, grayish-green coloured, fine grained, and shows a plagioclase-phyllosilicate texture. The foliation is dominated by phenocrysts of plagioclase that occur in a matrix mainly constituted by small-size plagioclase, carbonate, chlorite, biotite, sericite, and quartz.

c) The upper sedimentary sequence (the Riacho Sêco Unit) is a complex succession of quartz-chlorite-sericite schist, graywacke, conglomerate, quartz-carbonaceous-schist and tuff. Schists, that derived of volcanic material, are the dominant rock in the hanging wall of the gold-bearing zones. Here also, the relation between carbonaceous material (i.e. graphic schists within
Figure 4 - Block-diagram of the disposition of oreshoots defined by isopachs, Fazenda Brasileiro (C-orebody) and Fazenda Riacho do Incó (E-orebody) gold mines. Note that the orebodies are apparently parallel to the ductile stretching lineation. The level number expresses the height with respect to the sea level.

Figure 5 - Synthetic block diagram that summarize the geometric pattern of quartz veins within the Fazenda Brasileiro mines. The Fazenda Brasileiro mine) is clearly established. Meta-graywackes form narrow levels that show granolepidoblastic texture and are composed by sericite, biotite, quartz, plagioclase, rock fragments and opaque minerals. The meta-graywackes sometimes grade into coarser epiclastic conglomerates characterized by felsic to intermediate volcanic pebbles dispersed within a matrix composed of carbonate, white mica, quartz, chlorite, scarse pyrite and hematite. Preserved sedimentary structures such as cross bedding can be observed.

Dacitic and dioritic bodies frequently intrude the intermediate and upper sequences. Dacites are abundant within Antas I and Antas III mines. They present a blasto-porphyritic texture with quartz and plagioclase porphyroclasts immersed into a matrix composed of small idiomorphic plagioclase, sericite, carbonate, quartz and opaque. Sericite in the matrix is generally oriented, giving a weak schistosity to the rocks. The medium grain diorite occurs under the form of large-size foliated bodies (Fig. 10) composed by euhedral plagioclase with blasto-intergranular texture where chlorite replaces original mafic minerals.

Mine Structures This part of the RIGB was dominated by the left-lateral ductile shearing (Fig. 11) associated to the emplacement of the main granites and attributed to the second tectonic event (D2 event, Alves da Silva et al., 1993, Alves da Silva 1994). The main gold deposits are included with four shear zones (fig. 10) that have been mainly defined on the basis of deformation analysis across prospecting trenches. From the economic point, the "shear zone 1"(SZ-1) and "shear zone 2" (SZ-2) are the most important (fig. 10) (alves da Silva and Matos, 1987). Antas I, Antas III and C-I mines are hosted by the shear zone 1, whereas Antas II is located along the shear zone-2.

STUDIES OF THE SHEAR ZONE 1 Within the SZ-1, a stretching lineation with average direction and dip close to 355/25 and 335/30 for Antas I/C-I and Antas III mines respectively can be recognized. Such a lineation is attributed to the D2 left-lateral shearing. Compressive duplex structures, defined by the imbrication of the meta-sediment/meta-dacite units (Kishida et al. 1991), have been described within the mines area. These structures, difficult to observe, are herein interpreted as relics of the DI tectonics.

The widespread occurrence, in the open pits, of breccias, cataclasites and britle to brittle-ductile faults clearly indicate the importance of the brittle deformation (Chauvet et al. 1991), probably due to hydraulic failure related to high fluid pressure (see the below discussion on the hydrothermal effects). In Antas I, faults are oriented N040,

Figure 6 - General attitude of the gold-bearing quartz veins in the Fazenda Brasileiro gold mine. Note the existence of quartz vein parallel and oblique with respect to the foliation. Qv - quartz vein. N-S and N120 (mine internal maps and Oliveira, pers. com., Fig. 11). The two former families re-use pre-existent discontinuities and concentrate the mineralization. Fracture analysis from trenches and drill cores demonstrates that normal faulting predominates.

STUDIES OF THE SHEAR ZONE 2 As a result of the less competent behavior of the rocks, the deformation style within the SZ-2 is marked by a more ductile character than in the SZ-1. The development of folds from open to sheath geometry can occur. The structuration becomes more complex from south to north. Toward the north, the lineation, marked by quartz rods, exhibits a strongly dispersed orientation. Southward, lineation presents a constant dip with an average value of 335/35. This direction is also that of the mineralized bodies, thus provided a good field guide for prospecting (Oliveira et al. 1988,
Figure 7 - a, b.- Microscopic aspect of quartz vein within the Fazenda Brasileiro mine showing uncompleted low-temperature dynamic recrystallization. Note the persistence of relictual large-size grains and the appearance of small-size new grains, me = mantle-core structure, Sh = Serrated boundary. c.- Microscopic aspect of quartz vein within the western portion of the Weber belt in which polygonal quartz reflect higher temperature conditions of deformation and recrystallization. Arrows indicate the location of triple point contact (T). d.- Boudinaged quartz vein at Canto II mine indicator of a dextral sense of shearing.

Figure 8 - Crystallographic fabrics of quartz axes for selected samples of the Weber belt. Sample locations, numbers of grains measured and contour values are indicated. Diagrams are Schmidt, lower-hemisphere, stereonets. In each diagram, the equator line (indicator of the foliation plane) has been oriented with respect to the north. See text for comments.
Ore description

Within the mines of the northern domain, mineralization is essentially represented by quartz vein. They occur following three types of geometry: i) vein parallel or oblique to the foliation (Fig. 12a); ii) complex arrangement that define a typical stockwork (Fig. 12b, c); and iii) fine injected veinlets that give a silicified aspect to the host lithology. The veins consist essentially in massive quartz and rare sulphides. The vein thickness ranges from few cm to 2 m.

Because they are localized along the same lithological contact, Antas I and Antas III present similar pattern that strongly differs from the more complex Antas II deposit (Fig. 11).

In Antas I/C I, the mineralized veins occurs mainly within the N040 trending brittle-ductile fault that follows the major lithological contact (Fig. 11). In surface, a large-scale quartz-vein actually constitutes 30% of the ore. This vein disappears with increasing depth and mineralization is then represented by brecciated carbonaceous schist injected by quartz veinlets. Minor mineralization (ca. 10%) can also be found within brecciated meta-dacite (Oliveira, pers. com.). The orebody geometry is estimated by the mapping of the mineralized levels at different altitude during mining exploitation (Fig. 13a). The result shows that mineralization occurs following a plane oriented N040 and dipping westward, roughly parallel to the lithological contact and the main foliation (Fig. 13a).

In Antas III, orebody is represented by silicified meta-dacite which also shows the effects of carbonatization and sulphidation (pyrite and arsenopyrite). Gold-bearing brecciated veins, that represent 40% of the ore, also develop along the contact between meta-dacite and meta-sediments. Subordinated mineralization is found in sulfide-bearing carbonaceous schist. Likely for Antas I, the mapping of the orebody with respect to the altitude demonstrates that mineralization follows the N-S trending foliation and lithological contact (Fig. 13b). The mineralization in the southern part of Antas III mostly occur associated with quartz veins that sometimes presents a complex geometry. In this area, meta-diories are largely represented (Fig. 10).

Within the Antas II gold mine, the principal mineralization (60%) is represented by carbonaceous-schist and meta-andesites that host larger quartz veins representative of the other 40% of the ore (Figs. 12a, 13c). These veins could show a more or less complex framework (Figs. 14b, c, d, e) that became extremely confuse towards the north (Fig. 14f). The schist and andesite appear like silicified and brecciated zones intruded by a swarm of mineralized quartz veinlets.

The distribution of Au content within main quartz veins and surrounding rocks for Antas II and III is outlined in Fig. 14. Gold content is erratic within the large quartz veins core whereas there is a tendency for higher Au values along the vein margins (Fig. 14b). Conversely, gold distribution is homogeneous within the surrounding rocks where mineralization occur as injected quartz veinlets. Native gold is also found freely under the form of 0.1 to 0.8 mm flakes within quartz veins or filling microfractures. Because of the lack of mineralization within the large quartz vein core, we can highlight the important role played...
by the interaction between fluid and wall-rocks in the gold precipitation process. Within the host-rocks, gold is also associated with sulphides (pyrite, arsenopyrite, pyrrhotite) and occurs as inclusions along grain boundaries, microfractures or attached to the crystal faces.

Although they present a N-S elongated pattern, the orebodies have a long axis which frequently dips toward the north, roughly parallel to the stretching lineation as illustrated in the schematic block-diagram (Fig. 15). However, if orebodies plunge parallel to the stretching lineation, the parallelism appears to be less marked than in the SMZ.

Quartz veins GEOMETRY Tentative classification of the quartz-veins of the Maria Preta gold mines has been proposed (Coelho 1994). However, the complexity of the vein pattern, as illustrated by different detailed maps of the mines (Fig. 14), does not allow us to divide the veins using the classical nomenclature of "shear" and "extension" veins (Hodgson 1989).

Most of the veins are approximately parallel to the regional foliation. In a detailed study, Neves (1991) has shown that 75% of the veins occur subparallel to the foliation (maximum angle of 10° between vein and foliation) with 22% strictly parallel. The veins trend NNW-SSE or NNE-SSW, dip toward the west (Fig. 14a), and measure a few centimeters in length and width. The largest can reach 25-30 m in length and 0.2-2.5 m in width (Fig. 14). Other economically important veins trend E-W (Figs. 14a, b, c). They are particularly well-developed within competent lithology such as dacite, diorite and gabbro (Antas II and III) and in Antas II. Except in Antas II where they are similar to the foliation-parallel veins (Figs. 14a, b), these veins are largely subordinated in abundance, size, width and gold content. It appears that, with rare exceptions (Fig. 14e), even E-W oriented veins are systematically parallel to the foliation that presents some inflexions perhaps due to late normal faulting (Figs. 14a, b, d). Within zones of extreme complexity for the foliation geometry, like north Antas II domain, a similar complex pattern is observed for the veins (Fig. 14f).

The occurrence of brecciated zones is also observed within mine areas and argues for an active cataclastic process. "Brecchia-vein" type results of the inclusion of broken and angular fragments of the wall rocks within a quartz-vein. Stockwork pattern is represented by quartz crystallization along their margins that indicate filling of open spaces during cyclic episodes of fracturing and quartz crystallization. Small-size veins intruded into diorite pods show orthogonal and fibrous quartz crystallization along their margins that indicate filling of open fractures by crack-seal process (Fig. 12f). The above described aspect of the vein deformation could be interpreted as the result of the combination of fracturing, quartz crystallization and moderate crystal-plastic process, certainly developed in ductile-brittle to brittle conditions (O’Hara and Haak 1992).

QUARTZ C-AXIS PREFERRED ORIENTATION Quartz measurements within the northern portion have been realized with the same analytical conditions that in the southern belt. The five selected samples are foliation parallel quartz veins coming from Antas I (sample GI-13a), Antas II (sample ALI-27a and AO-27b, Fig. 14b), Antas III (sample AK, Fig. 14a) and Riacho do Carneiro target, located 15 km north of the Antas area (sample AS-C). All samples were found within NS trending foliation except ALI-27b that is oriented EW (Fig. 14b). Large scale veins were always chosen except within Antas I where the size of the quartz vein just reaches few centimeters.

The results of the quartz <c> axis measurement display that only one sample presents a well-defined preferred orientation indicating a sinistral sense of shear (Fig. 16c). This sample, collected far from the Fazenda Maria Preta area, exhibits a strong recrystallized texture with elongated quartz grains (Fig. 12g) that is not representative of the gold-bearing quartz veins of the Antas mines. Sample GI-13c also yields an oblique girdle that could be interpreted as representative of a sinistral shear (Fig. 16a). For the three other samples, the quartz <c> axis diagrams do not show any evidence of preferred orientation (Figs. 16b, c, d), fact that is coherent with the poorly oriented textures of the samples ALI-27a and ALI-27b but inconsistent with the well recrystallized texture exhibited by the sample AK.

INTERPRETATION Because the mineralized quartz veins always parallel the regional foliation, they could be interpreted as syndeformational veins (Hodgson 1989). However, the lack of strong internal deformation combined with the paucity of clear preferential orientation of the quartz <c> axes within the veins eliminate this solution and favour the hypothesis of a late vein emplacement during a brittle stage of the deformation. This is strongly confirmed by the occurrence of intra- and intergranular cracks within the larger quartz grains (Fig. 12d). The quartz growth and associated mineralizing fluids are supposed to re-use the foliation anisotropy thus explaining the surprising parallelism. The sample AS-C that present evidence for plastic deformation can be interpreted as an earlier quartz vein that have suffered the ductile deformation before being percolated by mineralizing fluids.

HYDROTHERMAL ALTERATION Intense veining, high silicification and carbonatization are the most obvious signs of high fluid circulation in the Antas area. At microscopic scale, the hydrothermalism is generally marked by the growth of quartz, carbonate, albite, sulphides (pyrite, arsenopyrite, pyrrhotite), sericite and chlorite. Tourmaline and apatite have also been identified (R.P. Xavier, per. com.). In the dacite, the quartz veinlets show a symmetric, centimeter-scale, brownish halo witness for the hydrothermal alteration (Fig. 12h). The halo is symmetric when veins parallel the foliation and indented when veins are oblique. This indicates that fluid percolation was guided by the foliation planes anisotropy. The best-expressed alteration is found within the andesite in which fine grain schist levels characterized by carbonate-chlorite and subsequently sericite-chlorite-carbonate mineralogy occur. Within the diorite, hydrothermal alteration is marked by a characteristic kaolination and growth of carbonate.
Figure 12 - Photographs of the general features of the Fazenda Maria Preta deposits, a.- View of the large-size gold-bearing quartz vein parallel to the foliation in Antas II. And = andesite, Qy = quartz vein, b, c.- Typical stockwork pattern in dacitic lithologies from Antas III (b) and Antas I (c) mines. DC = dacite, Qy = quartz vein. d.- Grain size reduction aspects from quartz vein of Antas II expressed by undulose extinction, intra and inter-granular cracks and deformation bands, e.- View of the border of large quartz vein exhibiting sliver of the host rock, witness of multiple stages of opening, Antas II. Qz = quartz, S = host rock sliver, f.- Orthogonal and fibrous quartz crystallization along the margin of small-size veins intruded within dioritic pods, Antas III. Hr = host rock, Qc = quartz crystallization, g.- Riacho do Carneiro quartz vein displaying completely recrystallized texture and elongated quartz grains, h.- Brownish alteration halo around quartz veinlets within dacite, Antas I. Di = diorite, Qy = quartz vein, H = alteration halo.
Semi-quantitative optic spectrographic analyses of the characteristic lithologies from both SZ-1 and SZ-2 are shown in Tab. 1. Quartz veins composition of both zones only differs by a weak occurrence of Pb within veins of the SZ-2. Regarding the host-rocks composition, the significant changes between the two zones are i) less Mn within the diorite of the SZ-1; ii) the total lack of B, Cu and Pb in the andesite of the SZ-2 whereas these elements are present in the surrounding quartz vein. The implications of these chemical variations between quartz veins and surrounding lithologies on the mineralizing process will be discuss in the conclusion.

ORIGIN, TIMING AND TECTONIC CONTROL OF THE AU MINERALIZATION: A DISCUSSION

Main characteristics of the RIGB gold mineralization

The role played by the carbonaceous material in gold precipitation has been largely demonstrated and reported in the literature (e.g., Teagle et al. 1990). In the Rio Itapicuru gold mines, it has been clearly established in this study that carbonaceous material is always associated with the mineralization. A recent study suggests that the sulphidation of high Fe-bearing rocks (i.e., the CLX level) should be accompanied by reduction of the stability of the gold complexes thus promoted gold precipitation (Teixeira et al. 1990). However, the lack of Fe-rich lithology in the Canto mines argues against a generalization of the role played by this process in the whole RIGB. In fact, it seems that the main factor on metal concentration is the circulation of hydrothermal gold-rich fluids along preferred anisotropies represented by the ductile-brittle shear zone and the lithological contacts. A more brittle behavior of the Antas area mineralized quartz veins is observed. The importance of the ambient lithology like the existence of the CLX-GRX association added to the opportunity to concentrate gold. This model confirms the late concentration of gold with respect to the general tectonic evolution.

Origin and timing of the mineralization

Gold within the NMZ and SMZ are assumed to result from the same mineralizing event although some differences exist due to the lithological variations of the host rocks. If the economic mineralization is clearly related to late hydrothermal processes, an early syngenetic gold concentration has been suggested for the Fazenda Brasileiro deposit based on the existence of anomalous gold grades (from 0.1 to 1.0 ppm.) in un-mineralized zones of the CLX (Santos et al. 1988). A similar argument was used by Alves da Silva and Matos (1990, CVRD Company, internal report) and Silva and Rocha Netto (1993) for whom gold was originally located in the volcanic pile. A recent fluid inclusion study favours such an early syngenetic gold concentration created during a basin-related hot exhalative hydrothermal stage (Coelho 1994). Initial sea-floor hydrothermal activity forming auriferous exhalates was also invoked to account for a lot of Archean gold deposits (Hutchinson 1987).

Because gold orebodies display highly diversified host rock association, any attempts to link the genesis of important Au deposit to the nature of the surrounding lithology cannot be valid. Indeed, the intervention of a late stage of remobilization to account for the localized high metal concentration appears necessary. This may be an efficient mechanism that leaches gold from a great volume of rocks and precipitates it in grades of 6-8 g per ton in narrow zones. Using an average concentration of 2 ppb in the basalts, Reinhardt and Davison (1990) estimated that leaching of 35 km 3 of basalts would be necessary to explain the 110 tons of gold in Fazenda Brasileiro mine. Such volume is consistent with the surface of basalt existing between the Barrocas oluton and the Weber Belt (see Fig. 3a). The two major processes that

Figure 13 - Detailed structure of the Antas deposits. a.-Map arrangement of the orebodies from surface to level 160 based on 41 drilling bore holes. The number associated to the level is the altitude with respect to the sea level. Note that mineralization occurs following a plane oriented N040 and dipping westward, parallel to the general orientation of the foliation in Antas I. b.- Similar for Antas III, northern portion; c.- Detailed cross-section of the Antas II mine showing Au distribution within and around quartz veins (Modified from Oliveira et al., DOCEGEO internal report).
could explain the formation of hydrothermal fluids in order to leach and to concentrate gold within the RIGB are: magmatism and metamorphism.

**MAGMATISM** Granitoid emplacement largely dominates the tectonic evolution of the study area (Alves da Silva et al. 1993, Alves da Silva, 1994). The granite can provide the necessary heat for the supracrustal dehydration and thus might explain the mineralizing fluids of the RIGB (Boyle 1979, Burrow and Spooner 1989, Silva and Rocha Netto 1993). Additionally, the presence of boron in the ore (Antas area, Tab. 1), the occurrence of quartz-porphyry bodies and the existence of a late magmatic phase of tourmaline-bearing pegmatite within the Ambrósio pluton (Matos and Davison 1987), support a link between magmatism and mineralization. In the SMZ, mineralization has been considered to be contemporaneous to the Barrocas pluton emplacement (Reinhardt and Davison 1990). The geochronological data available both on the granite (Barrocas crystallization age of 2127 + 5 Ma, Pb/Pb evaporation age on zircon, Alves da Silva 1994) and on the mineralization ($^{40}$Ar/$^{39}$Ar biotite and muscovite ages bracketed between ca. 2083 and ca. 2031 Ma, Vasconcelos and Becker 1992) do not support this hypothesis. However, the thermal event due to a large granitic intrusion could last several tens of Ma and the subsequent hydrothermal process can persist more than 10 Ma (up to 54 Ma for several gold deposits around the world: Abitibi belt and Meguna terrain, Canada; Vitoria

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**Figure 14** - Small-size mapping of the main orebodies of Antas II and Antas III illustrating that gold-bearing quartz veins many of them parallel the foliation. Note the close relationship between gold occurrence and quartz veins although gold mainly concentrate along the margin of the large veins (i.e., map B and D). A cut-off 0.7 and maximum of 210 g Au/t were used for the An content histograms.
working in the area) and the low salinity of the fluid inclusion located within mineralized quartz veins are favourable arguments for metamorphic fluid to explain the mineralizing event of the RIGB. This hypothesis is supported by recent fluid inclusion and d\(^{18}O\) studies (Xavier 1993) that suggest a metamorphic origin with derived magmatic components (e.g., S and CO\(_2\)). Thus, the metamorphic influence on the leaching process cannot be seen, although the relative low grade of the regional metamorphism during the Transamazonian cycle does not favour this hypothesis (Silva 1987, Alves da Silva 1994).

**Tectonic control** A particularity of the RIGB gold deposits consists in the surprising parallelism between orebody long axis and the ductile event-related stretching lineation. This fact contrasts with the ductile-brittle/brittle features of the gold vein deformation. If such a phenomenon has been described for few gold mines (i.e., South Africa, Vearncombe et al. 1989), it does not represent the majority of case studies (i.e., the Canadian gold deposits, Poulsen and Robert 1989). This paradoxical situation involves two possibilities: gold is pre-syn deformation or gold is posterior and crystallizes following the direction of the ductile deformation features. In other words, we may question if: i) gold was precocious, and then experienced the whole deformation history and concentrated when host rock cooled down below the temperature of Au deposition or ii) gold was introduced later within the system (after the fixation of all CO\(_2\), sulphur, arsenic and potassium in the alteration halos). In the RIGB, the quartz veins and associated sulfide phases clearly overprint the mylonitic foliation (Marimon et al. 1986). Moreover, undeformed hydrothermal minerals (white mica, biotite, chlorite) are aligned along the mylonitic fabric thus suggesting that crystallization was guided by host rock anisotropy. This is confirmed by the predominance of fluid-assisted process during quartz-vein deformation. A satisfying model is that the fluids are channelized from the dilatation sites toward the shear zones, and that Au-deposition is guided by rock fabrics such as the linear anisotropy formed by the Transamazonian-related early ductile structures.

From the above, it seems that if metamorphic and magmatic sources could contribute to the RIGB mineralizing event, the influence of plutonism is predominant. The process can be divided into two stages integrated within the tectonic evolution proposed by Alves da Silva (1994). Earliest metamorphic fluids, generated during D\(_1\) thrust event, promoted the first stage of gold leaching from the volcanic pile. Progressively, the deformation evolved from thrust style toward strike-slip one coeval with the granitoid emplacement. The switch from horizontal (D\(_1\) event) toward vertical (D\(_2\) event) tectonic style would ease fluid circulation along vertical anisotropies. The emplacement of granites largely helped fluid circulation because i) they directly created shear zones, ii) metamorphic and magmatic components (e.g., S and CO\(_2\)) derived magmatic components. Thus, the metamorphic fluid to explain the mineralizing event of the RIGB. This hypothesis is supported by recent fluid inclusion and d\(^{18}O\) studies (Xavier 1993) that suggest a metamorphic origin with derived magmatic components (e.g., S and CO\(_2\)). Thus, the metamorphic influence on the leaching process cannot be seen, although the relative low grade of the regional metamorphism during the Transamazonian cycle does not favour this hypothesis (Silva 1987, Alves da Silva 1994).

**METAMORPHISM** The anomalous high background of Au in the volcanic rocks of the region (data got from the explorations companies region, Australia; Mother lode, California; e.g., Miller et al. 1994 and references therein). Thus, a long-lived hydrothermal activity due to the emplacement of the Transamazonian granites around ca. 2100 Ma could be at the origin of the gold mineralization of the RIGB. According to the radiometric dates, such an hydrothermal event may begin at ca. 2087 Ma, ca. 13 Ma after the major phase of Transamazonian granite intrusion (D\(_2\) event at ca. 2100 Ma, Alves da Silva 1994), and finishes few 10 Ma later, as illustrated by the \(^{40}\)Ar/\(^{39}\)Ar ages on mineralized samples (Vasconcelos and Becker, 1992).

**Figure 15**- Geometry of the main oreshoots within Antas I mine defined by drilling and showing a roughly-defined parallelism between oreshoot long axis and ductile stretching lineation.

**Figure 16**- Crystallographic fabrics of quartz axes for selected samples of the Fazenda Maria Preta area. Sample locations are indicated in figure 14 except for a and e. Numbers of grains measured and contour values are indicated at the right beneath each Schmidt lower-hemisphere diagram. The equator line (indicator of the foliation plane) for each diagram has been oriented with respect to the north. See text for comments.
The main features of the RIGB gold mineralizations are summarized as follows: 1) gold is mainly found in the arsenopyrite; 2) mineralization, always associated with carbonaceous material, are concentrated along shear zones that correspond to lithological contacts; 3) gold concentration process post-dates the diastrophic events (i.e., DI and D2) that characterize the Transamazonian cycle within the studied area, although gold emplacement is controlled by older lithological and structural anisotropies.

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