Geology of quartz-vein gold deposits in the Ipitinga Auriferous District, northern Brazil, southeastern Guiana Shield

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Géologie des gîtes filoniens à quartz-or du district aurifère d'Ipitinga, Brésil septentrional, sud-est du Bouclier des Guyanes

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Key words: Gold ores, Quartz veins, Paleoproterozoic, Structural control, Brazil, Guiana Shield.

Abstract

Orogenic gold-quartz vein deposits in the Ipitinga Auriferous District are hosted by Paleoproterozoic metavolcano-sedimentary sequences and coeval granitoids. Hosting structures are mainly the regional foliation and moderate- to high-angle reverse-oblique shear zones and faults, spatially related to major, terrane-boundary, shear zones. The main structural styles are shear/fault-fill veins, and, subordinately, extensional-oblique veins. Sericitization is the dominant silicate alteration, whereas pyrite is the main sulfide mineral. Syn- to late- tectonic veins show evidence of having been emplaced at moderate depths during a regional episode of progressive compressional deformation, following a metamorphic peak and, while hosting structures were still active.

Résumé

Les gîtes filoniens orogéniques à quartz- or du district aurifère d'Ipitinga sont encaissés dans des séquences volcano-sédimentaires et des granitoïdes contemporains d'âge paléoprotérozoïque. Les guides structuraux majeurs sont la foliation régionale ainsi que les zones de déformation ductile et les failles inverses à pendage modéré à fort, en relation spatiale avec les zones de déformation ductile majeure des limites de terranes. Le style structural dominant est celui de veines remplissant des failles ou des cisaillements, et moins fréquemment de veines obliques en extension. L'altération silicatée majeure est la séricitisation, tandis que la pyrite demeure le sulfure principal. Les veines syn- à tardi- tectoniques présentent des caractères de mise en place à profondeur modérée au cours d'un épisode de déformation progressive en compression, postérieur au pic du métamorphisme, alors que les structures de l'encaissant étaient encore actives.

Portuguese abridged version

O Distrito Aurífero de Ipitinga localiza-se na divisa entre os estados do Pará e Amapá, sudeste do escudo das Guianas (Figs. 1 e 2), e contém uma série de depósitos auríferos em veios de quartzo. Esses depósitos são descritos com relação a seus controles estrutural e litológico, estilo, texturas, alteração hidrotermal e formação / deformação.

Mapeamento geológico na escala 1:250.000 realizado pela CPRM/Serviço Geológico do Brasil em cerca de 35.000 km², permitiu a compartimentação tectono-estratigráfica dessa região em três domínios, de NE para SW, justapostos por grandes lineamentos transcorrentes, orientados na direção NW-SE (Ricci et al.*, no prelo; 2001a) (Fig. 2): o Terreno Antigo Cupixi-Tartarugal Grande, constituído dominantemente por gnaisses cinza mesoarqueanos; o Cinturão Jari (CJ), composto por complexos gnáissico-granulíticos mess e mesoarqueanos, com subordinados granitóides e charnockitos paleoproterozóicos; e o Orógeno Carecuru-Paru (OCP), formado por assembléia greenstone-granitóide paleoproterozóica (~2,14 Ga) e remanescentes arqueanos gnáissico-granulíticos.*

A estruturação regional é paralela aos grandes lineamentos (estruturas de primeira ordem) que limitam aqueles terrenos, o mesmo acontecendo com o arcabouço

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estrutural do Distrito Aurífero de Ipitinga. Neste distrito a estruturação é marcada pela xistosidade, em geral subvertical, das seqüências metavulcano-sedimentares e, localmente, dos granitóides, e por estruturas subsidiárias, de segunda e terceira ordens. Lineações de estiramento mineral indicam movimentos reversos e direcionais, havendo, em alguns casos, transposição de zonas de cavalgamento por outras transcorrentes. Esses elementos estruturais são interpretados como produtos de encurtamento crustal (D1) seguido de regime transcorrente (D2), provavelmente relacionados com a colisão entre o OCP e o CJ.

Os depósitos auríferos associam-se à assembléia greenstone-granitóide, principalmente na zona limítrofe entre OCP e CJ (Fig. 2). As estruturas hospedeiras são a foliação metamórfica regional, zonas de cisalhamento e falhas reversas-oblíquas, enquanto que as rochas hospedeiras são dominantemente metassedimentares (quartzitos, pelitos, formações ferríferas) e subordinadamente granitóides. Sericita é abundante na alteração hidrotermal, enquanto que turmalina e clorita ocorrem localmente. Os veios são pobres em sulfetos, que se restringem praticamente à pirita, com calcopirita e galena tendo sido observadas em uma única ocorrência. Os minerais hidrotermais substituem as paragêneses metamórficas regionais, indicando o caráter pós-pico metamórfico das mineralizações.

*O principal estilo de depósito corresponde a veios, tabulares ou irregulares, preenchendo estruturas concordantes ou não com a foliação regional (*fault-fill/shear veins*, veios extensionais-oblíquos). Arranjos de vênulas descontínuas, regulares ou não, também são encontrados (Fig. 3). Texturas maciça, sacaroidal e laminada (Figs. 4, 7, 10) são ubíquas. As duas primeiras indicam profundidades pelo menos moderadas para o alojamento dos veios, enquanto a última indica que os veios se posicionaram em estrutura ativa, atestando seu caráter sin a tarditectônico. Variações nas orientações, intensidade da deformação e estilos de veios podem ser relacionadas à relação temporal com as estruturas hospedeiras, a processos posteriores à formação dos veios e a configurações das tensões regional e locais, assim como a intrusões de granitóides nas seqüências metavulcano-sedimentares.*

O ambiente geológico em que se formaram as mineralizações, suas características estruturais, texturais e relações espaço-temporais com as rochas encaixantes e a evolução estrutural e metamórfica da área são compatíveis com o modelo de depósitos orogênicos, segundo conceito de Groves et al. *(1998), e similares a outros depósitos no Escudo das Guianas (e.g. Voicu* et al.*, 2001).*

Introduction

The Guiana Shield produced about 900 tons of gold in more than a century, mainly from alluvial deposits (Voicu *et al*., 2001). Primary gold deposits have been discovered and/or developed in the last decades in Venezuela, Guyana, Suriname and French Guiana, some of them containing 45 to 130 t of gold, such as Omai, Camp Caiman, Las Cristinas and Paul Isnard (Bertoni *et al*., 1998; Voicu *et al*., 2001). In a recent review of the gold metallogeny of the northern Guiana Shield (i.e., the non-Brazilian portion of the shield), Voicu *et al*. (2001) stated that: 1) most gold deposits are sited in close proximity to major structures; 2) on a local scale, deposits are hosted within, or around syn- to late-tectonic quartz veins; 3) deposits are hosted by a variety of rocks (detrital sedimentary rocks, tuffs, mafic volcanic rocks, felsic intrusions) that constitute a Paleoproterozoic low- to medium-grade granitoid-greenstone assemblage; 4) mineralization likely occurred between 1955 Ma and 2067 Ma; 5) limited fluid-inclusion and stable-isotope data are compatible with mesothermal deposits; and 6) deposits characteristics fit better with the orogenic model of Groves *et al*. (1998). Ledru and Milési (2001) also stressed the important role played by structures, attributing the main concentration of gold along the North Guiana Trough of French Guiana to a D2 tectonic phase (strike-slip regime) that took place at ca. 2014 Ma (Marcoux and Milesi, 1993).

In the Brazilian southeastern portion of the Guiana Shield (i.e., Amapá and NW Pará states), a few gold deposits are recognized, occurring in different gold districts and/or metallogenic provinces (see Carvalho *et al*., 1995; Dardenne and Schobbenhaus, 2001). These are Salamangone, Tartarugalzinho, Santa Maria, Vicente, and Cararã, with more than 35 tons of gold (present-day reserves plus past production) (Carvalho *et al*., 1995), as well as the recently discovered Amapari deposit, with reserves of 30 tons of oxidized ore (Borges, 1999 *apud* Dardenne and Schobbenhaus, 2001). Salamangone is hosted by a sheared tonalite-granodiorite pluton of Paleoproterozoic age (Nogueira *et al*., 2000), whereas the other deposits are hosted by metavolcano-sedimentary sequences (Carvalho *et al*., 1995; Spier and Ferreira Filho, 1999; Melo *et al*., 2001), and are also Paleoproterozoic.

In the Ipitinga Auriferous District (Fig. 2), northwestern Pará State, Carvalho *et al*. (1995) pointed out the existence of several alluvial prospects, one gold deposit (Cararã, quartz vein, ca. 10 t of Au), and a Au-Cu occurrence (volcanogenic massive sulfide - Faraco, 1997). This occurrence contains up to 10,000 ppm Cu, 49-79 ppm Ag, and 8.8-11 ppm Au determined in a mineralized layer of 0.5 m apparent thickness (Carvalho *et al*., 1991). Following the alluvial workings, a series of gold-quartz veins came to be exploited in the last decade by small prospectors (the so-called *garimpeiros)*. The longitudinal and vertical extent, and economic data of most of these veins are not yet known, since they are still undeveloped, and most of them represent surface exposures and minor underground

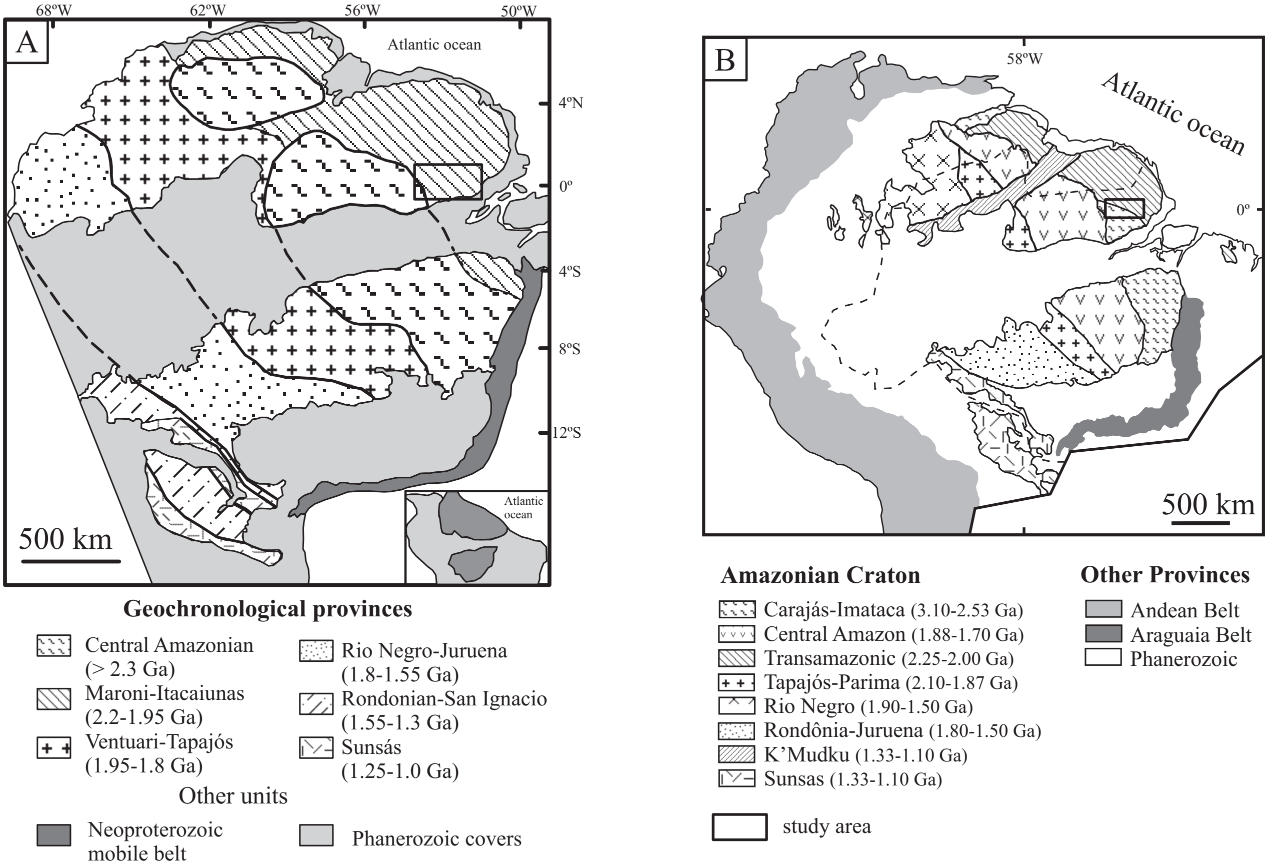

Fig. 1.- Location of the study area in relation to the geochronological subdivision of the Amazonian Craton according to A) Tassinari and Macambira (1999) and B) Santos *et al.* (2000).

Fig. 1.- Localisation de la zone étudiée par rapport aux entités géochronologiques du craton amazonien selon A) Tassinari et Macambira (1999) et B) Santos et al. *(2000).*

workings. Nevertheless, most are relatively well exposed and enable an assessment of their structural elements. The main geological features of seven of these veins and of the Carará deposit, which form a single class (Au-bearing quartz veins), will be addressed in this paper, based on field observations. Emphasis is given to regional lithological and structural controls, host rocks, wall-rock alteration, host structures, style, and internal structure and texture of the veins; formation and deformation of the veins are also discussed. These elements enabled the construction of a preliminary descriptive/geological model for the formation of the gold deposits in the district. The Au-Cu occurrence, which constitutes a different class of deposit (VMS - Faraco, 1997), is not discussed.

Regional geology

The Amazonian Craton is divided into two Precambrian shields, namely the Central Brazil (south) and Guiana (north). Tassinari and Macambira (1999) and Santos *et al.* (2000) further subdivided the craton into several geological-geochronological provinces (Fig. 1). Accordingly, the southeastern portion of the Guiana Shield is located in the Maroni-Itacaiúnas Province (~2.20 to 1.95 Ga) -– of Tassinari and Macambira (1999) or in the Carajás-Imataca (3.10 to 2.53 Ga) and Transamazonian provinces (2.25 to 2.00 Ga) of Santos *et al.* (2000). In any case, these authors described the provinces as composed of granitoids, metavolcano-sedimentary sequences and gneiss-granulite complexes. Tassinari and Macambira (1999) suggested a partially ensialic character for the tectonic evolution of the Maroni-Itacaiúnas Province, whereas Santos *et al.* (2000) considered both the Archean and Paleoproterozoic provinces as juvenile.

More recently, CPRM (Geological Survey of Brazil) undertook a regional mapping survey at 1:250,000 scale, supported by high-resolution airborne geophysics and zircon geochronology - the RENCA Project (Ricci *et al.*, in press) - covering ca. 35,000 km^2 of the Pará and Amapá states border (Figs. 1, 2). This survey allowed for a new improved tectono-stratigraphic subdivision of that part of the Guiana Shield (Ricci *et al.*, in press; Ricci *et al.*, 2001a, b; Rosa-Costa *et al.,* 2001; Vasquez and Lafon, 2001).

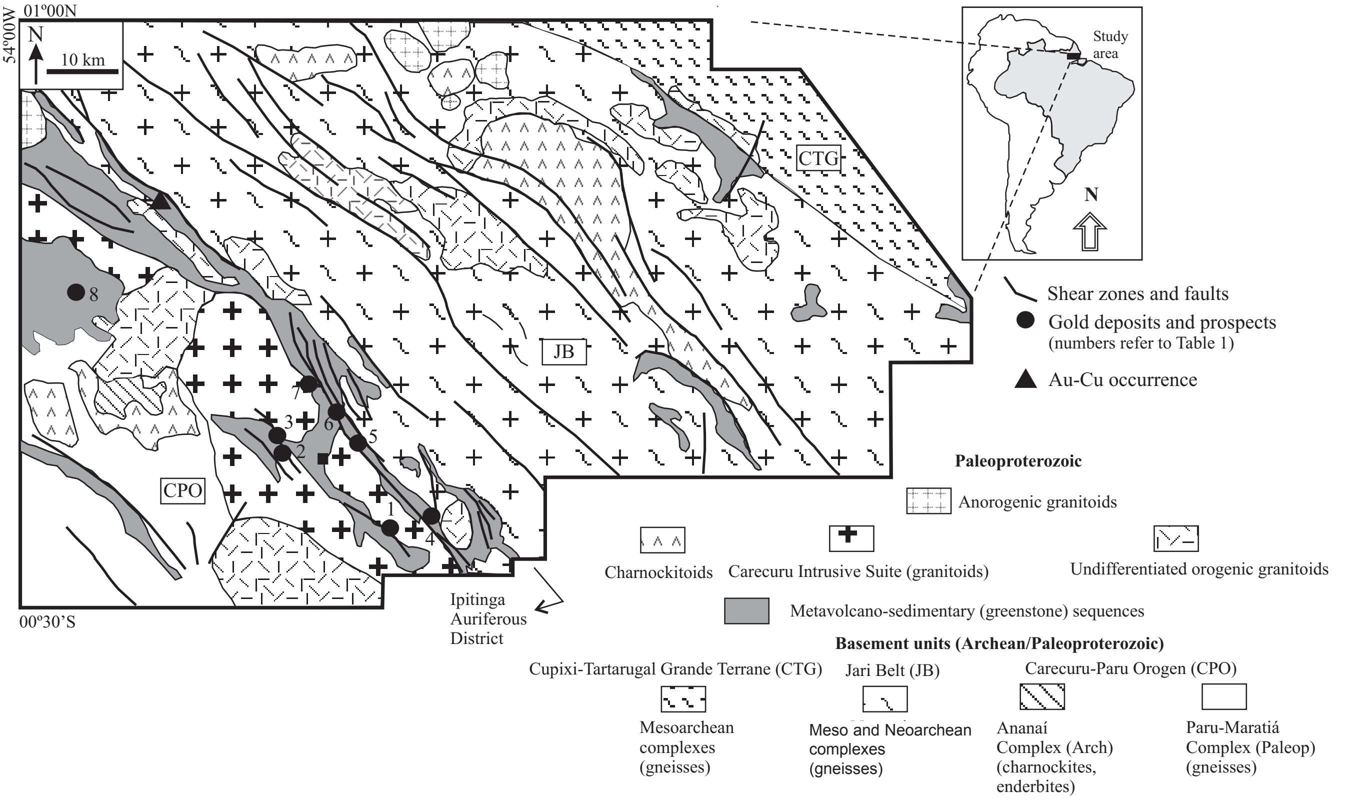

Fig. 2.- Simplified geological map of part of the southeastern Guiana Shield, showing the location of the studied Au deposits and propsects (Modified after Ricci *et al*., in press).

Fig. 2.- Carte géologique simplifiée du Sud du Bouclier des Guyanes montrant la localisation des gîtes et des prospects aurifères étudiés (modifié d'après Ricci et al.*, sous presse).*

Accordingly, from NE to SW, three different tectonic domains have been distinguished (Fig. 2) on the basis of lithological constitution, metamorphism, age of the basement complexes, and structural and geophysical patterns (Ricci *et al*., 2001a). The domains are juxtaposed and/or separated by crustal-scale faults and shear zones. The Cupixi-Tartarugal Grande Terrane is made up essentially of Mesoarchean gray amphibolite-facies gneisses, with subordinate migmatites and minor Paleoproterozoic granitoids. The Jari Belt is dominated by intensively sheared high-grade gneiss-granulite complexes of Meso and Neoarchean age, with subordinate Paleoproterozoic granitoids and charnockites. The Carecuru-Paru Orogen is composed of a Paleoproterozoic granitoid-greenstone assemblage, along with minor Archean gneiss-granulite remnants. Sm-Nd model ages (T_{DM}) of mafic metavolcanic rocks (McReath and Faraco, 1997) indicate maximum ages around 2.26 Ga for the supracrustal (greenstones) sequences, whereas associated granitoids have been dated at 2140 ± 1 Ma by single-zircon lead evaporation (Rosa-Costa *et al*., 2001). Most likely, this domain represents a magmatic arc (Ricci *et al*., 2001b).

Metavolcano-sedimentary sequences are widespread, occurring in all domains, but are better expressed at the boundary zone between the Paru-Carecuru Orogen and the Jari Belt, where most of the gold veins reported in this paper are located (Fig. 2). In addition to these major geological units, subordinate mafic-ultramafic complexes, and alkaline and granitic anorogenic magmatic rocks are also recorded.

Structural framework

The main regional structural features are large-scale, first-order lineaments that represent NW-SE-striking shear zones and faults (Fig. 2), extending for more than 100 km and which are readily seen on radar and satellite imagery, and on geophysical maps. They are tectonic boundary zones that separate different tectono-stratigraphic terranes (Ricci *et al*., 2001a), such as the central Jari Belt from the two others domains (Fig. 2). The Ipitinga lineament separates the Carecuru-Paru and Jari domains. It is a wide structural system made up of major and subsidiary faults and ductile shear zones (first- and second-order structures) (Fig. 2), which affected the supracrustal sequences in particular, and

	Deposit	Host rock	Structural style or host	Vein textures	Gangue mineralogy	Ore mineralogy	Vein orientation strike/dip
1	Divisão	tonalite	shear vein extensional-oblique (?)	saccharoidal massive	ser	cpy, py, gal	N85W/40NE N0E/SV
2	Nova Esperança	monzogranite	extensional-oblique (?)	saccharoidal laminated	ser	py	N85W/10SW
3	Castanhal	metapelite	shear vein / foliation controlled extensional-oblique?	laminated massive	ser, chl		N30W/60SW N60E/60SE
4	Catarino	quartzite	foliation controlled	massive saccharoidal laminated	ser, trm		N20W/35SW
5	Carará	quartzite	shear vein	saccharoidal massive	ser, trm		N20-55W/80SW
6	Mamão	metapelite meta-ultramafic	foliation controlled	saccharoidal massive	ser		N30-45W/60-85SW N50E/45SE-NW
7	Igarapé do Inferno	monzogranite	fault-fill vein? fracture controlled?	saccharoidal	ser, kf	py	N50W/58SW
8	Limão	iron-formation	shear vein	massive laminated schistose	ser	py	N80W/75SW

Legend: ser: sericite/muscovite, chl: chlorite, trm: tourmaline, kf: K-feldspar, py: pyrite, cpy: chalcopyrite, gal: galena; sv: subvertical

Table 1.- Main attributes of the gold deposits in the Ipitinga Auriferous District (numbers in the first column refer to Fig. 2).

Tabl. 1.- Caractères principaux des gîtes d'or du district aurifère d'Ipitinga (les nombres dans la 1ère colonne se rapportent à la figure 2).

has a spatial relationship with the gold mineralization discussed in this paper. This system has a complex history, involving early thrusting and late strike-slip displacement. The elongated metavolcano-sedimentary sequences are parallel to the strike of this fault/shear system.

Deformation has been dominantly of the simple shear type, with rocks exhibiting both foliation and elongation/stretching lineations. In the Ipitinga Auriferous District the structural Pattern is mainly defined by a penetrative NW-SE-trending subvertical foliation (schistosity), characterized by the preferred orientation of mica, chlorite and amphibole grains, and observed especially in the metavolcano-sedimentary sequences that occur at the boundary zone between those two tectono-stratigraphic terranes, and subordinately in the intrusive and broadly coeval (syn- to late-tectonic) granitoids. The regional foliation is parallel to the major tectonic discontinuities and becomes better defined on approaching them. In places, however, it is parallel to the contacts between the supracrustal sequences and the granitoid plutons. This schistosity has overprinted primary structures (stratification) of the rocks, which are no longer recognizable. A downdip to slightly oblique elongation lineation is contained in the foliation planes, and slickenlines are also present, especially at the contact between veins and their host rocks. The schistosity is locally folded into open to recumbent folds. A transcurrent deformation is evident, especially along the limit between the Carecuru-Paru Orogen and the Jari Belt, overprinting early thrust structures and showing both dextral and sinistral kinematic features. However, steep lineations dominate in the inner portions of the supracrustal sequences, suggesting limited strike-slip influence during the ductile deformation. These structural elements likely record a compressive deformation event, showing the effects of NE-SW shortening (D1) followed by the transcurrent deformation (D2). It is not clear whether the folding is associated with D1 or D2. Second- and third-order structures are also present, being both parallel and oblique to the strike of the first-order ones. They are dominantly moderate- to high-angle reverse to reverse-oblique in nature. A very similar structural evolution is described for metamorphic belts elsewhere (e.g., Robert *et al.*, 1995).

Geology of the gold deposits and vein classification

In this section, we describe the main geological attributes of the gold deposits (Table 1). Vein classification is based mainly on concepts of Hodgson (1989), Witt (1993), and Robert and Poulsen (2001), who take into account the nature of the host structure (structural site), the internal structure and textures of the veins, and the arrangement, shape, and relationships between veins and host structures (geometry). These attributes are observable in the field, at both outcrop and hand-specimen scales. Quartz textures and internal structures are classified according to Dowling and Morrison (1989) and Vearncombe (1993).

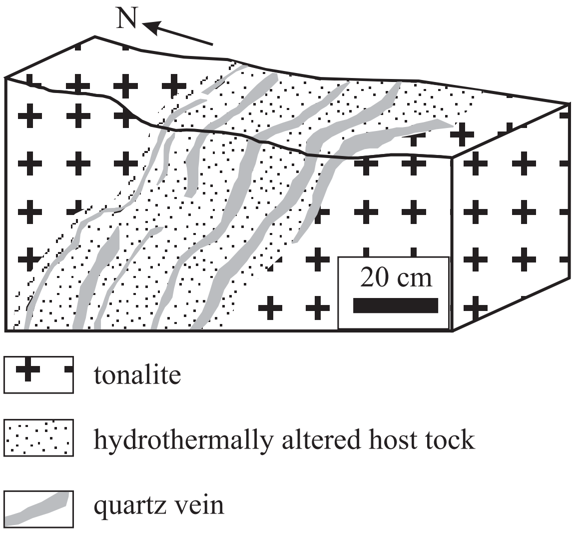

Fig. 3.- Block diagram showing the discontinuous veinlets enclosed by hudrothermally altered host rock at Divisão.

Fig. 3.- Bloc diagramme montrant les veinules discontinues dans l'altération hydrothermale de la roche encaissante à Divisão.

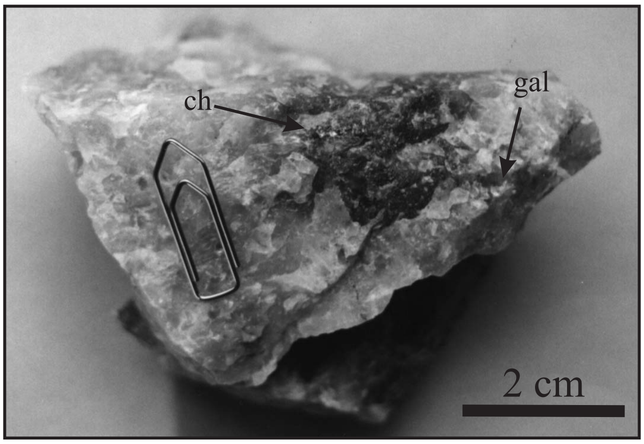

Fig. 4.- Photograph of the sulfide-bearing (arrows) quartz vein at Divisão. ch: chalcopyrite, gal: galena.

Fig. 4.- Photographie d'une veine de quartz à sulfures de Divisão. Flèches, ch : chalcopyrite ; gal : galène.

Regional lithological and structural controls

Gold mineralization is present in all the tectonic domains, but is rare in the Jari Belt, which lacks significant supracrustal sequences. All but one (Limão) of the Au-quartz deposits and prospects of the Ipitinga District are clustered in the southeastern portion of the district and occur typically within two sets of elongated Paleoproterozoic metavolcano-sedimentary sequences and intruding granitoids (Fig. 2). The main hosts are pelitic metasedimentary rocks, banded iron formations, mafic/ultramafic metavolcanic rocks, and, broadly, granitoids. This assemblage resembles granitoid-greenstone terranes formed in marginal volcano-sedimentary basins and magmatic arc environments (e.g., Condie, 1989). Most deposits are sited in close proximity with to large structures that either cut longitudinally or bound the metavolcano-sedimentary sequences, especially close to the contact with granitoids and in tectono-stratigraphic terrane limits (Fig. 2).

Description of the deposits

Divisão

Two roughly orthogonal ore zones are being exploited at Divisão. The main zone strikes N85ºW, dips 40ºNE and varies in style from a single vein, up to 1 m thick, to an anastomosed group of several thin and discontinuous quartz veinlets set in the hydrothermally altered host rock (Fig. 3). They are strongly fractured, probably due to late cataclasis, and internally show medium-grained (2-3 mm) quartz with a saccharoidal texture. The vein set is hosted in a shear zone, to which it is parallel, and cuts a broadly undeformed biotite-rich tonalite close to its contact with a supracrustal sequence dominated by mafic metavolcanic rocks and amphibolites. The shear zone is marked by the enrichment of sericite and by foliated rocks forming a narrow halo around the vein margins. It corresponds to the veined brittle-ductile shear zone type of Witt (1993), or to the shear vein type of Robert and Poulsen (2001). Kinematic indicators have not been confidently identified.

The other zone occurs in isolation. Striking N05ºE (subvertical) and up to 1 m, it is made up of massive, milky quartz and contains minor amounts of chalcopyrite, pyrite and galena (Fig. 4). It may represent an extensional-oblique vein. No crosscutting relationships could be established between the two main veins.

Nova Esperança

Gold mineralization at Nova Esperança is associated with a shallow dipping (10ºSW), 50 cm-thick quartz vein that strikes N85ºW. It is hosted by a brittle structure that cuts across an undeformed, coarse-grained monzogranite. The vein shows a laminated to saccharoidal texture and minor concentrations of cubic pyrite. In places, it consists of coarse-grained, milky and massive quartz, which lacks sulfide minerals. The laminated texture consists of quartz laminae separated by thin discontinuity (slip?) surfaces marked by aggregates of comminuted quartz. Internally, the laminae show saccharoidal and massive textures. Sericite occurs in fractures of the quartz. This vein is possibly of extensional-oblique nature.

Igarapé do Inferno

The Igarapé do Inferno mineralization is associated with a 50 cm-thick sulfide-bearing quartz vein, that strikes N50ºW and dips 58ºSW. Fine-grained subhedral pyrite grains occur as disseminations along the vein. The vein quartz is coarse -grained and shows a saccharoidal texture. It is hosted by an undeformed monzogranite (similarly to Nova Esperança), which shows strong kaolinization (supergene alteration of the original hydrothermal mineralogy, probably K-feldspar), along with remnants of sericite, around the vein walls. This hydrothermal envelope is relatively symmetrical with respect the vein. The vein plus the hydrothermal halo can be up to 3 m -thick. In addition, hydrothermal sericite fills fractures in the vein as well. The vein is discontinuous (lenticular?), and occasionally only the hydrothermally altered granitoid is observed. This vein can be interpreted either as a fault-fill or fracture-controlled vein (simple quartz vein, according to Witt, 1993).

Castanhal

The mineralization at Castanhal is associated with two quartz veins hosted by a highly strained pelitic metasedimentary rock. One quartz vein is up to 20 cm -thick with an attitude of N50º-60ºE/80ºSE, i.e. subparallel to the strike of the foliation of the host rock, and is surrounded by a centimeter-wide halo of inner sericitic and outer chloritic alteration (Fig. 5). This vein shows a laminated texture, defined by the alternation of quartz laminae separated by discontinuity surfaces that are parallel to the vein strike. Preliminary petrographic investigation shows that there is no clear microscopic difference between adjacent laminae, and no evidence of dislocation along the surfaces could be confidently characterized, due to the monomineralic composition of the vein.

The second vein strikes N30ºW and dips 60ºSW, cutting across the foliation of the host rock, which strikes E-W and dips, 85ºS, suggesting that foliation is folded. It averages 40 cm in thickness and is enveloped by a halo of hydrothermal alteration (sericite) a few decimeters wide. Irregularly-shaped pockets of hydrothermally altered host rock occur occasionally in the proximity of the vein. This vein shows a massive texture, and is locally fractured.

No crosscutting relationships could be observed between the two Castanhal veins. They can be interpreted either as a single vein that has been transposed and disrupted during progressive stages of increasing strain in a strike-slip shear zone (Fig. 6A), or as a set of shear (or foliation controlled) and extensional-oblique veins, respectively (Fig. 6B). The foliation of the host rock is discordant with respect to the regional structural pattern. This may be attributed to the nearby emplacement of the Carecuru Intrusive Suite granitoids (Fig. 2).

Mamão

Mamão comprises a series of open -pits and two underground workings aligned along a NW-SE-trending structure that can be traced for ~400 m, parallel to the regional trend. The host rock is a pelitic metasedimentary rock with prevailing foliation striking N30º-45ºW and dipping 60ºSW, having local inflections to north and northeast and highly variable dips, suggesting that the foliation is folded. Altered meta-ultramafic (amphibole-serpentine schist) rocks are present. Gold occurs in massive to saccharoidal (Fig. 7) quartz veins and in the enclosing, regular or not, hydrothermal halos. These halos are dominantly sericitic (+quartz) and vary in thickness from a few decimeters up to 4 m. Microfractures filled with sericite commonly crosscut both the quartz vein and the altered wall -rock. The veins are either subparallel to, or cut across the foliation, and are interpreted as fault-fill / shear veins, or as due to dilation of the regional foliation. Irregular sets of thin veins are also present locally.

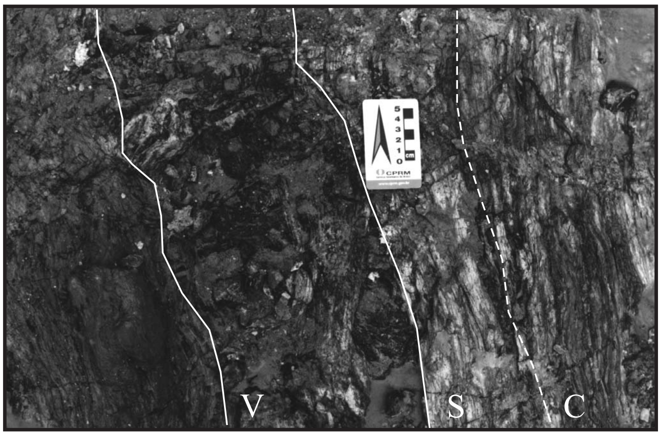

Fig. 5.- Vertical photograph showing the mineralized zone at Castanhal. V: vein; S: sericite zone; C: chlorite zone.

Fig. 5.- Photographie verticale de la zone minéralisée à Castanhal. V : veine ; S : zone à séricite ; C : zone à chlorite.

Carará

The Carará deposit holds reserves of 10 t of gold averaging 21.2 g/ton. The mineralized quartz vein is hosted by a strained tourmaline- and muscovite-bearing quartzite, which shows a NNW-SSE-striking foliation that dips steeply (75º-85º) SW. The foliation planes contain an elongation lineation generally down the dip or slightly oblique (70º/S30ºW). The quartz vein occupies the central part of a shear zone that shows remarkably schistose rocks up to a few decimeters thick around the vein. The schistosity planes are subparallel to the regional foliation and are highlighted by abundant hydrothermal muscovite and tourmaline. Tourmaline is better developed at the contact between the vein and the wall rock (Fig. 8). Muscovite and tourmaline grains show an elongation lineation that indicates reverse to slightly reverse-oblique movement along the vein. These structural elements are consistent with a high-angle reverse shear zone, and indicate that the shear zone was active at the

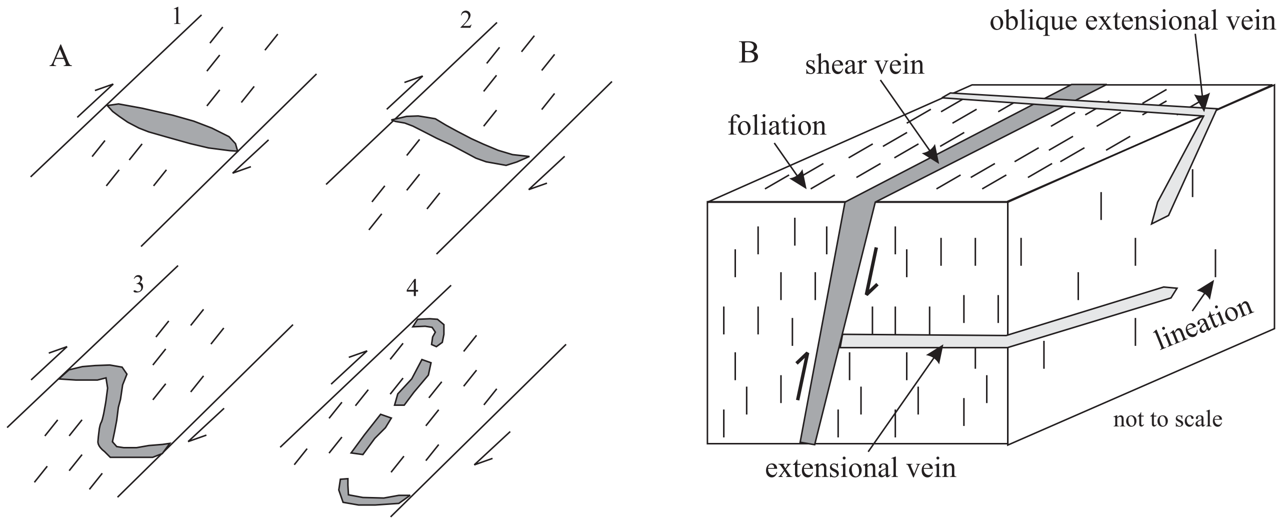

Fig. 6.- Sketches showing possible origins for the veins at Castanhal. A) incremental evolution of a folded and disrupted vein (adapted from Poulsen, 2001); B) block diagram with possible relationships between shear, extensional and oblique veins (after Robert and Poulsen 2001).

Fig. 6.- Croquis décrivant l'origine possible des veines à Castanhal. A) évolution d'une veine plissée et interrompue (adaptée de Poulsen, 2001) ; B) bloc diagramme avec les relations possibles entre les veines en cisaillement, en extention et extention obliques (d'après Robert et Poulsen, 2001).

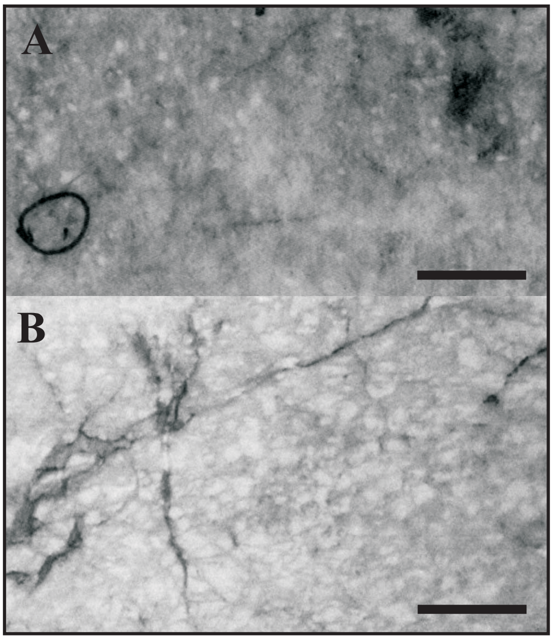

Fig. 7.- Photograph of polished sections showing the saccharoidal aspect of the quartz veins at Mamão (A) and Catarino (B). Scale bares are 1 cm long.

Fig. 7.- Photos de sections polies montrant l'aspect saccharoïde des veines de quartz à Mamão (A) et Catarino (B). Les barres d'échelle mesurent 1 cm de long.

time of vein formation, allowing the quartz vein to be classified as a (central) shear vein.

Gold mineralization is restricted to the quartz vein and its 10-50 cm-thick hydrothermal halo. The vein ranges from 15 cm to 3 m in thickness and can be traced 460 m along strike and at least 70 m in depth. Networks of microfractures filled with sericite and tourmaline crosscut both the quartz vein and the wall rock, and acted as structural sites where gold was deposited. The vein quartz shows massive to saccharoidal textures, and the absence of laminated texture with fragments of the wall rock inside the vein may be taken as indicative of a single stage of dilation and hydrothermal sealing (Cox, 1995). However, late dilation (fracturing) is indicated by the growth of thin extensional veinlets filled with fibrous tourmaline crosscutting the main quartz vein.

Catarino

The Catarino showing occurs in the southeastern part of the district, in the same structural and stratigraphic trend as the Carará deposit and Mamão occurrences. It shows several similarities to the Carará deposit, such as: the host rock is the same muscovite-bearing quartzite, striking N20ºW; the vein quartz varies from vitreous to milky in appearance and shows massive to saccharoidal (Fig. 7), locally laminated, textures; wall-rock alteration is characterized by coarse-grained muscovite + tourmaline + quartz (with higher contents of muscovite at the vein margins); tourmaline occurs either at the contact between vein and wall rock or separating laminae of quartz. Some of the main differences are: the shallow dip of the mineralized zone at Catarino (up to 35ºSW); the ore zone at Catarino consists of a series of thin (3-10 cm), subparallel, shallow-dipping veinlets (Fig. 9); no shear zone could be confidently demonstrated, since the variation in strain intensity between the host rock and the ore zone was not recognized. The vein sets may thus have formed, by dilation of the foliation. Gold is locally visible, occurring in the free state as platy, irregularly-shaped to rather rectangular particles, up to 0.5 mm long (rarely achieving 2.5 mm).

Limão

The isolated Limão prospect occurs in the northwestern part of the district (Fig. 2), but is surrounded by tens of alluvial workings. Mineralization produced a gold-bearing quartz vein, which is being exploited in an underground working down to 45 m. The vein ranges from 50 cm to 2 m in thickness (lenticular? boudinaged?), with a minimum length of 50 m, and is fringed by a sericitic hydrothermal halo, a few centimeters thick, marking the limits of the host ductile shear zone. Medium size pyrite occurs at the vein /wall rock contact, and very fine pyrite is disseminated throughout the vein. Gold seems to be restricted to the vein and to its contact with the host rock (a banded iron formation), since the hydrothermally altered rock is not being mined.

The vein strikes N80ºW, with a steep steep (75º) SW dip, and is parallel to the shear zone. The quartz grains are elongated down the dip of the foliation and striations in the vein walls indicate reverse movement, characterizing the host structure as a high-angle reverse shear zone. The internal structure of the vein varies across the strike (Fig. 10). At its hanging wall, the vein is marked by strong ductile deformation, showing a laminated/schistose aspect, with ribbon quartz alternating with slivers of altered wall-rock. Outside of this zone, the vein is still laminated (but not schistose), with individual quartz laminae being separated by discrete slip surfaces. Nevertheless, the vein is massive at its center, becoming laminated again towards the footwall. At this point, however, it does not show a schistose aspect as in the hanging wall; i.e. the structural variation is not symmetric. These features indicate that the vein formation occurred while the host shear zone was still active, and that deformation probably outlasted the vein formation. Similar behavior is described elsewhere, for instance, by Nguyen *et al.* (1998), who interpreted the vein development and deformation in the shear system in terms of cyclic variation of fluid pressure (fault-valve mechanism) and of the shear stress regime.

Discussion and concluding remarks

Gold-bearing quartz veins in the Ipitinga Auriferous District form a coherent group and share a number of recurring geological attributes. Greenschist-facies metavolcano-sedimentary rocks, especially metasedimentary, are the most common hosting lithologies, followed by coeval, more or less deformed granitoids. Sericitization is the main hydrothermal alteration, occurring in all deposits and indicating the important role played by hydration reactions. Tourmaline is present in deposits hosted by quartzites (some of them having diagenetic tourmaline in their original composition). The higher concentration of this mineral in the vein margins indicates a hydrothermal origin, at least by remobilization of the sedimentary tourmaline. Sulfide minerals, mainly pyrite, are only minor constituents. The hydrothermal minerals have overprinted the metamorphic assemblages and indicate the post metamorphic peak timing of the mineralization.

Fig. 8.- Photograph of the mineralized vein at Carará. Note the enrichment in tourmaline in the vein-wall rock contact (arrow).

Fig. 8.- Photo de la veine minéralisée à Carará. Noter l'enrichissment en tourmaline dans le contact veine-encaissant (flèche).

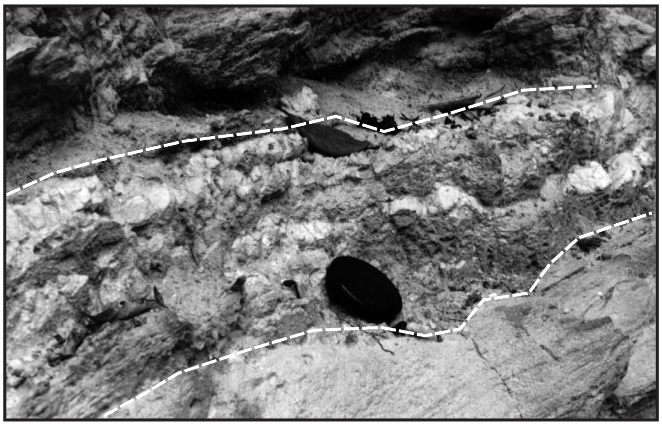

Fig. 9.- Photograph, taken in the horizontal plane, of a mineralised zone at Catarino. The dashed lines outline the sharp contact between the mineralized zone, formed by quartz veins (white) and enclosing hydrothermal halo (dark gray) and the unaltered host rock (light gray).

Fig. 9.- Photo prise dans un plan horizontal de la zone minéralisée à Catartino. Les lignes pointillées soulignent le contact net entre la zone minéralisée formée de veines de quartz (blanc) et le halo hydrothermal les emballant (gris foncé) avec la roche encaissante (gris clair).

Preliminary fluid inclusion studies also show, the importance of CO_2 in the hydrothermal system(s). An anhydrous, CO_2-bearing fluid was active during the deposit formation at Carará (Klein, 2002), whereas mixed CO_2-H_2O-salts fluids, trapped under mesothermal conditions, were predominant in other deposits (Klein, unpublished).

Fig. 10.- Photographs showing textural variation of the quartz vein at Limão. A) massive vein; B) laminated vein; C) laminated to schistose vein at the contact with the host rock.

Fig. 10.- Photos montrant la variabilité texturale des veines de quartz à Limão. A) veines massives ; B) veines laminées ; C) veines laminées à schistosées au contact de l'encaissant.

The rheological nature of the host rocks generally defines the deposit style and/or the nature of the hosting structure. Accordingly, veins hosted in the more competent granitoids show, in general, a more brittle behavior (Igarapé do Inferno, Nova Esperança) when compared to those hosted in the less competent metavolcano-sedimentary sequences (Limão, Carará). Moreover, veins hosted in the granitoids are distributed close to their contacts with the metavolcano-sedimentary sequences, which are common zones for strain localization (Cole *et al.*, 2000).

Some quartz veins are tabular. They are neither folded nor visibly boudinaged. This can be taken as evidence that they have not been significantly overprinted by deformation after their formation. Other veins show a variable thickness along the strike, a feature that can be ascribed to boudinage. The presence of both ductile and brittle structures in a single vein is also a common feature. In a few cases (e.g., Castanhal), veins may have been folded, but evidence is not conclusive. Preliminary petrographic investigation showed a weak (undulose extinction, subgrain development) to intense (recrystallization) ductile imprint (either during or after vein formation).

Internal structures and textures of the veins are indicative of displacement, stress regime and fluid pressure during the development of the shear zones / quartz-vein systems (Hodgson, 1989; Poulsen and Robert, 1989; Boulier and Robert, 1992; Cox, 1995), as well as of depth of vein formation (Vearncombe, 1993). The predominant textures displayed by the studied veins are laminated, massive and saccharoidal. Accordingly, the laminated texture is evidence of episodic slip and fault sealing, indicating that the veins were emplaced in active structures, whereas the saccharoidal texture indicates, at least, moderate crustal levels (mesozonal) for the vein emplacement. These features are commonly related to syn- to late-tectonic fault-fill / shear veins (Hodgson, 1989; Cox, 1995; Robert and Poulsen, 2001).

Veins occur near or between first-order, regional and district-scale shear zones, which were likely to have been active during the vein formation, allowing fluids to migrate through the crust and to be channeled to suitable depositional sites (hosting structures). These sites are the regional foliation, and the compressional, moderate- to high-angle, reverse faults/shear zones, interpreted as being second- and third-order structures, probably related to the first-order ones. The localization of deposits in subsidiary structures is probably due to a combination of factors, namely: 1) the rocks around major structures are more permeable, because these are sites of low mean stress, and hence allow higher fluid flux; and 2) the first-order structures are more ductile (aseismic), whereas the subsidiary ones are seismically active, leading to fluid-pressure fluctuations, which is a very important factor controlling gold precipitation (McCuaig and Kerrich, 1998, and references therein).

Veins occurring closer to the boundary of tectonostratigraphic blocks are mostly parallel to the regional foliation, whereas those occurring in the inner portion of the Carecuru-Paru Orogen (Fig. 2) show more variable orientations, either paralleling or crosscutting the foliation. Some foliation-parallel veins have their formation interpreted as resulting from dilation of the regional foliation (e.g., Tourigny *et al.*, 1989). Other veins were emplaced in shear fractures or in dilational sites of shear zones; these are fault-fill / shear veins. True extensional veins have not been recognized. Some discordant veins are possibly extensional-oblique in nature, but they are subordinate.

On the basis of (1) the geometric relationships of the Au-bearing veins with their hosting structures and the regional structural grain, (2) the syn- to late tectonic and post-peak metamorphic timing of the veins in relation to their hosts, (3) the type of the hosting structures, characterized as mostly reverse (± oblique) faults, and (4) the steep lineations recorded in the vein walls and in the foliation planes of the host rocks in the proximity of the veins, we are able to infer that the mineralization formed as part of a progressive compressional tectonic regime. This regime imparted a NE-SW crustal shortening, with the maximum ($\sigma 1$) and minimum ($\sigma 3$) principal stress components being, respectively, subhorizontal and subvertical.

Variations in style, in internal deformational characteristics and in the strain state, may be ascribed to vein emplacement during the development of the regional foliation and before the end of the progressive/incremental evolution of the host structure (e.g., Tourigny *et al*., 1989). This may be favored by fluctuating fluid pressures (Robert and Kelly, 1987). Processes acting after vein formation (e.g. folding, shearing), and controls exerted by other factors, such as layering, bedding, regional foliation and pre-existent inhomogeneities, may also affect and / or change the spatial position of the veins. The presence of pre-tectonic granitoids (acting as rigid bodies) and syn-tectonic granitoids (intruding the greenstone sequences) may have contributed as well.

Variation in the strike and style of the veins may be attributed to both far- and near-field stress configurations (e.g. Miller *et al*., 1995; Sibson, 2001). Accordingly, fluctuations in stress along the margins of crustal blocks (plates?) may cause changes in the strain configuration leading to episodic fluid pulses (far field), while fluctuations in fluid pressure at the deposit scale (near field) may have resulted in the observed stress configuration. The presence of vein systems and associated hydrothermal alteration indicate that faulting / shearing occurred in a high fluid flux regime in the crust (Cox, 1995). This occurs typically late during regional crustal shortening, which, in turn, is also associated with convergent plate boundaries (Yeats *et al*., 1997, quoted by Sibson, 2001). This is expected to have occurred during the convergence of the Carecuru-Paru magmatic arc and the Jari Belt, accounting for the architecture of the gold deposits in the Ipitinga Auriferous District.

Attributes of the Ipitinga Auriferous District, such as geological setting, structural styles, timing of structural evolution with respect to metamorphism, hydrothermal assemblage with low sulfide contents, and preliminary fluid inclusion data of the gold-bearing quartz veins, are comparable with those described for Paleoproterozoic gold deposits elsewhere in the Guiana Shield (e.g., Voicu *et al*., 2001 and references therein), and for late-orogenic gold deposits in the sense of Groves *et al*. (1998) and Witt and Vanderhor (1998).

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