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Geology of Paleoproterozoic Gneiss- and Granitoid-Hosted Gold Mineralization in Southern Tapajós Gold Province, Amazonian Craton, Brazil

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Abstract

Vein-quartz gold mineralization in Southern Tapajós Province is hosted by arc-related, calc-alkaline tonalitic orthogneisses (Cuiú-Cuiú Complex, 2033–2005 Ma) and post-collisional, calc-alkaline, K-rich granitoids (Creporizão Intrusive Suite, 1997–1957 Ma). The deposits are structurally controlled and form typically tabular bodies that parallel the hosting structures, and are characterized by quartz veins surrounded by halos of strongly altered wall rock, which are usually narrow and show weak to prominent ductile fabric. Steeply dipping fault-fill veins and shear veins account for 80% of the structural style, followed by breccia veins and lesser stockworks and veins hosted in low-angle reverse-oblique faults. Hosting structures vary from ductile-brittle to brittle in nature, and together with structural and textural evidence provided by the veins, indicate a wide range of depth of emplacement for the mineralization, from shallow to mid-crustal. Quartz and sericite are the main alteration minerals and pyrite is ubiquitous.

We modify current structural models for the Tapajós Province, proposing the NW-SE–trending strike-slip event that affected the Creporizão Suite, and transposed the gneissic banding of the Cuiú-Cuiú Complex as the second (D2) major structural event in the province, occurring broadly coeval with the emplacement of the late-stage plutons of the Creporizão Suite (~1.97–1.95 Ga). Emplacement of low-angle fault-hosted veins, shear veins, and fault-fill veins that show evidence of plastic deformation (i.e., most of the deposits in Southern Tapajós Province) are related to this structural phase.

Introduction

STRUCTURALLY CONTROLLED vein-quartz (lode) gold deposits are more commonly associated with metamorphic terrains, where they are hosted especially by low- to medium-grade metasupracrustal sequences, and minor intruding granitoids (granitoid-greenstone association) of Archean to Cenozoic age (Kerrich and Cassidy, 1994; Groves et al., 1998; Goldfarb et al., 2001). These gold deposits show a variety of structural styles, vein textures, and alteration mineralogy, depending on many factors, such as the composition and metamorphic grade of the host rock, timing of gold deposition with respect to metamorphism and deformation, structural regime, and depth of formation (e.g., Cassidy et al., 1998; Groves et al., 1998). Nevertheless, they are consistent as a class and have been classified as greenstone-hosted (Robert et al., 1997) or orogenic (Groves et al., 1998) gold deposits. Granitoids and granitic gneisses are also hosts for this type of gold mineralization, with deposits showing many of the attributes displayed by supracrustal-hosted deposits, and being considered a subgroup of the lode type of mineralization, at least within the Archean lode-gold deposits model (Cassidy et al., 1998).

The Tapajós Gold Province of the Amazonian Craton has produced about 600 metric tons (t) of alluvial gold in the past 40 years (Faraco et al., 1997). It is a major magmatic province and contains more than 100 sub-economic gold deposits and showings, mostly hosted by granitoids of different (Paleoproterozoic) ages and affinities, as well as by gneisses, felsic to intermediate volcanic rocks, and minor gabbroic and metavolcanic-sedimentary rocks (Coutinho et al., 2000; Klein et al., in press), distributed along several gold camps and small districts. Most deposits are Au-bearing quartz veins,

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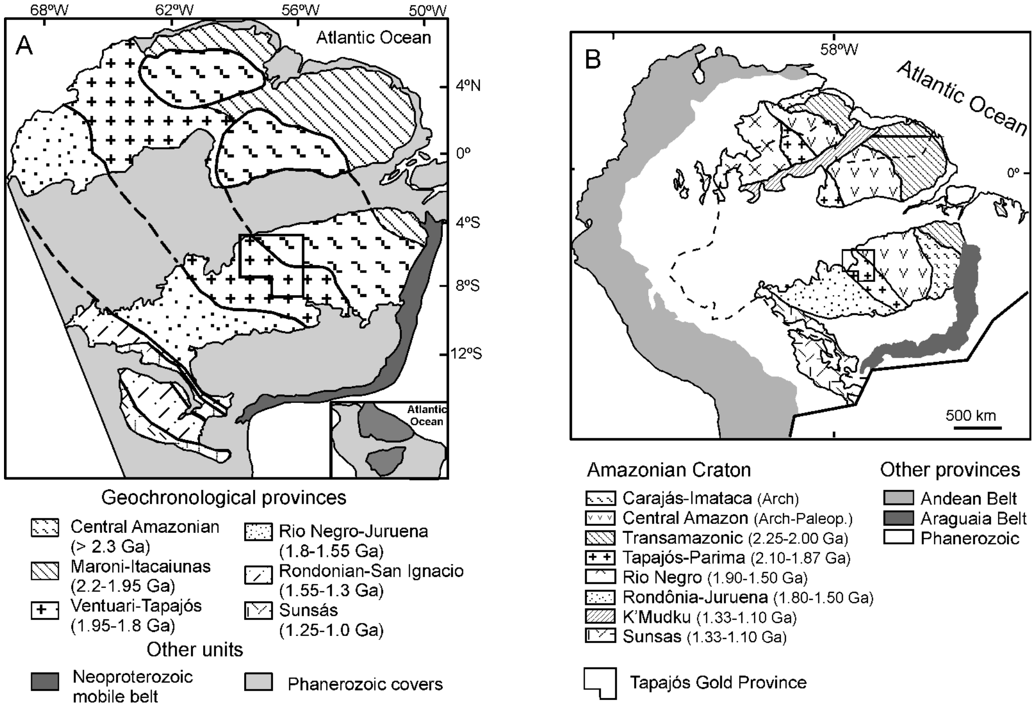

FIG. 1. Geochronological provinces of the Amazonian Craton according to (A) Tassinari and Macambira (1999) and (B) Santos et al. (2000).

with stockworks and dissemination occurring subordinately (Klein et al., 1999; Rosa-Costa and Carvalho, 1999; Coutinho et al., 2000), and distinct classifications (such as mesothermal, epithermal, intrusion-related, and orogenic) have been proposed for individual deposits or to the province as a whole (Dreher et al., 1998; Juliani, 2001; Klein et al., 2001; Santos et al., 2001).

In the southern portion of the Tapajós Province, a series of gold camps contain deposits and prospects typically hosted in orogenic gneisses (Cuiú-Cuiú Complex) and granitoids (Creporizão Intrusive Suite). The purpose of this paper is to summarize the geological attributes of these deposits, which are observable at regional, outcrop, and hand-specimen scales, with emphasis on their relationship with regional structures, structural styles, vein geometry, and internal structures and textures. Microscopic information is used when available. A revaluation of current structural models and a tentative classification of the deposits are made as well.

Geological Setting

The Tapajós Gold Province (TGP) is located in the central portion of the Amazonian Craton and is part of the Ventuari-Tapajós (according to Tassinari and Macambira, 1999) or Tapajós-Parima (in the sense of Santos et al., 2000) geochronological provinces (Fig. 1). The regional lithostratigraphy was defined by the mapping program performed by CPRM/Geological Survey of Brazil (Almeida et al., 2000; Bahia and Quadros, 2000; Ferreira et al., 2000; Klein and Vasquez, 2000; Vasquez and Klein, 2000). The results of this program (Fig. 2), along with the work of Santos et al. (2000, 2001), showed a protracted Paleoproterozoic magmatic, metamorphic, and tectonic evolution spanning the period from 2033 Ma to 1870 Ma.

The oldest rocks found in the TGP are the greenschist-facies metavolcano-sedimentary sequence of the Jacareacanga Group and the amphibolite-facies gneisses (± granitoids, migmatites, amphibolites) of the Cuiú-Cuiú Complex, both formed between 2033

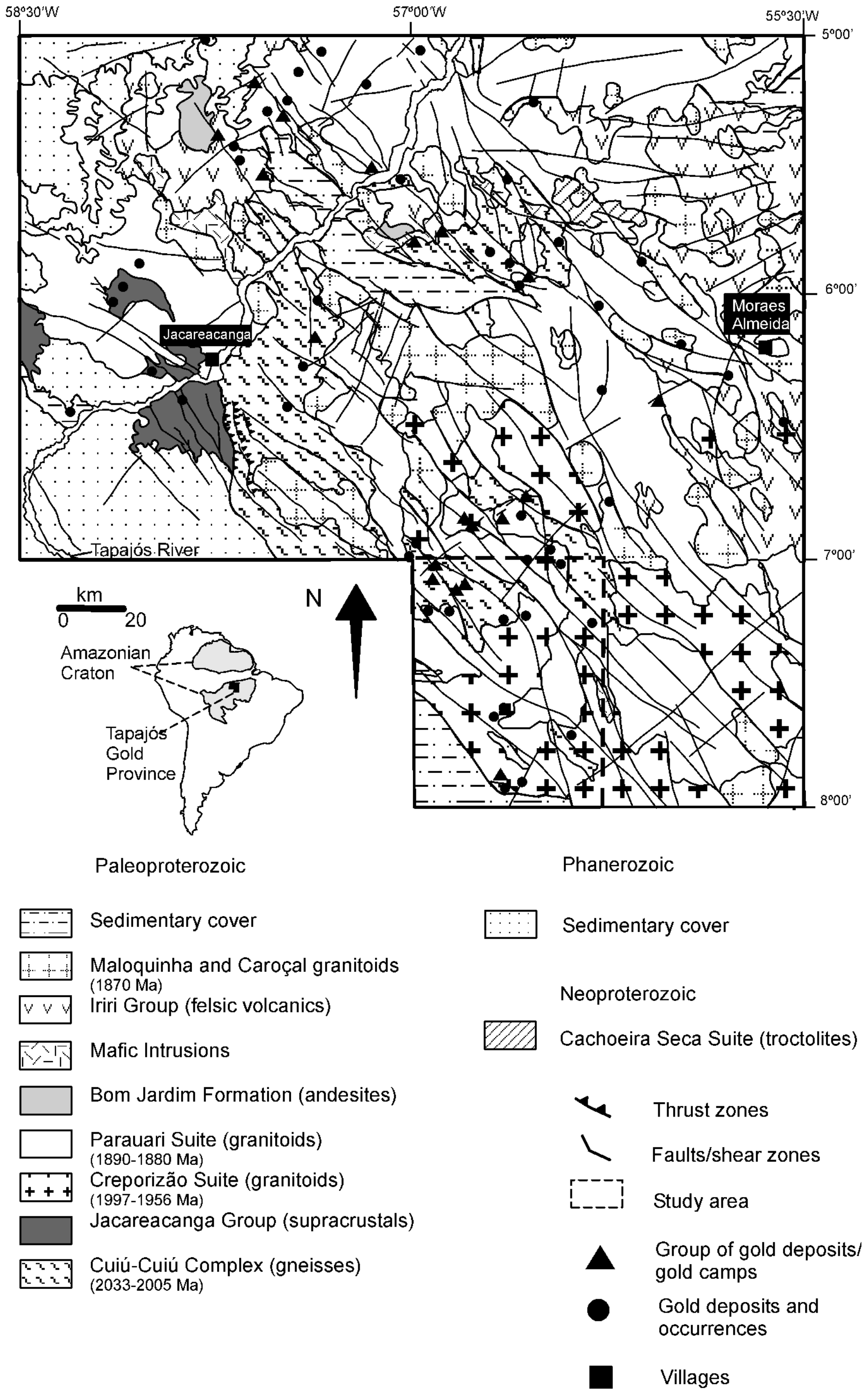

FIG. 2. Geological map of the Tapajós gold province (compiled and modified from Almeida et al., 2000; Bahia and Quadros, 2000; Ferreira et al., 2000; Klein and Vasquez, 2000; Vasquez and Klein, 2000), showing the distribution of the gold deposits/camps in the province.

and 2005 Ma (Santos et al., 2000, 2001). These metamorphic sequences have been intruded by calc-alkaline granitoids of the Creporizão (1.99–1.96 Ga) (Ricci et al., 1999; Vasquez et al., 2000), Tropas (1.90 Ga) (Santos et al., 2001), and Parauari (1.89–1.88 Ga) (Vasquez et al., 1999; Santos et al., 2000) intrusive suites, as well as by a series of gabbroic rocks at 1.87 Ga (Santos et al., 2001). Sedimentary deposits showing intra-arc characteristics formed at ~1.90–1.89 Ga (Santos et al., 2001). This orogenic period was followed by widespread felsic plutonic and volcanic activity at 1.87 Ga (Almeida et al., 1999; Vasquez et al., 1999; Santos et al., 2000; Lamarão et al., 2001; Klein et al., in press), related to extensional tectonics.

It is the consensus that the orogenic evolution of the province comprises the accretion of magmatic arcs and related sedimentary basins. However, the number of arcs that have accreted is still debatable. Santos et al. (2000, 2001) envisioned the evolution of the orogenic domain through the sequential accretion of four magmatic arcs dated at 2.02 Ga (Cuiú-Cuiú Complex plus Jacareacanga Group), 1.96 Ga (Creporizão Suite), 1.90 Ga (Tropas Suite), and 1.88 Ga (Parauari Suite). These accretionary events have been followed by post-collisional intracratonic (granitoid and mafic) magmatism and sediment deposition between 1870 Ma and 1780 Ma. Conversely, Vasquez et al. (2001) considered the Creporizão granitoids as post-collisional granitoids still related to the development of the Cuiú-Cuiú arc, instead of considering it to be a different arc (see discussion below).

Structural framework

Remote sensing imagery and geophysical evidence show that the main structural features of the Tapajós Province are major NNW-SSE– to NW-SE–striking, linear or sinuous, continuous to discontinuous lineaments, extending for tens to a few hundreds of kilometers (Fig. 2). Field evidence indicates that they represent mainly subvertical, sinistral strike-slip faults, and brittle-ductile shear zones. This strike-slip system has been interpreted as a progressive and episodic compressive event, with the maximum compressive stress vector (σ_1) around the east-west direction, as shown by geometric relationships of major and minor subsidiary structures (Santos, 1999, 2000; Klein and Vasquez, 2000). On a regional scale, these structures have controlled the ascent and emplacement of several generations of granitoids and volcanic and mafic rocks, as well as the establishment of sedimentary basins, and have outlined their present shape and geometry (Klein et al., 1997; Santos, 1999; Almeida et al., 2000; Klein and Vasquez, 2000). It is likely that at least some of these structures may have been reactivated during the tectonic evolution of the Tapajós Province. However, the timing of these events is not well constrained yet.

The oldest (D1) structural record is found in the west-central portion of Tapajós Province. It is defined by the NE-SW–trending gneissic banding of the Cuiú-Cuiú Complex and the schistosity of the volcano-sedimentary Jacareacanga Group (Almeida et al., 2001), produced by a compressive event, and is well preserved in the gneisses of the study area. This deformation is not seen in younger rocks, leading Santos et al. (2001) to establish the time interval of 2005–1974 Ma as the timing of D1, which may have been synchronous with the metamorphic peak. Santos et al. (2001) defined a second deformational event (D2) represented by a high-angle, N10E-striking, sinistral strike-slip shear zone of ductile-brittle character, affecting especially the Tropas Suite in the western-central portion of the province, and only locally affecting the Creporizão and Parauari suites. They placed the timing of this event to between 1894 and 1883 Ma. Furthermore, they suggested that the brittle deformation, which is younger than 1883 Ma and which affected the Creporizão and Parauari granitoids, could have been produced during the shallow emplacement of the Maloquinha granitoids.

However, this structural evolution does not explain satisfactorily the brittle-ductile deformation imprinted on the granitoids of the Creporizão Suite (1997–1957 Ma) that are older than the Tropas Suite (1.90 Ga). The Creporizão granitoids show a magmatic foliation subparallel to a subvertical tectonic foliation that strikes NW-SE, and is clearly related to a brittle-ductile strike-slip regime. This event has not been detected either in the Tropas Suite, as stated by Santos et al. (2001), nor in younger rocks (Parauari and Maloquinha suites, volcanic rocks). Furthermore, Almeida et al. (2000, 2001) documented the transposition of the gneissic banding of the Cuiú-Cuiú rocks by NW-SE strike-slip shear zones. Still, a whole-rock Rb-Sr isochron age of 1965 ± 16 Ma was reported by Tassinari (1996) for granitoids of the Creporizão Suite. This age is close to the zircon ages (U-Pb, Pb-evaporation) for the late-stage granitoids of the Creporizão Suite, and may indicate that the emplacement of the post-collisional plutons was broadly coeval with the regional NW-SE deformational event (Ricci et al., 1999; Vasquez et al., 2001).

Hence, we postulate a reappraisal of the structural evolution of the Tapajós Province, as follows. An early deformation stage (D1) is represented by the compressive event that imparted the gneissic banding of the Cuiú-Cuiú Complex and the schistosity of the Jacareacanga Group, occurring probably between 2005 and 1997 Ma. D2 is represented by the NW-SE–trending strike-slip event that affected the granitoids of the Creporizão Suite and overprinted the gneissic banding of the Cuiú-Cuiú rocks, occurring at ~1.97–1.95 Ga. D3 is related to the NNE-SSW strike-slip ductile shear zones that affected the Tropas Suite between 1894 and 1883 Ma. Younger structures may have been reactivated and/or generated during the emplacement of the widespread Maloquinha granitoids, and are related to extensional tectonics.

Gold deposit models

Studies of individual deposits in the Tapajós Gold Province have been focused on fluid-inclusion properties and/or alteration assemblages, leading to the proposition that the deposits fit epithermal to mesothermal models (Dreher et al., 1998; Klein et al., 2001; Nunes et al., 2001; Ronchi et al., 2001). Province-scale models have been developed by Coutinho et al. (2000), Santos (2000), and Santos et al. (2001). Santos (2000) presented a structural model relating the formation of the gold-quartz veins to the regional-scale strike-slip fault system. Coutinho et al. (2000) classified the deposits of the Tapajós Province as mesozonal/epizonal orogenic deposits and suggested two phases of mineralization, based on model ages of sulfide minerals, at 1.96 Ga and 1.88 Ga. Both phases postdated the regional metamorphic peak, and have been associated with compressional to transpressional tectonics at the convergent plate margin of the accretionary orogen. Lead and stable (O, H) isotopes, together with fluid-inclusion data, suggest deep sources for gold mineralization (magmatic to juvenile), with possibly meteoric water added in some deposits at shallow crustal levels.

Santos et al. (2001) proposed two classes of gold deposits—orogenic and intrusion related. Orogenic deposits have been subdivided into: (1) turbidite-hosted, consisting of mesozonal quartz-pyrite veinlets or disseminations in ductile structures cutting the supracrustal rocks of the Jacareacanga Group; (2) magmatic arc-hosted, consisting of mesozonal quartz-pyrite-carbonate veins and disseminations hosted in ductile-brittle structures cutting the gneisses of the Cuiú-Cuiú Complex and the granitoids of the Tropas Suite. Intrusion-related deposits have been subdivided into: (1) epizonal quartz-pyrite veins and pyrite disseminations emplaced in shallow extensional brittle structures (similar to Korean-type deposits) cutting K-rich granitoids of the Creporizão, Parauari, and Maloquinha suites, frequently associated with mafic dikes; (2) epizonal disseminations and stockworks, with hydrothermal magnetite, hosted in mafic and sedimentary rocks, and sharing some characteristics with porphyry-type deposits. Using Pb and Ar isotopes, Santos et al. (2001) determined the timing of the intrusion-related deposits as being around 1.86 Ga. They have not established the age of the orogenic deposits, but have suggested that it might be similar to the age of the intrusion-related deposits, with mineralization differing in style, host rocks, and depth of emplacement. They argued that the orogenic deposits would be related to the final stages of evolution of the Parauari arc, whereas the intrusion-related deposits would be related either to the Parauari arc or to post-collisional granitoids (Maloquinha Suite).

Epithermal deposits have been described by Jacobi (1999), Corrêa-Silva et al. (2001), Juliani (2001), and Nunes et al. (2001) for the east-central portion of the province. The deposits are hosted by felsic to intermediate volcanic rocks and associated volcaniclastic rocks, and consist of both low-sulfidation (adularia-sericite) and high-sulfidation (quartz-alunite) types. Indirect dating suggests that mineralization formed at ~1.88 Ga, and $\delta^{34}S$ data indicated a magmatic-hydrothermal source for the mineralizing fluids and 330ºC to 140ºC as the formation temperatures (Juliani, 2001; Nunes et al., 2001). Dreher et al. (1998) also considered the epithermal model for the Joel and David deposits. However, Corrêa-Silva et al. (2001) questioned this classification and argued that the adularia present in the Davi and Joel deposits is hosted in mafic rocks and could be related to this mafic magmatism. Also, Santos et al. (2001) argued that these two deposits lack many important features of classic epithermal deposits, such as the relationship with contemporaneous volcanic rocks (the deposits are hosted by gabbro and granitoid, respectively), the low silver and adularia con-

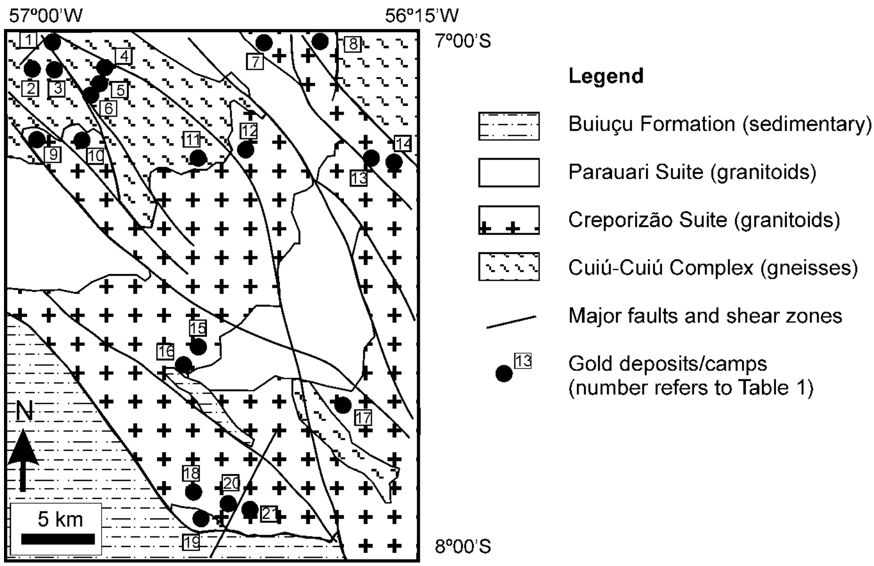

FIG. 3. Geological map of the Southern Tapajós Province showing the location of the gold deposits addressed in this study.

tents, and the absence of native silver and silver sulfosalts in the ore mineralogy.

Gold Deposits in the Southern Tapajós Province (STP)

More than 20 deposits and showings are distributed in several gold camps along the STP (Fig. 3). These mineralizations are discussed below, in terms of host rocks, wall rock alteration, and structural control. The classification of structural styles of the veins is based mainly on the concepts of Hodgson (1989) and Robert and Poulsen (2001), taking into account the type of host structure, and the internal structure and textures of the veins. The main attributes are summarized in Table 1.

Host rocks

Gneisses and orogenic granitoids are the main hosts for gold deposits in theTapajós Gold Province and account for virtually all the host rocks in STP (Table 1). The gneisses belong to the Cuiú-Cuiú Complex. They consist of gray orthogneisses of tonalitic and granodioritic composition bearing microgranular enclaves of diorites and quartz-diorites, along with granitoids and rare migmatites and amphibolites. Structurally, the gneisses show a pervasive ductile fabric, striking NNE-SSW or NW-SE, and migmatitic features are subordinate. The geochemical characteristics of trace elements (LILE, HFSE, REE) are compatible with those of primitive, arc-related calc-alkaline granitoids (Vasquez et al., 2001). They are dominantly metaluminous, with lenses of peraluminous to strongly peraluminous leucogranitoids occurring subordinately. Santos et al. (2000, 2001) obtained zircon U-Pb SHRIMP ages between 2033 Ma and 2005 Ma for this complex.

The hosting granitoids are related to the Creporizão Intrusive Suite, which holds irregular- to sigmoidal-shaped batholiths and stocks (Fig. 2) of hornblende- and/or biotite-bearing granitoids and metagranitoids of syenogranitic to tonalitic composition. The granitoids are either foliated or granoblastic, and the latter show preserved primary features, such as euhedral phenocrysts of K-feldspar, undeformed microgranular enclaves, and synplutonic dikes. Very often they show an igneous banding, marked by the orientation of the K-feldspar phenocrysts that parallels the NW-SE–trending tectonic foliation. Field, mineralogical, and textural evidence indicates emplacement of the granitoids in a crustal level compatible with greenschist, or up to middle-amphibolite metamorphic conditions (Ricci et al., 1999), and the presence of enclaves of gneisses from the Cuiú-Cuiú Complex is evidence of

TABLE 1. Summary of Attributes of Gold Deposits of the Southern Tapajós Province[1]

No.	Camp or deposit/ (number of veins)	Structural style	Internal structure	Host rock / (stratigraphic unit)	Gangue mineralogy	Ore mineralogy	Vein orientation (strike/dip)	Selected references
1	Goiano (2)	Breccia	Cataclastic	Foliated granitoid (CIS)	mus	py	N50E/88SE; N20W/88NE; N0E/80E	Santos, 1997
2	Sudário (4)	FFV (± mafic dike)	Massive, cataclastic	Granitoids (CCC)		py	N40-60E/70-88SE-NW	Rosa-Costa and Carvalho, 1999
3	Comandante Machado (2)	FFV	Massive, comb	Foliated granodiorite (CCC)	mus	py	N40E/70SE and N50W/65SW	Rosa-Costa and Carvalho, 1999
4	Patinhas	Shear vein	Massive, sheared	Granodiorite (CCC)	ep	py, cpy	N20E/68SE	Rosa-Costa and Carvalho, 1999 Klein et al., 2000
5	Pau d'Arco (3)	FFV	Veinlets, saccharoidal	Quartz-dioritic gneiss (CCC)	mus, kf, chl, ep	cpy, py	N30E/65SE	Klein et al., in press
6	Comandante Renan (2)	Shear vein	Massive	Tonalitic gneiss (CCC)	chl, ep	py	N0-30E/6088SE	Klein et al., in press
7	Tauari	FFV	Massive	Granitoid (CIS)	chl, ep		N30E/85NW	Klein et al., in press
8	Ouro Mil	Breccia + mafic dike	Networks	Granitoid (CIS) + mafic dike			N70E/70NW	Santos, 1997
9	Céu Azul	Breccia	Comb, fiber	Granodiorite (CIS)	qz, kf, ser, ep, hem		N70E/88SE	Klein et al., in press
10	Água Limpa	Breccia		Granodiorite (CIS)			N60W/70NE	Klein et al., in press
11	Roque Santeiro (2)	FFV	Massive	Tonalitic gneiss (CCC)	chl	py	N45E/75NW N40W/88NE	Klein et al., in press
12	Tabocal	FFV	Massive	Monzogranite (CIS)			N70E/80NW	Klein et al., in press
13	Vietnam	Shear vein	Laminated	Monzogranite (CIS)	ser	py	N70E/75NW	Klein et al., in press
14	Novo Vietnam	Shear vein	Massive, laminated	Monzogranite (CIS)	ser	py	N55E/80SE	Klein et al., in press
15	Independência	Stockwork	Massive, vuggy	Aplitic monzogranite (PIS?/CIS?)	mus	py	N45-80E/10-60SE	Klein et al., in press
16	São Raimundo	LARF		Monzogranite (CIS)	ep		N45-60E/25-40SE	Rosa-Costa and Carvalho, 1999
17	Bom Jesus	FFV	Laminated	Granitoid (CIS)	ser, kf	py, cpy, gal	N90E/88S	Santos, 1997
18	Boa Vista/Zé Pedro	FFV		Monzogranite (CIS)		py	N70E/80SE	Rosa-Costa and Carvalho, 1999
18	Boa Vista/Mineiro-1	Shear vein + breccia	Massive, laminated	Monzogranite (CIS)	qz, ser, carb, chl	py, cpy	N30E/88SE	Vasquez and Klein, 2000
18	Boa Vista/Mineiro-2	FFV	Massive	Monzogranite (CIS)	chl, ser, ep	py	N20E/75SE	Vasquez and Klein, 2000
18	Boa Vista	LARF	Massive, saccharoidal	Mafic volcanic and schist (?)	ser	py, aspy	N45-80W/30-45SW	Klein et al., in press Rosa-Costa and Carvalho, 1999
19	Planalto	FFV	Massive	Granitoid (CCC)			N40E/75SE	Klein et al., in press
20	Babilônia	FFV	Massive	Monzogranite (CIS)	ser	py	N45W/45SW	Klein et al., in press
21	São José	FFV	Massive, saccharoidal	Monzogranite (CIS)	ep		N45W/63NE	Klein et al., in press

[1]Legend: FFV = fault-fill vein; CIS = Creporizão Intrusive Suite; CCC = Cuiú-Cuiú Complex; PIS = Parauari Intrusive Suite; mus = muscovite; ser = sericite; ep = epidote; kf = K-feldspar; chl = chlorite; carb = carbonate; qz = quartz; py = pyrite; cpy = chalcopyrite; aspy = arsenopyrite; gal = galena.

the intrusive character of the granitoids. Whole-rock geochemistry (Lamarão et al., 2001; Vasquez et al., 2001) has shown that the Creporizão Suite represents calc-alkaline, metaluminous to peraluminous, medium- to high-K, arc-related granitoids. The REE patterns show that they are more evolved than the Cuiú-Cuiú granitoids and gneisses. U-Pb and Pb-evaporation dating of zircon (Ricci et al., 1999; Vasquez et al., 2000; Santos et al., 2000, 2001; Lamarão et al., 2001) indicate crystallization ages between 1997 Ma and 1957 Ma. This late timing with respect to the Cuiú-Cuiú Complex, along with the geochemical characteristics, the structural and metamorphic differences, the lack of volcano-sedimentary basins associated with the Creporizão granitoids, and their common association with regional strike-slip shear zones, led Vasquez et al. (2001) to consider the Creporizão Suite as representing a post-collisional magmatism, still related to the development of the Cuiú-Cuiú magmatic arc, and not an individual arc (Creporizão arc), as proposed by Santos et al. (2001).

Ore mineralogy and wall-rock alteration

Many prospects are still undeveloped, and workings are restricted to the oxidized (saprolite) zone, where veins and structures are well preserved, but hydrothermal alteration in the immediate host rock is overprinted by secondary processes. Hence, information in these cases is restricted to the vein assemblage and, in a few cases, to distal alteration, which can be seen tens or a few hundreds of meters off of the mineralized zone.

Pyrite is the dominant sulfide mineral (Table 1), occurring in most of the deposits, in general as disseminations, filling fractures, and cavities in the quartz veins, in the contact between vein and host rock, or, less commonly, forming decimeter-wide aggregates (Fig. 6). Chalcopyrite follows pyrite in importance, always occurring in association with pyrite, whereas galena and arsenopyrite occur only locally.

The gangue mineralogy shows little variation, with white mica being the main mineral (following quartz) present in the quartz veins, occurring, however, in small amounts. White mica is also widespread in the hydrothermally altered wall rocks, occurring in association with quartz, minor amounts of chlorite, and scarce carbonate, K-feldspar, and epidote.

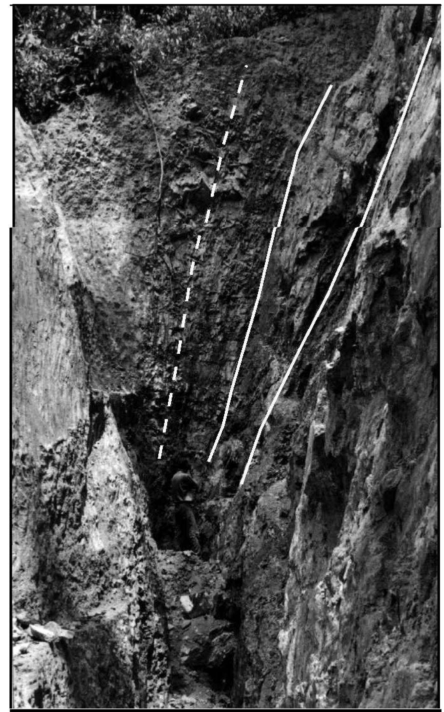

FIG. 4. Photograph of the surface exposure of a fault-fill vein (outlined by the heavy lines) at Mineiro-2. The hydrothermal envelope is outlined by the dashed line.

Structural control

Investigation of mesoscopic and macroscopic features of deposits of the STP showed that they are strictly structurally controlled in all scales. Regional structures may have played important roles, acting as conduits for mineralizing fluids and controlling the distribution of the deposits. The gold camps are located close to, or bounded by, major, first-order faults and shear zones, located in low-strain domains between them and rarely within these deformation zones (Figs. 2 and 3). At camp and deposit scales, the orientation of the mineralized veins is controlled by the orientation and/or geometry of the hosting, lower-order structures (Klein et al., 1999; Santos, 1999, 2000).

Structural styles and internal structure

Fault-fill veins. This type is by far the most common structural style in STP and in the province as a whole (Klein et al., 1999). The deposits consist of a single quartz vein emplaced in subvertical structures (Fig. 4). These are mostly faults, with subordi-

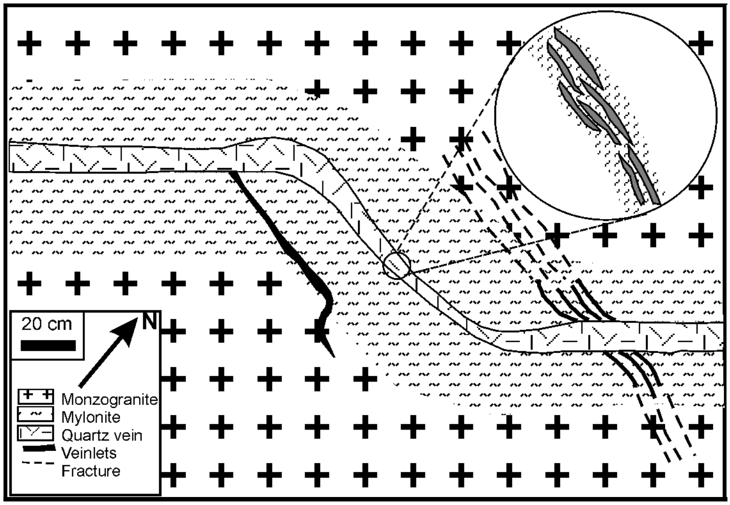

FIG. 5. Sketch map (plan view) of the shear vein at Novo Vietnam. The vein is surrounded by mylonitized wall rock and shows extensional veinlets attached on both sides. The vein is massive to laminated and continuous, but is formed by discontinuous veinlets (inset) between the two bends.

nate narrow brittle-ductile shear zones. Their orientations are variable, with concentrations of veins along the N20°–70°E and N40–50W directions. The veins are centimeter- to decimeter-thick and consist of milky quartz, with minor (<5%) K-feldspar, white mica, chlorite, and sulfide minerals. Occasionally, thin extensional–oblique, quartz to quartzo-feldspathic veinlets occur attached to the main quartz vein (Fig. 5). The internal structure of the veins is dominantly formed by massive quartz (Fig. 6). Laminated, saccharoidal, and open-space filling (comb) textures and hydrothermal breccias are subordinate. A few veins are positioned at the contact between mafic dikes and the altered country rock, or even cut across the dikes, suggesting, in these cases, their late timing with respect to the dikes. In one situation (Pau D'Arco), mineralization lacks a major quartz vein (only a few discontinuous veinlets are present), and occurs as disseminations in the hydrothermal zone that surrounds a subvertical strike-slip fault.

Shear veins. In greenstone-hosted deposits shear veins are usually described as fault-fill veins, because they occupy faults and the central parts of shear zones (Hodgson, 1989), and because it is considered difficult to define if the veins formed as a result of displacements along a shear fracture, or as the result of dilation of preexisting shear fractures or ductile fabric (e.g., Robert and Poulsen, 2001 and references therein). In STP, shear and fault-fill veins share a series of characteristics. However, in this paper we prefer to classify them separately, at least for descriptive purposes, because shear veins differ from fault-fill veins by the fact that they have been emplaced in ductile-brittle structures (Comandante Renan, Novo Vietnam; Fig. 5) and/or show effects of ductile deformation, such as quartz grains with undulose extinction and deformation bands surrounded by small, recrystallized subgrains (Patinhas), microscopic shear zones (Mineiro-1), and ductile fabric either in the vein or in the immediate host rock (Novo Vietnam) (Fig. 5). The internal structure is chiefly massive to laminated and sheared (Figs. 6 and 7). Extensional features, such as breccias and en echelon sulfides (Fig. 7) also are present.

Low- (to moderate-) angle reverse-oblique faults. Two examples have been observed. At the Boa Vista gold field, along with fault-fill and breccia veins present in several occurrences, the main mineralization consists of a series of subparallel, vertically stacked sigmoidal quartz veins (Fig. 8A), separated by hydrothermally altered and strongly foliated host rock (schist). The veins show variable thickness, from a few centimeters up to one meter, and strike to N45°–80°W, dipping 30° to 45° to the southwest. Internally, the milky veins show massive to saccharoidal textures. Small amounts of pyrite and minor

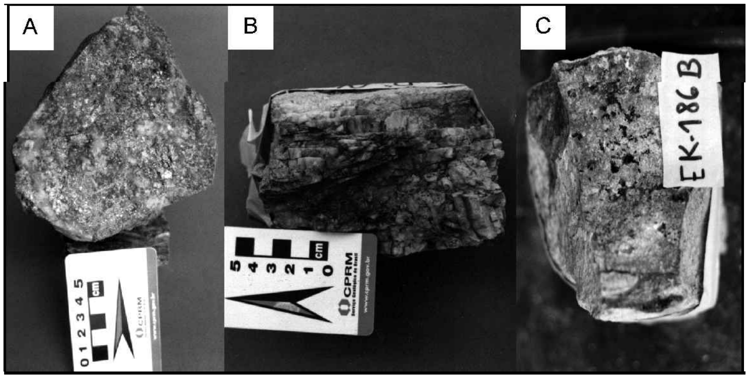

FIG. 6. A. Milky massive quartz with high pyrite contents at Patinhas. B. Sheared, sulfide-poor quartz vein (Patinhas). C. Quartz vein with sulfide minerals filling cavities (Novo Vietnam).

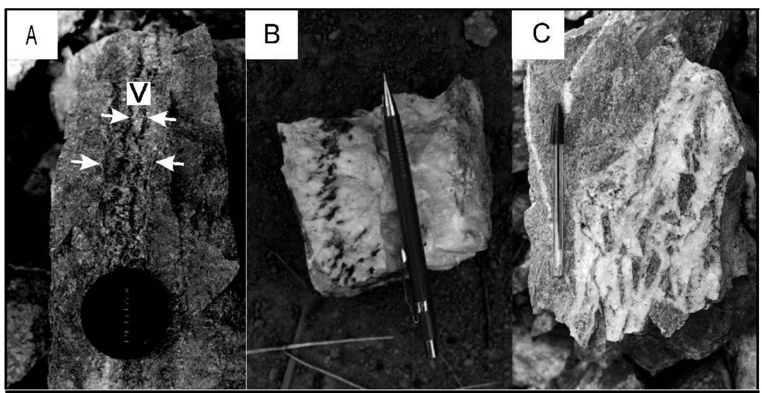

FIG. 7. Vein structures at Mineiro-1. A. Laminated quartz-pyrite veinlet (V) crosscutting the hydrothermally altered host rock. Alteration is zoned and symmetric (arrows). B. Milky massive quartz with extensional fracture filled by sulfide minerals with an en echelon distribution. C. Hydrothermal breccia formed by quartz (white) and hydrothermally altered host rock (grey).

arsenopyrite are disseminated throughout the veins and altered wall rock. Pyrite occurs filling small fractures in quartz as well, and sericite is present both in the vein and in the immediate wall rock.

Given the weathered character of the terrain, fresh rocks could not be observed in the mineralized zone, and the nature of the host rock could not be confidently determined. A few tens of meters off the mineralized zone, an undeformed porphyritic mafic volcanic rock crops out. The region, in turn, is dominated by granitoids of the Creporizão Suite that is the host for all other occurrences in the same gold field. The hosting schist may derive from one of these two rock types by a combination of intense deformation and high fluid:rock ratios. Alternatively, it may represent a fragment of the metavolcano-sedimentary sequence of the Jacareacanga Group, which has not as yet been recognized in this portion of the Tapajós Province, occurring as mega-xenoliths or roof pendants within the granitoids of the Creporizão Suite.

In the São Raimundo deposit, mineralization occurs in narrow hydrothermal halos enveloping anastomosed shear/fault planes in brittle-ductile shear zones (Fig. 8B). The hosting shear zones strike N45º–60ºE and dip 25º–40º SE, and the mineralized zones are up to 2 meters thick (Rosa-Costa and Carvalho, 1999). Quartz is generally absent and occurs

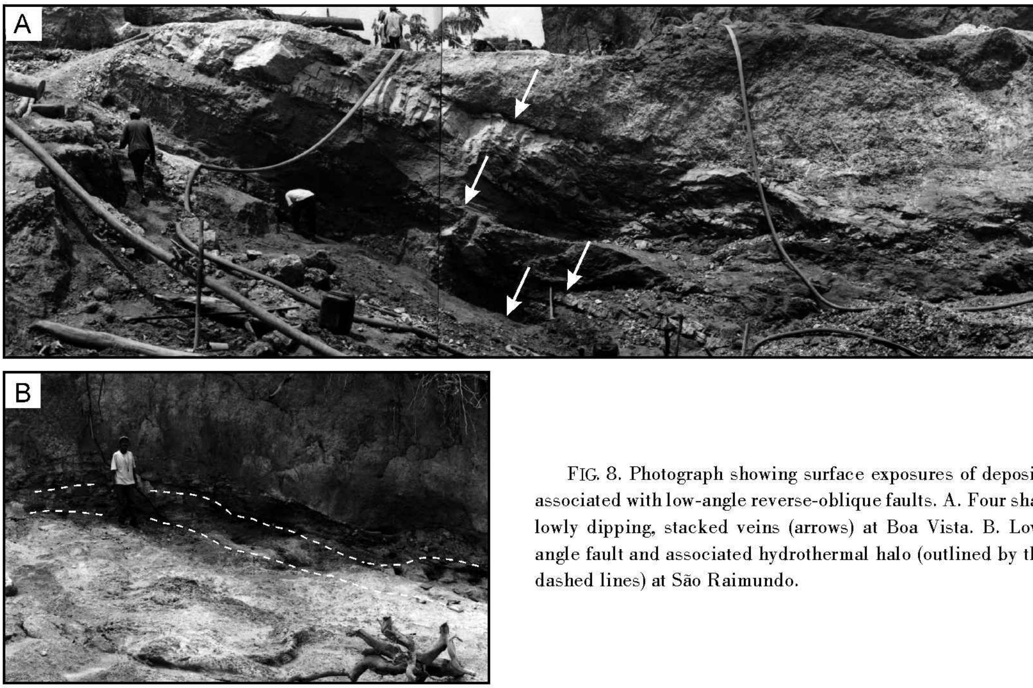

FIG. 8. Photograph showing surface exposures of deposits associated with low-angle reverse-oblique faults. A. Four shallowly dipping, stacked veins (arrows) at Boa Vista. B. Low-angle fault and associated hydrothermal halo (outlined by the dashed lines) at São Raimundo.

only as small, isolated, and discontinuous veinlets positioned in the fault planes. The host rock is a monzogranite of the Creporizão Suite.

Breccia veins. Four main occurrences have been recorded, forming tabular structures of less than 1 m in thickness. The breccia veins at Céu Azul and Água Limpa consist of fragments of milky quartz with angular to rounded shape, ranging in size from mm to a few cm (Fig. 9), set in a fine-grained, reddish to greenish hydrothermal matrix composed of quartz, feldspar, and hematite, along with fine-grained sericite and epidote. Microscopically, different quartz fragments show textures such as comb and rosettes, indicating the shallow emplacement of these veins (Dowling and Morrison, 1989; Vearncombe, 1993). At Goiano and Ouro Mil the breccias have less matrix, and the quartz fragments are more angular than in the two other examples.

Brecciation occurs also as a minor portion of a shear vein at the Mineiro-1 prospect in the Boa Vista gold camp. These breccias also differ from the former by the fact that the angular quartz fragments are set in a matrix composed of altered wall rock (Fig. 7C).

Stockworks. This style has been identified at the Independência deposit. It consists of multidirectional quartz veins, a few centimeters thick, enveloped by narrow halos of hydrothermal alteration. The veins are generally widely spaced, occurring in an area of ~100 m × tens of meters. Locally, however, they are closely spaced, with several individual hydrothermal halos overlapping each other, forming larger areas of hydrothermally altered host rock. The quartz has a milky to smoky character, and shows cavities usually filled by sulfide minerals. Epidote and white mica are common gangue minerals. In places, large pockets of hydrothermal alteration, lacking quartz veins, are observed as well. Minor stockworks and networks (the veins, as a whole, show the same orientation of the vein/breccia) occur at Ouro Mil, in both margins of the main breccia vein (Santos, 1997).

Discussion and Concluding Remarks

Gold deposits in the Tapajós Province are hosted in a variety of metamorphic and magmatic rocks. In Southern Tapajós Province (STP), with one exception, only orthogneisses of the Cuiú-Cuiú Complex and orogenic granitoids of the Creporizão Suite are known hosts for gold. Hosting granitoids are dominantly monzogranitic in composition, whereas the orthogneisses show tonalitic and granodioritic compositions.

The deposits have been classified in a few structural styles, according to the hosting structure, structural regime in which they have been formed, and internal structures and textures of the veins. Accordingly, fault-fill and shear veins are the dominant style, followed by subordinate occurrences of veins hosted in low-angle reverse-oblique faults, breccia veins, and stockworks. More than one style may occur in the same gold camp and even in a single deposit.

Fault-fill and shear veins, as well as breccia veins, form moderately to steeply dipping tabular bodies that seldom exceed one meter in thickness, and are hosted by strike-slip faults and shear zones, to which they are parallel. The vein quartz is dominantly massive, with laminated, saccharoidal, and comb textures occurring subordinately. Shearing and cataclasis of the veins is widespread, suggesting, along with other textural and structural evidence, their positioning in active faults and shear zones, or deformation after formation. In most cases, quartz, white mica, and pyrite compose the vein mineralogy and, along with minor chlorite, carbonate, epidote, and K-feldspar, they overprint the primary mineralogy of the hosting granitoids and the amphibolite-facies paragenesis of the hosting gneisses.

The breccias have likely been produced during fracture propagation by physical brecciation, which occurs when the amount of stress exceeds the brittle resistance of the rock, by mechanisms such as tectonic comminution and/or fluid-assisted brecciation (Jébrak, 1997). Furthermore, they indicate active seismic slip during mineralization (Robert and Poulsen, 2001).

The origin of the large stockwork at Independência may be ascribed to hydraulic fracturing occurring over a cupola of a small aplitic granitoid, related to or intruding the regional coarse-grained monzogranite of the Creporizão Suite. In the latter hypothesis, it could be related either to a late-stage pluton of the Creporizão Suite or to a younger granitoid suite (Parauari). This definition requires geochronological support.

Deposits and gold camps show strong structural control at all scales. The hosting structures have been formed under a dominantly brittle-ductile to brittle regime, and consist of strike slip faults, shear fractures, intersection and bending of faults, and lithological and/or lithostratigraphic contacts. Extensional fractures have not been characterized as hosting structures, because evidence of displacement and/or shearing is virtually always present in the veins. Extensional features are present, however, as en echelon arrays of sulfide minerals and as veinlets attached to the main longitudinal fault veins. Deposits hosted in granitoids show a more brittle behavior, whereas those hosted in gneisses tend to display more ductile features. This can result either from the depth of vein formation or from high fluid/rock ratios, even in shallow levels of the crust.

FIG. 9. Breccia vein at Céu Azul.

Formation of deposits occurred in a range of crustal depth, from mesozonal to epizonal conditions, as indicated by the internal structure of the quartz veins and by the nature of the hosting structures. This is also supported by fluid inclusion studies in a few deposits, such as Guarim (Klein et al., 2001) and Patinhas (Klein et al., 2000), both deposits hosted in gneisses of the Cuiú-Cuiú Complex. Fluid composition is nearly identical, but P-T data, along with textural and structural evidence, suggest that Guarim (outside STP) formed between 4 and 7 km, whereas Patinhas (within STP) formed at deeper levels.

Hence, shear veins and fault-fill veins may be considered, at least in part, and from a structural view, as a single class of structural style, with their differences being ascribed to different depths of emplacement and structural overprint. It is not our intention, however, to state that all of these veins formed in a single gold-forming event. The issue of how many mineralizing events have occurred in the Tapajós Province is still unresolved.

Santos (1999, 2000), studying 23 deposits throughout the province (including three deposits in STP), reported a set of characteristics similar to those we have found in STP. He concluded that all deposits are related to a regional NW-SE–trending strike-slip fault system, and that the orientation of the lower-order hosting structures is compatible with Riedel's system, with the direction of the main stress vector around the E-W direction. Orientations that do not fit the model may be related to heterogeneities in the local stress field. However, nothing has been said about the timing of this strike-slip system in relation to the magmatic, metamorphic, and tectonic evolution of the province.

Coutinho et al. (2000) reported model ages that cluster around 1.96 Ga and 1.88 Ga, and maintained that these two ages reflect two mineralizing epochs. Santos et al. (2001) invoked a single event at 1.86 Ga. However, as stated by Santos et al. (2001), the tectonic regime at 1.86 Ga is brittle. This model does not explain the ductile emplacement and/or deformed mineralization hosted especially by the Cuiú-Cuiú gneisses and by the metavolcano-sedimentary sequences. Another (older?) mineralizing phase is thus required.

We proposed early in this paper that the major strike-slip regime that affected the Creporizão Suite and older units likely occurred between 1.97 and 1.95 Ga. Mineralization hosted in the Cuiú-Cuiú gneisses (at least in STP) is post-tectonic and post-metamorphic with respect to the host rocks, since hosting structures clearly crosscut the metamorphic banding, and the hydrothermal mineralogy is retrogressive in relation to the metamorphic paragenesis. Deformation affecting the Creporizão granitoids is brittle-ductile to brittle, whereas deformation affecting younger granitoids is brittle. Thus, it is valid to infer as a working hypothesis that, at least in part, gold mineralization in STP formed during regional strike-slip deformation and emplacement of late-stage plutons of the Creporizão Suite, at ~1.97–1.95 Ga, a time interval that is in agreement with that obtained by Coutinho et al. (2000). The structures may have been reactivated during younger deformational episode(s), and gold deposits may have formed at this stage as well.

The challenge is to decipher which deposits formed at each metallogenic epoch. From a structural point of view, it is likely that the deposits in Southern Tapajós Province that have been emplaced at deeper levels of the crust and that show evidence of plastic deformation (i.e., the shear veins and the deposits hosted in low-angle reverse-oblique faults; see Table 1) formed in the older phase. Fault-fill veins that occur in association with these deposits in the same gold camp (e.g., Boa Vista) probably formed in the same event. The rest of the fault-fill veins (with textures and structures indicating emplacement in shallow, brittle structures, associated or not with mafic dikes and showing no association with shear veins in the same gold camp), as well as the breccia veins and stockworks, may have formed either in the older or in the younger phase. We do not have elements to define this. This requires much more isotopic data, along with additional fluid-inclusion and stable-isotope information to constrain physico-chemical conditions of gold deposition, as well as knowledge of the sources and nature of the mineralizing fluids and the absolute timing of gold deposition.

The attributes shown by the gold deposits in STP (namely, the regional structural setting, deposit style, vein textures, and hydrothermal mineralogy) along with scarce fluid-inclusion data fit with both the orogenic (magmatic arc-hosted) and intrusion-related models as proposed by Santos et al. (2001), the latter sharing characteristics with Korean-type deposits (Robert et al., 1997) as well.

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