ASH-FLOW CALDERA- AND PORPHYRY-RELATED PALEOPROTEROZOIC GOLD AND BASE METAL MINERALIZATIONS IN THE TAPAJÓS GOLD PROVINCE: POTENCIALITIES AND EXPLORATION GUIDELINES

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The Tapajós Gold Province (TGP) is located at the boundary of the Tapajós–Parima (TPP) and Central Amazonian (CA) provinces (Fig. 1). The location of this boundary and its geologic significance is not well defined, although it had been considered as a suture zone (Tassinari and Macambira, 1999; Santos *et al*., 2000).

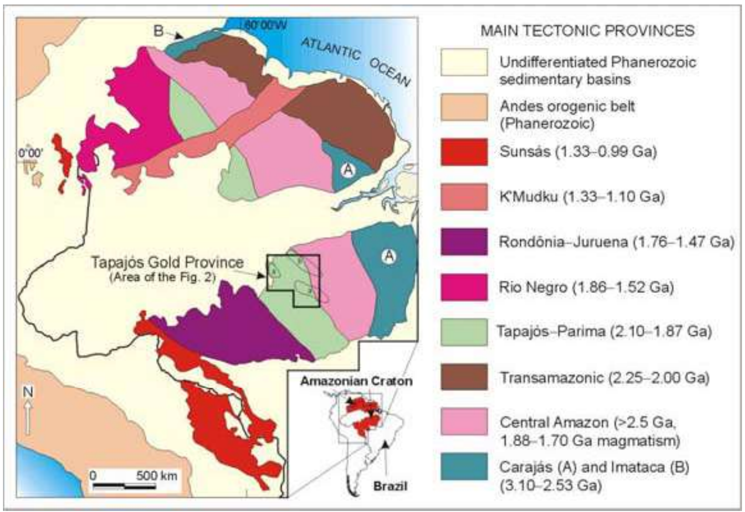

Figure 1 - Location of the Tapajós Gold Province and the main geochronological –tectonic provinces of the Amazonian Craton, according to Santos et al. (2000). Tentative delineation of potential belts for Cu–Au porphyry (a) and for Au, and Cu–Mo–(Au) mineralizations (b).

The Au mineralizations of the TGP are concentrated in the TPP, which was formed during at least two ocean–continent orogenies between 2.10 to 1.87 Ga. The TPP is essentially composed of a ~2.1 Ga volcano-sedimentary sequence (Jacareacanga Group) and the magmatic arcs of the Cuiú-Cuiú Complex (~2.01 Ga), Creporizão Intrusive Suite (1.97–1.95 Ga), Rio das Tropas Tonalite (~1.90 Ga), and Parauari Intrusive Suite (~1.88 Ga). Calc-alkaline andesitic to rhyolitic volcanic and volcaniclastic rocks of the Iriri Group (1.88 Ga) overlie the previous units, and are crosscut by the anorogenic Maloquinha Intrusive Suite (~1.87 Ga). Paleoproterozoic fluvial and marine units and several mafic intrusions also occur in the TGP (Fig. 2). The basement of the CA is not well exposed and studied but, at least in part, it is Archean (Santos *et al*., 2000). Large units of intermediate to acid volcanic rocks and fluvial clastic sedimentary units overlay the basement, and are crosscut by mafic dikes and sills, and A-type granites (Santos *et al*., 2000).

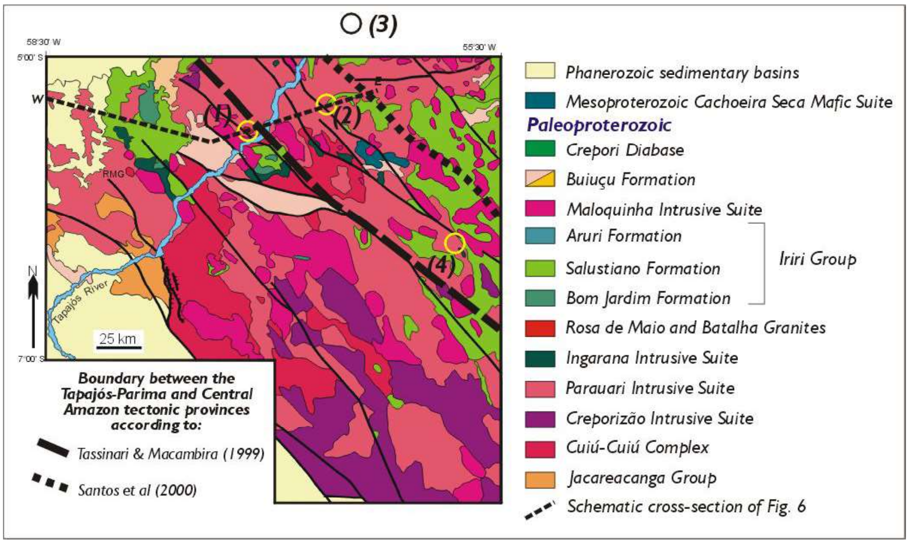

Figure 2 - Geological map of the Tapajós Gold Province (see references in Julianit et al., 2005). (1) Batalha Au-Granite; (2) High-sulfidation gold mineralization; (3) Low-sulfidation Cu—Mo–(Au) mineralization, and (4) Au–(Cu) Palito mineralization.

In the TGP, the Iriri Group was originated in several large nested ash-flow caldera complexes. The pre-caldera units are composed of basaltic andesitic, andesitic, rhyodacitic, dacitic, rhyolitic and ignimbritic flows, and dikes of the Salustiano and Bom Jardim formations (Fig. 3). Latite, trachyandesite, ash- and crystal tuffs, and acid to intermediate hyaloclastites are also present. The syn-caldera units consist of several large ash-tuff deposits with subordinated rhyolite flows of the Aruri and Salustiano formations. These volcanic rocks are interfingered and are partially covered by Paleoproterozoic marine and fluvial sedimentary sequences. The post-caldera units are represented mainly by rhyolite and ignimbrites, which encompass ring composite volcanoes and domes, which occur as vents along rings and within the calderas. Tuffs, epiclastic sandstone and lacustrine sediments compose the intra-caldera deposits. Intrusions of granophyric stocks, and rhyolitic and rhyodacitic porphyry dikes crosscut the volcanic sequence (Fig. 3).

Gold mineralization types in the TGP are mainly: mesothermal orogenic; epithermal and mesothermal in shear zones, granite-hosted, intrusion-related, metasedimentary-hosted, epithermal volcanic-hosted high- (quartz–alunite) and low- (adularia–sericite) sulfidation, and porphyry-related (Batalha and Palito granites) deposits (Santos *et al*., 2001; Klein *et al*., 2001; Juliani *et al*., 2002; 2004; 2005).

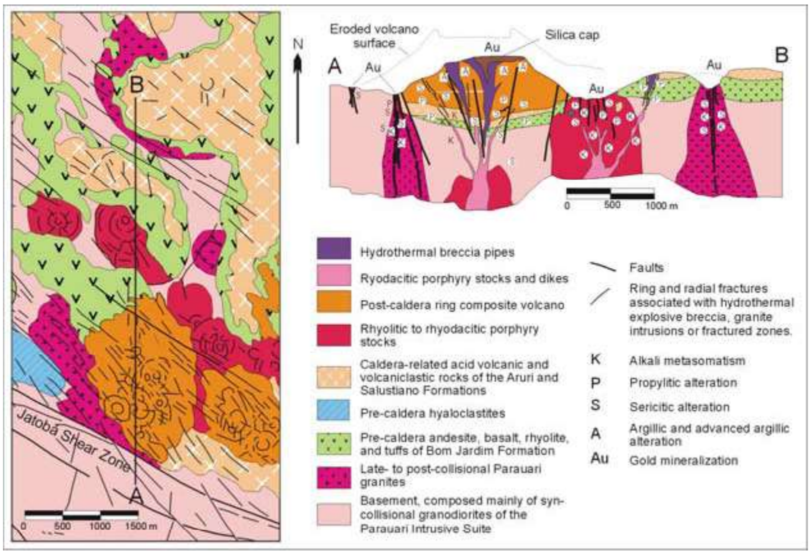

Figure 3 - Geological map and schematic cross-section of the high-sulfidation mineralization area.

The high- and low-sulfidation mineralizations occur in the caldera ring volcanoes. They are associated with intrusions of dikes and stocks of rhyodacitic to rhyolitic porphyries (Fig. 3). Strong and large hydrothermal alteration zones in volcanic and volcaniclastic rocks are associated with these porphyry intrusions.

The high-sulfidation gold mineralization (HSM) occurs in hydrothermal breccia pipes affected by advanced argillic alteration with alunite–natroalunite (alunitite, veins and disseminated), pyrophyllite, andalusite, diaspore, rutile, kaolinite–dickite, woodhouseite–svanbergite, pyrite, chalcopyrite, bornite, covellite, sphalerite, enargite–luzonite, and very small grains of native Au, Ag, and Cu. In the core of this zone, a massive to brecciated silica body, which flares upwards, is present (Fig. 3). This silicification zone has alunite and subordinated pyrophyllite in shallow levels and sulfide-rich zones in deeper levels. The zone of advanced argillic alteration with alunite is enveloped by an advanced argillic alteration zone with rare alunite and without andalusite, indicating lower temperature in these external haloes. Narrow zones of argillic alteration, composed by clay-rich rocks with veins of coarse kaolinite occur in the outer parts of the previous zone. The advanced argillic alteration zone grades outside to a large propylitic halo in shallow parts, and to sericitic alteration in deeper levels, especially when close to altered porphyry dikes. A hematite-rich silica cap, with abundant vugs filled by diagenetic quartz, occurs on the top of the hydrothermal breccia bodies. Relicts of druses are common in these rocks. At least two pulses of hydrothermal fluids were recognized. These pulses generated several alunite textural types (Juliani *et al.*, 2005). The first pulse was more pervasive and cooler than the second one. The latter resulted in brecciation of the silica cap and generation of high-temperature fine-grained alunite (A_5-type) veins that crosscut alunitites, and coarse-grained alunite branching veins (A_3-type alunite). Undeformed alunite shows Ar–Ar maximum age of 1869 ± 2 Ma. Recrystallization of alunite in shear zones occurred at 1805 ± 2 Ma.

Oxygen and hydrogen isotope data (Fig. 4) for fluids in equilibrium with minerals from different parts of the HSM system reveal mixing trends involving magmatic and externally derived fluids. Hotter fluid pulses responsible for A_5-type alunite have a predominant magmatic signature and fluids in equilibrium with sericite from deeper parts suggests evolution from magmatic vapor. Calculated isotopic compositions for the fluids associated with the lower temperature alunite (A_3-type), pyrophyllite and kaolinite could be associated with two evolutionary trends. These trends could indicate a contribution of seawater, followed by influx of low-latitude highly evaporated waters, to the hydrothermal system. This suggests that during the late Paleoproterozoic the Amazonian Craton was located in an arid equatorial environment.

The low-sulfidation Cu–Mo–(Au) mineralization is located 50 km north of the HSM (Fig. 2), at the border of another caldera complex. The geological setting and the hydrothermal system evolution of this mineralization is similar to that of the HSM, but the silica cap is not present and the erosion and deformation related to shear zones are more intense.

Porphyry-related mineralizations are represented by the Batalha (Au) (Juliani *et al*., 2002) and Palito (Au–(Cu)) granites. Both granites exhibit a local early sodic metassomatism, which was followed by an intense stage of K-metassomatism that resulted in crystallization of microcline and green biotite, and local silicification. Propylitic hydrothermal alteration overprints the K-metassomatism, which occurred in pervasive to fissure-controlled styles in the Batalha Granite, and essentially as a fissure-controlled alteration in the Palito Granite.

The mineralizing event is associated with a sulfide-bearing sericitic alteration predominantly along fissures in both granites. The types of alteration and the evolution of the hydrothermal system are similar to those observed in rhyolitic and rhyodacitic porphyry dikes in the HSM and LSM areas. The biotite halogen content and fO_2 conditions of the Batalha Granite are similar to those of Au-rich porphyry, but this granite was emplaced in mesozonal crustal level (Juliani *et al.*, 2002). This precludes the classification of its Au mineralizaion as a porphyry-type. However, the Palito Granite is a semi-eroded dome-like granophyric body, which crosscuts shallow-emplaced porphyritic granites (Rio Novo Granite), possibly correlated to the Parauari granites, rhyolitic Rio Novo porphyries, and early tonalite–granodiorite to quartz diorites. The hydrothermal alteration is very strong in the Palito body, and the mineralization is represented by sulfide-rich or clean quartz veins, metric massive chalcopyrite ± covellite veins, and pyrite ± Cu-sulfide mineral lenses and veins. Massive sulfides veins are locally crosscut by hydrothermal brecciated sulfide veins, and veinlets with network structure are also present. All vein generations are commonly sheared. The intensity of the K-metassomatism, the ore grade and the size of mineralized veins decrease towards the host Rio Novo Granite. The external alteration halo is predominantly a propylitic zone. These geological evidences observed in the Palito Mine suggest that this Au–(Cu) mineralization could represent the first porphyry-type mineralization in the TGP.

In the TGP, the presence of minor alkaline flows within the calc-alkaline volcanic rocks of the Iriri Group (Dall'Agnol *et al.*, 1999) suggests a possible back-arc tectonic environment for the caldera complexes with epithermal mineralizations (Juliani *et al.*, 2005). The interfingering of volcanic and volcaniclastic units of the Iriri Group with fluvial and marine Paleoproterozoic sedimentary units indicates a marine incursion in the back-arc basin. The $\delta^{13}C$ (PDB) and $\delta^{18}O$ (SMOW) values of carbonate veins from propylitized dacites and basalts range between –2.3 to 1.8‰ and 5.2 to 10.3‰, respectively. These $\delta^{13}C$ and $\delta^{18}O$ values are also similar to those of Yilgarn spilites (Kerrich, 1990), reinforcing this interpretation.

The geologic setting of the TGP, the presence of HS and LS mineralizations, the relationship of this mineralization with late- to post-collisional granites of the Parauari magmatic event, and the association of the Palito Granite with less evolved granitic rocks, suggest for this area a high potential for the ocurrence of Au−Cu mineralization in the intra-arc environment, and of Au and Cu−Mo−(Au) mineralization along the back-arc basin, besides the associated epithermal volcanic-hosted mineralizations. According to this interpreted environment, the presence of Besshi, SEDEX and VHMS base metal, and Au reef deposits (Fig. 5) cannot be ruled out for the TGP.

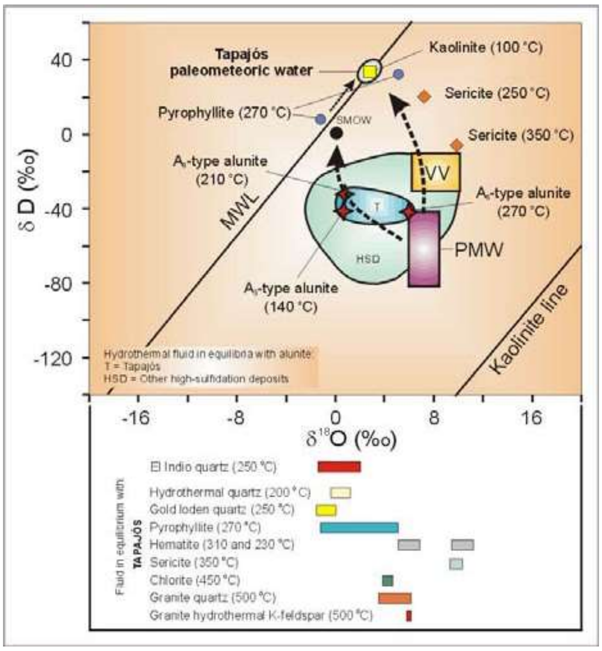

Figure 4 - Oxygen and hydrogen isotope compositions of hydrothermal minerals of the high-sulfidation system. Hydrogen isotope fractionation: Zheng (1993); oxygen isotope fractionations: oxygen isotope fractionation: Rye et al. (1992); Suzuoki et al. (1976); Lambert & Epstein (1980).

One consequence of the above discussion is that the definition of the geologic limits of the Amazonian provinces, and their orogenies, is fundamental for mineral exploration in the TGP. However, the following arguments: a) integrated field-work studies; b) the continuity of all Paleoproterozoic geological units across the TPP−CA boundary (Fig. 2); c) stable and radiogenic isotopic data; d) the preservation of the shallowest parts of hydrothermal systems, including the silica cap in the HSM, which strongly support a tectonically stable setting for the TGP during late Paleoproterozoic; e) the lack of deformation and metamorphism along the TPP–CA boundary; f) the absence of island-arc lithologic associations; and g) the formation of the Iriri rocks in calderas in a possible back arc environment over the "suture" at 1.87 Ga, are not in agreement with the current proposed model of island-arc–continent collision between the TPP and the CA around 1.80 Ga, and respective limits, as proposed by Tassinari and Macambira (1999) and Santos *et al.* (2000). As indicated by the ~1.8 Ga age of recrystallized alunite in slickensides of the NW−SE shear zones, which cut the HSM, the defined boundary between these provinces (Figs. 1 and 2) could represent only late tectonic structures, and not Paleoproterozoic suture.

In conclusion: the exploration guidelines for epithermal and porphyry deposits in the Tapajós Gold Province should take in account; a) the regional stratigraphy of the volcanic rocks; b) the relationship of the volcanic rocks with the evolution of the calderas; c) the petro-chemical nature (alkaline or calc-alkaline) of the volcanic sequences; d) the tectonic environment of volcanism; e) the erosion level of the volcano-sedimentary covers, and the depth of emplacement of the batholiths, stocks and dikes of the Parauari granites; f) types and dimensions of the hydrothermal alteration haloes; and g) the tectonic polarity, and the suture trends. The presence of younger (~1.75 Ga) and older (~2.0 Ga) volcanic sequences in the TGP, also imply that the ages of the volcanic units must be constrained in order to correlate them with the 1.88 Ga Iriri Group, which hosts the HS and LS mineralizations.

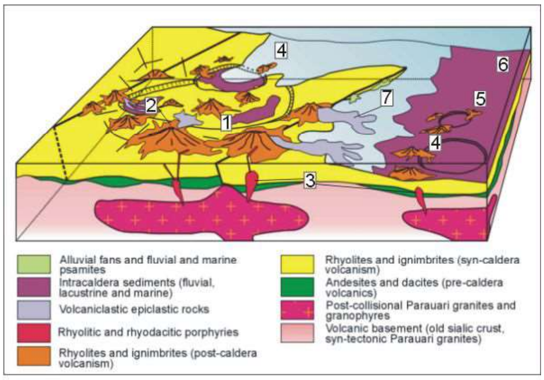

Figure 5 - Interpreted Paleoproterozoic geologic environment of the TGP, with HSM (1) and LSM (2), and possible porphyry (3), VHMS (4), SEDEX (5), Besshi (6) and reefs gold mineralizations (7).

The factual and genetic models, already depicted, are of utmost importance for the Au–Cu exploration modeling for the TGP, and other similar Brazilian cratonic segments.

Based on this genetic model, potential zones for occurrence of volcanic-hosted Au and Cu−Au HS and LS, and Au, Cu−Au and Cu−Mo−(Au) porphyry deposits are tentatively delineated in the Figure 1.

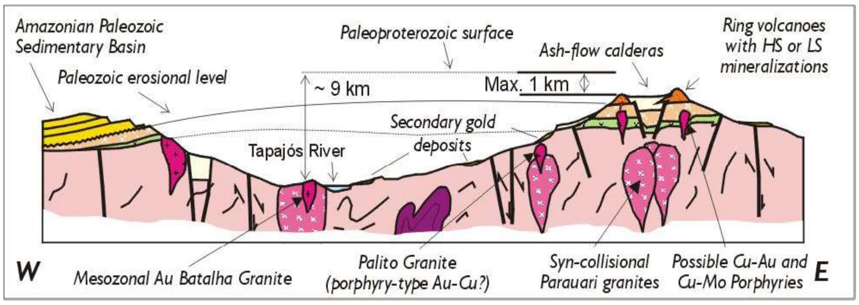

Figure 6 - Schematic cross-section (without scale) of the Au–Cu mineralization system, and paleo and actual erosional surfaces in the TGP.

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