OROGENIC GOLD DEPOSITS IN TAPAJÓS MINERAL PROVINCE, AMAZON, BRAZIL

COUTINHO, M.G. da N, 2 SANTOS, J.O. S., 3 FALLICK, A. E. and 4 LAFONT, J.M. 1 Geological Survey of Brazil – CPRM, Rio de Janeiro, RJ and 2 Manaus, AM, Brazil, 3 Scottish Universities Research and Reactor Centre, Glasgow, Scotland, 4 Federal University of Pará, Belém, Brazil.

Introduction
Many metamorphic terranes of different ages, contain gold-bearing quartz veins, which appear to be formed during compressional to transpressional deformation processes at convergent plate margins in accretionary and collision orogens. In both orogens the mineralized veins are emplaced over a unique depth range for hydrothermal ore deposits, in which gold deposition may occur from 15-20 km to the near surface environment (see Groves et al., 1998). However, deposits at the upper and lower end of the spectrum are relatively rare, and documentation has been dominated by those so-called mesothermal deposits (Gebre-Marliam et al., 1993).

In Tapajós Mineral Province, Amazon, Brazil, primary gold deposits are widespread, hosted by different rock-types, and represent the upper crustal end-member of the crustal depth spectrum of those so-called mesothermal deposits from greenwich and lower-amphibolite facies environments. The deposits show features characteristic of both Archean lode-gold mesothermal deposits, and epithermal precious-metal mineralization. The aim of this paper is to demonstrate that the Tapajós gold mineralization represents a shallow crustal end-member of Proterozoic orogonic mesoazonal/epizonal gold.

Regional Geology
The Tapajós Mineral Province (90,000 km²) located on the central-south of the Amazon Craton underwent a tectonic Proterozoic (Orosirian) orogenesis, comprising four plume-driven events; the development took place during a time period of 140 Ma. Geochronological data (using SHRIMP and conventional U-Pb and Pb-Pb in zircon studies) indicate that the three first events (Carua-Cutiaú, Creporizão and Paraúna) extended from 2,010 to 1,870 Ma (Santos et al., 2000). These events are associated with magmatic arcs, related to subduction processes. Based on geochemical characteristics of the granitoids (Brown et al., 1984), the arcs change from primitive to normal in character. The magmatism is calc-alkaline and, according to the alumin-action of the granitoids is metaluminous to peraluminous, and represent I-type granites. The fourth event (Maloguinha) dated at 1,870 Ma is associated with partial melting of the old crust and consists of A-type post-collapse granites. This magmatism is sub-alkaline and high K and suggests formation in a magmatic mature arc, at shallow crustal level. The ΣNd data of rocks older than 1,880 Ma range from 0 to positive values indicating juvenile crust, while negative data are identified in younger granitoids (Maloguinha; Santos et al., 2000). Igneous rocks (mafite and ultra-mafite, tholeiite rocks) dated at 2,100 Ma, and basic cale-alkaline rocks, enriched in K with ages of 1,950 and 1,879 Ma, also occur. The felsic volcanism consisting of andesite, basalt-andesite, trachyandesite, latite, rhyolite, dacite, pyroclastic rocks and ignimbrites, represents multiple volcanic pulses in the province from 1,888 to 1,878 Ma.

Intracratic magmatic activity associated with crustal shortening and dated at 1,760 Ma resulted in the emplacement of rapakivi and alkaline granites (1,580 to 1,579 Ma); tholeiitic alkali-basalts (1,099 Ma); and dolerite dyke swarms (0,514 Ma and 0.180 Ma).

Metamorphism is characterised by primary textural preservation, and ranges from amphibolite to greenschist facies. The oldest rocks (schists and metasedimentary rock >2,100 Ma) show prominent metamorphic foliation along a N-S trend with a steep dip to the S-SW. The older granitoids (Cutia-Cutiaú Complex) exhibit a similar deformation pattern and the same regional trend as the oldest rocks, suggesting that both units were deformed under a thrust fault regime in a far stress field where σ₁ > σ₃ > σ₂. However, magmatic banding-foliation and pluton-related brittle faulting are common. Most of the brittle deformation shown by the granitoids from the second (Creporizão) and third (Paraúna) arcs may have originated during the intrusion of the younger granitoids (Maloguinha) that were emplaced at shallow crustal levels.

Structural studies indicate three deformation events (see Coutinho et al., 2000):
(i) A compressional event (1, 96 Ma) developed under ductile regime resulted in three lineament trends: NW-SE, dextral, and N-S and NS-W, both sinistral. Thrust faults are also present.
(ii) A compressional to transpressional event (1,88 Ma) that took place under ductile-brittle conditions, resulted in the strike-slip system and formed: sinistral transcurrent faults (N40°-50°W; N10°-30°W; N70°-80°W); dextral transcurrent faults (N-S; N15°E; N10°-30°W; N70°-80°W); extensional faults (N85°E to E-W) and brittle thrust fault with thrusting from E to W;
(iii) An extensional fault system related to rifting and vertical movement of the crust, which allowed the rise of theleitic basaltic magma at approximately 0,18 Ma.

Mineralization
The Tapajós gold mineralization is characterised by the following geological features:
(i) Host rocks: gold mineralization is associated with metamorphic terranes at greenschist facies, which posidates peak regional metamorphism at amphibolite facies. The gold occurs in a variety of host-rocks, such as basement rocks (tonalitic and granitic gneisses), metasedimentary rocks (1,895 Ma), basic rocks (gabbro, 1,878 Ma in age) and felsic metavolcanic rocks; however, granitoids which show variable deformation patterns and ages represent the most common host-rock-type for the gold deposits.
(ii) Structural: The mineralization occurs in quartz veins (lode-gold), developed in associated with (a) a compressional event under a ductile regime, and also in (b) compressional to transpressional event (strike-slip system), ranging from ductile-brittle to dominantly brittle. Stockworks are also very common in all host rocks. Mineralized breccia is also developed. Several type of gold-bearing quartz veins include: sheared, extensional, stockworks, tension gashes, pull apart and brecciated. The quartz shows different texture-type: open space, laminated, crack and
seal, comb, crustiform and vuggy. The fibrous habit of chalcocody was identified under the microscope and is consistent with δD values of silica phases. Massive sulphide (pyrite with gold) veins formed along the S planes (plane of schistosity fabric).

(iii) Wallrock alteration: hydrothermal activity in the deposits involved several phases of veining and/or brecciation, and associated alteration and mineralization, which vary with the wallrock type and crustal level. However, lateral zonation of alteration phases is less than 1 m width. Amphibole and biotite are common at the mineralization associated with the ductile regime, while carbonate is more abundant in the brittle deformation regime. Propylitic alteration (chlorite-calcite-epidote assemblage) forms part of the alteration in basic host rocks (gabbros) and felsic volcanic rocks (andesite and trachyandesite). Argillie wallrock alteration (quartz-kaolinite-chlorite) is abundant at ductile regime developed in granitoids. However, alkali metasomatism involving K-feldspar, sericitization and albitization, represents the most expressive alteration at all host-rock types. Sulphidization is dominated by pyrite. Addition of significant amounts of SiO₂ is common.

(iv) Ore mineralogy
The deposits are polymetallic quartz veins with ~5% of sulphide minerals. The mineral assemblage in veins developed under ductile conditions consists of magnetite, ilmenite, rutile, hematite, pyrrhotite, chalcopyrite and galena. In veins related to ductile-brittle regime, the minerals assemblage consists of magnetite, rutile, hematite, pyrrhotite, chalcopyrite, galena, sphalerite (Cd-rich), molybdenite, tetrame, teinite, tellurobismuthite and cobaltite. Visible gold is associated with silver in both quartz vein types. Gold/silver ratios vary from 4 (for the first vein-type) to 10 (for the second vein-type). The weathering minerals are: leucoxene, goethite, limonite, covellite and calcosite.

(v) Lead isotope data
The lead isotopic compositions of 32 sulphides (galena and pyrite) from gold-bearing quartz veins of 17 deposits were analysed to determine the time of gold precipitation. The modelages (Doe and Stacey, 1974) indicated two phases of mineralization at 1,960±10,10 Ma and 1,880±10,10 Ma. The multiple stages of gold deposition suggested by the lead modelage is consistent with the structural control of the gold-bearing quartz veins. The results of the Pb-isotopic analysis of the sulphides plotted on a standard 206Pb/204Pb x 207Pb/204Pb and 208Pb/204Pb x 206Pb/204Pb plumbotectonics model diagram (Zartman and Doe, 1981; Fig. 2) indicated that the Pb isotopic composition fits on the Pb orogenic curve or close to the Pb upper crust. The involvement of deep crustal Pb within the ore fluids indicates that the hydrothermal system has deeply sourced fluids. The small degree of isotopic variation of the data show reasonably homogeneous isotopic compositions.

(vi) Fluid inclusions
The different proportions of liquid and vapour define three types of fluid inclusions: H₂O-CO₂ (water-vapour), CO₂-rich (vapour-rich) and H₂O (aqueous) inclusions. According to this study there are two types of deposits: (a) CO₂-rich characterised by: 5 to 15 CO₂ mol %; salinity 3 to 6 wt%NaCl; temperature 260 to 340°C; pressure 1.3 to 4 kbar, indicating a crustal depth of 4 to 7 km; (b) Aqueous-rich and CO₂ poor characterised by: < 5% CO₂ mol %; salinity 3.0 to 1.5 wt%NaCl; temperature 220 to 300°C; pressure 0.3 to 1.4 kbar, indicating a crustal depth of 0.5 to 1.5 km.

(vii) Stable isotope data
Oxygen and hydrogen isotope determinations were made on 20 deposits representing the different geological and structural settings, where argilliferous quartz veins are hosted by different lithologies. The analysis for all quartz veins show a restricted range of δ¹⁸O values. The highest value is 13.6 per mil, while the lowest is 9.4 per mil. This result can be explained by either: (i) relatively constant temperature of mineralization; or (ii) homogenous hydrothermal fluid δ¹⁸O values. However, structural control of the mineralized veins suggests a range of crustal level for deposition. Thus, the homogenous δ¹⁸O values are more likely due to homogenous isotopic composition of the fluid. The δ¹⁸O results show a range from -2.9 to 8.6 per mil. The variation in the δD values of the hydrothermal system is -21 to -56 per mil, although two samples show lower values (-66 and -80). The lower δD values may be related to chalcocodic silica as indicated by the fibrous texture that occurs in quartz. As shown in Fig. 2, δ¹⁸O and δD values are mostly in the range for magmatic fluid and juvenile water fields (deep source ore fluid). However, a possible component of meteoric water was added to the hydrothermal system at upper crustal levels, based on the fact that some deposits hosted by brittle structures are enriched in aqueous fluid inclusions and poor in CO₂.

(viii) Geotectonic setting
According to the Condie’s (1992) concept, the significant portions of the Tapajós Mineral Province are composed of accreted terrane. Despite limited exposure, geochronological (Santos et al., 1997) and geochemical data in rocks (Coutinho et al., 2000; Klein et al., 2000) indicate that much of this region comprises accreted terranes (juvenile crust) that were added to Amazon Craton during the Paleoproterozoic: deposition of sediments at 2.100 Ma; intrusion of pre-tectonic plutons (I-type granitoids) at 2.011 to 2.006 Ma; strong compressional deformation, amphibolite-grade metamorphism and emplacement of syntectonic plutons (I-type granites) at 1.997 to 1.957 Ma; post-tectonic intrusion of plutons (I-type granitoids) at 1.897 to 1.880 Ma; development of a compressional to transpressional ductile-brittle event at 1.888 Ma; emplacement of A-type post collision granites at 1.833 to 1.880 Ma; intrusion of anorogenic granites (rapakivi) at 1,580 to 1,570 Ma; extension fault system; alkaline to theoleitic basic magmatism at 1,099 Ma; and intrusion of dolerite dyke swarms at 0.514 to 0.180 Ma. The two gold mineralization phases post-date the deformation and are syn-post magmatism.

Conclusion
This study suggests that the Tapajós gold mineralization was formed during compressional to transpressional deformation processes at convergent plate margin in accretionary orogen. The deposits are interpreted to represent Proterozoic mésozonal to epizonal gold deposits deposited from a similar, but variously evolved, ore fluid at a variety of crustal depths. Therefore, this model suggests that the shallow deposits are seated on the east side of the province, where the pluto-volcano system is well preserved, while the deposits with transition character occur mostly in the basement (central domain), where the erosion level has a profound influence on preservation.

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Figure 2. Diagram of the calculated water δD (per mil) x δ18O (per mil SMOW) in fluid inclusions from the gold-bearing quartz veins, Tapajos Province (23 analyses). References are added for comparison (i) magmatic fluid, (ii) juvenile water and (iii) metamorphic fluid (Taylor, 1979); Archaean gold deposits from mesothermal deposits from Superior and Slave provinces, Canada (Kerrich, 1989) and Norseman-Wiluna Belt, Western Australia (Golding and Wilson, 1988); Canadian Cordilleran (Nesbitt and Muelenbachs, 1988); Carlin-type trend deposits (Sawkins, 1990); porphyry-type deposits, British Columbia (Diron et al., 1995), epithermal deposits (Field and Fijarek, 1985). The meteoric water and geysers lines were also included (Hodgson, 1993).