OROGENIC GOLD DEPOSITS IN TAPAJÓS MINERAL PROVINCE, AMAZON, BRAZIL

[1] COUTINHO, M.G. da N, [2] SANTOS, J.O. S., [3] FALLICK, A. E. and [4] LAFON, 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-Mariam *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 greenschist and lower-amphibolite facies environments. The deposits show features characteristic of both Archaean 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 orogenic mesozonal/epizonal gold.

Regional Geology

The Tapajós Mineral Province (90,000 km^2) located on the central-south of the Amazon Craton underwent a tectonic Proterozoic (Orosirian) orogenesis, comprising four volcano-plutonic 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 (*Cuiú-Cuiú, Creporizão and Parauari*) 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 alumina-saturation index, the granitoids range from metalumious to peraluminous, and represent I-type granites. The fourth event (*Maloquinha*) dated at 1,870 Ma is associated with partial melting of the old crust and consists of A-type post-collision granites. This magmatism is sub-alkaline and high K and suggests formation in a magmatic mature arc, at shallow crustal level.

The $\in$Nd 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 (*Maloquinha*; Santos *et al.*, 2000). Igneous rocks (mafic and ultra-mafic, tholeiitic rocks) dated at 2,100 Ma, and basic calc-alkaline rocks, enriched in K with ages of 1,990 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.

Intracratonic magmatic activity associated with crustal rifting 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-NW trend with a steep dip to the S-SW. The older granitoids (*Cuiú-Cuiú* 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 σ_1 ~70^0. 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 the third (*Parauari*) arcs may have originated during the intrusion of the younger granitoids (*Maloquinha*) 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 NE-SW, 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 (N40^0-50^{0}W; N10^0-30^{0}W; N70^0-80^{0}W); dextral transcurrent faults (N-S; N15^{0}E; N10^0-30^{0}W; N70^0-80^{0}W); extensional faults (N80^{0}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 tholeiitic 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 postdates 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 with (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 chalcedony was identified under the microscope and is it 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). Argillic 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 SiO_2 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, pyrrotite, chalcopyrite and galena. In veins related to ductile-brittle to brittle regime, the minerals assemblage consists of magnetite, rutile, hematite, pyrrotite, chalcopyrite, galena, sphalerite (Cd–rich), molybdenite, tetradymite, teineite, 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 model-ages (Doe and Stacey, 1974) suggested two phases of mineralization at 1.96 Ga and 1.88 Ga. The multiple stages of gold deposition suggested by the lead model-age 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 $^{207}Pb/^{204}Pb$ x $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ x $^{206}Pb/^{204}Pb$ plumbotectonics model diagram (Zartman and Doe, 1981; Fig. 2) indicated that the Pb isotopic composition fit 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: H_2O-CO_2 (water-vapour), CO_2-rich (vapour-rich) and H_2O (aqueous) inclusions. According to this study there two types of deposits: (a) CO_2-rich characterised by: 5 to 15 CO_2 mol %; salinity 3 to 6 wt%NaCl; temperature 260 to 340^{0}C; pressure 1.3 to 4 kb, indicating a crustal depth of 4 to 7km; (b) Aqueous-rich and CO_2-poor characterised by: : < 5 CO_2 mol %; salinity 0.3 to 1.5 wt%NaCl; temperature 220 to 300^{0}C; pressure 0.3 to 1.4 kb, 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 auriferous quartz veins are hosted by different lithologies. The analysis for all quartz veins show a restricted range of $\delta^{18}O_{quartz}$ 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 $\delta^{18}O$ values. However, structural control of the mineralized veins suggests a range of crustal level for deposition. Thus, the homogenous $\delta^{18}O_{quartz}$ values are more likely due to homogenous isotopic composition of the fluid. The $\delta^{18}O_{H2O}$ results show a range from 2.9 to 8.7 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 chalcedonic silica as indicated by the fibrous texture that occurs in quartz. As shown in Fig. 2, $\delta^{18}O_{H2O}$ 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 CO_2.

(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 Paleopropterozoic: 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 granitoides) 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 1,883 to 1,880 Ma; intrusion of anorogenic granites (rapakivi) at 1,580 to 1,570 Ma; extensional fault system; alcaline to tholeiitic 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 Tapajos gold mineralization was formed during compressional to transpressional deformation processes at convergent plate margin in accretionary orogen. The deposits are interpreted to represent Proterozoic mesozonal 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 pluton-volcano system is well preserved, while the deposits with transition character occur mostly in the basement (central domain), where the erosion level has a profund influence on preservation.

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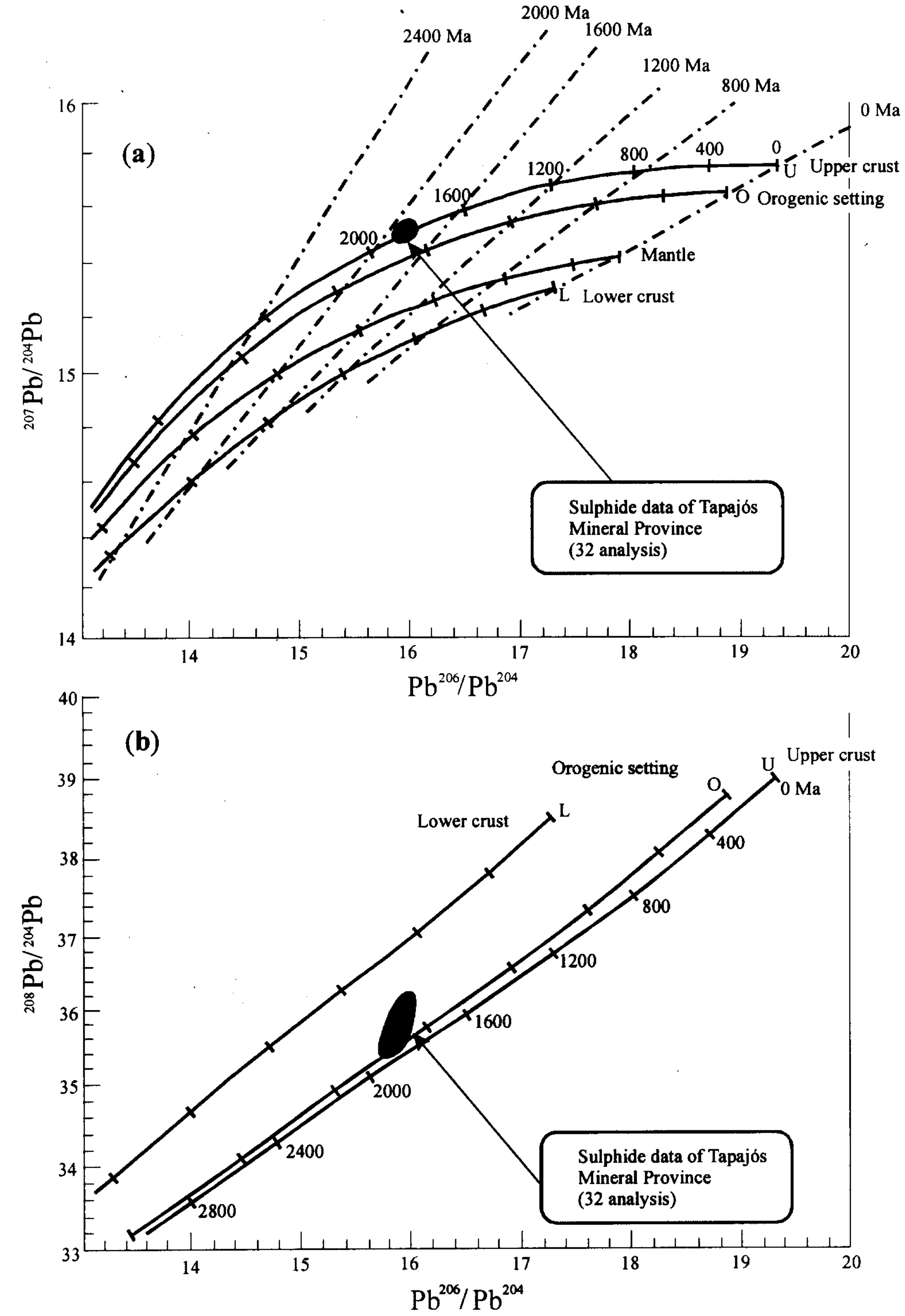

Figure 1 Diagrams showing the lead isotopic ratios (a) $^{206}Pb/^{204}Pb$ x $^{207}Pb/^{204}Pb$ and (b) $^{206}Pb/^{204}Pb$ x $^{208}Pb/^{204}Pb$ in sulphides from Tapajós Province, according to Zartman and Doe (1981).

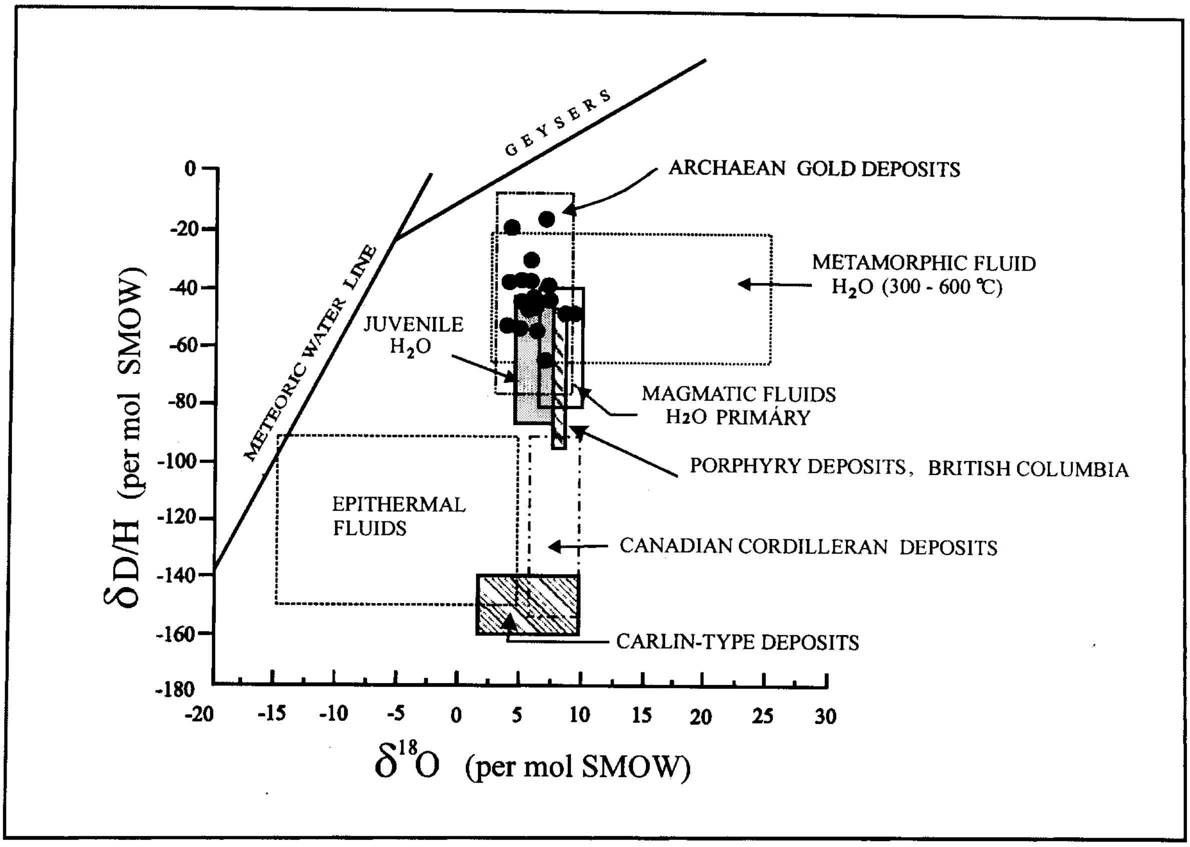

Figure 2. *Diagram of the calculated water $\delta^{18}O$ (per mil) x δ D (per mil SMOW) in fluid inclusions from the gold-bearing quartz veins, Tapajós Province (23 analysis).*
References are added for comparison (i) magmatic fluid, (ii) juvenile water and (iii) metamorphic fluid (Taylor, 1979); Archaean 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 Fifarek, 1985). The meteoric water and geysers lines were also included (Hodgson, 1993).

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