Geology and Metallogeny of Neoarchean and Paleoproterozoic Copper Systems of the Carajás Domain, Amazonian Craton, Brazil

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Abstract. The copper deposits of the Carajás Domain in the southeastern Amazonian craton (Brazil) are grouped into iron oxide-copper-gold (IOCG) and Cu-polymetallic systems. These systems represent multiple ore-forming hydrothermal events that took place in the Neoarchean (2.70 Ga and 2.56 Ga) and Paleoproterozoic (1.88 Ga) during the reactivation of regional-scale shear zones. The world-class Neoarchean (2.70 Ga and 2.56 Ga) IOCG systems were emplaced at deeper crustal levels compared to the Paleoproterozoic analogues. The Neoarchean and Paleoproterozoic Cu-polymetallic deposits are typically shallow hydrothermal systems and as a contrast to the IOCGs result in lower sulfidation state and more reduced ore assemblages. Mixing of high temperature hypersaline metalliferous fluids with other fluid types is a marking feature in both copper system groups and a trigger to ore precipitation. While a magmatic fluid source still remains unclear, non-magmatic brines (e.g. bittern fluids) seem to be an important component in the Neoarchean IOCG systems. A-type magmatism, on the other hand, could have acted as source of fluids or heat to move non-magmatic brines to form the Paleoproterozoic copper systems.

1 Introduction

The copper reserves in Brazil are in the order of 11 Mt (1.5% of the world), ca. 85% of which concentrated in the Carajás Province, an Archean crustal segment in the southeastern Amazonian Craton, northern Brazil. This province is divided into two tectonic domains: the Rio Maria Domain in the south and the Carajás Domain (CD) in the north.

The CD consists of Mesoarchean (3.0 – 2.83 Ga) basement rocks, with TTG-like gneisses-migmatites, orthogranulites and calc-alkaline granitoids, overlain by Neoarchean metavolcano-sedimentary sequences of the Itacaiúnas Supergroup and Rio Novo Group (*ca*. 2.76 to 2.73 Ga) and metasiliciclastic rock units of the Águas Claras Formation (*ca*. 2.65 Ga - 2.70 Ga as minimum ages of sedimentation). Magmatic events are represented by *ca*. 2.75 Ga mafic-ultramafic intrusions, 2.75 - 2.70 Ga and locally *ca*. 2.56 alkaline granites, and ca.1.88 Ga A_2-type granites (Xavier et al. 2012).

A variety of copper deposits is concentrated in the CD and may be broadly divided into two systems, namely iron oxide-copper-gold (IOCG) and copper – polymetallic. Collectively these systems yield resources of more than 8 billion tonnes of Cu-Au ore at 0.9 wt% Cu and 0.2 g/t Au to the CD.

This work summarizes the main geologic characteristics of these two copper systems of the CD, placing emphasis on their hydrothermal alteration types, mineralization styles and ages, fluid regimes and isotopic signatures. Critical issues are also raised that currently hamper the development of a unifying genetic model for these systems in the CD.

2 Copper systems of the Carajás Domain

2.1 Iron oxide – copper – gold (IOCG) deposits

This group includes the most economically important deposits of the CD (100 – 990 Mt @ 0.77 – 1.4 % Cu and 0.28 – 0.86g/t Au). These are structurally controlled by regional-scale WNW-ESE–striking brittle-ductile shear zones in the northern and southern sectors of the CD, close to the contact between the basement and supracrustal units. Mesoarchean basement gneisses/granitoids, remains of greenstone belt rocks, as well as Neoarchean metavolcano-sedimentary units of the Itacaiúnas Supergroup, gabbro/diorite, quartz-feldspar porphyry and A_2-type anorogenic granite may be hosts to the IOCG systems (Xavier et al. 2012). Geochronological data reveal that the Carajás IOCG systems were emplaced during multiple hydrothermal episodes during the Neoarchean and Paleoproterozoic with the ore-forming events marked at: (i) 2.72 – 2.68 Ga, represented by the Sequeirinho - Pista deposit at the Sossego mine (245 Mt @ 1.1 wt. % Cu, 0.28 g/t Au), Cristalino deposit (500 Mt @ 1.0 wt.% Cu; 0.3 g/t Au) and satellite deposits, including Bacuri, Bacaba, Castanha, Visconde and Pedra Branca, all in the southern sector; (ii) 2.56 Ga recorded at the Salobo mine (1.11 Gt at 0.69 % Cu and 0.43 g/t Au) and Igarapé Bahia/Alemão deposit (219 Mt @ 1.4 wt.% Cu, 0.86 g/t Au) in the northern sector (Moreto et al. 2015a,b). The Paleoproterozoic IOCG events have been constrained at 1.90 Ga and 1.88 Ga, having as examples the Sossego-

Curral deposit (Sossego mine) and Alvo 118 (*ca*. 170 Mt @ 1.0% Cu and 0.3 g/t Au) deposit, also in the southern sector of the CD (Grainger et al. 2008; Moreto et al. 2015a).

The Neoarchean 2.72 – 2.68 Ga IOCG systems are generally emplaced at deep crustal levels. In the southern sector of the CD the IOCG deposits commonly show distal sodic - calcic alteration, with albite - scapolite – hastingsite - actinolite – epidote, followed by variable combinations of more proximal calcic - ferric (actinolite - magnetite - apatite) and/or potassic - ferric (K-feldspar and biotite - magnetite) alteration types that commonly envelop chalcopyrite - pyrite - sigenite - magnetite - actinolite - chlorite - apatite - allanite breccias (e.g., Sequeirinho – Pista, Cristalino, Visconde and Pedra Branca deposits; Fig. 1A; Xavier et al. 2012). The copper ore zones at the Bacaba, Castanha, and Bacuri deposits are associated with chlorite-epidote alteration with distal potassic-ferric alteration envelopes (Moreto et al. 2015b).

In Neoarchean 2.56 Ga IOCG systems from the northern sector of the CD, sodic – calcic (hastingsite-actinolite) alteration followed by silicification, iron-enrichment with almandine - grunerite – tourmaline - magnetite, and potassic - ferric alteration (biotite – magnetite) are common at the Salobo, Grota Funda, Furnas and GT46 deposits (Melo et al. 2016). These alteration types envelop massive magnetite lenses containing disseminated bornite–chalcocite (e.g., Salobo; Fig. 1B), magnetite – chalcopyrite - actinolite breccias (e.g., Grota Funda), chalcopyrite - bornite - magnetite veins, stockworks and breccias (e.g., Furnas) or contain chalcopyrite disseminations along the mylonic foliation (e.g., GT46). Dissimilar from the above IOCG examples of the northern sector, sodic-calcic (actinolite + albite + scapolite + epidote) and potassic (biotite) alteration at the Igarapé Bahia/Alemão deposit are replaced by chlorite – carbonate (calcite + siderite) - apatite - tourmaline associations in strongly foliated zones which wrap around massive magnetite + chalcopyrite ± bornite ± pyrite breccias within the Itacaiúnas Supergroup (Xavier et al. 2012).

Comparatively with the Neoarchean examples, the Paleoproterozoic IOCG systems represent hydrothermal systems developed at shallower crustal levels and controlled predominantly by brittle structures. These systems are generally characterized by poorly developed or absence of sodic-calcic or calcic-ferric alteration, but commonly display strong and pervasive potassic - ferric (K-feldspar and biotite with magnetite) alteration. This alteration stage is commonly overprinted by extensive zones dominated by chlorite - epidote - calcite or sericite that host the copper-gold ore. The ore forms breccia (Sossego-Curral; Fig. 1C) and vein systems (Alvo 118) containing quartz, calcite, actinolite, magnetite/hematite, apatite and sulfides (chalcopyrite – pyrite - siegenite). In both Neoarchean IOCG systems, the Fe-Cu-Au association is generally accompanied by variable concentrations of P-LREE-U-Ni-Co-Pd.

2.2 Copper - polymetallic deposits

These deposits contain reserves of < 50 Mt @ < 2% Cu and include as main examples the Breves (50 Mt – 1.22% Cu, 0.75g/t Au, 2.4g/t Ag, 1200g/t W, 70g/t Sn, 175g/t Mo, 75g/t Bi), Estrela (Cu-Au-Li-Be-Sn-W-Mo), Águas Claras (Cu-Au-W), Gameleira (Cu-Au-Co-F-U-Mo-REE), Santa Lucia (Cu-Au-Bi-Sn-W-Mo), and Tarzan (Cu-Co) deposits.

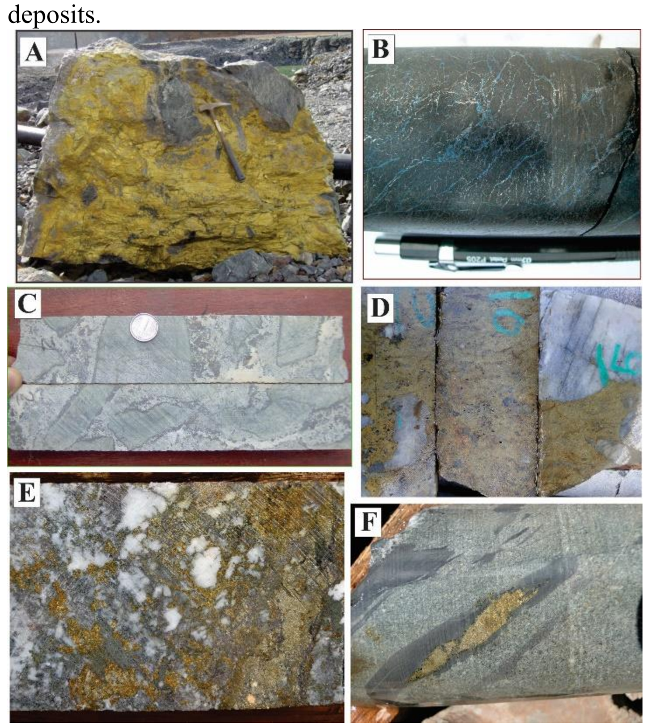

Figure 1. Mineralization styles of Neoarchean and Paleoproterozoic Cu systems in the Carajás Domain. **a** 2.70 Ga Sequeirinho IOCG ore breccia (Sossego mine) with clasts of actinolite-magnetite in a chalcopyrite-rich matrix. **b** Massive magnetite with chalcosite-bornite seams at the 2.56 Ga Salobo IOCG deposit. **c** calcite-quartz-apatite-actnolite-magnetite ore breccia of the 1.90 Ga Sossego deposit (Sossego mine) containing angular clasts of strongly chloritized granophyric granite. **d** Quartz-apatite-chalcopyrite-pyrite-pyrrhotite-sphalerite vein breccia of the 2.70 Ga Santa Lucia Cu-polymetallic deposit. **e** 1.88 Ga (?) sediment-hosted Tarzan Cu-Co deposit. Chalcopyrite-pyrite-quartz-chlorite ore zone. **f** Chalcopyrite nodule within a pelite rip-up clast in a greywacke sequence of the Igarapé Bahia/Alemão IOCG deposit.

General characteristics of these deposits include: (i) structurally controlled by brittle structures; (ii) styles of mineralization dominated by vein systems, stockworks and breccias with abundant quartz; (iii) very low contents (e.g., Águas Claras, Estrela) or lack of iron oxides (magnetite/hematite) related to copper mineralization; (iv) important potassic alteration with biotite (e.g., Estrela and Gameleira) or hydrolytic alteration dominated by chlorite-sericite (e.g. Águas Claras, Tarzan) or of greisen-type with phengitic muscovite (e.g., Breves and Santa Lucia; Figs. 1D-E); (v) lower sulfidation and more reduced ore assemblages consisting of variable combinations of chalcopyrite - pyrite - arsenopyrite - pyrrhotite – sphalerite - galena; (vi) geochemical signature similar to the IOCG systems, but with more elevated values of granitophile elements such as W, Sn and Bi.

The age of the ore-forming events for the Cu – polymetallic systems has been constrained at *ca*. 1.88 Ga, on the basis of SHRIMP II $^{207}Pb/^{206}Pb$ ages in monazite and xenotime (e.g., Breves) and bulk ore Sm-Nd isochron (e.g., Estrela), which is broadly coeval with the widespread *ca*. 1.88 Ga A_2-type granites (Grainger et al. 2008). However, recent SHRIMP II $^{207}Pb/^{206}Pb$ analyses performed on ore breccia-related monazite grains have yielded a mean age of 2,688 ± 27 Ma for the Santa Lucia Cu-polymetallic deposit revealing that ore-forming conditions for these copper systems may have also prevailed coevally with the Neoarchean IOCG systems.

3 Multiple Neoarchean and Paleoproterozoic hydrothermal events

Overprinting of temporally distinct hydrothermal events, some of which associated with copper ore formation, has been suggested at the scale of individual Carajás IOCG deposits (Moreto et al. 2015a,b): 2.76 Ga (molybdenite Re-Os) recorded in early chalcopyrite-calcite veins and 2.70 Ga (monazite U-Pb) for the ore stage at the Bacuri deposit; ages of 2.68 Ga and 2.06 Ga acquired in both cores and rims of different ore-related monazite grains at the Bacaba deposit.

Different styles of copper mineralization are commonly registered at individual deposits, such as magnetite – chalcopyrite – actinolite breccias and chalcopyrite – pyrite quartz veins with or without magnetite, such as at the Neoarchean Cristalino and Grota Funda deposits. Despite of the lack of geochronological data, these features have been accounted as indirect evidence of possible overprinting of Neoarchean and Paleoproterozoic mineralizing events. In addition, finely-laminated sedimentary units at the Neoarchean (*ca*. 2.56 Ga) Igarapé Bahia/Alemão IOCG and Paleoproterozoic (?) Tarzan Cu-polymetallic deposits commonly display rounded chalcopyrite nodules (Fig. 1F). Although undated, these nodules may represent the earliest hydrothermal precipitation of copper in the province (> 2.76 Ga?; diagenetic origin?).

4 Fluid regimes and isotopic signatures

Fluid inclusion data for both Neoarchean and Paleoproterozoic IOCG systems point to similar trends in fluid evolution. These trends consistently involve highly saline (35−70 wt % $Na\text{-}Cl_{equiv}$) and hot (>500°C) metalliferous brines, and lower temperature (generally <250°C) aqueous fluids of low to intermediate salinity, with or without the participation of $CO_2 \pm CH_4$-rich fluids (Xavier et al. 2012). LA-ICP-MS fluid inclusion analyses show that IOCG hypersaline brines are Na-Ca-Fe-dominated (> 1%) and strongly enriched (> 0.1% up to 1%) in K, Sr, Ba, Mn, Zn, and Pb. Copper concentrations in these IOCG brines are mostly in the range of a few hundred parts per million or less.

Fluid inclusion studies reveal that fluid regimes for the Carajás Cu – polymetallic systems also had the participation of highly saline (> 30 wt% NaCl eq.) Na-Ca-rich aqueous fluids and low-salinity aqueous-carbonic fluids (> 350°C) that progressively mixed with aqueous fluids of lower to moderate (0.2 – 26.2 wt% NaCl eq.) salinity and lower temperature (130 °C – 230°C) (e.g., Breves and Estrela). CO_2-rich fluids are lacking in some deposits and fluid evolution takes place essentially with aqueous fluids of variable salinities (0.3 – 45 wt% NaCl eq.) and temperatures (360 - 160°C) (e.g., Águas Claras and Gameleira).

The calculated $\delta^{18}O$ and δD isotopic compositions of the ore-forming fluids range from 4.8‰ to 10‰ and from -74‰ to -39‰, respectively, for the Neoarchean (e.g., 2.70 Ga Sequeirinho-Pista, Castanha and Bacaba) and Paleoproterozoic (e.g., 1.88 Ga Sossego-Curral) IOCG systems in the southern sector of the CD. These values suggest that magmatic fluids might be associated with early hydrothermal alteration stages in these deposits. However, fluid evolution in these cases is accompanied by the introduction of $\delta^{18}O$-depleted and more δD-enriched fluids, isotopically similar to seawater values (e.g., Sequeirinho-Pista and Bacaba; Xavier et al. 2012). In addition, variable light and heavy $\delta^{11}B$ values in tourmaline (-8‰ to 11‰ at the Sequeirinho-Pista deposit) and fluid inclusion Cl/Br-Na/Cl systematics further support mixed sources for the ore-bearing fluids, including magmatic and modified seawater (e.g., bittern brines generated by seawater evaporation; Xavier et al. 2012). The Neoarchean (ca. 2.56 Ga) Igarapé Bahia/Alemão and Salobo IOCG deposits in the northern sector of the CD show calculated $\delta^{18}O_{H2O}$ values in the 5‰ - 16.5‰ and in the 6.6‰ - 12.1‰ ranges, respectively, compatible with magmatic fluids, but that have undergone strong crustal rock interactions. Nevertheless, heavy $\delta^{11}B$ values of 14‰ to 26.5‰ in tourmaline from these deposits, in combination with calculated δD_{H2O} in the range of -30‰ to -10‰ (at 400°C) and Cl/Br-Na/Cl systematics for the Igarapé Bahia/Alemão deposit point to an important involvement of non-magmatic fluids (seawater-derived fluids; Xavier et al. 2013).

The fluid evolution trend in Paleoproterozoic IOCG systems is broadly similar to the Neoarchean analogs, with the influence of $\delta^{18}O$-depleted hydrothermal fluids (−1.8 ± 3.4‰ at 300°C) suggestive of influx of surficially derived waters of meteoric or basinal origins (Sossego-Curral and Alvo 118 deposits).

Fluids in equilibrium with the hydrothermal assemblages at the Cu – polymetallic Breves and Estrela deposits have calculated $\delta^{18}O$ and δD values of -1.2‰ to 10.2‰ and -47‰ to -78‰, respectively. These data, together with fluid inclusion halogen data, are also compatible with magmatic fluids, but also point to mixing of external fluids, either meteoric or modified seawater during the ore-forming events. $\delta^{11}B$ values of ore-related vein tourmaline from the Breves deposit range from -3.6‰ to 1.8‰ and corresponding δD values vary from -116 to -99‰, compatible with magmatic signatures (Xavier et al. 2013).

In situ sulfur isotope analysis of sulfide minerals by SIMS defines three distinct $\delta^{34}S$ ranges: (i) -3.3‰ to +3.0‰ for the Neoarchean IOCG deposits; (ii) +2.5‰ to +4.7‰ for the Paleoproterozoic IOCG deposits; and (iii) -0.4‰ to +0.9‰ for the Cu-polymetallic systems (Santiago 2016). These sulfur isotope compositional ranges support contributions of magmatic sulfur, as well as and input of heavy sulfur from surficial reservoirs (e.g., sulfate from evaporated seawater or meteoric fluids) for both Carajás IOCG and Cu – polymetallic systems.

5 Discussion and concluding remarks

Copper metallogeny in the CD may have initiated as early as 2.76 Ga with the formation of diagenetic chalcopyrite (e.g., Igarapé Bahia/Alemão and Tarzan deposits) during the deposition of the rift-related Itacaiúnas Supergroup shallow marine volcano-sedimentary sequences. The Neoarchean and Paleoproterozoic Carajás Cu systems (IOCG and Cu – polymetallic deposits) are broadly controlled by regional WNW-ESE -striking transpressive shear zones that likely mark limits of tectonic blocks in the Carajás Mineral Province. Field relationships and geochronological data have indicated that nucleation and/or reactivation of these regional-scale structures may have taken place during the closure of the Itacaiúnas Supergroup rift system at *ca*. 2.68 Ga – 2.63 Ga (Tavares 2015). Reactivation of regional structures in the northern CD (e.g., Cinzento lineament) occurred at a later and still poorly constrained episode *ca*. 2.61 Ga – 2.52 Ga (Tavares 2015). These tectonic events have probably acted as first order controls for deep-seated fluid circulation and emplacement of Neoarchean and Paleoproterozoic Cu systems in the CD.

It is noteworthy that the Neoarchean Cu systems postdate the 2.76-2.74 Ga ultramafic-mafic and anorogenic granitic intrusions. In addition, A-type felsic magmatism was also poorly developed or recognized during the 2.70 Ga and 2.57 Ga (e.g., Old Salobo granite) tectonic events. As a consequence, the genetic link between ore-forming fluids of magmatic origin and copper mineralization, as suggested by stable isotope data, remains difficult to be clearly defined. This genetic link is more straightforward for the Paleoproterozoic IOCG and Cu-polymetallic systems, as they broadly overlap with the widespread ca. 1.88 Ga A_2-type granites recognized in the Amazonian craton.

The current knowledge on the Carajás Domain copper metallogeny allows to conclude that: (i) IOCG and Cu-polymetallic systems are the result of multiple structurally-controlled ore-forming hydrothermal episodes emplaced at different crustal levels during the Neoarchean and the Paleoproterozoic; (ii) fluid regimes seem broadly similar for both copper system types and point to mixing of high temperature hypersaline metalliferous fluids with other fluid types as an important trigger to copper mineralisation; (iii) the origin of these fluids is still controversial, but non-magmatic brines (e.g. bittern fluids) seem to be an important component in the Neoarchean IOCG systems; (iv) felsic magmatism could have acted as source of fluids and/or heat to move non-magmatic brines to form the Paleoproterozoic copper systems; (v) the formation of different but coeval copper systems are likely dependent upon a combination of deposit-scale factors, such as, sulfur availability, sulfidation state and redox conditions during fluid evolution.

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