

STABLE ISOTOPE AND MINERAL CHEMISTRY CONSTRAINTS ON THE EVOLUTION OF THE JATOBÁ COPPER DEPOSIT, CARAJÁS MINERAL PROVINCE

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INTRODUCTION

The Carajás Province, located in the Amazon Craton, represents an important metallogenetic province. The Cu-Au deposits at Carajás deserve attention due to their high volume of hydrothermal magnetite and elevated contents of REE, P, Ni, Co, Pd, and U, similar to those of iron oxide-copper-gold (IOCG) deposits (Hitzman *et al.*, 1992).

Several deposits (e.g. Sossego, Jatobá, Castanha, Bacaba, Bacuri, Visconde, Cristalino, Borrachudos; Monteiro *et al.*, 2008; Silva *et al.*, 2014; Moreto *et al.* 2015) may represent distinct portions of a large mineral system connected by similar genetic processes. The identification of paragenesis, hydrothermal alteration patterns, mechanisms of fluid-rock interaction and sources of metals, fluids and ligands in each deposit, however, is necessary to link them and unravel their evolution.

This contribution aims to decipher the hydrothermal history recorded in the Jatobá deposit by means of detailed paragenetic characterization of hydrothermal alteration and Cu-Au-(Ni-Zn) ore, accompanied with the identification of variations in the isotope and mineral chemical composition during the relative temporal evolution of the system.

THE JATOBÁ COPPER DEPOSIT: HOST ROCKS AND HYDROTHERMAL ALTERATION

The main host rocks of the Jatobá deposit comprise metarhyodacite ($2,700 \pm 16$ Ma, U-Pb LA-ICP-MS in zircon) and amygdaloidal metabasalt, in addition to felsic metavolcaniclastic breccias and mafic metalapilli and metacrystal metatuffs, which are cut by metadiabase dikes. The least-altered and deformed rocks, mainly derived from mafic protoliths, record effects of lower greenschist facies metamorphism. Sodic plagioclase and actinolite (I) represent the metamorphic paragenesis in such rocks.

Hydrothermal alteration was strongly controlled by the Canaã shear zone development, however intense alteration also was developed pervasively in isotropic rocks. Early hydrothermal alteration encompasses silicification, sodic (albite I, scapolite I), sodic-calcic (ferro-pargasite), and potassic (biotite I, tourmaline, Cl-apatite I, Ce-allanite I) alteration. Almond-shaped albite (I) or scapolite (I) porphyroclasts involved by pressure shadows occur in mylonitic rocks, indicating that the blastesis of these minerals was previous to the shear zone development.

The main syntectonic hydrothermal alteration stages comprise sodic-calcic (scapolite II), calcic (actinolite II, Cl-apatite II, Ce-allanite II, quartz) and potassic (Cl-K-hastingsite I, biotite II, quartz-Co-magnetite IV, Cl-apatite III, Ce-allanite III) alteration controlled by the development of mylonitic foliation.

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Massive magnetite bodies (IV; up to 60 m), represent proximal envelopes of mineralized zones and are well developed along the contact zones between metarhyodacites and metabasalts and within the latter. These magnetites are cut by fibrous actinolite (II) and Cl-apatite. Actinolite also surrounds the massive magnetite bodies, sometimes promoting their brecciation.

Late tectonic hydrothermal alteration is represented by pervasive chlorite alteration and scapolite (III) veins, which are cut by scapolite (IV), Cl-K-hastingsite (II) and biotite (III) veinlets.

COPPER-(NICKEL) MINERALIZATION

The copper-(nickel) mineralized zones in the Jatobá deposit comprise swarms of vertical to subvertical orebodies spatially related to metadiabase dikes and contact zones between rhyodacites and metabasalts. The mineralized zones were formed in four stages, coeval to ductile and ductile-brittle deformational events.

The mineralization stage (I) was related to syntectonic calcic alteration, especially to actinolite (II) formation in metarhyodacites. Replacement fronts and breccias have predominance of Ni-pyrrhotite, Ni-pyrite and Cl-apatite (II), and subordinately, Co-chalcopyrite, Ce-allanite II, Co-pentlandite, quartz and Ce-monazite. In addition, fine Ni-pyrrhotite crystals, actinolite (II), magnetite (IV) and subordinate quartz constitute replacement fronts and brecciated zones with up to 40 cm.

The mineralization stage (II) was temporal and spatially related to the development of the syntectonic potassic alteration (II), which pervasively and indiscriminately affects the main host rocks of the Jatobá deposit. Mineralized zones are developed in portions where biotite (II) was formed at the expense of actinolite (II) in mylonitic rocks. These are represented by a system of strongly oriented and interconnected bodies with biotite (II), Cl-apatite (III), Co-magnetite (IV), ilmenite (I), Ce-allanite (III) and quartz, besides discrete portions containing Ni-pyrite and Co-chalcopyrite. Breccia zones with expressive formation of biotite (II) and Co-chalcopyrite (\pm Ni-pyrite \pm Ni-pyrrhotite) affecting the preexisting bodies of massive magnetite are also observed.

The third mineralizing stage recognized in the Jatobá deposit is distinguished from the others because it is controlled by brittle structures and associated with veins with typical open-space filling textures. It was coeval to the late paler brown or green biotite (III), scapolite (IV), F-Cl-apatite (IV), and Cl-K hastingsite (II). Co-chalcopyrite and siegenite I (\pm Co-pyrite, \pm Co-magnetite, \pm cassiterite).

The late mineralization stage (IV) was the most expressive at Jatobá. It was coeval to widespread chlorite (II), quartz, epidote and calcite development. It occurs in a variety of branching veinlets, which cut out and isolate portions of rock that have been previously altered, thus giving a breccoid aspect to the rock. In these chlorite-rich domains, veinlets with Co-chalcopyrite, Co-pyrite, sphalerite, molybdenite, uraninite and monazite occur. Other late vein types comprise those with quartz-chalcopyrite-K (\pm molybdenite, Co-pentlandite, and siegenite II) and fine veinlets with chlorite-chalcopyrite, W-bearing hematite, rare earth carbonates (bastnäsite, coskrenite and sahalalite), Co- and Ni-pyrite, sphalerite, ilmenite, marcasite, leucocoxene and adularia.

MINERAL CHEMISTRY

The pre-tectonic scapolite (I), the syntectonic scapolite (II), and the post-tectonic fibrous scapolite (III) reveal gradual increasing of Cl (0.798-1.016 apfu), Si and Na contents during the paragenetic evolution. The scapolite (IV) from late veinlets, however, has intermediate Si, Na, Ca, Al^{IV} and Cl contents (Cl = 0.764-0.897 apfu).

Chlorine-bearing amphibole and biotite are also ubiquitous in the Jatobá deposit. In general, ferro-pargasite from distal zones and hastingsite (I) and (II) of mineralized zones have higher Cl contents than actinolite (I) and (II). The lowest Cl contents are related to actinolite (II) from early mineralization zones, which are spatially related to massive magnetite-(apatite) bodies. The chlorine content in biotite defines two main groups. The group 1 encompasses distal pre-tectonic biotite (I) and syntectonic biotite (II) from proximal and mineralization zones and is characterized by lower Cl and relatively higher Mg and Ti contents in relation to group 2. The group 2 comprises late biotite (III) from mineralized and barren zones, which has higher Cl, Na and Fe^{2+} contents. Interestingly, in the two groups biotite from barren and mineralized zones can be differentiated by its Cl or Ti contents.

Chlorite alteration developed in the transition from ductile structural regime to a dominantly ductile-brittle regime, resulting in chlorite from distal (I) and mineralized zones (II). The first is the product of replacement of scapolite, amphibole, and biotite and has chamosite composition and $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ ratios between 0.62 and 0.68. The chlorite (II) is associated with the mineralization stage (IV) and has clinocllore composition with $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$ ratios between 0.40 and 0.45. Different chlorite geothermometers indicate maximum temperatures of 330 °C for distal chlorite and 386 °C for chlorite (II), according to Jowett (1991).

The magnetite composition is controlled by the chemical environment in which it grows and by physico-chemical conditions during its formation (Depuis & Beaudoin, 2011). In the Jatobá deposit, magnetite has variable Ti contents (Mt II = 0 – 2059 ppm; Mt III = 49 – 2741 ppm; Mt IV = 0 – 2224 ppm) with the highest values in magnetite related to massive magnetite (Ti = < 29,700 ppm). The coexistence of syntectonic magnetite (IV)-ulvöspinel and magnetite-ilmenite could point to high-temperature conditions of magnetite formation. In addition, the magnetite has also high Cr + Ni + Cu (up to 1632 ppm) and V (Mt III = 2303 – 2343 ppm; Mt IV = 1088 – 3200 ppm) contents.

STABLE ISOTOPES

The sulfur isotope compositions of pyrrhotite and chalcopyrite of the Jatobá deposit indicate lower values ($\text{d}^{34}\text{S} = 0.27$ to 0.85 ‰) for sulfides from the mineralization stages (I) and (II) in relation to those of the mineralization stages (III) and (IV). The latter have d^{34}S values of 0.78 to 1.80 ‰.

The oxygen and hydrogen isotope analysis were carried out on mineral pairs formed in distinct stages of the system evolution. The oxygen isotope composition of early magnetite-quartz from veins related to massive magnetite permitted the temperature estimates for the pre-mineralization stage. The calculated temperature was the highest (558 °C) recorded at Jatobá. Conditions for the mineralizing stages (II), (III) and (IV) were estimated based on the isotope composition of biotite II-quartz (507 °C), biotite III-quartz (422 °C) and chlorite-quartz (327 °C). The oxygen and hydrogen isotope composition of fluids in equilibrium with these mineral phases, at the estimated temperatures, were calculated using known equilibrium fractionation factors. Hydrothermal fluids in equilibrium with magnetite-quartz have d^{18}O values of 9.18 to 9.53 ‰ and dD values of -30.250 . Lower d^{18}O (5.41 to 6.79 ‰) and dD values (-31.6 to -44.880) were obtained for minerals formed during the mineralizing stages (II) to (IV).

CONCLUDING REMARKS

The Jatobá deposit is hosted by felsic and mafic metavolcanic and metavolcaniclastic rocks attributed to the Itacaiúnas Supergroup. A general evolution from sodic, iron, (sodic)-calcic, potassic to chlorite alteration was recognized at Jatobá. Extensive syntectonic scapolite-hastingsite-biotite alteration zones and massive magnetite-(apatite) bodies enveloped by actinolite-rich zones are recognized. The gradual increase in Cl contents of scapolite (I) to (III) indicated a progressive evolution from hypersaline fluids and limited

influx of diluted fluids in the system. Four mineralization stages occurred at Jatobá. The early stages (I and II) were coeval to shear zone development and accompanied by actinolite and thereafter by high-temperature biotite formation. These stages have decreasing contents of Ni and Co and pyrrhotite concentration and evolved from replacement fronts controlled by mylonitic foliation to hydraulic breccia zones. The third and fourth mineralizing stages reflect a change in structural conditions and were controlled by ductile-brittle and brittle structures. These stages were coeval to low-temperature biotite and chlorite and have higher chalcopyrite contents. The high V, Ni and Cr concentration in Jatobá magnetite points to high-temperature conditions (about 500-700°C), especially during the early nickel-enriched mineralization event. These conditions are similar to those of magnetite formed in IOA, IOCG and porphyry deposits. The sulfur isotope compositions for all sulfide generations indicate magmatic-derived sources. In addition, the oxygen and hydrogen isotope composition of the hydrothermal fluids match that of the primary magmatic water and vapor and allows discarding the contribution of externally-derived fluids. These data indicate a system evolved from high-temperature magmatic fluids, similar to those recognized in relatively deep portions of IOCG mineral systems. Late mineralization stages were developed after significant system exhumation. Ductile-brittle and brittle structures enabled the most expressive chalcopyrite precipitation, accompanied by temperature decrease (< 380 °C) and may reflect overprinting of a late hydrothermal event.

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REFERENCES

- Hitzman, M.W., Oreskes, N., Einaudi M.T., 1992. Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. *Precamb. Res.* 58: 241–287.
- Jowett, E.C. 1991. Fitting iron and magnesium into the hydrothermal chlorite geothermometer. GAC/MAC/SEG Joint Annual Meeting, Program with Abstract, 16, pp A62.
- Monteiro, L.V.S., Xavier, R.P., Carvalho, E.R., Hitzman, M.W., Johnson, C.A., Souza Filho, C.R. and Torresi, I. 2008. Spatial and temporal zoning of hydrothermal alteration and mineralization in the Sossego iron oxide-copper-gold deposit, Carajás Mineral Province, Brazil: parageneses and stable isotope constraints; *Mineralium Deposita*, 43, 129-159.
- Moreto, C.P.N., Monteiro, L.V.S., Xavier R.P., Creaser, R., Dufrane, A., Tassinari, C.G., Sato, K., Kemp T.I.S., Amaral, W.S. 2015b. Overprinting of Paleoproterozoic on Archean Iron Oxide -Copper-Gold System at the Sossego Deposit, Carajas Province: Re-Os And U-Pb Geochronological Evidences. *Economic Geology*, 110:809-835.
- Silva, A.R.C., Villas R.N.N., Lafon J.M., Craveiro G.S., Ferreira V.P. 2015. Stable isotope systematics and fluid inclusion studies in the Cu–Au Visconde deposit, Carajás Mineral Province, Brazil: implications for fluid source generation. *Miner Deposita*, 50:547-569.