THE EVOLUTION OF THE IGARAPÉ BAHIA DEPOSIT: EVIDENCES OF A SYNGENETIC COPPER MINERALIZATION SUPERIMPOSED BY AN IOCG SYSTEM

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INTRODUCTION

The Igarapé Bahia deposit is located in the northern part of the Carajás Domain in the Carajás Province. It was the biggest gold mine during the 90's, producing 3,119 ounces of supergene gold an has primary ore estimated reserves of 219 Mt @ 1.4% Cu and 0.86 g/t Au (Tallarico et al. 2005). The deposit is hosted by the metavolcanosedimentary sequence of the Neoarchean Igarapé Bahia Group (Sumidouro and Grota do Vizinho formations), Itacaiúnas Supergroup, and metasedimentary units of the Águas Claras Formation of uncertain age. Genetic models for the Igarapé Bahia deposit firstly included a syngenetic exhalative origin for the copper-gold mineralization, similar to that of volcanic-hosted massive sulfide deposits (VHMS, Almada and Villas 1999, Dreher *et al.* 2005, 2008). The high magnetite content, in contrast, is typical of an epigenetic mineralization linked with an iron oxide-copper-gold (or IOCG) hydrothermal system (Tallarico *et al*. 2005). The processes answerable for the host rocks, including tectonic setting and ages, and different styles of mineralization at Igarapé Bahia are still barely comprehended. In addition, if the evolution of its orebodies (Alemão, Acampamento Norte, Acampamento Sul and Furo 30) are similar remain uncertain. This study show new geological evidences for the evolution of the Igarapé Bahia deposit, including origin and age of the host rocks, paragenetic evolution, timing of mineralization, and sulfur isotope and chemical composition of different generations of chalcopyrite.

ANALYTICAL PROCEDURES

Detailed petrographic studies and SEM characterization of the least-altered and, hydrothermally altered rocks and ore zones were performed in the Institute of Geosciences at University of Campinas. U-Pb geochronology analyses were carried out in an ICP-MS Element XR (Thermo Scientific), coupled with an Excite.193 (Photon Machines) laser ablation in the Isotope Geology Laboratory at the Institute of Geosciences at University of Campinas. Trace elements in chalcopyrite were measured using an ICP-MS XseriesII (Thermo) coupled with a CCT (Collision Cell Technology) at the Isotope Geology Laboratory in the Institute of Geosciences at University of Campinas. Stable isotope ratios were analyzed using MC-ICP-MS Neptune (Thermo Finnigan) coupled with laser New Wave UP213 Nd:YAG, in the Geochronology Laboratory of the University of Brasília

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HOST ROCKS AND SYNGENETIC COPPER MINERALIZATION

Host rocks at Igarapé Bahia include the lower Sumidouro and upper Grota do Vizinho formations of the Igarapé Bahia Group (Fig. 1). The lower sequence comprises basic and acid metavolcanic rocks, metagabbros and banded iron formation. Enclaves of fine-grained deformed granites within metagabbros yielded upper an intercept age of 2,935 ± 36 Ma (MSWD = 0.85).

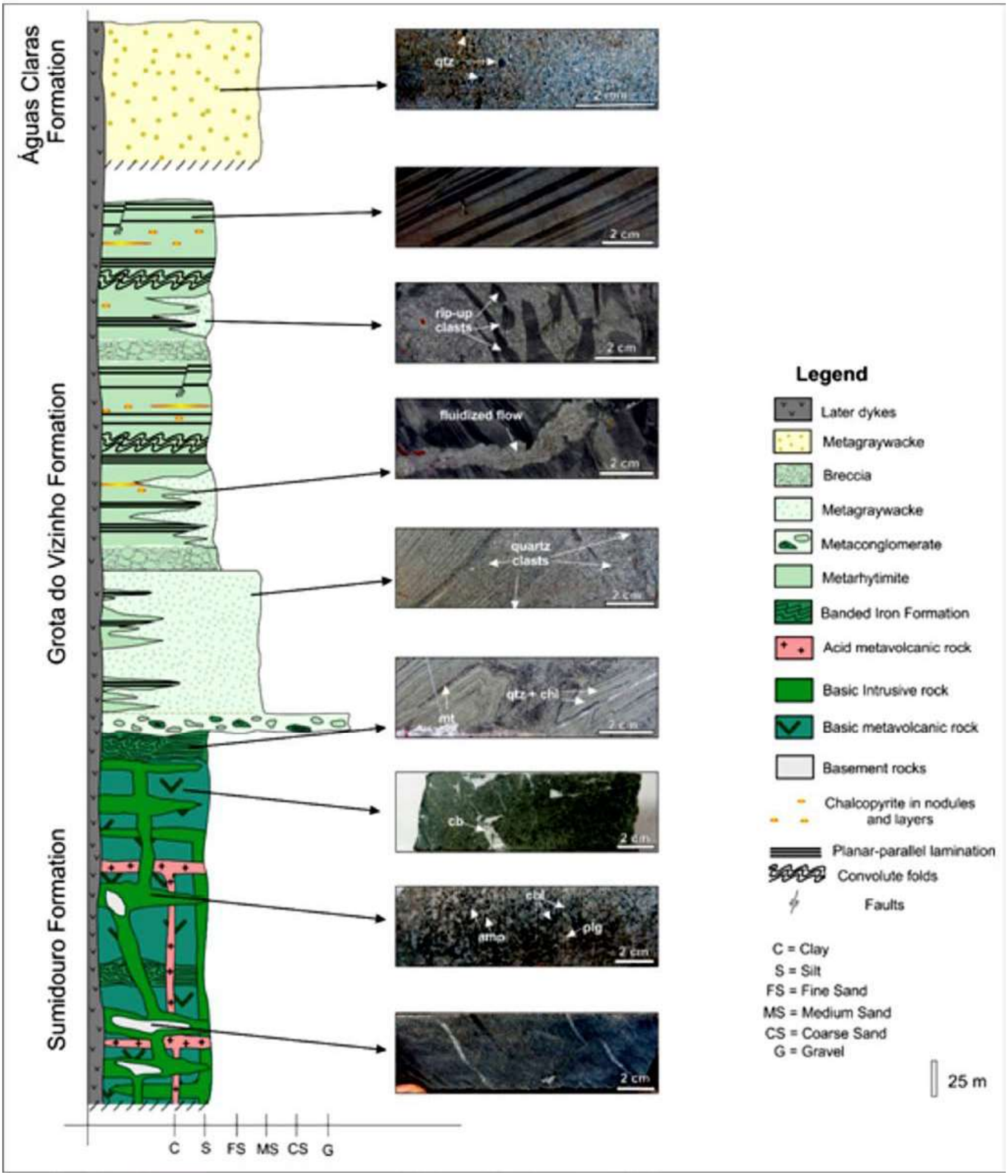

Fig. 1. Schematic stratigraphic column of the Igarapé Bahia Group and Águas Claras Formation within the Igarapé Bahia deposit, with associated lithotypes in the right side.

Metagraywackes from the Águas Claras Formation, better recognized in the Alemão and Acampamento Norte orebodies, also host the Igarapé Bahia deposit. They are ductile deformed, hydrothermally altered and mineralized in some parts. These rocks show detrital zircon population with ages in 2.81 – 2.89 Ga and 2.91 – 3.03 Ga and maximum age at 2,774 Ma. Later phaneritic, fine-grained, undeformed mafic dykes crosscut the main host rocks.

Chalcopyrite nodules and layers are ubiquitous within the metarhytmites, concordant with the plan-parallel bedding. They do not show feeders or extensive hydrothermal alteration halos; however they are commonly associated with chlorite and quartz in its edges. Monazite, xenotime, molybdenite, cobaltite and galena occur as tiny inclusions in chalcopyrite.

HYDROTHERMAL ALTERATION AND COPPER-GOLD MINERALIZATION

The iron oxide-copper-gold mineralization at Igarapé Bahia are enveloped by extensive zones of hydrothermal alteration. These halos evolve from (i) initial calcic-sodic alteration (actinolite-scapolite-epidote) followed by (ii) K-(Fe) alteration with biotite and subordinated grunerite, (iii) tourmaline and (iv) Fe-carbonate formation. The latter was synchronous with magnetite formation and pre to syn chalcopyrite precipitation.

Ore zones encompass primarily chalcopyrite and magnetite with subordinated bornite and pyrite. Ductile deformation and hydrothermal brecciation were coeval with the development of the IOCG hydrothermal system and generated steeply dipping orebodies. Uraninite, galena, cobaltite, molybdenite and ETR-rich minerals usually comprise the ore mineralogy. The uncommon ore geochemical signature with high contents of W, Sn and Nb, due to the presence of scheelite, cassiterite, wolframite, pyroclore and fergusonite, is a remarkable feature at Igarapé Bahia. Gold is strongly associated with As- and Ag-bearing minerals. U-Pb monazite dating in the Alemão orebody revealed the timing of mineralization with a $^{207}Pb/^{206}Pb$ age of 2,559 ± 34 Ma.

Later quartz-carbonate-chalcopyrite veins take place in the four orebodies of the Igarapé Bahia deposit and might be controlled by brittle structures.

d^{34}S SULFUR ISOTOPE AND TRACE ELEMENTS IN CHALCOPYRITE

Sulfur isotope analyses carried out on chalcopyrite nodules and layers yielded $\delta^{34}S$ values of +0.29‰ at Acampamento Sul and from +1.04 to +1.56‰ at Furo 30 orebody. Chalcopyrite nodules and layers display positive anomalies of Rb, Th, La and Pb and high values of Ni + Co (25.3 – 10982 ppm) and Bi (36.4 – 136 ppm).

On the contrary, chalcopyrite from the magnetite-rich zones (i.e. IOCG system) exhibit higher $\delta^{34}S$ values ranging from +1.36 to +5.35‰ at Alemão and from +2.25 to +4.13‰ in the Furo 30 orebody. They exhibit positive anomalies of U, La, Pb and Nd, with high values of U (2.22 – 247 ppm), Sn + W (9.85 – 54.26 ppm) and Y + Nb (8.1 – 61.2 ppm). Less fractionated pattern [$(La/Yb)_N$ = 6.35 to 35.85], elevated ΣREE contents (36.64 to 767.96 ppm) and negative to positive Eu anomalies (Eu*/Eu = 0.61 to 1.96) are also typical of chalcopyrite from the magnetite-rich zones.

CONCLUDING REMARKS

The lower Sumidouro Formation at Igarapé Bahia deposit was formed in a volcanic-dominated setting at 2,748 ±34 Ma (Tallarico et al. 2005), with bimodal magmatism and banded iron formation precipitation. Fine-grained granite within the metagabbroic rocks of the Sumidouro Formation suggest that basement rocks are present at Igarapé Bahia as xenoliths in the lower sequence. The Grota do Vizinho Formation represents the establishment of a volcaniclastic-siliciclastic setting. Brecciated layers, convolute folds and rip-up clasts found in the metagraywackes evidence that they are reworked volcaniclastic rocks. They were formed during successive turbiditic flows affecting the pelagic sedimentation of metarhytmites, which caused the interdigitation of the metagraywackes and metarhytmites. Detrital zircon from the metagraywackes is mainly derived from the Mesoarchean basement rocks.

A sea-floor hydrothermal system was associated with exhalative activity. Evolved seawater infilled the open spaces when the sediment was still porous and permeable, where chalcopyrite nodules and layers precipitated (Dreher et al. 2005). They might represent a stratabound, syngenetic mineralization synchronous with the Grota do Vizinho Formation. The sulfur isotope composition of chalcopyrite nodules (+0.29 to +1.56‰) indicate that sulfur has magmatic signature and was likely leached from the volcanic rocks. This may also explain the high contents of Ni, Co and Bi of chalcopyrite nodules.

The metagraywackes from the Águas Claras Formation might represent epiclastic rocks and clearly host the IOCG mineralization at Alemão orebody, indicating that its deposition is older than the age of mineralization (i.e. 2.57 Ga). Detrital zircon of these metagraywackes point to Mesoarchean basement rocks as the main sources.

Detailed characterization of the hydrothermal alteration distribution revealed no significant differences in the paragenetic evolution among the orebodies. The copper-gold orebodies, represented by ductile deformed rocks and hydrothermal breccias, are enveloped by tourmaline-carbonate and chlorite formation, with minor zones of sodic-calcic and K-(Fe-alteration). Chalcopyrite associated with magnetite-rich zones show $\delta^{34}S$ values from +1.36 to +5.35‰, suggesting that sulfur was in part derived from thermochemically-reduced sulfate, which may have been initially incorporated into sulfides in the metasedimentary sequence. Sulfur isotope compositions and trace element contents clearly distinguish chalcopyrite from magnetite-rich zones and chalcopyrite nodules and layers.

Timing of mineralization, according to ages obtained in the Alemão (2,559 ± 34 Ma) and Acampamento Sul (2,575 ±12 Ma; Tallarico et al. 2005) orebodies, implies that Igarapé Bahia deposit formed in a single metallogenetic event at 2.57 Ga, also recognized at Salobo (Réquia et al. 2003, Tallarico et al. 2005, Melo et al. 2016). This metallogenetic event, not recognized in the IOCG deposits of the Southern Copper Belt (Moreto et al. 2015a, b), might be restricted to the northern part of the Carajás Domain, but its geological significance remains uncertain.

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REFERENCES

Almada M.C.O., Villas R.N. 1999. O depósito Bahia: um possível exemplo de depósito vulcanogenênico tipo Besshi arqueano em Carajás. Revista Brasileira de Geociências **29**: 579-592.

Dreher A.M., Xavier R.P., Taylor B.E., Martini S. 2008. New geologic, fluid inclusion and stable isotope studies on the controversial Igarapé Bahia Cu-Au deposit, Carajás province, Brazil. Mineralium Deposita **43**:161−184.

Melo G.H.C., Monteiro, L.V.S., Xavier, R.P., Moreto, C.P.N., Santiago, E.B.S., Dufrane, S.A., Aires, B., Santos, A.F.F. 2016. Temporal evolution of the giant Salobo IOCG deposit, Carajás Province (Brazil): constraints from paragenesis of hydrothermal alteration and U-Pb geochronology. Mineralium Deposita. **52**: 709-732.

Moreto C.P.N., Monteiro L.V.S., Xavier R.P., Creaser R.A., Dufrane S.A., Tassinari C.C.G., Sato K, Kemp A.I.S., Amaral W.S. 2015b. Neoarchean and Paleoproterozoic Iron Oxide-Copper-Gold events at the Sossego deposit, Carajás Province, Brazil, Re-Os and U-Pb geochronological evidence. Economic Geology, **110**: 809–835.

Réquia K., Stein H., Fontboté L., Chiaradia M. 2003. Re–Os and Pb–Pb geochronology of the Archean Salobo iron oxide copper–gold deposit, Carajás Mineral Province, northern Brazil. Mineralium Deposita, **38**:727–738.

Tallarico F.H.B., Figueiredo B.R., Groves D.I., Kositcin N., McNaughton N.J., Fletcher I.R., Rego J.L. 2005. Geology and SHRIMP U-Pb geochronology of the Igarapé Bahia deposit, Carajás copper-gold belt, Brazil: an Archean (2.57 Ga) example of iron-oxide Cu-Au-(U-REE) mineralization. Economic Geology **100**: 7-28.