Revista Brasileira de Geociências 30(2):230-233, junho de 2000

THE IGARAPÉ BAHIA CU-AU MINERALIZATION, CARAJÁS PROVINCE

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ABSTRACT The Igarapé Bahia Cu-Au mineralization is hosted by an Archean, low-grade metavolcano-sedimentary sequence. The orebodies define an ellipsoidal structure and are associated with subvertical breccia units located at the contact between two distinct units of the host sequence. Mineralized breccias include fragments of both footwall and hanging wall, which are cemented by variable amounts of chlorite, siderite, magnetite, chalcopyrite, K-bearing phases and minor U-REE-minerals. Quartz diorite dikes that disrupt the host rocks show a variety of textures, ranging from weakly altered granophyric terms to intensely venulated and brecciated rocks. Hydrothermal alteration of dikes includes propylitization, potassification and local albitization. Based on ore petrology and geochemical data (major elements, REE, oxygen and carbon stable isotopes) it is proposed that the progressive interaction of a hot saline and acid, deep-seated fluid with a low-temperature less saline and oxidizing meteoric solutions is the most likely depositional mechanism of the Igarapé Bahia mineralization. The resemblance of the alteration styles of mineralized breccias and dioritic dikes suggest that both have interacted with the same hydrothermal fluid. Thus, the dioritic dikes could have been the source of heat and of magmatic fluids during the final stages of epicrustal emplacement.

Keywords: Carajás Province, Igarapé Bahia, copper, gold, uranium, rare earth elements

INTRODUCTION The Carajás Basin (Itacaiúnas Supergroup) is located in northern Brazil, on the eastern border of the Archean Amazon Craton (Docegeo 1988) (Fig. 1). Basement rocks consist of gneiss and migmatite of the Xingú Complex (*ca.* 2.8 Ga - Machado *et al.* 1991) and the E-W-trending orthogranulites of the Pium Complex (*ca.* 3.0 Ga - Rodrigues *et al.* 1992). The Carajás Basin includes metavolcano-sedimentary rocks, of different metamorphic grades, deposited during Late Archean time (*ca.* 2.75 Ga - Machado *et al.* 1991). Sandstone and siltstone of a marine environment (Águas Claras Formation – Araújo and Maia 1991), overlie these rocks. The Carajás Basin was intruded by granitic magmas of distinct ages and compositions. Archean intrusions include granites and diorites of the Plaquê Suite (*ca.* 2.74 Ga - Huhn *et al.* 1999) and younger alkaline granites (*ca.* 2.5 Ga) such as the Estrela Complex (Barros *et al.* 1992) and the Old Salobo Granite (Machado *et al.* 1991). Paleoproterozoic intrusions (*ca.* 1.88 Ga – Machado *et al.* 1991) include several anorogenic granitic plutons (e.g. Central Carajás Granite, Cigano Granite).

A striking feature of the Carajás Basin is the large number of Cu-Au mineralizations that are stratigraphically and tectonically related. These are collectively known as the Carajás Copper-Gold Belt, including the Igarapé Bahia Deposit. The proposed genetic models for the Igarapé Bahia Deposit are: (a) syngenetic, volcanic-associated or Besshi-type deposits (e.g. Ferreira Filho 1985, Almada 1998), (b) hydrothermal Fe-oxide Cu-Au-(U-REE) mineralization (e.g. Huhn 1996, Tallarico 1996, Tazava 1999), (c) epigenetic mineralization related to anorogenic Proterozoic granitic plutons (e.g. Lindenmayer *et al.* 1998) and (d) multistage genesis involving remobilization of primary Archean mineralization during Proterozoic time (e.g. Ribeiro 1989).

The purpose of this work is to present the diagnostic geological attributes, *i.e.* the descriptive model (Barton 1993) of the Igarapé Bahia primary mineralization. The present study includes the results of fieldwork, petrography, geochemistry (including REE, oxygen and carbon stable isotopes) and mineralogical investigation by XRD, SEM and EMPA. Finally, the data are modelled to investigate the fluid constraints and discuss the genetic alternatives.

GEOLOGY OF THE IGARAPÉ BAHIA DEPOSIT

The Igarapé Bahia Group The Igarapé Bahia Deposit is hosted by metavolcano-sedimentary rocks with very low-grade hydrothermal-metamorphic assemblages (Igarapé Bahia Group). Ductile deformation is absent and primary structures and textures are usually preserved. Volcanic rocks including aphanitic, vesicular and microporphyritic

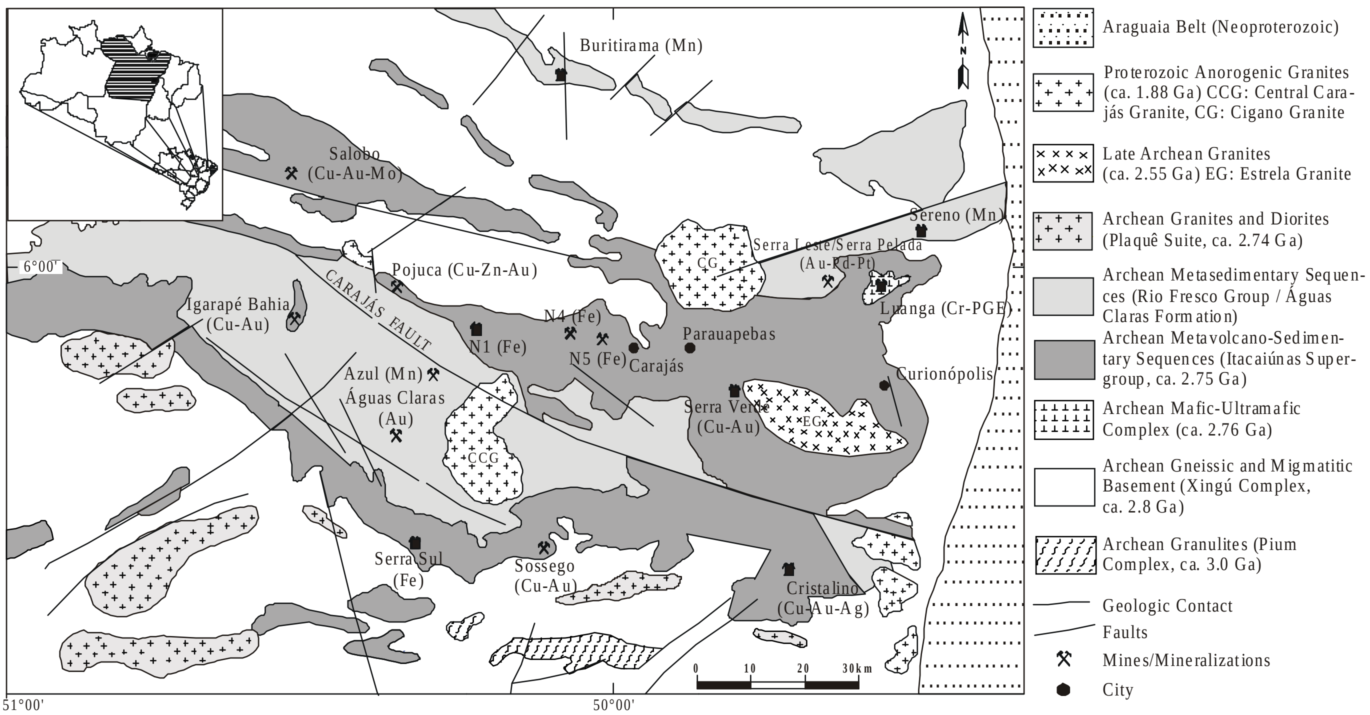

Figure 1-Simplified geological map of the Carajás Copper-Gold Belt (based on Docegeo 1988, Araújo and Maia 1991, Barros and Barbey 1998).

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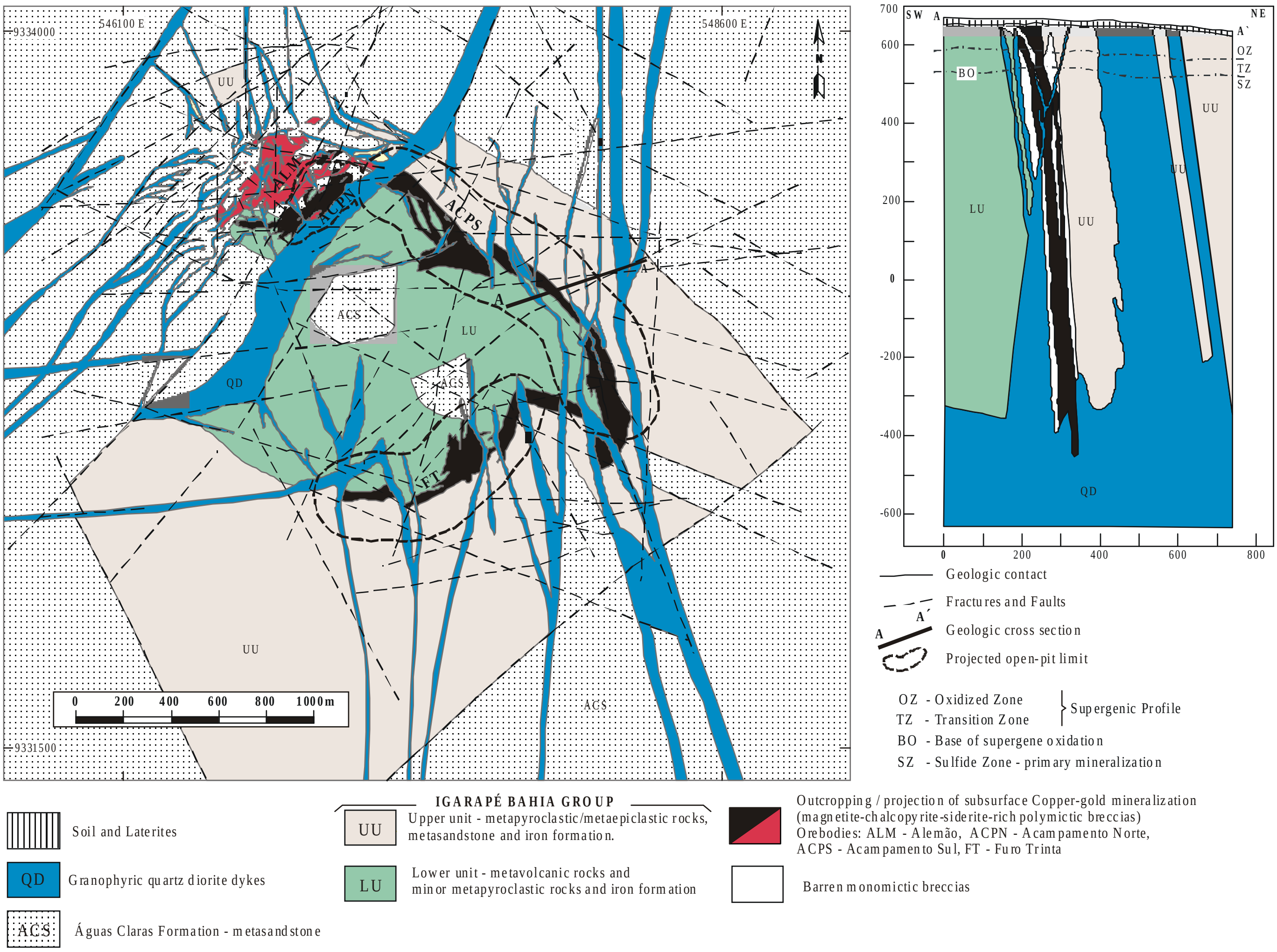

Figure 2-Geological map of the Igarapé Bahia Copper-Gold mineralization and geological cross section A-A' through the Acampamento Sul Orebody (modified from CVRD/DOCEGEO 1996, unpublished).

varieties, and minor crystal tuffs and ironstones dominate the lower unit. The upper unit is composed of lithic tuffs, crystal tuffs, laminated epiclastics, ironstone, epiclastic conglomerates and sandstone (Fig. 2).

These rocks display extensive hydrothermal alteration. Primary phases are completely replaced by a mixture of quartz and chlorite. Siderite, chalcopyrite and magnetite occur either disseminated or in veins. Veining of host rocks becomes progressively more intense towards the Cu-Au mineralization, eventually with jigsaw textures and breccia development. Laminated epiclastic rocks exhibit stratabound replacement textures with the development of cm-scale chalcopyrite beds and nodules, both connected to stockwork vein systems. The nodules bent the primary bedding and are also transgressive with respect to lamination.

Águas Claras Formation The Igarapé Bahia Group is overlain by sandstone of the Águas Claras Formation. The contact between them is characterized by normal faults. Occasionally the sandstone hosts massive chalcopyrite veins ranging from a few mm up to 1-m thick.

Quartz diorite dikes A set of fractures and normal faults control the emplacement of quartz diorite dikes, which disrupt the metavolcano-sedimentary rocks and the Águas Claras sandstone. Zones of intense alteration and veining, where apophyses and contact breccias are common, mark the contact between dikes and the host sequence. Chlorite-rich albitites and concentrations of almandine neoblasts in the host rock locally border the apophyses.

Quartz diorite shows a granophyric texture with primary andesine phenocrysts (An ~ 30 mol%) rimmed by coronas of quartz-albite intergrowth. Matrix includes albite, quartz, and minor K-feldspar and ilmenite. The dikes display hydrothermal alteration of varied intensity. A continuum spectrum including weakly altered to intensely venulated and brecciated rocks is observed. Primary plagioclase is converted to albite + calcite + chlorite + epidote, and ilmenite is oxidized to rutile + magnetite. Secondary K-feldspar, biotite and muscovite are related to potassic alteration. Quartz diorites also host sulfide minerals (chalcopyrite and rare pyrite, galena, sphalerite and molybdenite) either disseminated or in veins. Uraninite and REE-minerals (monazite, apatite, xenotime, and parisite) are associated with the alteration of the diorite dikes.

THE COPPER-GOLD MINERALIZATION The host metavolcano-sedimentary sequence together with the Furo Trinta (FT), Acampamento Sul (ACPS) and Acampamento Norte (ACPN) Orebodies outcrop in a structural window surrounded by the Águas Claras Sandstone. The outcropping orebodies define a semicircular structure at the surface. Although covered by a discordant layer of sandstone, the Alemão (ALM) Orebody also integrates this structure at depth and is connected to the ACPN Orebody by way of normal faults (Soares *et al.* 1999). The orebodies consist of steeply dipping (~75°) Cu-Au-bearing breccias located at the contact zone between the upper (hanging wall) and the lower (footwall) units of the host metavolcano-sedimentary sequence. The orebodies dip outward and the strike is concordant with bedding of host rocks.

Breccia types, hydrothermal alteration and veins The Cu-Au breccias are essentially polymictic, thus classification was based on matrix mineralogy leading to the following groups: chlorite breccias, siderite breccias and magnetite breccias. Angular fragments ranging from a few mm to over 20 cm in diameter of both footwall and hanging wall are cemented by variable amounts of hydrothermal matrix. Chlorite breccias and siderite breccias exhibit the same matrix mineralogy but the amounts of these specific minerals are distinct. The matrix is fine-grained and includes Fe-chlorite, siderite, magnetite, chalcopyrite, quartz and minor tourmaline.

Magnetite breccias exhibit a granular matrix of euhedral magnetite in association with Fe-chlorite, Cu-sulfides, siderite, grunerite, quartz, K-feldspar, stilpnomelane, biotite and minor tourmaline, muscovite and fluorite. The association defines a distinctive Fe-(K)-metasomatic zone. Magnetite is stoichiometric and constantly Ti-free.

At the ACPS and FT, mineralization is preferentially related to siderite breccias, while at the ACPN and ALM, it is associated with magnetite breccias. Chlorite breccias broadly occur at the margins of all orebodies and are also mineralized.

Chloritization is the most common and widespread alteration observed. Mg-chlorite (50>*mg*>30) is typically associated with calcite, dolomite and quartz in barren and distal altered host rocks, while Fe-chlorite (30>*mg*>12) is paragenetic to siderite and magnetite in Cu-Au-bearing breccias (mg = 100Mg/[Mg+Fe_{total}], in cation per unit formula). In this work chlorite thermometry (Cathelineau 1988) was calculated for a variety of rocks. The calculated mean temperatures are: 321°C for altered metavolcanic rocks, 339°C for chlorite breccias, 321°C for magnetite breccias, 375°C for siderite breccias, 313°C for altered quartz diorites and 369°C for chalcopyrite nodules from host rocks.

Several vein types crosscut the breccias and the host rocks. Veins are usually discordant to bedding and occasionally exhibit comb structures. The most frequent varieties are: (a) calcite + chalcopyrite ± fluorite ± stilpnomelane, (b) ankerite ± chalcopyrite ± gold, (c) siderite + calcite + quartz + chlorite + chalcopyrite, and (d) chalcopyrite ± biotite ± K-feldspar ± tourmaline ± REE-minerals. Vein chronology is unknown due to the recurrences and unclear crosscut relations.

Ore mineralogy Hypogene copper mineralization consists of chalcopyrite and traces of chalcocite, digenite and covellite that occur as rims on chalcopyrite in grain boundary driven oxidation reactions. Magnetite breccias, unlike other breccias, include chalcopyrite intergrown with bornite, indicating a relatively higher oxidation state of the fluid. Traces of pyrite are observed as inclusions in chalcopyrite as a function of local sulfur excess. The major copper mineralization is juxtaposed to gold mineralization in all orebodies. Additional, sub-economic copper concentration occurs in veins, nodules or disseminated in marginal altered host rocks with negligible gold content. Native gold occur as fine particles, usually between 5 to 20 mm, included in gangue minerals (quartz, siderite and chlorite), chalcopyrite and occasionally in magnetite. Silver is a byproduct occurring as hypogene Au-Ag alloy (up to 12 wt% Ag), hessite (Ag_2Te) and argentite/acanthite (Ag_2S).

Supergene alteration and related ore types At the Igarapé Bahia Deposit weathering is responsible for the development of a thick oxidized profile, where gold and copper are segregated and reconcentrated leading to the formation of different ore-types. The oxidized zone extends from surface to 150-m depth. It constitutes a gold-bearing gossan (total reserves in December 1999 of 18.5 Mt ≅ 1.97 gAu/t) from which approximately 11 t Au per year are mined. Total Au production is *ca.* 60 t to the present. The gossanous transition zone occurs from 150- to 200-m depth, where supergene solutions have percolated and precipitated metals, originating a secondary Cu-Au ore (9.5 Mt ≅ 2.45 gAu/t, 3.83 wt% Cu). The hypogene Cu-(Au) mineralization (219 Mt ≅ 0.86 gAu/t, 1.4 wt% Cu) occurs beneath 200-m depth.

Ore Geochemistry The mineralized breccias contain anomalous concentrations of FeO_T (25-64 wt%), Cu (0.5-11 wt%), U (28-380 ppm), Au (0.5-15 ppm), Ag (4-52 ppm), Ba (26-200 ppm), F (390-31000 ppm), P (900-6200 ppm) and REE, particularly La (260-2300 ppm) and Ce (450-4400 ppm). Breccias are also enriched in MnO (0.5-3 wt%), CaO (0.5-9 wt%), Mo (50-200 ppm) and Zn (150-450 ppm) relatively to host rocks. The intercorrelated behavior of all these elements suggests a common metasomatic origin and reflects the interplay of Fe-metasomatism, sulfidation, chloritization and carbonate alteration. Traces of barite, fluorite, galena, altaite, sphalerite, molybdenite, uraninite, apatite, monazite, xenotime, bastnäsite and parisite as inclusions in chalcopyrite and gangue minerals account for the Ba, F, Pb, Zn, Mo, U, REE and P enrichment. The high manganese content is related to siderite, which contains up to 7 wt.% MnO.

The REE-distribution patterns of breccias are similar for different types, and show a strong enrichment in LREE (Fig. 3). Distribution patterns of the metavolcanic rocks, dioritic dikes and breccias show equivalent shape, but the absolute concentrations are quite distinct. Iron formations show a completely distinct pattern. REE minerals are unequivocally related to hydrothermal activity. Thus, rather than reflecting petrologic information concerning the primary system(s), REE patterns are suitable to monitor the intensity of the hydrothermal alteration. The contrasting La/Lu ratios of host metavolcanic rocks (70-250) and breccias (1000-2500) indicate the preferential concentration of LREE by the hydrothermal solution(s). Additionally, the similarity between the distribution patterns of altered metavolcanic rock, breccias and diorite dikes suggests that these rocks underwent a common alteration process.

Stable isotope analyses were performed in calcite and siderite from veins and matrix of mineralized breccias (Oliveira *et al.* 1998). Carbon isotopes yield a narrow range of $\delta^{13}C$ (-9.3 to –5.8‰), while oxygen isotopes presented a wider variation of $d^{18}O$ (0.7 to 9.4‰). The results are plotted in Fig. 4, comparatively to other well-known reservoirs.

DISCUSSION The results of chlorite geothermometry, that yielded a range between 313-375ºC for the Igarapé Bahia hydrothermal system, are in accordance with previous fluid inclusion homogenization temperatures of Ribeiro (1989) and Lindenmayer *et al.* (1998). The equilibrium gold-hessite provides additional support for this thermal range (Markham 1960).

According to the thermodynamic calculations of Mickucki and Ridley (1993), the equilibrium siderite-magnetite-chalcopyrite ± bornite, at 300°C and 2 kbar, indicates high fO_2 (10^{-29} to 10^{-31}) and low a_{SS} (a_{SS} ~ 10^{-3}) for the Igarapé Bahia hydrothermal system. At greenschist temperatures and high CO_2 content, Fe-oxides equilibrate with siderite instead of minnesotaite/greenalite, with grunerite being stable only at upper greenschist and amphibolite temperatures (Frost 1979). Thus, the equilibrium siderite-magnetite (ACPS and FT) indicates a distinctively high CO_2 content in the fluid in relation to magnetite breccias, while the pair grunerite-magnetite (ALM and ACPN) denotes relatively higher temperatures. The inferred CO_2 enrichment of fluid phases is supported by the fluid inclusion data of Almada (1998) who reported aqueous, aqueous-carbonic and carbonic compositions.

The calculated thermal range coupled with the high fO_2 of the Igarapé Bahia hydrothermal system are consistent with Cu and Au transport via Cl-complexes, which are active in acid, saline and oxidizing fluids (Davidson and Large 1994). In high-temperature, saline and acid solutions, REE and U are complexed preferentially by chloride with or without the competition from fluoride, $CO_{2(aq)}$ or phosphorous species depending on the relative abundance of the ligands (Gieré 1996). These ions were clearly active in Igarapé Bahia and promoted a selective concentration of LREE, only possible under acid to neutral conditions (Gieré 1996).

The narrow range of negative values of $d^{13}C$ together with the indication of high fO_2, denote a homogeneous deep-seated carbon source from which carbonate minerals were precipitated with limited pH variations. The wider range of $d^{18}O$ values is interpreted as resulting from the mixture of deep-seated solutions with meteoric fluids that respectively account for the high and low $d^{18}O$ values. This fluid mixing hypothesis is in agreement with previous fluid inclusion studies of the Igarapé Bahia hydrothermal system that demonstrated the existence of two distinct groups: (a) 150-430°C and up to 40% $NaCl_{eq}$ and (b) 100-150°C and ~10% $NaCl_{eq}$ (e.g. Ribeiro 1989, Lindenmayer *et al.* 1998). Stable isotope and fluid inclusion data, both

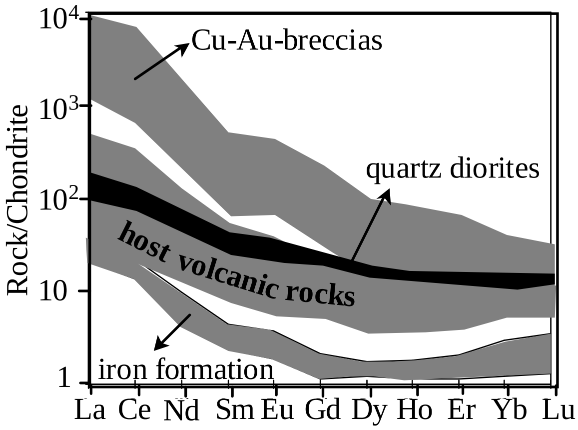

Figure 3-Chondrite normalized REE patterns of mineralized breccia, host metavolcanic rocks and banded iron formations from the Igarapé Bahia Deposit. Chondrite composition according to Evensen et al. (1978).

suggest that the progressive interaction of a hot saline and acid magmatic fluid with a low-temperature oxidizing and less saline meteoric solutions is the most likely depositional mechanism of the Igarapé Bahia ore. Persistent fluid mixing over a focused heat source possibly triggered Cu, Au, U and REE deposition through fO_2 and temperature decrease and pH increase.

At deposit scale, primary structures are preserved and ductile elements such as lineation, foliation and satellite folds were not observed. Brittle deformation is extensive and includes fractures and normal faults. Map analysis together with the outward dip of the bedding suggest that the structural framework of the Igarapé Bahia Deposit resulted from pluton emplacement that caused roof uplifting and lateral shouldering of wall rocks along faults. These brittle processes are typically related to near surface plutons (Paterson *et al.* 1991). The resemblance of the alteration styles of mineralized breccias and

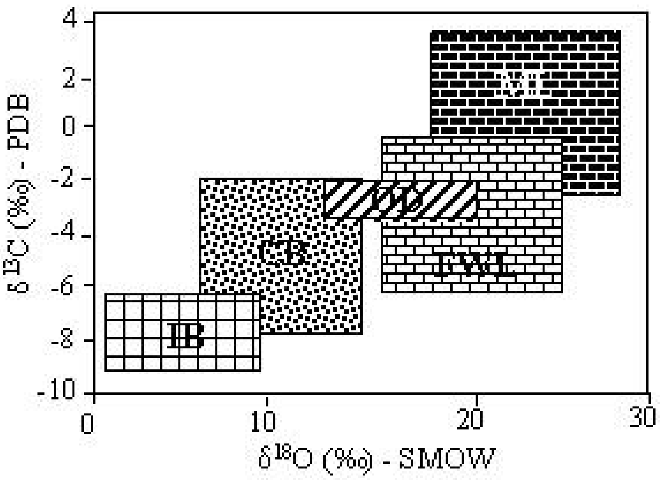

Figure 4 - $\delta^{13}C$ vs. $\delta^{18}O$ diagram showing the isotopic composition of siderite and calcite from the Igarapé Bahia mineralization (IB), relative to carbonatites (CB), the Olympic Dam mineralization (OD), freshwater limestone (FWL) and marine limestone (ML). Fields for CB, OD, FWL and ML after Oreskes and Einaudi (1992).

dioritic dikes suggest that both have interacted with the same hydrothermal fluid. Thus, the dioritic dikes could have been the source of heat and magmatic fluids during the latest stages of epicrustal emplacement.

The origin of the stratabound morphology of the Igarapé Bahia orebodies remains a matter of debate. One could speculate that it derives from primary exhalative processes or from epigenetic stratabound replacement and brecciation. The brecciation and veining of both footwall and hanging wall, together with the presence of sub-economic chalcopyrite concentrations in the Águas Claras sandstone, suggest an epigenetic origin.

The alteration styles, ore mineralogy and fluid composition of the Igarapé Bahia Deposit are analogous to other intrusion-related hydrothermal Fe-oxide-(Cu-Au-U-REE) deposits (Hitzman *et al.* 1992). On the other hand, the confinement of all known mineralizations of the Carajás Copper-Gold Belt to the Itacaiúnas metavolcano-sedimentary sequences suggests that primary processes could have pre-concentrated metals. Thus, a multi-stage genesis involving the superposition of Archean exhalative processes and further hydrothermal-magmatic activity seems plausible. Mellito (1998) documented a similar process at Salobo, where Archean syngenetic mineralization was reconcentrated during the Late Archean time due to tectonic and magmatic activity.

The composition of the dikes favors an Archean age for the magmatic activity at Igarapé Bahia, since the dioritic magmatism in the region is bracketed within the interval of 2.55 to 2.74 Ga. Additional support is provided by the Rb-Sr bulk-rock age of 2,577 ± 2 Ma of the Igarapé Bahia host metavolcanic rocks (Ferreira Filho 1985). This age is inconsistent with the minimum age of *ca.* 2.6 Ga of the overlying Águas Claras Sandstone (Dias *et al.* 1996), and may indicate thermal resetting of the Sr isotopic system during the emplacement of Late Archean (*ca.* 2.55 Ga) intrusions.

Acknowledgments To the Companhia Vale do Rio Doce for the permission to publish their private data. The authors are thankful to all the geologists of the Igarapé Bahia mine, especially José Luzimar Rego for enthusiastic discussions during fieldwork. We acknowledge the referees of RBG and also all the anonymous reviewers that improved our original manuscript. We are also indebted to FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for the grants #98/14401-5 and #99/03058-0. We are thankful to the Multi User SEM laboratory (IG-UNICAMP) funded by FAPESP grant #95/06401-7.

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Contribution IGC-078
Received February 2, 2000
Accepted for publication April 30, 2000