**THE IGARAPÉ BAHIA CU-AU MINERALIZATION, CARAJÁS PROVINCE**

**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, magnete, 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 acidic, 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 epicitral 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 Plum 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 aphantic, vesicular and microphyritic
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 chlorite breccies and siderite breccias. Angular fragments based on matrix mineralogy leading to the following groups: chlorite + magnetite + chalcopyrite + siderite-rich polymictic breccias. 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 to over 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 granophytic 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 veined 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 dikes 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 Trinita (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 ACPS 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 breccias, and are also mineralized.

Chloritization is the most common and widespread alteration observed. Mg-chlorite (50-300 mg) is typically associated with calcite, dolomite and quartz in barren and distal altered host rocks, while Fe-chlorite (300-12 mg) is paragenetically with siderite and magnetite in Cu-Au-bearing breccias (m = 1000 mg/Mg, Fe-lin). 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 509°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 structure. The most frequent varieties are: (a) calcite + chalcopyrite ± fluorite ± stilpnomelane, (b) ankerite ± chalcopyrite ± gold, (c) siderite + calcite + quartz + chalcopyrite, and (d) chalcopyrite ± biotite ± K-feldspar ± tourmaline ± REE-minerals. Vein chlorinity is unknown due to the recurrences and unclear crosscut relations.

Ore mineralogy Hypogene copper mineralization consists of chalcopyrite and traces of chalcolite, digenite and coevalite 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 altered breccias, altered bornite. Native gold occur as fine particles, usually between 5 to 20 mm, included in gange 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,Te) and argentite/acantheme (Ag,Sn).

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 recondensed 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 150 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 (25-64 wt%), Cu (0.5-11 wt%), U (28-380 ppm), Au (0.5-15 ppm), Ag (0-3.2 ppm), Ba (26-200 ppm), F (390-3300 ppm), P (5-620 ppm), and particularly Sr (260-2300 ppm) and Ce (450-4400 ppm). Breccias are also enriched in NbN (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, alata, sphalerite, molybdenite, uraninite, apatite, monazite, xenotime, bastnasite and parsite as inclusions in chalcopyrite and gange minerals account for the Ba, P, 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, diorite 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

![](https://example.com/figure3.png)

**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 epithermal deposit. This involving over a focused heat source possibly triggered Cu, Au and REE deposition through $\text{F}_2$ 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 outcrop dip of the bedded suggest that the structural framework of the Igarapé Bahia Deposit resulted from pluton emplacement that caused roof upfiling and lateral shouldering of wall rocks along faults. These brittle processes are typically related to near surface plutons (Patterson et al. 1991). The resemblance of the alteration styles of mineralized breccia 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 magmatic fluids during the latest stages of epithermal 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 breciation. The brecciation and veneering 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 (Cu-O-Au-U-REE) deposits (Hitzman 1991). On the other hand, the confinement of all known mineralizations of the Carajás Copper-Gold Belt to the Itacainas 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 by tectonic and thermal events.

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 2.57±2 Ma of the Igarapé Bahia host metavolcano-sedimentary 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.

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References


